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Algorithms for Management of a Multi-Platooning System of IVC-enabled Autonomous Vehicles, with High Traffic Capacity

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***Abstract*— Intra-platoon positioning management strategies to deal with safe and efficient advanced traffic management system operation are proposed in this paper. New algorithms to ensure high traffic capacity are proposed, and Matlab/Simulink-based simulation results are reported. Recently, we proposed new algorithms to mitigate communication delays using anticipatory information, both from the platoon's leader and the followers, with significant impact on the improvement of platoon string stability [5].**

In this paper, we argue that maintaining a constant spacing between platoons' leaders has a positive impact on the traffic capacity of the whole system. As such, when the leader and eventually other vehicles immediately behind it leave the platoon, the new leader must accelerate to reach the position of the previous leader, to ensure inter-leader constant spacing and, consequently, enough spacing to be eventually occupied by new followers.

We developed a novel architecture where each vehicle consists of two distinct modules: a leader and a follower. Based on Matlab/Simulink-based simulation, the new algorithms are assessed, and simulation results presented. The obtained simulation results confirm that the proposed algorithms adapt the acceleration pattern, ensuring similar timings for all possible cases of the previous position of new leaders in the platoon, when performing their repositioning maneuvers.

I. INTRODUCTION

Urban traffic congestion is a growing problem, very difficult to deal with. Increasing road capacity through construction of new roads is hardly an option, since urban space is finite. Moreover, more roads do not necessarily mean that congestion will decrease.

The major problem is how to improve road capacity, while reducing travel time and traffic congestion. However, if vehicle density is high, traffic jams are known to occur among common traffic, when perturbations exist [1]. Platooning may help to improve lane capacity, if constant spacing is used [2]-[3]. Additionally, some conditions should be met to ensure both high traffic flow and high traffic density: the use of autonomous vehicles; autonomous vehicles do not share the road with conventional vehicles; autonomous vehicles use dedicated tracks, operating on a nonstop basis from origin to destination [4]; tracks use off-line stations; vehicles' maneuvers exiting the tracks to stations, as well as entering the tracks from stations, are performed cooperatively; the system is managed by an hierarchical advanced traffic management system (ATMS); the ATMS should control the platoon leaders' appropriate operation, the admission of vehicles into the system avoiding congestion even when operating close to its maximum capacity, and the management of empty vehicles to deal with asymmetrical transportation demand.

Recently, we addressed the problem of platoon stability under the negative effects of communication delays [5]. Control methods to ensure platoon string stability are described in [3], and we have proposed new information updating algorithms to mitigate the effects of platoon intra-vehicle communication delays [5]. Our main goal was to ensure platoon string stability under the unavoidable presence of communication delays. To achieve our goal, we aimed to enclose the communication, computation and actuation delays within an upper bound delay, managed at a higher level so that delays do not have significant impact on the platoon string stability.

In this paper, we continue to address the problem of how to ensure high and constant traffic flow of a system operating at high traffic densities. As such, to ensure smooth and efficient operation of a transportation system based on autonomous vehicles, an advanced traffic management system (ATMS) should avoid congestion while allowing high traffic flow and high vehicle density. So, we address the improvement of the proposed hierarchical ATMS [5] at a higher level, aiming to ensure high capacity operation of the traffic system, avoiding speed variations of platoons or individual vehicles as much as possible, and keeping enough space availability to permanently accommodate up to eight vehicles per platoon. As such, the ATMS controls the system with the objective to maintain a constant spacing between platoons' leaders, even when vehicles exit the main track to stations, or enter the main track from stations, which cause platoons to change in dimension. Vehicles exiting from platoons' tail do not raise concerns. However, when a leader vehicle leaves the platoon, strategies must be implemented to avoid slowing down the platoons behind, which would occur if the new leader keeps its current inter-platoon positioning while other vehicles join the platoon. So, the new leader must accelerate within some conditions. This way, spacing behind the platoon is large enough to be occupied by new vehicles joining the platoon, without perturbing constant speed of platoons that follow behind. Intra-platoon and inter-platoon positioning management strategies are proposed in this paper, to lead each new platoon's leader to the position occupied by the previous leader, maintaining all its followers close behind, under a control loop as described in [5].

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II. RELATED WORK

In [7], Varaiya addressed key issues related to highly automated intelligent vehicle highway systems (IVHS). Swaroop *et al.* [2], [7] investigated various platooning control strategies. Alvarez and Horowitz [8] researched the conditions to achieve safe platooning under normal mode of operation. Horowitz and Varaiya described in [9] a five-layer automated highway system control architecture, involving the infrastructure and the vehicles. Rajamani *et al.* [10] presented a controller of platoons with constant spacing, concluding that autonomous control is not enough to ensure string stability. He found that only with IVC is the string stability of vehicle platoons achieved. The method was experimentally evaluated in field tests. Recently [11], Broggi's team completed a three month journey, with four autonomous electric vehicles equipped to drive in leader-follower configuration. In [5] we proposed new algorithms to mitigate communication delays on platoons of IVC-enabled autonomous vehicles. Using anticipatory information, both from the platoon's leader and the followers, we have managed to improve platoon string stability. The obtained results, from simulations performed in Matlab/Simulink, suggested that the proposed information updating schemes were appropriate. Fei-Yue Wang [12] proposed a three-level hierarchical architecture, applying concepts of agent-based control to networked traffic and transportation systems. In [13] we addressed the implementation of autonomous vehicle platooning capabilities in SUMO traffic simulator [14].

III. MOTIVATION

Platooning presents major advantages. However, maintaining a desired intervehicle spacing in platoons demands a tight control of each vehicle. For the case of human-driven vehicles, intervehicle spacing is defined through a constant time headway, which means that spacing is proportional to speed [15]. The human reaction time, typically around one second, leads to the lack of string stability in human-driven vehicle platooning. This means that the spacing between vehicles may decrease toward the end of the platoon when the lead vehicle decelerates, leading to possible collisions.

A. Traffic Flow Improvement

Lane capacity may be increased by using platoons with tightly constant spaced vehicles [6]. The formulation to determine lane capacity is as follows:

$$C = v\frac{n}{ns+(n-1)d+D} \tag{1}$$

where C represents the number of vehicles (veh/s), d the intra-platoon spacing (m), D the inter-platoon spacing (m), s the vehicle length (m), v the steady-state speed (m/s), and n the number of cars in each platoon. Based on (1), Table I presents some values, for $s = 3\,m$ and $v = 54\,km/h$. The reason for the choice of this reference speed was made as a compromise between two conflicting objectives: ensuring safe operation by the use of a conservative speed value, and maintaining a favorable maximum traffic flow, using a high enough speed value. The spacing for the case of free vehicles ($n = 1$), shown in Table I is consistent with the minimum gap from the time headway model, since human drivers present reaction times of about one second. With, for example, platoons of 8 vehicles each, lane capacity is more than doubled (5510) when compared with the free vehicle case (2348), despite the use of an inter-platoon spacing ($30\,m$) greater than the spacing of individual vehicles ($20\,m$). For higher velocities, there is a slight improvement of the lane capacity for the case of free vehicles, whereas the capacity of platoons of 8 vehicles doubles, if the speed is also doubled [5]. Table I also presents the data obtained through SUMO simulations, performed as described in [5].

By the fundamental relation of traffic flow theory:

$$q = u \times k \tag{2}$$

where q represents traffic flow (veh/h), u is the vehicle speed (km/h), and k the vehicle density (veh/km). Figure 1 shows the fundamental diagram of traffic flow [16], and the equivalent for the case of constant spacing platooning of autonomous vehicles with constant inter-platoons' leaders distance. The data for conventional vehicles represented by a continuous line is related with the free flow case. The dotted line represents the case where the critical density k_c is attained, approximately at $50\,veh/km$, near the maximum flow value (lane capacity), around $2600\,veh/h$. Above this critical density, traffic state begins to enter in a congestion

TABLE I
LANE CAPACITY USING PLATOONS

v	n	d (m)	D (m)	C (veh/h)	SUMO	k (veh/km)
54 km/h	1	–	20	2348	2600	44
	5	1	30	5510	5510	102
	8	1	30	7082	7082	131
	15	1	30	9101	9100	169
	20	1	30	9908	9915	183

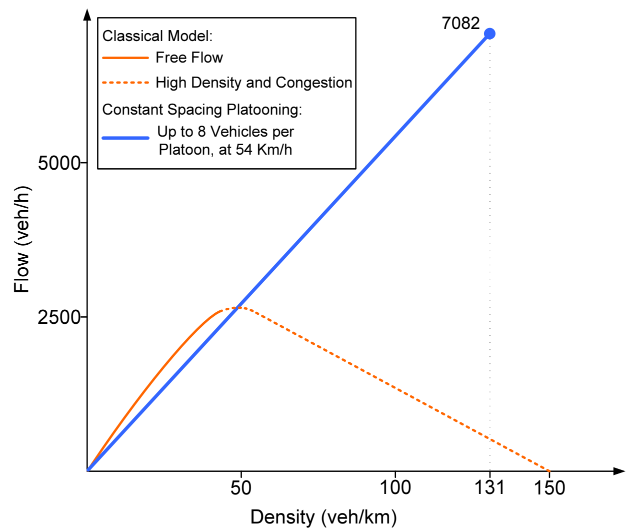


Fig. 1. Diagram of Traffic Flow for conventional vehicles and platooning of autonomous vehicles (k-q diagram).

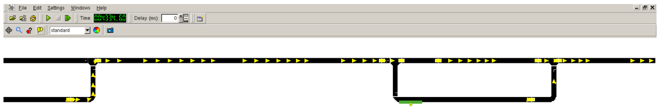


Fig. 2. SUMO setup of platoons of autonomous vehicles with off-line stations, showing vehicles entering the main track (partial view).

phase, where vehicles are closer to each other and moving slower, until traffic comes to a full stop, at a jam density k_j, typically about $150\,veh/km$. For the case of constant spacing platooning of autonomous vehicles, the data were obtained through several SUMO simulations, with a new complete scenario setup, using the new features added as described in [13] (see Fig. 2). In Fig. 1, the values for platoons of 8 vehicles represent the case of inter-vehicle spacing of $1\,m$ within each platoon, and $30\,m$ of inter-platoon distance, which leads to a distance between platoons' leaders of $61\,m$. We can see that a value of $7082\,veh/h$ is attainable, even with the platoons' vehicles limited by a velocity of $54\,km/h$. The top of the line is upper-bounded, since we establish the corresponding vehicle density, of $131\,veh/km$, as the maximum vehicle density of the system. This way, the system operates always within the free flow equivalent of conventional traffic, while presenting a very high capacity.

It is important to acknowledge that such traffic system, being automated, does not ensure, by itself, the absence of traffic congestion. In fact, for a traffic system to operate with such high traffic flow, the admittance of vehicles should be limited, to ensure that a maximum density would never be surpassed. Otherwise, congestion could occur, lowering the traffic flow value.

B. Rules to Ensure High System Capacity with Platoons

For platoon dimensions of seven or less vehicles, the data in Fig. 1 represent the cases of platoons where the distance of the leaders of the platoons remain constant ($61\,m$ for the present case). The aforementioned cases present lower vehicle densities than those we could obtain if the inter-platoon spacing were constant and, consequently, lower flow values, for the same platoon dimensions, as Fig. 3 clearly shows. For example, for the case of platoons with 5 vehicles each, and considering a constant speed of $54\,km/h$, with the inter-platoon distance of $30\,m$, the resultant vehicle density should be of $102\,veh/km$, and the traffic flow of $5510\,veh/h$. With 5-vehicle platoons, with their leaders $61\,m$ apart, and for the same speed, the vehicle density presents a lower value of $83\,veh/km$, and the traffic flow is of $4426\,veh/h$. There is an important reason to use this approach. In fact, if constant inter-platoon distance is used, congestion avoidance may not be ensured by the system, albeit being automated. For example, consider a circular track where platoons with 5 vehicles each, with constant inter-platoon distance of $30\,m$, evolve in formation. Consider also that it is necessary to use full system capacity, with platoons of 8-vehicle each. Subsequently, three more vehicles will be inserted just behind each platoon. When the first 5-vehicle platoon receives the three extra vehicles, the platoons immediately behind it will

Fig. 3. Traffic flow for two different strategies of autonomous vehicles platooning, for a constant speed of $54\,km/h$.

have to brake, in order to maintain the inter-platoon distance of $30\,m$. Two different scenarios may now be considered, both with the same consequences: (i) the communication delays between platoons are mitigated and are not considered; (ii) the communication between platoons present some delay. In (i), all platoons would brake simultaneously, including the platoon in front of the platoon receiving the three extra vehicles, in a continuous self-feeding process, leading to an eventual stop of the whole system. In (ii), the braking platoons would create a well known "shock wave" propagating upstream, in the opposite direction of the platoon movement, with a speed related to the involved communication delays. The number of completed platoons (from 5 to 8 vehicles) depends on the track length. However, as soon as the wave would reach the front of the completed platoons, it would continue to propagate more intensely, leading to an eventual congestion in a matter of time. Either way, it becomes clear that the track can not cope with these extra vehicles and maintain the inter-platoon distance of $30\,m$. There is just not enough space for all of them.

Differently compared to the case of constant inter-platoon spacing, the proposed constant spacing between platoons' leaders ensure that there is always enough spacing behind each platoon to accommodate as much as vehicles needed to complete the platoon, when a platoon is not complete (eight vehicles), without forcing the platoons behind to brake in order to ensure the inter-platoon distance of $30\,m$. As such, full system capacity is always ensured by the ATMS. When traffic demand is lower, incomplete platoons will be spaced by more than $30\,m$, which benefits safety. One could also argue that a considerable higher density could be attained under the considered scenario, if the inter-platoon spacing of $30\,m$ were occupied by more vehicles, forming an almost continuous platoon. In this case, it is true that densities around $245\,veh/km$ could be obtained. However, this assumption is not realistic or viable. Firstly, vehicles

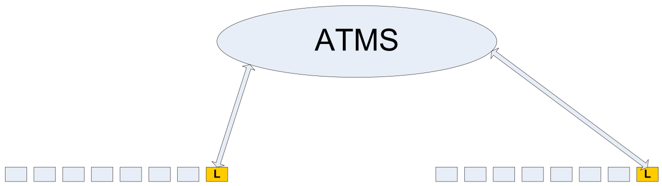


Fig. 4. Hierarchical ATMS (partial view).

must be able to enter the main track, which requires a safety gap. Secondly, vehicles must also be allowed to exit the main track, which may require extra spacing to execute the exit or entrance maneuver. Those maneuvers could impose speed variations on the platoons. However, on a system operating at such high traffic density, speed variations must be avoided, since they may induce spontaneous congestion. As such, we propose such automated transportation system to be based on platooning of autonomous vehicles, with constant spacing between each two consecutive platoons leaders, managed by a hierarchical multilayered ATMS, with safety concerns in the top of the priority list.

C. Assumptions

Constant spacing platooning present major advantages. Firstly, vehicle density is increased, which benefits system capacity. Secondly, inter-platooning distance is always present, allowing to securely insert vehicles on the main track to complete platoons, or allowing vehicles to maneuver to get out the track. Finally, since vehicles evolve in platoons with a tight constant spacing, energy consumption reduction is achievable.

In the present stage of our research, some assumptions are made: only longitudinal control of vehicles is assumed; we only consider platoons of autonomous vehicles; each considered platoon dimension is about $31\,m$ long (8 vehicles $3\,m$ long and $1\,m$ apart); the vehicles' dynamics are considered identical; the vehicles use the control and communication methods described in [5]; the information updating scheme IV, proposed in [5], is used.

IV. HIERARCHICAL MULTILAYERED ATMS

Figure 4 shows a partial view of ATMS that integrates zone agents responsible for controlling the platoon leaders. We intend to isolate this level from the platoon's management level, where each leader must control its platoon's followers. Vehicles leaving the platoon must perform the maneuvers of exit, autonomously. When traffic demand is high, complete 8-vehicle platoons under the constant spacing policy between platoons' leaders, present leaders' spacing of $61\,m$, and inter-platoons' spacing of $30\,m$. Lower traffic demand leads to incomplete platoons (seven vehicles or less). However, leaders' spacing will be maintained ($61\,m$). Even when low traffic demand leads to the presence of isolated vehicles, they must occupy precise positions, separated by a multiple of the inter platoons' leaders defined distance ($61\,m$ in the present case), and perform as leaders. This rule may appear too restrictive in respect of the delay that

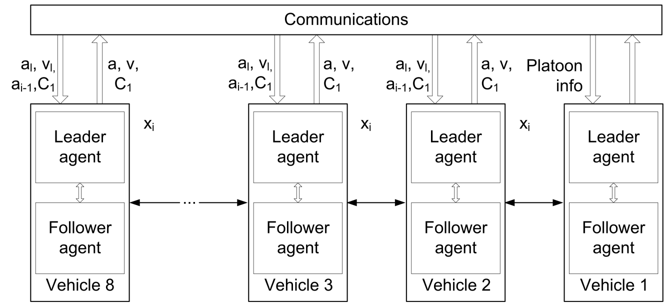


Fig. 5. Information flow diagram of agent-based platoons.

may be imposed upon free vehicle's entrance in the main track. However, two arguments should be enough to justify it. Firstly, for a speed of $15\,m/s$ ($54\,km/h$), the maximum time overhead imposed to the vehicle entering the track is about $4\,s$ only. Secondly and more important, this rule always ensures a deterministic safety gap between vehicles, allowing an appropriate management of new vehicle entrance, whether to evolve alone, or to join another vehicle to form a platoon. Moreover, if incomplete platoons are already in place, there is always enough space behind them to insert vehicles, until a maximum of eight per platoon.

When a leader leaves the main track, the lead vehicle of the remaining vehicles of the platoon must assume leadership, while avoiding overloading the higher level of ATMS. Moreover, the new leader must accelerate to reach the position that previous leader would be occupying. This way, we are able to isolate higher ATMS layers of dealing with such platoon details, ensuring that leaders always occupy the right positions. Since the ATMS may transmit to all leaders their acceleration pattern in time periods of the order of several seconds, the ATMS is able to manage a considerable amount of platoons simultaneously.

To accomplish the task of new leader repositioning, each vehicle consists in two modules, a leader agent and a follower agent, as depicted in Fig. 5. As such, every vehicle may assume leadership of a platoon, or follower behavior, depending on the circumstances. Moreover, the level of leadership is independent, whether is external (real) or internal (virtual), which means that a new real leader may externalize commands from its internal follower, and its internal follower, in turn, may track (and follow) its internal leader. These behavior patterns will be further clarified in the next section, where the proposed algorithms are described.

V. POSITIONING ALGORITHMS

We propose a constant spacing policy between platoons' leaders, of $61\,m$ from front bumper to front bumper, for the reference speed of $15\,m/s$. As such, when a platoon leader leaves the track, a follower will take its place, becoming the new platoon's leader, with the following procedures, to ensure a constant spacing between platoons' leaders:

- initially, the leader uses its internal leader agent (LA) to command the platoon, and followers use their internal follower agents (FA);

TABLE II
PARAMETERS OF THE SIMULATION MODEL

Parameter	Symbol	Value
Time step	T_s	$1\,ms$
Maximum acceleration	a_{max}	$3\,ms^{-2}$
Leader's acceleration	a_{upp}	$2\,ms^{-2}$
Leader's deceleration	a_{low}	$-2\,ms^{-2}$
Maximum deceleration	a_{min}	$-4\,ms^{-2}$

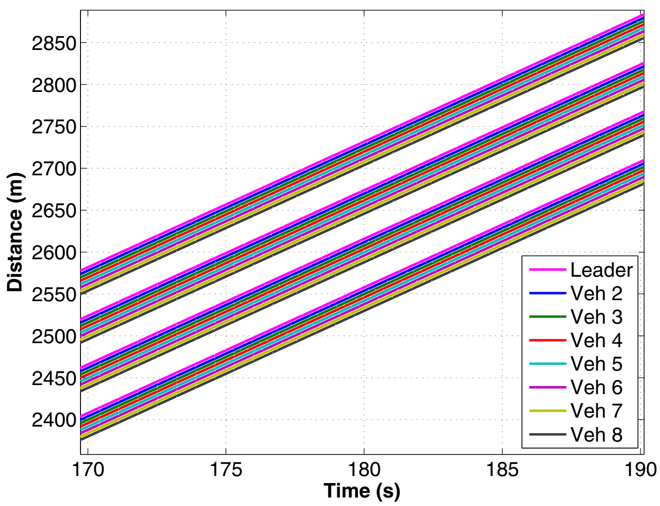


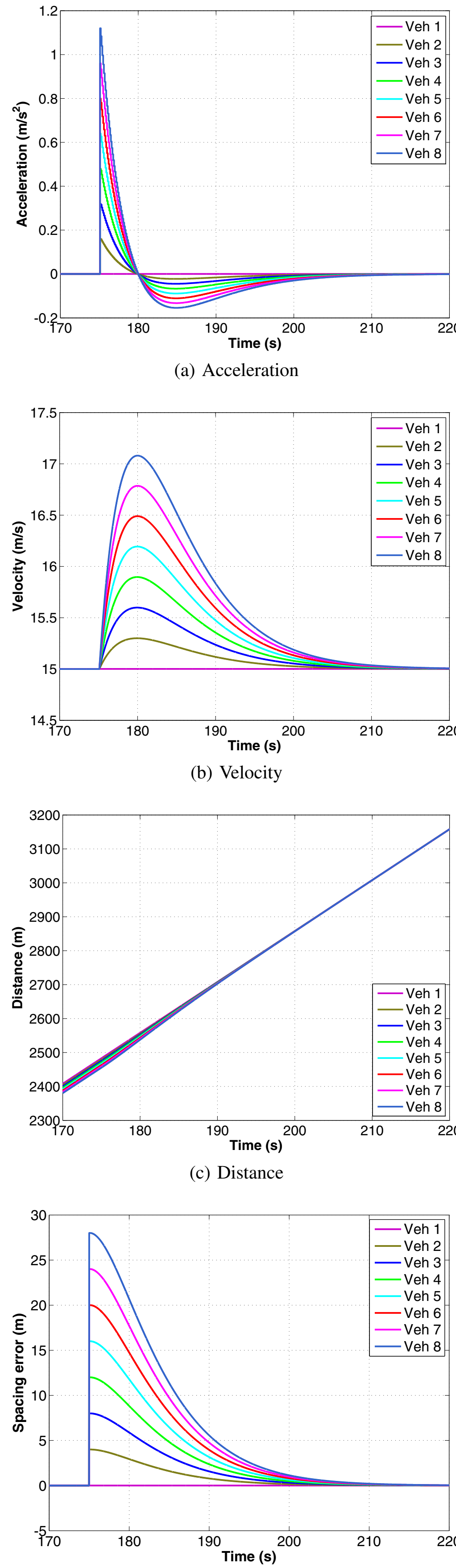
Fig. 6. Multi-platooning system evolving at $54\,km/h$.

- the leader transmits information about its current objectives to the new leader of the platoon;
- the new leader of the platoon assumes external (real) leadership;
- internally, the new leader activates its internal LA, maintaining the internal FA activated;
- internal FA changes the objective value of tracking error L_i of (5) in [5], from $4\,m$ to $0\,m$;
- this action leads to an immediate increase of the spacing error of the new leader's FA of $0\,m$ to $n \times 4$, where n is the number of platoon's front vehicles that left tracks;
- the new leader's internal FA maneuvers to attain its internal LA positioning;
- followers of the new leader behave as usual;
- internal LA continues receiving commands from a upper level of the ATMS, changing its behavior accordingly;
- when the tracking error becomes lower than a predetermined threshold value, LA assumes the command of the platoon operations;
- this process is transparent to all remaining followers.

With this scheme, maximum capacity should be ensured, whereas congestion may be avoided.

VI. RESULTS

To assess the appropriate operation of the proposed algorithms, several simulations were carried out in Matlab/Simulink [17]. All models include eight-vehicle platoons with IVC-enabled autonomous vehicles. Each vehicle



(a) Acceleration

(b) Velocity

(c) Distance

(d) Spacing error

Fig. 7. Tracking of leader's positioning without perturbation

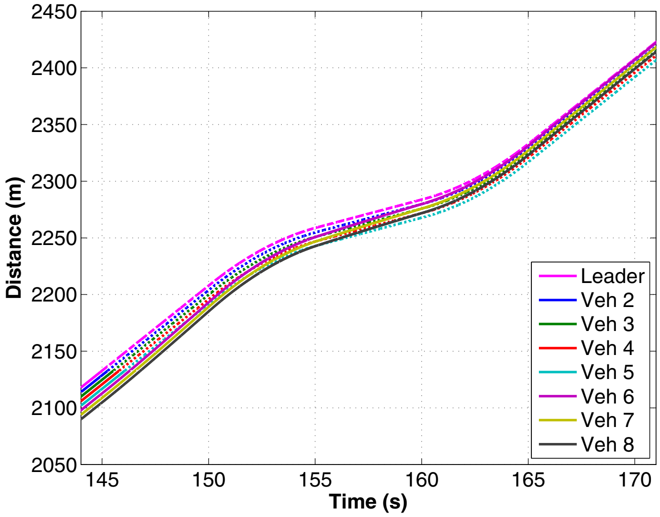


Fig. 8. New leader reaching previous leader position, with representation of the virtual path that exiting vehicles would perform.

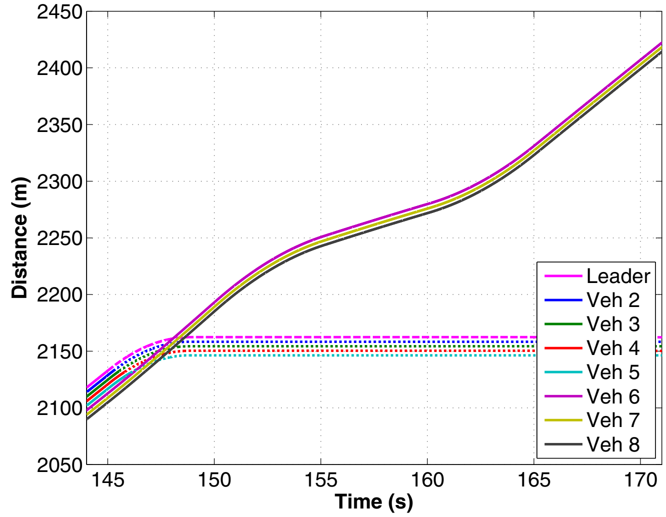


Fig. 9. New leader reaching previous leader position, with a full stop of exiting vehicles to a station. The braking maneuvers are performed off-line.

is simulated by a model consisting of two modules: a leader and a follower. Table II presents the parameters used in the Matlab/Simulink simulations.

Fig. 6 presents a multi-platooning system evolving on the main track at $54\,km/h$, with platoons separated by $30\,m$. Fig. 7 presents aggregate results from the repositioning mechanism of the seven possible cases, without any perturbation. We can observe in Fig. 7a that the maximum acceleration applied to the new leader is of $0.16\,m/s^2$ if only the previous leader vehicle leaves. However, if two vehicles exit, the third one, becoming the new leader, is accelerated to a maximum of about $0.32\,m/s^2$. In the case of the fourth vehicle, the maximum applied acceleration is of about $0.48\,m/s^2$. And so forth $(0.64; 0.8; 0.96)$, until the 8^{th} vehicle's case $(1.12\,m/s^2)$. As such, the acceleration is proportional to the position occupied by the vehicle in the platoon. Consequently, speed increasing is higher for the cases when vehicles in the tail of the platoons assume leadership (Fig. 7b). Fig. 7c presents the repositioning maneuvers for all possible cases of new platoon's leadership. As what concerns the spacing error (Fig. 7d), it is equal to $n \times 4$, where n is the number of platoon's front vehicles that left the main track. As we can see, after $30\,s$, the spacing error is bellow $1\,m$, independently of which case occurred (1 to 7 front vehicles leaving the platoon). This means that the time needed to reach minimum tracking error does not depend of the previous position of the new leader.

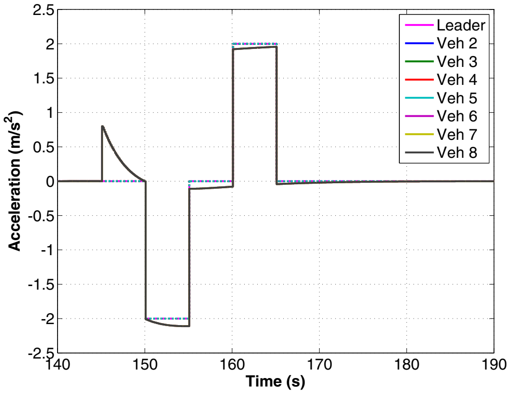
Fig. 8 depicts the platoon's behavior when five leading vehicles leave the main track. It is shown that the sixth vehicle, becoming the leader at $145\,s$, accelerates to reach previous leader's position, while being followed by vehicles close behind. The virtual trajectories of the vehicles that left the main track are depicted, to show that the remaining vehicles perform repositioning maneuvers, as expected. Fig. 9 depicts what really happens, since the vehicles that left the main track brake on a deceleration track, and will come to a full stop when reaching an off-line station.

To assess the robustness of the algorithms, a perturbation on the acceleration was applied (see dotted line in Fig. 10a), while the repositioning maneuver was taking place. The internal LA of the new leader, serving as a reference for the FA, applied the acceleration pattern, in spite of not being yet the real platoon's leader. Meanwhile, the FA continued trying to reach the virtual position of the previous leader, adapting its acceleration pattern accordingly. Even considering this perturbation, the resultant acceleration (Fig. 10a), and consequent velocity (Fig. 10b) are such that the spacing error profile is not affected (Fig. 10c).

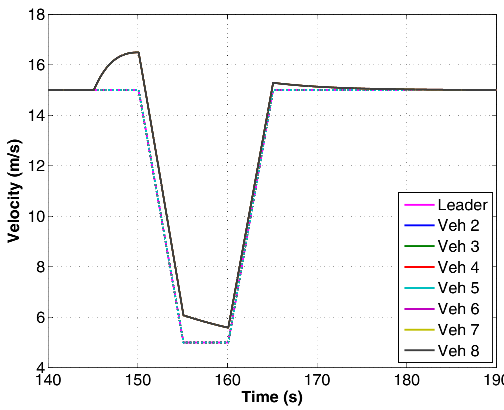
VII. Key Points

We can outline the following points as concerns the proposed algorithms and attained results:

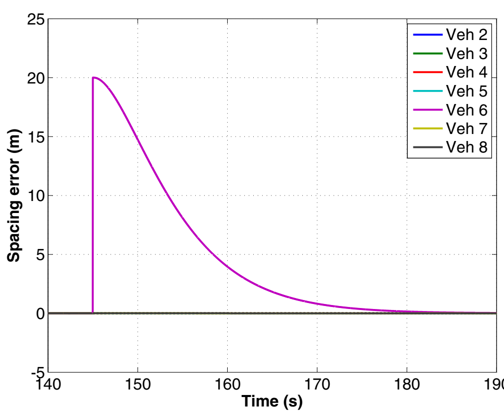
- a multi-platoon system with intra-platoons' constant spacing benefits from using constant speed;
- a multi-platoon system with inter-platoons' constant spacing leads to speed changes that may cause congestion and are uncomfortable to passengers;
- a multi-platoon system with inter-platoons' leaders constant spacing ensure constant speed and safe operation, continuing to allow high system capacity achievement, when necessary;
- to ensure inter-platoon leaders' constant spacing, vehicles evolving alone must occupy precise positions, whose distance is multiple of the inter-platoons' leaders spacing;
- if demand is low, some of the positions mentioned in the previous item may be empty;
- vehicles entering the main track behind incomplete platoons must join those platoons as soon as possible;
- no vehicle is admitted to the system behind a complete platoon;
- if a platoon's leader leaves the main track, the lead vehicle of the remaining platoon's vehicles must perform



(a) Acceleration



(b) Velocity



(c) Spacing error

Fig. 10. Acceleration profile, resultant speed and spacing error

the actions described in Section V, to achieve previous leader's position.

VIII. CONCLUSION

A simulation engine for platoons of autonomous vehicles was designed and implemented in Matlab/Simulink. Methods to ensure high system capacity and vehicle density with safe and efficient operation were reported, and algorithms to maintain platoons' leaders positioning were proposed and assessed through simulation scenarios. New leaders' repositioning maneuvers present a very stable behavior, even when subjected to significant acceleration patterns. The simulation results suggest that the proposed algorithms are appropriate to the problem under study.

Although exiting maneuvers of vehicles from the middle of the platoon do not affect platoons following behind, since a minimum inter-platoon distance is ensured by these algorithms, detailed protocols on how vehicles could perform repositioning maneuvers to create extra spacing to undertake such actions is a subject that deserves further study. Future work will also address more detailed joining and splitting maneuvers of platoons, under the presented scenario as well as on new scenarios implemented in Matlab/Simulink and in SUMO traffic simulator.

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