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Urban Platooning Using a Flatbed Tow Truck Model

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Abstract— **Finding solutions to traffic congestion is an active area of research. Many ideas have been proposed to reduce this problem, among of this ideas is moving in platoon. The constant time headway policy (CTH) is a very important platoon control policy, but it is too conservative and induces large inter-vehicle distances. Recently, we have proposed a modification of CTH [1], [2]. This modification reduces inter-vehicle distances and makes CTH very practical.**

This paper focuses on the control of platoons in urban areas. To control the vehicles, we assume that the longitudinal and the lateral dynamics are decoupled. We take into account a simplified engine model. We linearize the two dynamics using exact linearisation technique. Then, we use the modified CTH control law, adapted to urban platoons, for the longitudinal control and the robust sliding mode control for lateral control.

The stability and the safety of the platoon are also studied. The conditions of stability of homogeneous and nonhomogeneous platoons are established. The conditions to verify the safety of the platoon for the longitudinal control (assuming stable and accurate lateral control) are exhibited. The weaknesses (large inter-vehicle distance, weak stability near low frequencies) of the CTH are solved.

The improved performance and the safety of the platoon are verified by simulation using TORCS (The Open Racing Car Simulator). A platoon consisting of ten vehicles is created and tested on a curved track, keeping a small desired intervehicle distance. The stability and safety of the longitudinal and lateral controls are tested in many scenarios. These scenarios include platoon creation, changing the speed and emergency stop on straight and curved tracks. The results demonstrate the effectiveness of the proposed approach.

I. INTRODUCTION

Nowadays, traffic congestion represents an important problem due to the increasing number of cars. Solving this problem will help to reduce other related problems, such as pollution, safety and fuel consumption. Many ideas have been proposed, ranging from integrating some changes in the infrastructure to inventing new, alternative transportation systems (carpooling and car-sharing...).

Platooning using automated cars seems to be a promising idea. It increases traffic density and safety, while decreasing fuel consumption and driver tiredness [16]. Many highways platooning projects have been implemented but haven't been deployed yet. The most famous projects are the platooning project in the PATH program [19], [20], CHAUFFEUR [11] and SARTRE [17]. However, research is still going on for urban and even highway applications.

The control of the platoon deal with lateral and longitudinal dynamics of each vehicle which are generally coupled. Decoupling this two dynamics is straightforward when using a static vehicle model [7], however a static model can't be used in high speed applications. It is more difficult to decouple the two dynamics when using a dynamic model adapted when moving at high speed on curved roads. On highway applications, with low curvature roads, it is common to assume that the two dynamics are decoupled. Longitudinal and lateral control laws are then designed independently [20]. In urban areas, [9] has proposed lateral model supposing that it is sufficiently independent from longitudinal model. Other researchers have built lateral and longitudinal controllers independently, the parameters of the lateral controller have been calculated for each speed, and they have been saved in a lookup table [15].

The stability of the platoon is defined as string stability [14], [20]. In essence, it means that all the states of the platoon are bounded if the initial states (position and speed errors) are bounded and summable. A sufficient condition for string stability requires that the error does not increase as it propagates through the platoon.

Inter-vehicle distances can be constant (Constant spacing policy) or variable (variable spacing policy). The constant spacing policy leads to high traffic density, but it requires reliable inter-vehicle communication to transmit leader information. On the other hand, variable spacing can operate in fully autonomous mode and can ensure string stability just by using on-board information [12], at the cost of *large inter-vehicle distances*.

The simplest and most common variable distance policy is CTH [20], [21]. In [1], [2] we have proposed a modification of CTH for highway platooning. This modification reduces the inter-vehicle distances, to become nearly equal to the desired distance. In [3] we applied the previous work on urban platoon control. *Coupled* dynamic and kinematic models were used for longitudinal and lateral dynamics respectively. In longitudinal control, we used the modified CTH. In lateral control, we used sliding mode control. In [1] we proposed a new platoon model, called "flatbed tow truck platooning model". We also have improved the performance of the longitudinal control by taking the engine model into account and using the modified CTH. A comparison, with the classical CTH, was made to show the effectiveness of the modified law. Stability and longitudinal safety conditions were also obtained. The safety of the platoon in many critical situations has been studied in [4].

In this paper, we assume that the longitudinal and lateral dynamics are *decoupled*. The two dynamics are linearized separately using exact linearization techniques. Sliding mode control is used to get robust lateral control. The tow truck

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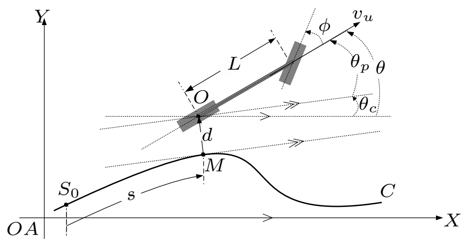

Fig. 1. Bicycle Model

model is generalized to urban platoons. The stability of homogeneous and non-homogeneous platoons and the safety of the longitudinal control are discussed assuming robust lateral control. The weakness (large inter-vehicle distance, weak stability near low frequencies) of the CTH are solved.

This paper is organized as follows: In section II, models for the vehicle and platoon are presented. Control is developed in section III. String stability of the platoon and control safety are proved in section IV. Then in section V, we show simulation results. Conclusions and perspectives are presented in section VI.

II. MODELING

The lateral and longitudinal dynamics of road vehicles are only coupled under maneuvers that involve relatively high lateral forces, when the tire friction ellipse limits traction forces and body motions cause load transfers. Those are generally encountered in emergency conditions or extremely sporty driving, and are not encountered when driving vehicles at low speeds in urban areas. So we assume that the two dynamics are decoupled [9] and we linearize and control each of them separately. As in [9], we use the same static lateral model and we use a similar dynamic longitudinal model with higher order to ensure more stability and safety. The control laws are totally different and we find stability and safety conditions and discuss the case of non-homogeneous platoon.

A. Longitudinal Dynamic Model of the Vehicle

We can improve stability and safety while reducing the inter-vehicle desired distance obtained in [2], [9] by taking into account the model of the engine.

Using Newton's law and taking into account the model of the engine we get the longitudinal dynamic model. Then by applying exact linearization we get a linear system [18]:

$$\ddot{v} = W_1 \tag{1}$$

where v is the speed of the vehicle, and W_1 is the control input for the linearized system.

B. Lateral Model Of The Vehicle

We use the classical Ackerman car model given in [8]. In this model, the car is represented as a bicycle (fig. 1), without taking slippage into account. In general, this model can be used for lightweight vehicles running at low speeds on sufficiently solid ground (asphalt).

This model can be reformulated with respect to the reference path C instead of the absolute frame [8], [9]:

$$\begin{aligned} \dot{s} &= \tfrac{cos\theta_p}{1-d\ c(s)}\ v_u\ ,\ \dot{d} = sin\theta_p\ v_u \\ \dot{\theta}_p &= (\tfrac{tan\phi}{L} - \tfrac{c(s)\ cos\theta_p}{1-d\ c(s)})\ v_u \end{aligned} \tag{2}$$

where $[OA, X, Y]$ is an absolute frame, C is the reference path, O is the center of the rear wheel of the vehicle, M is the point of C closest to O, s is the curvilinear coordinate of point M along C, $c(s)$ denotes the curvature of path C at M, $\theta_c(s)$ stands for the orientation of the tangent to C at M(with respect to the absolute frame), θ is the heading of the vehicle, with respect to frame $[OA, X, Y]$, $\theta_p = \theta - \theta_c(s)$ denotes the angular deviation of the vehicle with respect to C, d the lateral deviation of the vehicle with respect to C, ϕ is the steering angle (angle between the front wheel and the body axis), L is vehicle wheelbase, and v_u is the vehicle speed along the longitudinal axis.

The only singularity of this model appears when the vehicle is on the reference path center of curvature ($d = \frac{1}{c(s)}$). This can be avoided, in practical situations, if the vehicle is well initialized.

Steering cannot be instantaneous. The steering system can be modeled as a first order system [19]:

$$\dot{\phi} = -\frac{1}{\tau_s}\ \phi + \frac{c_2}{\tau_s}\ u_2 \tag{3}$$

where ϕ is the front-steering angle, τ_s is the steering time constant, c_2 is a gain and u_2 is the vehicle's steering-angle-command input.

From (2), taking the derivative of $\dot{\theta}_p$ we get:

$$\ddot{\theta}_p = \gamma_1\ \dot{\phi} + \gamma_2 + \gamma_3 \tag{4}$$

where:

$\rho = \frac{cos\theta_p}{1-c(s)d}\ ,\ \gamma_1 = \frac{v_u}{L\ cos^2\theta_p}\ ,\ \gamma_2 = (\frac{tan\phi}{L} - c(s)\ \rho)\ \dot{v_u}$

$\gamma_3 = -(\rho\ \dot{c}(s) - \frac{c(s)sin\theta_p\dot{\theta}_p}{1-c(s)d} + \frac{\rho\ c(s)}{(1-c(s)d)}(c(s)\dot{d} + \dot{c}(s)d))v_u$

with the condition $\theta_p \neq \frac{\pi}{2} + \pi\ k\ ,\ k = 0, 1, 2...$

An exact linearity of this model is obtained by taking a ***new control input*** W_2 such that $u_2 = \frac{W_2}{\beta_2} - \beta_1$

where $\beta_1 = -\frac{\gamma_1}{\tau_s}\ \phi + \gamma_2 + \gamma_3,\ \beta_2 = \frac{c_2}{\tau_s}\ \gamma_1$

This yields the following linearized lateral system:

$$\ddot{\theta}_p = W_2 \tag{5}$$

with the condition that $v_u \neq 0$.

So we get a new linear model of the vehicle, given by (1) and (5) with two decoupled inputs W_1, W_2.

C. Platoon Model

The platoon is a set of vehicles following each other, running at the same speed and maintaining a desired distance l between two consecutive vehicles.

Curvilinear parameters are used for urban applications, assuming a point mass model for each vehicle. In the sequel, l is the desired curvilinear inter-vehicle distance, s_i is the curvilinear coordinate of the i-th vehicle, $e_i = s_{i-1} - s_i - l$ is the spacing error of the i-th vehicle, N is the number of vehicles in the platoon.

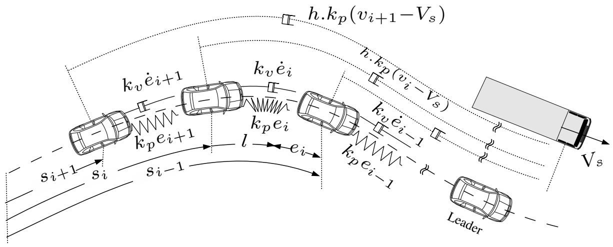

Fig. 2. Longitudinal Platoon Model

In [1], we proposed a new platoon model called flatbed tow truck model. In the proposed model, the virtual forces between the vehicles are represented by a classical one-directional spring-damper system. The amplitude of these forces were proportional to the linear spacing and speed errors. In addition, a virtual truck moving at speed V_s was added. To increase stability, a damping force proportional to the velocity difference between the vehicle and the truck was added. We can generalize this model to be used for urban platoons by making the amplitudes of the forces proportional to the curvilinear variables, as represented in fig. 2 and 3.

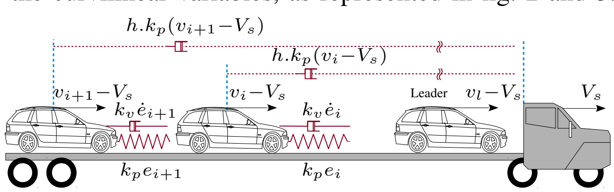

Fig. 3. Flatbed tow truck model

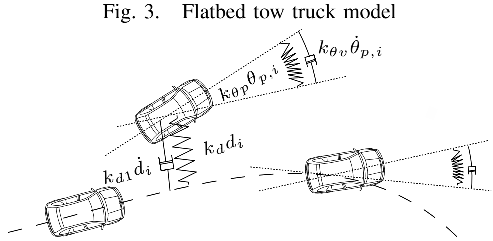
Fig. 4. Lateral Platoon Model

The lateral model shown in fig. 4. It consists of two springs and two dampers. The angle spring generates an attractive moment toward zero, the amplitude of which depends on the angle error θ_{pi}. The damper force depends on the speed of changing of this angle ($\dot{\theta}_{pi}$). Finally, the amplitudes of the second spring and damper are proportional to the lateral distance error d, and its rate of change $\dot{d}$ respectively.

III. CONTROL

A. Longitudinal Control

Introducing the virtual truck in the new longitudinal model enables us to deal with relative speed instead of absolute speed, which enhances the performance of the longitudinal control and reduces the distance required to ensure string stability. This model is a modification of the Classical Time Headway policy by adding a new term V_s. This term makes the inter-vehicle distances proportional to relative velocities $v_i - V_s$ instead of being proportional to absolute velocities v_i, which largely reduces the inter-vehicle distances.

We propose the following curvilinear spacing error:

$$\delta_i = e_i - h_i \ (v_i - V_s) \tag{6}$$

Where h_i is the time headway constant for the i-th vehicle, V_s is a common speed value shared by all vehicles of the platoon. It must be the same for all the vehicles at any sampling time. We will discuss later how to set the parameter V_s.

The control law of the i-th vehicle is given by:

$$W_{1i} = -k_{a_i} \ a_i + k_{v_i} \ (v_{i-1} - v_i)_i + k_{p_i} \ \delta_i \tag{7}$$

where a_i is the acceleration of the i-th vehicle, k_{a_i}, k_{v_i} and k_{p_i} are constants coefficients for the i-th vehicle. For a homogeneous platoon all the vehicles use the same control gains, denoted as k_a, k_v and k_p . In the sequel we assume a homogeneous platoon unless otherwise mentioned.

B. Lateral Control

In lateral control, we use the sliding mode control. We define a sliding surface ψ as follows:

$$\psi = \dot{\theta}_{pi} + k_{\theta p} \ \theta_{pi} + k_d \ di \tag{8}$$

where $k_{\theta p}, k_d$ are weighting coefficients. The controller should provide an input that satisfies the following:

$$\dot{\psi} = -K \ \psi \tag{9}$$

with K a positive constant.

So from equations (9) (8) and (5), we get the following control law:

$$W_{2i} = -K \ \psi - k_{\theta p} \ \dot{\theta}_{pi} - k_d \ \dot{d}_i \tag{10}$$

which leads to a stable system.

IV. STABILITY AND SAFETY

A. String Stability of Longitudinal Control:

The general string stability definition in the time domain is given in [20]. In essence, it means that all the states are bounded if the initial states (position and speed errors) are bounded and summable. In the following we will study the cases of homogeneous and non-homogeneous platoon.

1) Homogeneous platoon: In [14] we find a sufficient condition for string stability is given ($\|e_i(t)\|_\infty \leq \|e_{i-1}(t)\|_\infty$), 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 defined by:

$$G_i(p) = \frac{E_i(p)}{E_{i-1}(p)} \tag{11}$$

$E_i(p) = \mathcal{L}(e_i(t))$ is the Laplace transform of $e_i(t)$. then a sufficient condition for string stability is:

$$\|G_i(p)\|_\infty \leq 1 \quad and \quad g_i(t) > 0 \quad i = 1, 2..N \tag{12}$$

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

We calculate the propagation transfer function $G_i(p)$ for homogeneous platoon using equations (1), (6), (7) and (11) and assuming precise and stable lateral control:

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

To ensure stability we must verify condition (12) so we get the sufficient conditions [1]:

$$\begin{aligned}&\left\{k_a^2 \geq 2\ (k_v + k_p\ h) \text{ and } k_p^2\ h^2 + 2\ k_p\ (k_v\ h - k_a) \geq 0\right\}\\ &\textbf{or}\left\{h\ k_a \geq 2 \text{ and } k_a^2 \geq 2k_v \text{ and } 2k_v \geq k_a^2 - \xi\right\}\\ &\textbf{or}\left\{h\ k_a \geq 2 \text{ and } k_a^2 \leq 2k_v \text{ and } 2k_v \leq k_a^2 + \xi\right\}\end{aligned} \tag{14}$$

where $\xi = \sqrt{4k_a k_p (k_a h - 2)}$.

Conditions 14 shows that string stability is not related to V_s: the only constraint is that the value must be shared by all the vehicles at any sampling time. So we can choose any value for V_s (*e.g.* the medium speed of the platoon, leader's speed or the minimum speed in the platoon...).

2) Non homogeneous platoon: To check the stability of the non homogeneous platoon, the condition given in (12) is no longer sufficient, so we calculate the dynamics of error using equations (1), (6), (7) and (11), assuming precise and stable lateral controlg:

$$E_i(p) = G_{N_i}(p)\ E_{i-1}(p) + G_{M_i}(p)\ (v_i(p) - V_s(p)) \tag{15}$$

$$\begin{aligned} G_{N_i}(p) &= \frac{k_{v_{i-1}} p + k_{p_{i-1}}}{p^3 + k_{a_i} p^2 + (k_{v_i} + k_{p_i} h_i) p + k_{p_i}} \\ G_{M_i}(p) &= \frac{k_{p_{i-1}} - k_{p_i}}{p^3 + k_{a_i} p^2 + (k_{v_i} + k_{p_i} h_i) p + k_{p_i}} \end{aligned} \tag{16}$$

To check the string stability of the platoon we try to find an upper limit of the error, so that we will be sure that the errors will not explode to infinity. So we try to find the error of the "infinity" vehicle and we find an upper limit for this error.

From (15) we calculate the relation between e_i and e_1:

$$\begin{aligned} E_i(p) = &\prod_{j=2}^{i} G_{N_j}(p)\ E_1(p) + \\ &\sum_{j=2}^{i} G_{M_j}(p) \prod_{k=j}^{i} G_{N_k}(p)\ (v_j(p) - V_s(p)) \end{aligned} \tag{17}$$

We take $||G_N(\omega)||_\infty = \max_i(||G_{N_i}(\omega)||_\infty)$ and $||G_M(\omega)||_\infty = \max_i(||G_{M_i}(\omega)||_\infty)$

For any positive impulse functions $g(t) = \mathcal{L}^{-1}(G(p))$, where $\mathcal{L}^{-1}(.)$ is the inverse Laplace transform, we have [20]:

$$||g(t)||_1 = ||G(\omega)||_\infty \tag{18}$$

So for positive $g_N(t) = \mathcal{L}^{-1}(G_N(p))$ and $g_M(t) = \mathcal{L}^{-1}(G_M(p))$ we get:

$$\begin{aligned} ||e_i(t)||_\infty \leq &||G_N(\omega)||_\infty^{i-2}\ ||e_1(t)||_\infty + \\ &||G_M(\omega)||_\infty \sum_{j=2}^{i} ||G_N(\omega)||_\infty^{i-j}\ ||v_j(t) - V_s(t)||_\infty \end{aligned} \tag{19}$$

$$\begin{aligned} ||e_i(t)||_\infty \leq &||G_N(\omega)||_\infty^{i-2}\ ||e_1(t)||_\infty + \\ &||G_M(\omega)||_\infty \frac{1 - ||G_N(\omega)||_\infty^{i-2}}{1 - ||G_N(\omega)||_\infty}\ \max_j \sup_t |v_j(t) - V_s(t)| \end{aligned} \tag{20}$$

We can make sure that the first term tends to zero. when $i \longrightarrow \infty$ by making $||G_N(\omega)||_\infty < 1$ because $||e_1||_\infty$ is bounded by the leader acceleration as in eq (22). $||G_N(\omega)||_\infty < 1$ is ensured by taking $k_{v_{i-1}} \leq k_{v_i}$ (so $h_{i-1} \geq h_i$ when we choose $k_{v_i} = 1/h_i$) and $k_{p_{i-1}} < k_{p_i}$, in addition to the conditions given in (14). $||G_M(\omega)||_\infty$ is bounded if $k_p \neq k_a^2 k_v/(1 - k_a^2)$; then the second term can be proved to be limited when $||G_N(\omega)||_\infty < 1$. So it is possible to ensure the stability of a non-homogeneous platoon by imposing the previous conditions on the "worst" case and by taking **increasing gain** k_p and **decreasing time headway** h_i.

We can see that the weak stability of CTH, when the transfer function becomes equal to 1 near low frequencies ($G_N(0) = 1$), is solved by taking increasing k_p and decreasing h. This can make $||G(\omega)||_\infty$ always smaller than 1.

B. Safety:

We will only study the safety of the platoon in case of the hard braking of the leader. This is the most important critical scenario. We also assume that the lateral control always keeps the vehicle on track.

In a stable platoon, the error e_1 between the leader and the first vehicle is always the largest error in the platoon in case of any changes in the leader motion. So if the amplitude of this error in the worst braking scenario is lower than l (the spacing is larger than zero) the safety of the platoon will be guaranteed. So we must find the dynamics of the first error. We choose $V_s = v_{leader}$ and we calculate the transfer function of the first error in the platoon using the equations (1), (6) and (7):

$$G_1(p) = \frac{e_1(p)}{a_{leader}(p)} = \frac{p + k_a}{p^3 + k_a\ p^2 + (k_v + h\ k_p)\ p + k_p} \tag{21}$$

where $a_{leader} \in [a_{max}, a_{min}]$ is the leader's acceleration, a_{max}, a_{min} are the maximum acceleration and deceleration respectively. So we can see that the maximum error amplitude is defined by the acceleration of the leader. By taking a positive $g_1(t)$ and from (18) and (21) we can get an upper limit for the first error:

$$\|e_1(t)\|_\infty \leq \|G_1(\omega)\|_\infty\ \max(|a_{max}|, |a_{min}|) \tag{22}$$

To ensure platoon safety, e_1 must remain smaller than the desired distance l in the worst deceleration scenario. So if we verify the following condition, safety will be ensured:

$$\|e_1(t)\|_\infty \leq \|G_1(\omega)\|_\infty\ \max(|a_{max}|, |a_{min}|) < l \tag{23}$$

Then sufficient safety conditions can be obtained:

$$\begin{aligned} &\left\{\begin{aligned} &k_p > \tfrac{|a_{min}|}{l} k_a \text{ and} \\ &k_a^4 + 8\ k_p\ k_a + 4\tfrac{a_{min}^2}{l^2} < 4\ (k_v + k_p\ h) k_a^2 \end{aligned}\right\} \textbf{or} \\ &\left\{\begin{aligned} &k_p > \tfrac{|a_{min}|}{l} k_a \text{ and } k_a^2 > 2\ (k_v + k_p\ h) \text{ and} \\ &(k_v + k_p\ h)^2 > 2k_p\ k_a + \tfrac{a_{min}^2}{l^2} \end{aligned}\right\} \end{aligned} \tag{24}$$

We can see that the safety of a *homogeneous* platoon is defined by the maximum acceleration and the desired inter-vehicle distance, and it is not related to its velocity.

V. SIMULATIONS

Simulations have been performed using TORCS. TORCS is a popular car racing simulator for academic purposes [13]. It features a sophisticated physics engine (aerodynamics, fuel consumption, traction...) as well as a 3D graphics engine for visualization fig. 5.

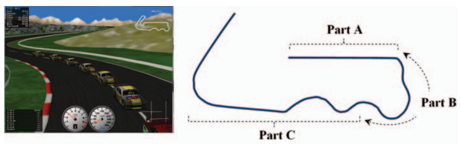

Fig. 5. TORCS window and test track

A curved track, shown in fig. 5, was chosen to test the stability of lateral and longitudinal control laws. A platoon of 10 identical cars moves along this track. The first part of the track is nearly straight (part A), to verify the longitudinal string stability during platoon creation and during speed changes. In the platoon creation phase, the vehicles accelerate from stationary state until they reach a speed of 25 km/h, keeping the desired inter-vehicle distance $l = 1\ m$. Then at $t = 60\ s$, the platoon accelerates from 25 km/h to 60 km/h to check string stability on a straight track. Then the platoon passes the curved part (part B) with fixed speed to check the lateral control stability. Finally, we verify the stability of both controls together and the safety of the longitudinal control when passing the last curved part (part C). Safety is verified by performing emergency stop, applying maximum allowed deceleration (decelerating from 60 km/h to stop). Then the platoon accelerates from stationary state to 60 km/h so we can verify string stability together with the lateral control stability.

We take the maximum acceleration equal to $5\,m/s^2$, which exceeds the comfort accelerations of $3.4\,m/s^2$ defined by AASHTO [6], and also exceeds the ability of most vehicles. We choose a maximum deceleration equal to $5\,m/s^2$, which also exceeds the comfort limit. The maximum and minimum jerks J are imposed by the requirement for comfortable ride and not by the vehicle limitation [10], so $J = \pm 6\,m/s^3$. Control parameters are chosen so that the system is stable and safe $k_v = k_a/h, k_p = 12, h = 4, k_a = 2.4$.

In [2], [3] we showed the advantages of using our new control law compared to classical CTH: the inter-vehicle distances are reduced from 30 m at a speed of 50 km/h, to 5 m. In the present work we can see in fig. 6 that we have reduced the distance even more (here 1 m). We can see also in the same figure in part A (the straight line) that the system is string stable during platoon creation and during speed changes, since the spacing error decreases as it propagates through the platoon, and the final inter-vehicle distance is equal to the desired distance l.

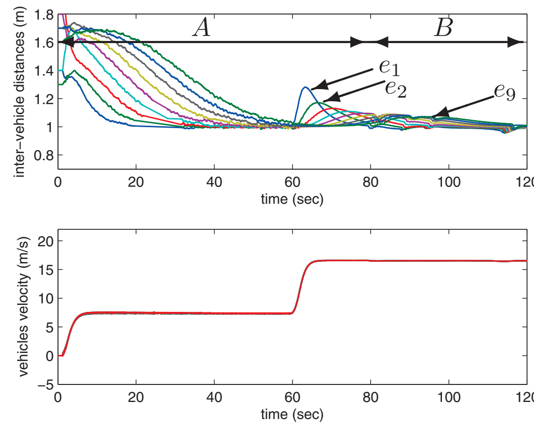

Fig. 6. Inter-vehicle distances and vehicle's speeds (parts A, B).

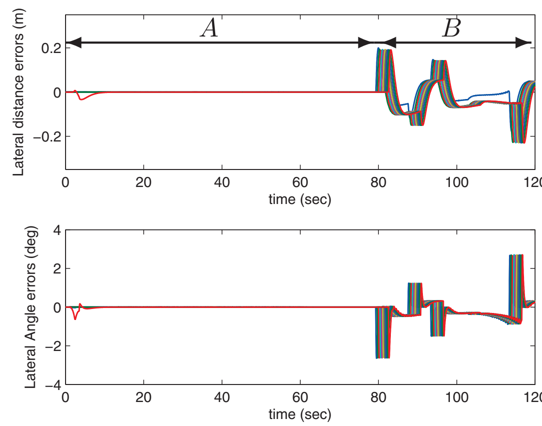

Fig. 7. Lateral angle and distance errors (parts A, B).

On part B of fig. 7, we can see that the lateral control is stable. Error values are very small (angle error $< \pm 3\ deg$ and distance error $\pm 25\ cm$). The results also show that the lateral control has very small effect on the inter-vehicle distances, which keep converging toward the desired distance.

Finally, on part C of fig. 8 and fig. 9, we test the stability of the two controls together and the safety of the longitudinal control. The results confirm that the system is string stable during emergency stop modes and during full acceleration modes. The lateral control is also stable and accurate. But we can see that the performance of the lateral control degrades when the platoon finishes the emergency stop. This degradation is due to the linearization singularity around $v_i = 0$. To avoid this singularity, another lateral control for very low speed must be used. In our simulation, we choose to make the platoon move at very low speed at the end of the emergency stop mode. Finally, we can see that the platoon is safe (the minimum inter-vehicule distance is bigger than 0.5 m); no collision happens when performing the emergency stop while passing the curved path C.

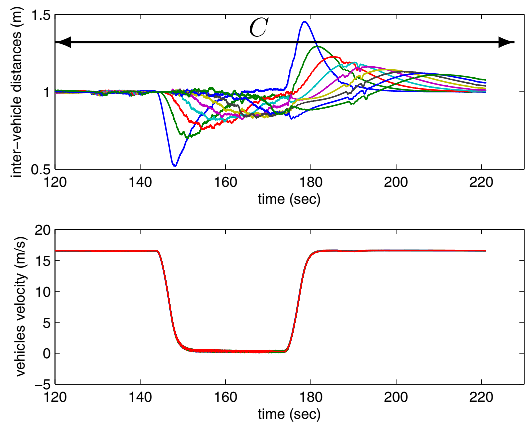

Fig. 8. Inter-vehicle distances and vehicle's speeds during emergency stop and acceleration (part C).

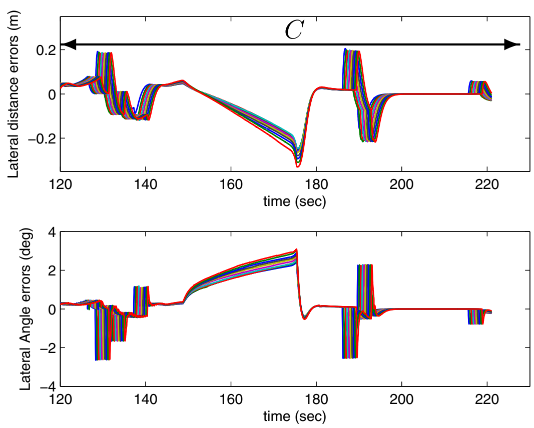

Fig. 9. Lateral angle and distance errors during emergency stop and acceleration (part C).

VI. CONCLUSION

In this paper, we have addressed the control of the platoons in urban areas. A decoupled dynamic longitudinal model and a kinematic lateral model are used and have been linearized. The lateral dynamics are controlled using sliding mode control and accurate performance is obtained. The longitudinal dynamics are controlled using a modified CTH control law taking into account a simplified engine model.

We have enhanced our previous works by reducing the spacing while maintaining string stability and ensuring safety. In addition, we extended our work by applying it to urban platoons and finding stability conditions for non-homogeneous platoons.

We can see that by applying the modified CTH to a non-homogeneous platoon we get rid of the main two weaknesses of the CTH. The first weakness is the weak stability near low frequencies, which is solved by taking increasing gain and decreasing time headways. The second weakness is the large spacing, which was already solved by introducing V_s.

Currently, a more realistic model is being studied [5], taking into account lags of actuators, sensing and communication delays.

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