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Exploring the impact of autonomous vehicles in urban networks and potential new capabilities for perimeter control*

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Abstract—Recently there has been an enormous effort towards the development and field deployment of autonomous vehicles (AV). These developments have a direct impact on road traffic characteristics, as AV can also be used as sensors, actuators, and generally as effective components of an online traffic management system. In this work, we explore through microsimulation how AV can affect the network performance on urban networks. It is demonstrated through simulation experiments, that for mixed traffic (i.e. AV and conventional vehicles), different penetration rates of AV can reduce the density (i.e. congestion) and increase the capacity (i.e. throughput) of the network. Furthermore, new emerging capabilities for perimeter control in urban regions are explored, by utilizing new sources of data that can become available. A new feedback-based regulator is developed, which uses AV speed measurements as the state-feedback variables. The regulator is demonstrated to work equivalently well with a well fine-tuned regulator that uses loop detectors occupancy measurements (i.e. accumulation estimates) from all the links of the network. The speed-based feedback perimeter flow regulator performs significantly well even for very low penetration rates of AV (e.g. 5%), resulting in reduced delays for the users and less congestion in the urban region. Although the regulator has sparse measurements only from AV it can achieve the same improvement with the accumulation-based regulator that has the whole picture of the network.

I. INTRODUCTION

Recent technological advancements in the fields of automotive industry, robotics, sensors, and communications, have made the development of vehicle automation and communication systems viable. Although the idea of autonomous vehicles (AV) was first illustrated by General Motors as early as 1939 at the Highways & Horizons exhibit in New York, widespread research and industrial development of AV was brought to fruition following the DARPA Grand Challenges in the 2000s. An overview of the historical developments in vehicle automation and communication systems (e.g., automated highways, vehicle cooperative systems, automated vehicle control) leading to the state of practice today can be found in the reviews [1], [2], [3]. The fact that field deployments of AV in cities seems nowadays more realistic than ever, has motivated a growing interest to understand how modern transportation systems will evolve

when these technologies become available at scale. Unlike conventional human piloted vehicles, AV have the capability to significantly reduce the headway between vehicles, and potentially increase network capacity without increasing the physical infrastructure. As AV may have remarkably different operating characteristics compared to the conventional vehicles, an open question is how to model traffic conditions when the flow is mixed, i.e., composed by both AV and non-AV. Nevertheless, while some theoretical studies have mentioned that AV usage can result in doubling the capacity of intersections (see e.g. [4]), this performance might get downgraded by effects of limited urban infrastructure, mainly due to spillbacks and infeasibility of full coordination of all major axes in an urban network.

During the last decade, there has been an enormous interdisciplinary effort by the automobile industry and numerous research institutions worldwide towards the development, testing, and field deployment of AV, with the main focus to improve road safety, driver and passenger convenience, and environmental effects of traffic flow. AV are typically developed to benefit the individual vehicle, without a clear view or complete understanding for the implications, potential advantages and disadvantages they may have for the resulting modified traffic characteristics. These developments, however, have a direct impact on road traffic efficiency as well, and could therefore be exploited to relieve road networks from the significant congestion problems and their negative consequences. AV could also be used as sensors, actuators, and generally as tools towards a new era of traffic management.

In this work, we focus on urban networks and we explore through microsimulation how AV can affect the network performance. More specifically, we utilize the operational Macroscopic Fundamental Diagram (MFD) of a city, which can demonstrate in real-time a functional relationship between the macroscopic variables of the network, i.e., flow, density, and speed [5]. Moreover, AV have the potential to communicate frequently with a traffic control center, transmitting their location, speed, destination, etc. This information is utilized here to exploit real-time control feasibility. A new feedback-based regulator is developed, which uses AV speed measurements as the state-feedback variables. This new type of data has the challenge that it is much noisier than traditional loop detectors measurements, due to low AV penetration rates. The speed-based feedback perimeter flow regulator performs significantly well even for very low penetration rates of AV (e.g. 5%), resulting in reduced delays for the users and less congestion in the urban region.

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II. SIMULATION ANALYSIS OF MIXED TRAFFIC

Simulation investigations as well as relevant field operational tests indicate that AV can also affect, in a positive or negative way, the traffic flow at varying levels. On the one hand, there is a threat for a deterioration of the overall traffic conditions, if AV are merely serving their individual user aims in a myopic and/or selfish way. For example, guiding individual AV to shorter time routes (to avoid congested network parts) may be beneficial under low penetration rates. However, as the percentage of AV that receive the corresponding routing instructions increases, the proposed alternative routes may become more congested, and generally, the traffic situation at the network level may deteriorate. On the other hand, in contrast to conventional vehicles, AV have the capability to significantly reduce the headway between vehicles, something that can increase the capacity without the need for installation of physical infrastructure. An interesting research question is how to model traffic conditions when the flow is composed of a mix of AV and non-AV. In [6], [7] various aspects of the problem of modelling mixed flow are addressed. A detailed review of various approaches to model different levels of automation for mixed traffic streams is presented in [8]. There are also a few studies in the literature that investigate the characteristics and stability of traffic flow under various automation and cooperative environments with mixed flows [9], [10]. Nevertheless, further research is necessary in order to fully exploit the AV traffic management potential in a manner that is safe, understandable, and acceptable to the driver and other stakeholders. In this context, it is important to work towards developing the foundations for a new era of future urban traffic management research and practice. This new research effort is indispensable in order to accompany, complement and exploit the evolving AV deployment, so as to ensure a continuous, lasting and efficient solution to the major societal and environmental problem of urban congestion.

A. AV special characteristics

In this work, we define the variable $\lambda \in [0, 1]$ as the fraction of AV in the traffic flow (i.e. penetration rate of AV). In principle, AV may operate with a much smaller spacing compared to conventional vehicles (CV), due to the fact that the perception-interpretation-reaction time of an AV may be significantly reduced compared to humans. As a result, the traffic characteristics (and therefore the MFD) depends not only on the density of traffic, but also the composition of the mixed flow (i.e. AV and CV), as indicated by λ . The larger the fraction of AV, the smaller the spacing between vehicles at a given speed, and consequently a larger flow (production) can be maintained.

Initially, in order to assess the impact of AV to the traffic flow we conduct a series of numerical experiments based on microsimulation. The traffic flow contains a mix of human piloted and automated vehicles. The test case network is a replica of the network used in [11] and corresponds to a part of the CBD of Barcelona in Spain (Figure 1).

Fig. 1. Map of the case study area.

A traffic scenario is carefully constructed to contain a mix of free flow and congested traffic conditions. The numerical simulations are conducted in Aimsun [12], which is a microscopic traffic simulation software. One on-peak-hour demand profile is simulated which is presented in Figure 2 (one hour peak demand plus two hours with zero demand in order to make sure that the network empties of vehicles in all the scenarios and the obtained results are comparable). The simulation time-step used within Aimsun is set at 0.2 seconds. In this work, for modelling the AV, we adopt a simple approach, where the automated vehicles are assumed to drive sufficiently like humans, only with enhanced capabilities (e.g., reduced perception reaction time, desired time headway, etc.).

Two classes of vehicles are simulated, namely, conventional vehicles (CV) and AV. The AV class is created in Aimsun based on the car class with the reaction time modified to be 0.2s (equal to the time-step), while the reaction time of humans is 0.8s. These parameter allows the AV stream to generate a higher traffic capacity. Finally, the human-related stochasticity of all parameters is removed from the AV class, by setting the standard deviation of the appropriate parameters equal to 0. Such parameters include the minimum headway (which is also affected by the change in the reaction time), the speed acceptance, and the minimum stopping distance. The nominal values of such parameters are set at the mean values of the car class (CV have also some standard deviation in contrast to AV).

Fig. 2. Demand profile for microsimulation (3-hours duration).

B. Impact of mixed traffic on MFD

As mentioned earlier, in the microsimulation environment of Aimsun software, a subset of the vehicles are identified as automated, and consequently their properties are distinct from the vehicles simulated under typical human operated characteristics. Note that in the present work we focus only on AV, and we do not explore connectivity between vehicles in the traffic stream. Connectivity can create non-local effects in the traffic stream (e.g., advanced warning of slow downs) that are treated, for example in [13]. Here, AV are assumed to use only local information to operate the vehicle, thereby eliminating non-local effects. A similar approach has been followed in [14] for developing estimation algorithms under mixed traffic conditions. Traffic signals are operating at fixed time plans, while an adaptive consideration or other type of signal control (e.g. reservation policies) could be a future research priority.

To this end, Figure 3 demonstrates the impact of the mixed traffic to the network MFD of the CBD of Barcelona. The color represents the penetration rate for each simulation run. It is clear from the figure that different penetration rates of AV can reduce the density (i.e. congestion) and increase the capacity (i.e. throughput) of the network. As λ increases from 0 to 1, the network MFD is gaining some capacity (around 15% difference comparing $\lambda = 0$ and $\lambda = 1$). Moreover, it is obvious that the more AV in the network the less congestion, as MFDs for high penetration rates do not get many traffic states on the right part of MFD (congested regime). Interestingly, even for 100% penetration rate, the network experiences congestion and states in the decreasing part of the MFD.

C. System performance for different penetration rates

Different statistics are defined in order to assess the results of the simulation experiments. Here, we present the average delay per vehicle (in s/km) and the space mean speed. Figure 4 shows the simulation results for all the range of penetration rates. It is clear that both the delay and space

Fig. 3. Total production vs. accumulation (MFD) for different penetration rates of AV (represented by color bar).

Fig. 4. Average delay (in sec/km) and space mean speed (in km/hr) for various penetration rates.

Fig. 5. A 3-dimensional MFD between accumulation of CV, AV and total production from all vehicles.

mean speed have a monotonic (almost linear) improvement as λ increases from 0 to 1. This means that the more AV in the mixed traffic, the better for the traffic conditions, and the optimal value is always for $\lambda = 1$, i.e. only automated vehicles in the roads of the network. Finally, Figure 5 presents a 3D MFD, where the production of the network is depicted as a function of AV and CV. In all figures it is illustrated that the network performance improves with the increased utilization of AV.

III. NEW CONTROL CAPABILITIES WITH AV

Another aspect that is studied in this paper is to explore the control capabilities given some small penetration rate of AV. An underlying assumption is that AV can be used as moving sensors. This is rather reasonable, as the technologies that already exist justify that AV will be able to communicate data to some centrally located control center (e.g. their position, speed, info about their surroundings, etc.). These new types of measurements can revolutionize traffic operations in the near future. Given the observation of Figure 3 that traffic congestion will still remain due to the increased demand (even at smaller extend), it becomes important to integrate smart control strategies within AV environments. While in a fully autonomous world, traffic signals might not be necessary, it is expected that in the next 5-10 years mixed traffic of AV and CV will occur. Thus, perimeter control and

Fig. 6. Microsimulation model with intersections selected to be “gated”.

restriction of flows in congested city centers can be proved beneficial for the network and decrease delays.

Accurate speed data, even for a small percentage of the traffic flow, can provide sufficient information to be used as input for feedback-based regulators. In this work, we demonstrate by simulation replications the feasibility and efficiency of such a controller, i.e. one that is based on sparse speed measurements of a ratio of the urban flow. In order for this test to be as reliable as possible, we compare this controller to a well used controller in the literature that utilizes data from loop detectors (i.e. higher penetration rate than AV – almost 100%).

Figure 6 shows the traffic network of Barcelona as simulated in Aimsun. The microscopic model contains all the actual information of the real network, including pre-timed fixed plans for all the signalized intersections, and well calibrated parameters about the network characteristics, driving behaviour, and OD patterns. Here, the control actuators are selected to be the intersections that are entering the network. The CBD is considered one protected region and congestion in this area needs to be prevented. A “gating” strategy is required that can efficiently regulate the gates of the network (i.e. boundary intersections), by controlling the inflow. The red dots in the picture represent all the selected gated intersections, where the signal plans can be modified accordingly, in order to optimize mobility in the CBD region. Vehicles that are blocked from entering (by appropriately modifying the green phases), are modelled by Aimsun in virtual queues (VQ), and they wait there until the gating strategy allows them to enter. These VQ deteriorate the total delay of the system, but at the same time the fluidity of the protected region is increased, and the overall throughput can be improved (see e.g. [15], [16] for more details).

A. Feedback control based on accumulation measurements

The simple feedback-based regulator that has been proposed in [15] to protect the region of interest is the following

$$u(k) = u(k-1) - K_P [n(k) - n(k-1)] - K_I [n(k) - \hat{n}] \quad (1)$$

where $k = 0, 1, 2, \dots$ is the discrete time index, $u(k)$ denotes the flow that is allowed to enter the protected region for

the cycle $[kT, (k+1)T]$ (which can be readily modified to green time durations for the corresponding traffic lights, as described in [11]), $n(k)$ is the accumulation of vehicles inside the region at time kT , $\hat{n}$ is an accumulation set-point for the regulator, and $K_P, K_I \in \mathbb{R}_+$ denote the proportional and integral gains of the PI regulator. This type of regulator is well studied and extensively fine-tuned in [15], [17] and it is used here only as a benchmark, in order to assess the performance of a new regulator that is based on speed measurements (with limited data from AV mobile sensors).

B. Feedback control based on AV speed measurements

In the same principle as in (1), we can denote a PI feedback regulator which receives speed measurements as the state feedback. To this end we can use the regulator

$$u(k) = u(k-1) - K_P [s(k) - s(k-1)] - K_I [s(k) - \hat{s}] \quad (2)$$

where $s(k)$ is the speed of AV inside the region at time kT , $\hat{s}$ denotes a speed set-point for the regulator, and $K_P, K_I \in \mathbb{R}_+$ are the proportional and integral gains of the PI regulator that need to be defined.

An important underlying assumption is that the speed measurements obtained from AV are assumed to be representative of the speed of all vehicle types. This assumption is motivated by the fact that in free flow, both vehicle types will have the same average speed (e.g., as established by the speed limit), and in congestion, the AV are obstructed by other (human operated) CV, and consequently adapt the same speed due to the difficulty of overtaking. This assumption is a critical one, and will be exploited in the present work to establish if it is appropriate for control and generally traffic management purposes. In case that AV are separated from CV in dedicated lanes, more advanced control strategies have to be developed.

In order to define $\hat{s}$ many simulation experiments with AV are executed. Then, by observing the MFDs, one can define the critical accumulation that maximizes the production of the network. Following a similar approach, one can study the speed MFD (Figure 7) and identify the critical speed $\hat{s}$ that corresponds to the critical accumulation. After many simulation runs we were able to denote the critical speed $\hat{s} = 11.5 \text{ km/h}$ as shown in Figure 7.

Fig. 7. Definition of speed set-point $\hat{s}$ for the PI feedback regulator.

C. Controllers' fine-tuning

One key performance indicator for the PI controller is the fine-tuning of the regulator gains. The gain parameters of both PI regulators used in this paper are fine-tuned by a trial-and-error procedure, until some performance convergence criteria are met. Table I presents the gain values that have been obtained after the fine-tuning procedure for both regulators. Moreover, it presents the two thresholds for activating and deactivating the controller in real-time, based on state measurements. These thresholds are also defined by trial-and-error and traffic engineering practice.

IV. MICROSIMULATION ASSESSMENT

This section presents detailed results for the numerical simulations. First some qualitative results are presented that demonstrate the feasibility of the speed controller that is based on AV measurements. The simulations demonstrate that this controller is virtually equivalent to the accumulation controller, that gets information for all the links of the network and measures almost all the flows and each and every vehicle in the network. Then, some tables with simulation statistics are presented to illustrate qualitatively that the two controllers are quite similar and the same level of improvement can be achieved by both (the speed controller actually outperforms the accumulation one, but this is mostly a matter of fine-tuning). However, the speed controller makes use only of some penetration rate of AV, that act here as moving sensors and provide feedback states. In this section we focus only on two representative penetration rates, namely 5% and 20% ($\lambda = 0.05$ and $\lambda = 0.2$), due to space limitations and redundancy of the observations.

A. Qualitative comparison (MFDs)

For each case we run 10 different replications in Aimsun, with random seeds, that generate stochastic results. Here, we choose to present the best and worst case every time, as well as the average values of the statistics and the standard deviation in the next section. Figure 8 illustrates the vehicle accumulations for the pre-timed no control case, the accumulation controller, and the speed controller. For every case the best and worst replications out of the 10 are presented. The left sub-figure refers to 5% penetration rate and the right to the experiments with 20%.

For the same simulated scenarios we present the evolution of the network space mean speed in Figure 9 ($\lambda = 0.05$) and Figure 10 ($\lambda = 0.2$). It is clear from these two figures that the cases with the controllers have higher mean speed, i.e. lower congestion in the network. Finally, Figure 11 presents the trajectories of the control decisions for these two scenarios.

TABLE I
PARAMETERS OF THE TWO REGULATORS.

AC parameters	$\hat{n}$	K_P	K_I	thresh.on	thresh.off
	13'000	0.0003	0.0001	$0.8 \cdot \hat{n}$	$0.7 \cdot \hat{n}$
SC parameters	$\hat{s}$	K_P	K_I	thresh.on	thresh.off
	11.5	0.4	0.1	$1.5 \cdot \hat{s}$	$1.7 \cdot \hat{s}$

Fig. 8. Accumulation evolution over time for no control case, accumulation control, and speed control, for the best (i.e. minimum delay among all replications) and worst replication (i.e. maximum delay among all replications), for 5% (left) and 20% (right) penetration rates.

Fig. 9. Speed evolution over time for the same scenario presented in Figure 8 ($\lambda = 0.05$).

Fig. 10. Speed evolution over time for the same scenario presented in Figure 8 ($\lambda = 0.2$).

The blue lines correspond to the accumulation controller, while the green to the speed controller (the red lines denote the maximum, minimum, and starting point of the controller respectively). Note that the speed controller remains active for more time compared to the accumulation. This is something that is related to the thresholds for activating and deactivating the controllers. Close to the end of the presented simulation the network is almost empty, but due to some local gridlock the space mean speed has not fully recovered (only some vehicles move in the network but with low speeds), and this fact keeps the controller active. At the same time, the accumulation controller has been deactivated due to the low number of vehicles and the intersections have gone back

Fig. 11. Control decisions $u(k)$ over time for the same scenarios presented in Figure 8; $\lambda = 0.05$ (left) and $\lambda = 0.2$ (right).

to the pre-timed signal plans.

B. Quantitative comparison

Table II and Table III present all the statistics for the simulations. The results are the average values for the 10 different replications. Also, the improvements in terms of percentages are presented for both controllers. The speed controller (SC) clearly improves the situation as compared to the no control case (NC), but it also achieves slightly better performance than the accumulation controller (AC).

V. CONCLUSIONS

The impact of AV in traffic flow characteristics is studied in this paper. First, simulations are performed in order to assess the effect of mixed traffic to the MFD and generally the congestion of an urban network. Then, control capabilities that are based on AV measurements are explored. A new feedback-based type regulator is proposed that receives speed measurements as the state feedback. In general, speed regulators are not broadly used, as speed is a measurement that is quite noisy and in principle exhibits high oscillations. This is a shortcoming of these type of measurements that needs to be carefully taken into account when designing a regulator that is based on speed measurements. Nevertheless, our experiments show that one can derive efficient controllers that can successfully utilize sparse and incomplete speed measurements. The controller proposed here is shown to achieve similar performance (or better) with a well tuned controller from the literature that utilizes loop detectors measurements. Overall, with a very simple control structure (PI scheme) and limited noisy measurements, one can manage to achieve similar performance with other very demanding (in terms of data) control schemes.

TABLE II

PERFORMANCE INDICATORS OF THE SIMULATED SCENARIOS ($\lambda = 0.05$).

Criteria	NC	AC	SC	(%)
Delay (s/km)	485.01	353.52	322.46	-33.51
Space-mean speed (km/h)	6.55	8.60	9.29	41.68
Mean queue (veh)	7594	4725	4125	-45.68
Mean VQ (km/h)	10403	11487	14006	34.63
Vehicles served (veh)	113060	112930	111750	-1.16

TABLE III

PERFORMANCE INDICATORS OF THE SIMULATED SCENARIOS ($\lambda = 0.2$).

Criteria	NC	AC	SC	(%)
Delay (s/km)	453.6	334.88	309.58	-31.75
Space-mean speed (km/h)	6.95	9.00	9.62	38.32
Mean queue (veh)	7169	4538	4050	-43.51
Mean VQ (km/h)	9963	11277	14279	43.31
Vehicles served (veh)	113000	112900	112470	-0.47

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