The Flatbed Platoon Towing Model for Safe and Dense Platooning on Highways

Alan Ali, Gaëtan Garcia, Philippe Martinet

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Alan ALI *Student member, IEEE,* Gaëtan GARCIA and Philippe MARTINET *Member, IEEE,*

***Abstract*—Optimizing the inter-distances between vehicles is very important to reduce traffic congestion on highways.**

Variable spacing and constant spacing are the two policies for the longitudinal control of platoons. Variable spacing doesn't require a lot of data (position, speed...) from other vehicles, and string stability can be obtained using on-board information only. However, inter-vehicle distances are very large, and hence traffic density is low. Constant spacing offers string stability with high traffic density, but it requires data communication between the vehicles, at least from the leader.

In this paper, a new platoon model and a modification of the variable spacing policy are proposed. This modification is effective to decrease the distances between the cars, making them nearly equal to the constant spacing policy. It also enables increasing string stability. This new approach doesn't require heavy communication between the vehicles. The new model is based on an unidirectional spring-damper model between vehicles, with the vehicles loaded on a virtual flatbed tow truck. From this configuration, conditions of stability and safety of homogeneous platoon are derived.

Based on this new model, a control has been derived and evaluated by simulation with a perfect system model using Matlab, and with a more realistic vehicle model using TORCS (The Open Racing Car Simulator). The simulation consists of a platoon of ten vehicles, moving on highways, with a desired inter-vehicle distance equal to 1 meter. The stability and the safety of the platoon are tested during platoon creation, changing the speed and emergency stop. The good results demonstrate the effectiveness of the new approach.

***Index Terms*—Platoon, String stability, Safety, Time headway, Highways, Traffic density.**

I. Introduction

THE problems of traffic congestion, pollution, and people safety are becoming more and more important due to the increase in the number of cars.

Proposed solutions to these problems on highways differ from those in urban areas. On highways, road curvature is smaller and there are less obstacles. Under normal conditions, cars move faster than in urban areas.

Some proposed ideas require changes to the infrastructure (automatic speed limits, roads monitoring, reversible lanes...) Other ideas rely on automated vehicles to increase traffic density and to avoid longitudinal oscillations of the platoon. Driving in platoon has many advantages: it increases traffic density and safety, while simultaneously decreasing fuel consumption and driver tiredness [13].

A. ALI is with Institut de Recherche en Communications et Cybernétique de Nantes (IRCCYN), Ecole centrale de Nantes (ECN), 44300 Nantes, France

G. GARCIA is with Ecole centrale de Nantes (ECN), 44300 Nantes, France

P. MARTINET is with Institut de Recherche en Communications et Cybernétique de Nantes (IRCCYN), Ecole centrale de Nantes (ECN), 44300 Nantes, France

There are many projects on highways platooning, such as the platooning project in PATH program(Partners for Advanced Transit and Highways) [15], [19], SARTRE Project [13], and CHAUFFEUR 2 project [3]. In addition, GCDC (Grand Cooperative Driving Challenge) competition in 2011 addressed the application of automated vehicle following in everyday traffic, which is characterized by an unstructured environment consisting of vehicles of various types and instrumentation [10]. Nevertheless, researches are still going on for highways and urban areas platooning.

From the modeling and control point of view, it is possible to decouple the longitudinal and lateral behaviors, when road curvature is assumed to be low, or by using techniques like chained systems theory [22]. Another technique presented in [8], [12] is to build lateral and longitudinal controllers independently, the parameters of the lateral controller being calculated for each speed. Lateral control can be performed using different modalities like 3D laser (as used by the famous Google car), magnetic markers (PATH project)[15], vision sensors [14], [3]... So in a highway environment, it is common to concentrate on longitudinal behavior, including modeling and control.

Platoon models can be found in [19], [25], ranging from systems which do not include communication between the vehicles to systems which use full communications between the vehicles. Other authors have built physics-inspired models of the platoon: [2] considers the platoon as a multi-agent system, in which the agents (vehicles) interact according to physical phenomena or mimic animal interaction behaviors, [25], [26] represents the interactions as virtual spring-damper systems, while [1] models the forces between the vehicles as Newton forces.

In platooning applications, the desired behavior of a vehicle is generally defined by a desired distance to the previous vehicle in the platoon. Stability of the platoon control is very important. Platoon stability requires that inter-vehicle distance errors do not amplify as they propagate along the platoon, and have the same sign in order to avoid collisions. This is called String Stability. Its definition is given in the time domain in [19] and a sufficient stability condition in the frequency domain can be found in [11].

Local control uses data from adjacent vehicles only, while global control depends on additional data from at least the leader. In local control, the car is totally autonomous: it does not require sophisticated sensors, and can be used in all environments, but trajectory tracking and inter-vehicle distances keeping are not very accurate. Global control is more accurate, but it requires more sophisticated sensors, sometimes

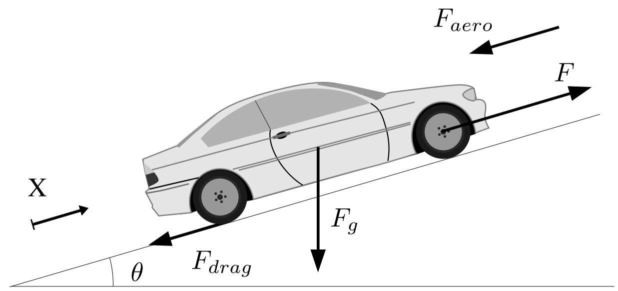

Fig. 1. The applied forces

adaptation of the environment where it is used, and finally it requires very reliable communication systems.

Two policies are used to control the spacing between vehicles: constant spacing and variable spacing [20], [23], [25]. Variable spacing usually doesn't require a lot of data from other vehicles. In addition, it can ensure string stability using on-board information only [7], [27], but inter-vehicle distances vary with speed and can be very large [6], [21], hence traffic density is low. Constant spacing achieves both string stability and high traffic density, at the cost of inter-vehicle communications.

Constant Time Headway (CTH) is the simplest and most common variable spacing policy [21]. Variable time headway can vary linearly with speed, with relative speed [24], or even with vehicle dynamics and road conditions [6].

In this paper, we concentrate on the longitudinal control of homogeneous platoons on highways. We propose a modification to the time headway policy, develop the corresponding dynamic control law, study the stability of the platoon and demonstrate the effectiveness and safety of the new approach for small inter-vehicle distances. The new control law proposed in this paper, is a modified constant time headway, and is a mixture of local and global decentralized controls.

This paper is organized as follows. Section 2 describes the vehicle and platoon models. The control and string stability are presented in section 3. Section 4 presents the simulation results. Finally, section 5 discusses the most important advantages of the proposed approach, and compares it with existing approaches.

II. Modeling

In the case of platooning on highways, where the road curvature is small, it is known that longitudinal and lateral controls can be considered as decoupled. In this paper, we also make this safe assumption, which allows us to consider longitudinal control only.

A. Longitudinal Dynamic Model of the Vehicle

According to Newton's law, we can write the dynamic equation of any vehicle in the platoon shown in Fig. 1 as [17]:

$$m\ \ddot{x} = F + F_g + F_{aero} + F_{drag}$$

$$m\ \ddot{x} = F - m\ g\ sin(\theta) - \frac{\rho\ A\ C_d}{2}\ \dot{x}^2\ sgn(\dot{x}) - d_m \quad (1)$$

Since the vehicles are assumed to travel in the same direction at all times, then we have $sgn(\dot{x}) = 1$

The engine of the vehicle is modeled as a first degree system [17], and is given by the following equation

$$\tau \dot{F} = -F + u \quad (2)$$

So the model of the vehicle can be represented in Fig. 2:

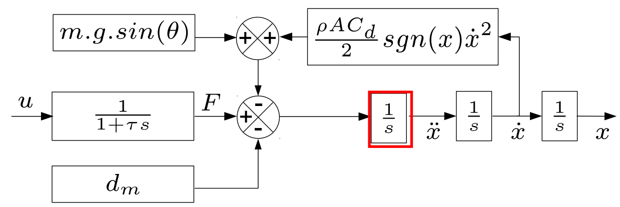

Fig. 2. Dynamic model of the car

where:

- m: Mass of the vehicle.
- x: Position of the vehicle along X axis.
- F: Force produced by the vehicle engine.
- F_g, F_{aero}, F_{drag}: Gravitational force, and aero-dynamical and mechanical drag forces respectively.
- g: Acceleration of gravity.
- θ: Angle between the road surface and the horizontal plane.
- ρ: Specific mass of the air,
- A, C_d: Cross-sectional area and drag coefficient of the vehicle.
- d_m: Amplitude of the mechanical drag force.
- τ: Time constant of the engine of the vehicle.
- u: Control input to the vehicle engine.

By taking the derivative of (1) and substituting (2) in the resulting expression, we get the following:

$$m\ \dddot{x} = -F/\tau - m\ g\ cos(\theta)\ \dot{\theta} - \rho\ A\ C_d\ \dot{x}\ \ddot{x} + u/\tau \quad (3)$$

We can use exact linearization to linearize the previous system. We obtain a linear model of the longitudinal dynamics of the car by taking:

$$u = \tau(m\ W + F/\tau + m\ g\ cos(\theta)\ \dot{\theta} + \rho\ A\ C_d\ \dot{x}\ \ddot{x}) \quad (4)$$

F can be computed from (1).

Then, we get:

$$\dddot{x} = W \quad (5)$$

where W is the new control input for the linearized system shown in Fig. 3.

It is clear that the resulting dynamics of the vehicles are independent of their particular characteristics m, τ, A, C_d [18].

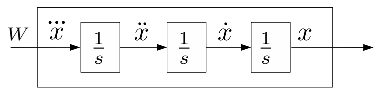

Fig. 3. Linearized car model

B. Platoon Model

The platoon consists of many vehicles following each other. The first vehicle is the leader; it may be driven manually or automatically. The other vehicles follow each other, moving at the same speed v_d and keeping a desired distance L between two consecutive vehicles, as shown in Fig. 4.

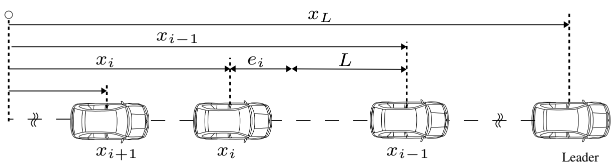

Fig. 4. A platoon

We define the spacing error of the i-th vehicle assuming a point mass model for all vehicles:

$$e_i = \Delta X_i - L \tag{6}$$

where:

- $\Delta X_i = x_{i-1} - x_i$: real spacing between car number i and its predecessor, car number $i-1$.
- x_i: position of i-th vehicle.
- L: desired inter-vehicle distance.

The kinematic evolution of the spacing error is given by:

$$\dot{e}_i = \dot{x}_{i-1} - \dot{x}_i = v_{i-1} - v_i$$

where $v_i = \dot{x}_i$ represents the speed of the i-th vehicle.

The longitudinal model of the platoon, shown in Fig. 5, is a set of vehicles virtually connected by one-directional spring-damper systems, and a virtual truck which are set to drive at a speed V, the value of V being known to all vehicles of the platoon. The spring-damper systems are said to be one-directional because they apply forces to the upstream vehicle only (the system that "connects" vehicle i to vehicle $i-1$ applies forces to vehicle i only). This is recalled on Fig. 5 by the fact that the spring-damper systems are drawn attached to the upstream vehicle, not to the downstream vehicle.

The force applied by each spring depends on the inter-vehicle distance, it acts as an attraction force when the inter-vehicle distance is larger than the desired distance L, and as a repulsive force when it is smaller. The force of the inter-vehicle damper (shown in solid line) depends on the speed difference between two consecutive vehicles. A second damper, shown with the rods in dotted lines, virtually connects each vehicle to the virtual truck. Its force depends on the difference between the speed of the vehicle and the speed of the virtual truck V, and it plays an important role in ensuring platoon stability.

This model is equivalent to the model shown in Fig. 6. In the new model the vehicles in the platoon are carried by a

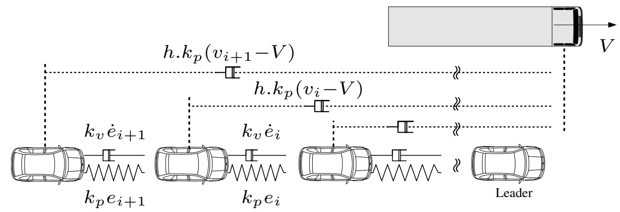

Fig. 5. Longitudinal Platoon Model

virtual *flatbed tow truck* which moves at a speed V, and the i-th vehicle moves with a speed $v_i - V$ relative to the truck. This new model will enable us to reduce the inter-vehicle distances while maintaining platoon stability. We will study the stability around operating point $v_i = V$ and prove stability regardless of the value of operating point V.

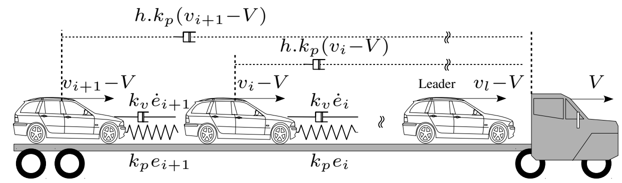

Fig. 6. Truck-Platoon model

III. Platoon Control, Stability and Safety

A. Control Objectives

The main objectives of the control law are:

1) Maintain the inter-vehicle distance equal to L, and make all vehicles move at the same speed so $\dot{e}_i = 0$,
2) Ensure string stability of the platoon (the spacing error must not increase as it propagates through the platoon),
3) Ensure safety (absence of collisions),
4) Increase traffic density,
5) Keep the system stable in case of total loss of communication.

B. Control Law

In the constant spacing control, the control law drives e_i to 0 so the inter-vehicle distance converges to L. But, in order to ensure string stability and robustness, data communication between vehicles is necessary, at least from the leader to the other vehicles.

In the time headway policy, a new term is added to the previous error, which eliminates the need for communication with the leader and increases string stability. The new spacing error is defined as:

$$\delta_i = e_i - h\ v_i = \Delta X_i - L - h\ v_i \tag{7}$$

In this case, the control law drives δ_i to 0, so the steady state of the inter-vehicle distance is equal to $\Delta X_i = L + h\ v_i$. The inter-vehicle distance is proportional to vehicle speed and can become very large when the vehicle travels at high speed.

Adding the time headway term (hv_i) improves stability. Previous research which used the time headway policy has concentrated on optimizing the time headway constant h for a good compromise between stability and inter-vehicle distance [24], [6]. We have noticed that the improvement of adding the time headway term is not due to increasing the inter-vehicle distance, but to the fact that it is a function of speed. So, the main idea of this paper is to propose a new spacing error using the new proposed truck-platoon model shown in Fig. 6, defining the time headway term as proportional to the speed of the vehicle relative to the virtual truck, $v_i - V$, V being the same for all vehicles in the platoon at a given sampling time. We will discuss later how to set the parameter V. The error is now redefined as:

$$\delta_i = e_i - h\ (v_i - V) = \Delta X_i - L - h\ (v_i - V) \quad (8)$$

The new control law is defined by:

$$W_i = -k_a\ \ddot{x}_i + k_v\ \dot{e}_i + k_p\ \delta_i \quad (9)$$

which is represented in Fig. 7 for the i-th vehicle.

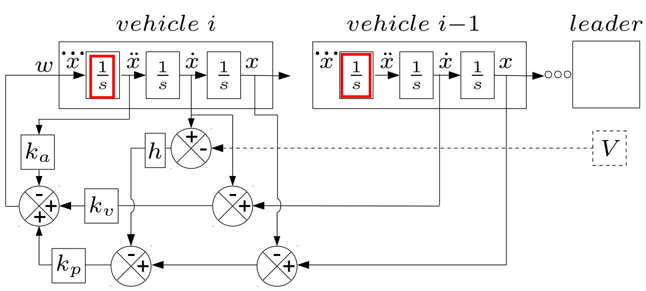

Fig. 7. Control scheme of the i-th vehicle

To verify the effectiveness of the new law, the string stability of the platoon under this control law must be analyzed.

C. String Stability Analysis

The general string stability definition in the time domain is given in [19]:

$$\forall \eta > 0,\ \exists\, \delta > 0$$

such that

$$maxS < \delta \Rightarrow \|e(t)\|_\infty < \eta$$

where

$$e_i(t) = x_{i-1} - x_i - L$$

$$\dot{e}_i(t) = \dot{x}_{i-1} - \dot{x}_i$$

$$e(t) = [e_1\ e_2\ ...\ e_i\ ...\ e_N]$$

$$\|e(t)\|_\infty = sup_i\, |e_i(t)|$$

$$S_i(t) = \textstyle\sum_{j=1}^{i} e_j(t)$$

$$maxS = max\left(\|e(0)\|_\infty, \|\dot{e}(0)\|_\infty, \|S(0)\|_\infty, \left\|\dot{S}(0)\right\|_\infty\right)$$

In essence, it means all the states are bounded if the initial states (position and speed errors) are bounded and summable.

A sufficient condition for string stability is given in [11]:

$$\|e_i\|_\infty \leq \|e_{i-1}\|_\infty \quad (10)$$

which means that the spacing error must not increase as it propagates through the platoon. To verify this condition, the spacing error propagation transfer function is calculated:

$$G_i(s) = \frac{e_i(s)}{e_{i-1}(s)} \quad (11)$$

A sufficient condition for string stability is given by:

$$\|G_i(\omega)\|_\infty \leq 1 \quad \forall\omega \quad and \quad g_i(t) > 0 \quad i = 1, 2..N \quad (12)$$

where $g_i(t)$ is the error propagation impulse response of the i-th vehicle.

So, to verify the string stability of a platoon using the new spacing error, the spacing error propagation transfer function $G_i(s)$ must be calculated:

$$G_i(s) = \frac{k_v\ s + k_p}{s^3 + k_a\ s^2 + (k_v + h\ k_p)\ s + k_p} \quad (13)$$

It should be noted that $G_i(s)$ is not a function of V. In addition, it is the same transfer function as in the classical time headway policy ($V = 0$).

The amplitude of $G_i(s)$ is:

$$\|G_i\| = \sqrt{\frac{k_p^2 + k_v^2\ \omega^2}{(k_p - k_a\ \omega^2)^2 + ((k_v + k_p\ h)\ \omega - \omega^3)^2}} \quad (14)$$

To ensure stability we must verify condition (12), so we get:

$$\omega^6 + \beta_1\ \omega^4 + \beta_2\ \omega^2 \geq 0 \quad \forall\omega \quad (15)$$

where:

$$\begin{aligned} \beta_1 &= k_a^2 - 2(k_v + k_p\ h) \\ \beta_2 &= k_p^2\ h^2 + 2\ k_p\ (k_v\ h - k_a) \end{aligned} \quad (16)$$

The previous inequality is equivalent to:

$$\omega^4 + \beta_1\ \omega^2 + \beta_2 \geq 0 \quad \forall\omega \quad (17)$$

There are two sufficient conditions for the inequality to hold:

1) The 2^{nd} degree polynomial in ω^2 has no root or a single root (the discriminant is negative $\beta_1^2 - 4\beta_2 \leq 0$).
2) The coefficients β_1 and β_2 are both positive.

This gives us the following sufficient conditions for string stability:

$$\left\{\begin{array}{l} k_a^2-2\ k_v-2\ k_p\ h\geq 0 \\ k_p^2\ h^2+2\ k_v\ k_p\ h-2\ k_a\ k_p\geq 0 \end{array}\right\}$$

$$\textbf{or}\left\{\begin{array}{l} h\ k_a\geq 2 \\ k_a^2\geq 2k_v \\ 2k_v\geq k_a^2-\sqrt{4k_ak_p(k_ah-2)} \end{array}\right\} \tag{18}$$

$$\textbf{or}\left\{\begin{array}{l} h\ k_a\geq 2 \\ k_a^2\leq 2k_v \\ 2k_v\leq k_a^2+\sqrt{4k_ak_p(k_ah-2)} \end{array}\right\}$$

The previous conditions are valid for homogeneous platoon. The homogeneous platoon is consisted of many cars with identical linearized models given in (5), all the cars use identical control law with the same parameters. Any variation of the dynamical parameters of any car must be taken into account by the linearizing stage to maintain the linearized model. Otherwise, the platoon will become non homogeneous. The stability of the non-homogeneous platoons is beyond the scope of this paper.

D. Safety of the platoon

In a stable platoon, the maximum error between vehicles is the error between the leader and the first vehicle. If we choose $V=v_{leader}$, then the transfer function of the first error in the platoon is given by:

$$G_1(s)=\frac{e_1(s)}{a_{leader}(s)} \tag{19}$$

$$G_1(s)=\frac{s+k_a}{s^3+k_a\ s^2+(k_v+h\ k_p)\ s+k_p} \tag{20}$$

where $a_{leader}\in[a_{min},a_{max}]$ is leader acceleration.

a_{max}: is the maximum acceleration, a_{min}: is the maximum deceleration.

The magnitude of this function is given by:

$$\|G_1(\omega)\|=\sqrt{\frac{k_a^2+\omega^2}{(k_p-k_a\ \omega^2)^2+((k_v+k_p\ h)\ \omega-\omega^3)^2}} \tag{21}$$

The amplitude of e_1 is defined by the acceleration of the leader. So we can find a bound of e_1, with the following relation:

$$\|e_1\|\leq\left\|\frac{e_1}{a}\right\|\ max(|a_{max}|\,,|a_{min}|) \tag{22}$$

To ensure platoon safety, e_1 must remain smaller than the desired distance L in deceleration mode, otherwise a collision may take place, so if we verify the following condition we will ensure the safety of the platoon:

$$\|e_1\|\leq\left\|\frac{e_1}{a}\right\|\ max(|a_{max}|\,,|a_{min}|)\leq L \tag{23}$$

so we get:

$$\omega^6+\alpha_1\omega^4+\alpha_2\omega^2+\alpha_3\geq 0\quad\forall\omega \tag{24}$$

where:

$$\begin{array}{l} \alpha_1=k_a^2-2(k_v+k_p\ h) \\ \alpha_2=(k_v+k_p\ h)^2-2k_p\ k_a-\frac{a_{min}^2}{L^2} \\ \alpha_3=kp^2-k_a^2\frac{a_{min}^2}{L^2} \end{array} \tag{25}$$

If we choose $\alpha_3\geq 0$, the following condition becomes a sufficient condition to satisfy (24):

$$\omega^6+\alpha_1\omega^4+\alpha_2\omega^2\geq 0\quad\forall\omega \tag{26}$$

which is equivalent to:

$$\omega^4+\alpha_1\omega^2+\alpha_2\geq 0\quad\forall\omega \tag{27}$$

The above inequality holds if the discriminant is negative (or zero) or the coefficients are positive (or zero).

This gives us the following sufficient conditions for platoon safety:

$$\left\{\begin{array}{l} k_p\geq\frac{|a_{min}|}{L}k_a \\ k_a^4-4\ (k_v+k_p\ h)k_a^2+8\ k_p\ k_a+4\frac{a_{min}^2}{L^2}\leq 0 \end{array}\right\}$$

$$\textbf{or} \tag{28}$$

$$\left\{\begin{array}{l} k_p\geq\frac{|a_{min}|}{L}k_a \\ k_a^2\geq 2\ (k_v+k_p\ h) \\ (k_v+k_p\ h)^2\geq 2k_p\ k_a+\frac{a_{min}^2}{L^2} \end{array}\right\}$$

IV. Simulations

The control laws have been checked using Matlab and The Open Racing Car Simulator (TORCS) to get more realistic results (as it takes more phenomena into account) and to have visual output (Fig. 14) when applying the new spacing error.

A platoon of ten identical cars moves on a nearly straight track (low curvatures). The desired inter-vehicle distance (bumper-to bumper distance, so we omit all the cars lengths from all following figures) is fixed to $L = 1\,m$. The maximum studied speed is $140\,km/h$. The control parameters are chosen so that the platoon is stable and safe $k_p = 12$, $h = 4$, $k_a = 2.4$, $k_v = k_a/h$.

In this simulation, three scenarios are studied:

1- The creation of the platoon starting from the stationary state (part A).

2- Changing the speed of the platoon (from $40\,km/h$ to $140\,km/h$) to verify string stability in the extreme acceleration case (part B).

3- Performing an emergency stop when moving with the maximum speed to check safety (part C).

At the same time, a comparison between our control law and the classical CTH control law is presented using the same parameters.

In all simulations, the leader is driven automatically. The profile of the *desired* speed of the leader of the platoon is shown in figure 8. We take the maximum acceleration equal to $5\,m/s^2$, which exceeds the comfort acceleration limit and the ability of many vehicles. The comfort deceleration defined by AASHTO [5] is $3.4\,m/s^3$. We choose a maximum deceleration equal to $5\,m/s^2$, which also exceeds the comfort limit. The maximum and minimum jerks are imposed by the requirement for comfortable ride and not by the vehicle limitation [4]. We take them as $\pm 6\,m/s^3$.

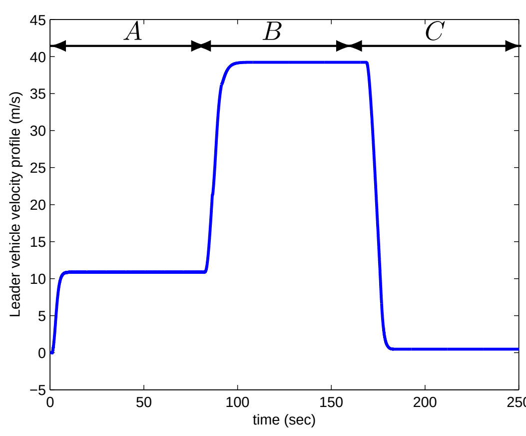

Fig. 8. Leader's speed profile

A. Matlab results

The linearized car model given in equation (5) has been used in the simulations run under Matlab. It represents the ideal situation and is used to check the validity of the control law without any disturbances.

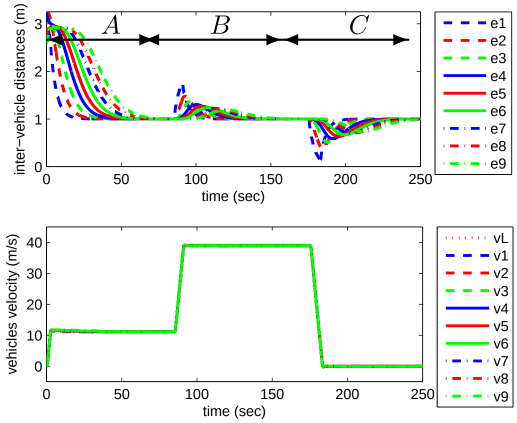

Fig. 9. Inter-vehicle distances and velocities using the new control law (Notice the order of magnitude of the distance)

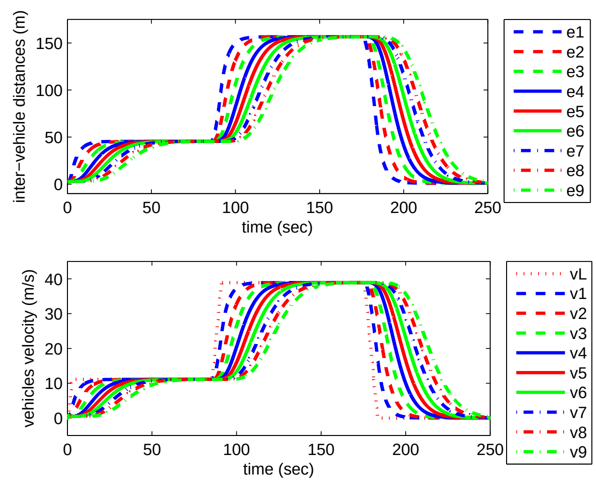

Fig. 10. Inter-vehicle distances and velocities using the classical constant time headway law (Notice the order of magnitude of the distance).

We first compare the inter-vehicle distances using our control law (shown in Fig. 9) to the inter-vehicle distances using classical CTH control law (shown in Fig. 10). When using CTH, the inter-vehicle distances are proportional to vehicle speed, and can become very large at high speed. On the contrary, the inter-vehicle distances in our case are much smaller: they are nearly equal to the desired distance, with small errors during dynamic changes.

The creation of the platoon from the stationary state is shown in Fig. 11. The speed of the vehicles converges towards the speed of the leader and the inter-vehicle distances converge towards the desired distance.

The stability of the platoon is clearly shown in Fig. 12 when the leader accelerates from $40\,km/h$ to $140\,km/h$. The errors decrease when they propagate through the platoon and they converge to zero, so the inter-vehicle distances converge towards the desired distance.

The safety of the platoon in case of an emergency stop is shown in Fig. 13. In this case, the leader drives at maximum speed and performs an emergency stop with the maximum

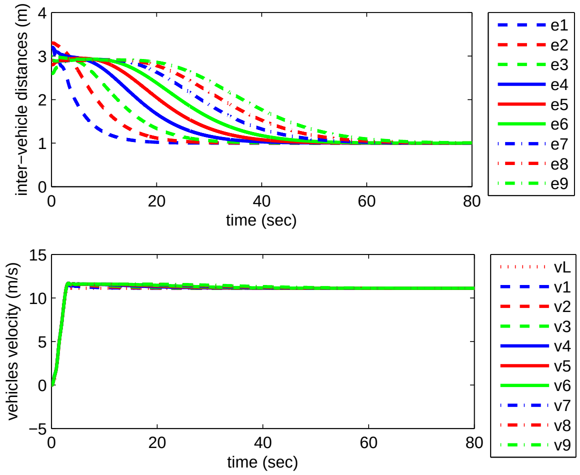

Fig. 11. Platoon Creation Matlab simulation (part A)

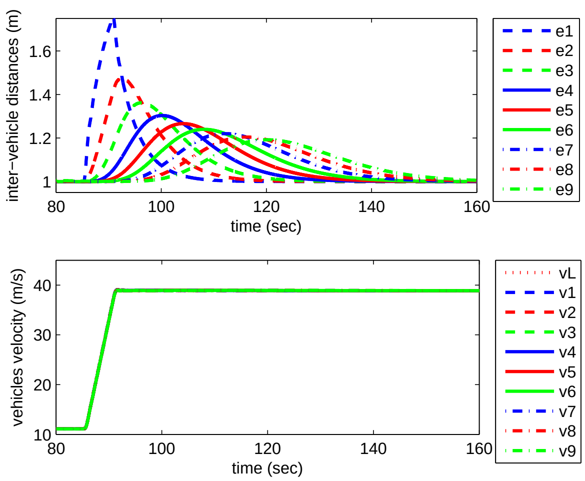

Fig. 12. Changing Platoon speed Matlab simulation (part B)

deceleration and maximum jerk. The inter-vehicle distances are always greater than zero, so no collision occurs.

As said before, the car model used under Matlab is a very simple, ideal model. To be more realistic and to take more physical phenomena into account, additional simulations have been performed using TORCS.

B. TORCS results

TORCS (Fig. 14) is one of the most popular car racing simulators [9]. It is written in C++ and is available under GPL license. TORCS presents several advantages for academic purposes, namely:

1) It lies between advanced simulators, like recent commercial car racing games, and a fully customizable environment, like the ones typically used by computational intelligence researchers for benchmark purposes.
2) It features a sophisticated physics engine (aerodynamics, fuel consumption, traction...) as well as a 3D graphics engine for the visualization of the races.

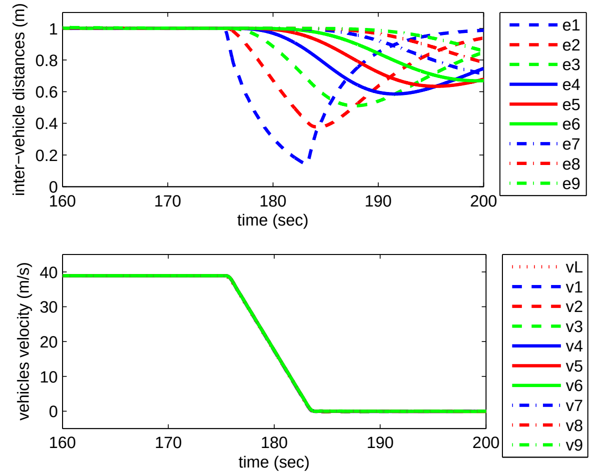

Fig. 13. Platoon safety during emergency stop Matlab simulation (part C)

Fig. 14. TORCS simulator

3) It was not designed as a free alternative to commercial racing games, but specifically to make it as easy as possible to develop your own controller.

Same simulations as under Matlab have been performed, taking into account the car model of equation (3), linearized using the linearizing input given in (4).

The comparison of the inter-vehicle distances using our control law and the classical constant time headway law are shown in Fig. 15 and Fig. 16 respectively. We can see the same results obtained in Matlab.

The creation of the platoon is also performed in TORCS. Again all errors converge towards zero and the inter-vehicle distances converge towards the desired distance as shown in Fig. 17.

The stability of the platoon is also verified in Fig. 18 and we get similar results to those obtained with Matlab.

Finally, the safety of the platoon can be checked in Fig. 19 which shows that the platoon remains safe with a more realistic car model.

V. Discussion

The proposed approach greatly reduces inter-vehicle distances, while ensuring stability. This result is obtained by making the distance proportional, not to speed, but to the

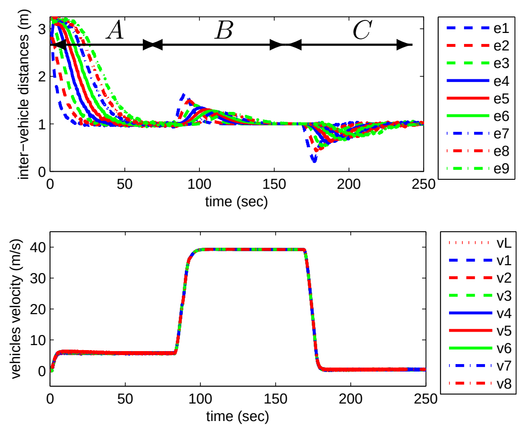

Fig. 15. Inter-vehicle distances and velocities using the new control law (Notice the order of magnitude of the distance)

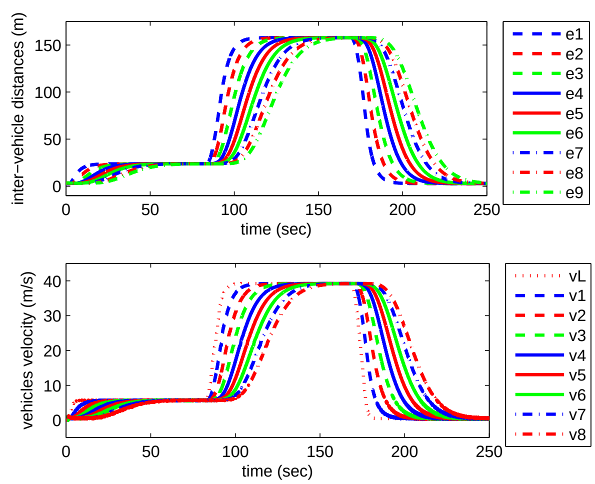

Fig. 16. Inter-vehicle distances and velocities using the classical constant time headway law (Notice the order of magnitude of the distance).

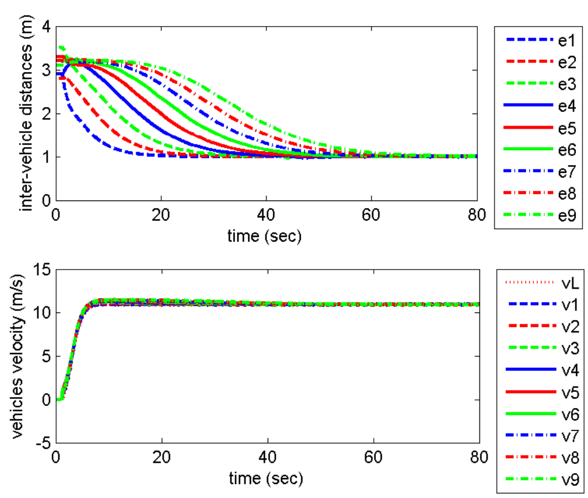

Fig. 17. Platoon Creation TORCS simulation (part A)

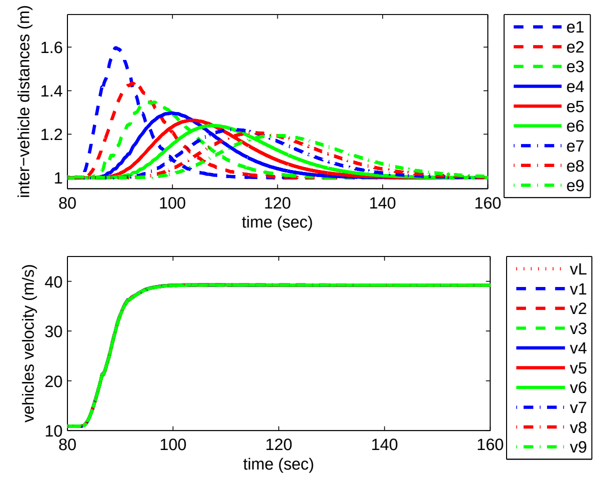

Fig. 18. Changing Platoon Velocity TORCS simulation (part B)

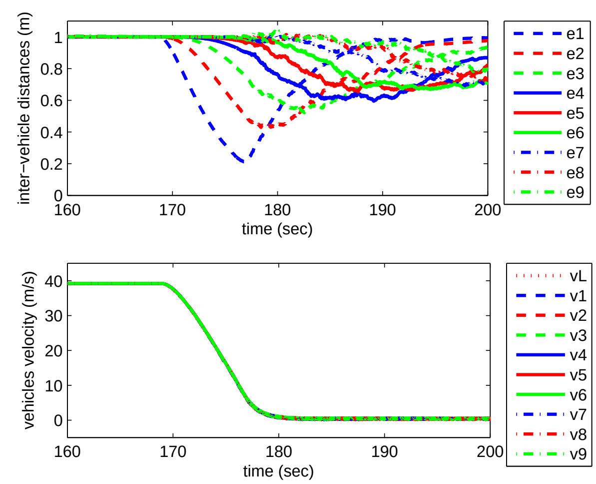

Fig. 19. Platoon safety during emergency stop TORCS simulation (part C)

difference between the speed of the vehicle and a common speed value shared by all vehicles of the platoon.

A. Advantages and comparison

Using the new spacing policy and the corresponding new control law, we get the following advantages:

String stability:

The propagation function $G_i(s)$ corresponding to the new control law does not depend on V. Actually, it is the same propagation transfer function as in the constant time headway, so with the same parameters for the new control law and the CTH law we get identical stability, regardless of the value of V.

Inter-vehicle distances:

The most important effect of the proposed modification is a large reduction of the inter-vehicle distances.

The inter-vehicle distance has been decreased from $\Delta X_i = L + h\ v_i$ (which can be very large at high speed) in the case of the classical time headway policy, to become $\Delta X_i = L + h\ (v_i - V)$, which is equal to L at equilibrium (by choosing a proper value of V) and slightly larger than L during transient phases. So during transient phases, the length of the platoon will be slightly different from the length of a platoon using constant spacing policy.

A compromise can be achieved between stability and inter-vehicle distances by changing h. Increasing h increases stability, but at the same time it has a negative effect on the inter-vehicle distance. In CTH, increasing h has a significant negative effect on ΔX_i. In our modified law, this negative effect is much smaller than in CTH, so we can increase h, and hence stability.

Collisions:

It is clear that the risk of a collision between the vehicles is increased as the inter-vehicle distances are reduced. In this work, we have presented the conditions to get a safe platoon even with a reduced distance between the vehicles.

Communication:

Sharing V between all the vehicles imposes exchanging data between the vehicles. We have seen previously that stability is not related to V, so the amount of exchanged data between the vehicles can be reduced by updating the value of V with a lower sampling rate than the sampling rate of the control of the vehicles.

Stability without communication:

String stability can be preserved even if the communication with the leader is totally lost, by switching to the classical time headway policy, which corresponds to setting $V = 0$ (fully autonomous mode). In this case, there is no need to communicate with the leader. So this law can keep the platoon stable even if the communication is totally lost. On the contrary, it has been proved that the constant spacing policy cannot be string stable, for an homogeneous platoon with an homogeneous control (all the gains are equal), without using any information from other vehicles [16].

Handshaking protocol, between the leader and other vehicles, is very important to detect any loss of communication. If any loss is detected, the leader will transmit an order to all vehicles to switch to fully autonomous mode ($V = 0$), while the vehicle which has lost communication, will automatically switch to this mode when it detects the communication loss.

Simplicity and type of required data:

The new control is as simple as the CTH law. It uses the same variables as CTH, plus a low frequency updating of the common speed parameter V (which may be the leader or platoon speed). This last variable is the only difference with the classical time headway policy, while the constant spacing policy is always more complicated, as it may require the acceleration or other information, at least from the leader.

B. Supervision of parameter V

As seen previously, the only condition to keep the platoon stable with the new control law is to make V identical for all vehicles at any sample time. So, any value for V (*e.g.* leader's speed, the medium speed of the platoon or the minimum speed in the platoon...) can be chosen.

To increase safety and to prevent collisions, one can choose $V = min(v_{Leader}, v_1, v_2...., v_N)$. This will always make $h(v_i - V) \geq 0$, so the spacing ΔX_i will be always bigger or equal to L, but of course this will increase the inter-vehicle distance during speed changes.

On the other hand, choosing $V = max(v_{Leader}, v_1, v_2...., v_N)$ will always make $h(v_i - V) \leq 0$, hence the spacing will be always smaller or equal to L. This will decrease the inter-vehicle distances during speed changes, but it will decrease the safety and may cause collisions. So it is not good to choose V larger or equal to the maximum speed in the platoon.

If we choose V as the medium speed of the platoon, the rate of change of V will be related to the dynamics of the platoon as whole. This dynamics is represented as heavy truck in our new model, which is much slower than the dynamics of the spacing errors. We have seen also that stability is not related to V, so we can update it at a lower updating rate than the sampling rate of each vehicle.

Lowering the update rate of V may introduce some steps in its values, which may have negative effects on the control, and hence on the performance. In this case V must be interpolated to get smooth changes.

VI. Conclusion

In this paper, the design of longitudinal control of platoons on highways has been addressed. A new platoon model and a modification of the classical time headway have been proposed. The conditions of platoon stability and safety have been found. Simulations have been performed under Matlab and TORCS. The desired distance between the vehicles is reduced to 1 meter without losing string stability and platoon safety. We have shown the simplicity of the proposed modification, and we have proved also the stability of the platoon at low update rate of the shared speed value, and even in case of total loss of communication.

In future work, we will study the robustness of the control law regarding the actuation and sensing lags, and regarding the communication delays. In addition, the comfort of the passenger we will be taken into account. This work will be also generalized to urban platooning application in order to reduce the traffic congestion through the control of the virtual tow truck speed in order to optimize the inter-vehicle distance. Finally, real evaluation must be done using a real system to check the effectiveness and reliability of our control.

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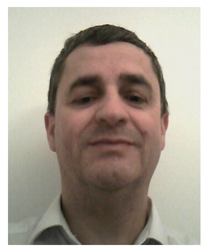
Alan ALI was born in 1981. He received the B.S. degree in Electronic Systems Engineering from the Higher Institute for Applied Science and Technology (HIAST), Damascus, Syria, in 2005, and the M.S. degree in Robotics from the Ecole central de Nantes, Nantes, France, in 2011. He worked as research engineer in Systems Control and Robotics department at HIAST from 2005 to 2010. At the same time he was designing CAD/CAM program for CNC machine, which was used in an industrial water-jet machines.

He is currently with Institut de Recherche en Communications et Cybernétique de Nantes (IRCCYN), Nantes, France. His research interests include modeling and control of urban platoons.



Gaëtan GARCIA Gaëtan Garcia received the PhD in robotics from Ecole Centrale de Nantes in 1989. He teaches mobile robots, industrial robot programming and robotics software. His interests include localization, computer vision and the development of robotics applications.

Philippe MARTINET Philippe Martinet graduated from the CUST, Clermont-Ferrand, France, in 1985, and he received the PhD degree in Electronics Science from the Blaise Pascal University, Clermont-Ferrand, in 1987. From 1990 to 2000, he was Assistant Professor with CUST in the Electrical Engineering Department, Clermont-Ferrand. From 2000 to 2011, he was Professor with Institut Français de Mécanique Avancée (IFMA), Clermont-Ferrand. He was performing research at the Robotics and Vision Group of LASMEA-CNRS, Clermont-Ferrand. In 2006, he spent 1 year as a Visiting Professor in ISRC at the Sungkyunkwan University in Suwon, South Korea. In 2011, he moved to Ecole Centrale de Nantes and he is doing research at IRCCYN. He was the Leader of the group GRAVIR (over 74 persons) from 2001 to 2006. In 1999, he set up a team in Robotics and Autonomous Complex Systems (over 20 persons). Between 2008 and 2011, he was Colead of a Joint Unit of Technology called ”Robotization Meets Industry”. Between 2009 and 2011, he was Colead of a Korea-France Joint Research Center on Cognitive Personal Transport Service Robots. His research interests include visual servoing of robots (position, image and hybrid based, omnidirectional), multi-sensor-based control, force-vision coupling, autonomous guided vehicles (control, enhanced mobility, uncertain dynamics, monitoring), modeling, identification and control of complex machines (vision-based kinematic/dynamic modeling identification and control). From 1990, he is Author and Coauthor of more than two hundred sixty references.