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Auto-adaptive and string stable strategy for intelligent cruise control

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Abstract: This study completes the study of a longitudinal control strategy based on a non-linear acceleration profile model. The model is thoroughly defined by a set of two design parameters that make the control policy auto-adaptive. The control strategy is safe and Stop&Go consistent. The string stability property of the control policy is also analysed. Simulation results show that the control policy has a good string stability property with high string stability margin with respect to Pipes and Chandler's control strategy.

1 Introduction

Intelligent transportation systems (ITS) implement control techniques to fight unsafe and uncomfortable driving trends [1]. Calling for highly multidisciplinary and complex studies, these systems achieve satisfactory results in terms of safety, comfort, robustness and efficiency. Several applications of ITS already equip vehicles in today's traffic. These implementations have evolved from simple constant speed conservation (cruise control systems) to a sophisticated real-time adaptive speed control [adaptive cruise control (ACC)].

In cruise control, the objective consists only of maintaining the vehicle speed at a velocity chosen by the driver. Such systems do not take into account dynamics of traffic ahead. This limitation is tackled by ACC techniques.

Not only does ACC comply with cruise control specifications, but it also automatically adjusts speed to guarantee a safe vehicular interdistance with leading moving automotives. The speed and following distance are monitored with less variation, compared to human driving [2]. A headway detecting device (a radar for instance) as well as a signal processing are required to analyse the dynamics of the immediate leading vehicle. The idea consists in making the controlled vehicle brake in a suitable way to avoid collision with obstacles ahead and to make it re-accelerate to reach a pre-set velocity to maintain as long as no obstacle is detected [3]. A variety of ACC systems from several manufacturers feeds the market of ITS. Some implementations of ACC use artificial intelligence techniques to simulate a human-like driving. Fuzzy control and artificial neural network are some of these methods [4, 5]. Conventional techniques, however, rely on mathematical representations of vehicles' dynamics [6–9].

In heavy traffic conditions, drivers have to perform tiring and repetitive manoeuvres of Stop&Go. For safety and comfort reasons, ITS systems have to handle these manoeuvres. This made Stop&Go systems come into play [10]. Stop&Go technologies increase driving comfort by smoothing traffic speed. ACC and Stop&Go techniques are complementary and are generally designed separately. Some recent works, however, have introduced strategies that perform together ACC and Stop&Go. For example, in [11] an analytical model, based on the physical law of compliant contact that is consistent with ACC as well as Stop&Go specifications is offered.

In the domain of ITS, approaches generally differ on the basis of safe interdistance management and the way comfort is evaluated.

1.1 Variety of interdistance management policies

Safe interdistance is commonly defined as the minimum interdistance that ensures avoidance of vehicles rear-front collision no matter how the driver of the leading vehicle behaves. A vehicle running at a given speed v_0 has a distance to stop depending upon the value of v_0. This distance, if that vehicle is assumed to brake with a constant braking rate of value a, can be evaluated as

$$d_{\text{stop}} = \frac{v_0^2}{2a} \tag{1}$$

Yet because of reaction time, a following vehicle will not start braking as soon as the leading vehicle does. This imposes that before starting manoeuvre to avoid a collision, the following vehicle runs over a distance that is proportional to the reaction time. Such considerations have led to a control strategy that is sometimes referred to as the Newtonian motion equation and is characterised by the following expression of safe interdistance d_{safe} [11–13].

$$d_{\text{safe}} = \gamma_1(v_f^2 - v_l^2) + \gamma_2 v_f + \gamma_3 \tag{2}$$

where γ_1, γ_2 and γ_3 are constants, v_f and v_l represent in this order speeds of following and leading vehicles. The first term of this equation expresses the relative braking distance, the second corresponds to the distance run during reaction time and γ_3 is the minimal constant distance to meet.

Another well-known interdistance control strategy is the 'Constant time-headway rule' that consists of maintaining an interdistance proportional to the reaction time. This strategy is the one indicated and required for drivers. The safe interdistance is then computed as

$$d_{\text{safe}} = \gamma_2 v_f + \gamma_3 \tag{3}$$

Many studies offer improvements of this control policy, with more and more complex algorithms for the determination of the headway. For example, in the context of cooperative vehicle convoys look-ahead control, when only the vehicle directly ahead is considered, lower bound for headway h is established as [14]

$$h \geq (2 - \sqrt{2})\frac{\alpha}{\beta} \tag{4}$$

In the strategy, accelerations and jerks of vehicles engaged are assumed to be bounded by α and β, respectively. The same work shows that if information on n leading vehicles of a convoy is taken into account, this bound changes to the following expression

$$h \geq \frac{2}{n(n+1)}\frac{\alpha}{\beta} \tag{5}$$

In [11, 15], safe interdistance is computed from a non-linear second-order model and depends only upon the maximal braking rate of the controlled vehicle and its initial speed. It is expressed in the following relation

$$d_{\text{safe}} = d_c + \sqrt{\frac{16}{27}\frac{v_0^2}{B_{\max 1}}} \tag{6}$$

where d_c is the minimal constant interdistance when the vehicles are stopped.

1.2 ITS facing traffic stability

Besides safety and comfort, string (or platoon) stability is an important characteristic of a good longitudinal control strategy. A traffic is said to be string stable when any disturbance to the motion is attenuated as it propagates along the vehicles convoy: the range errors decrease as they pass along the vehicle stream. In other words, string stability ensures that variation of preceding vehicle velocity does not lead to amplified fluctuations in following vehicle velocity. The string stability problem has been investigated since 1977 [16] and is proven to be guaranteed as long as the transfer function from the range error of one vehicle of the stream to that of its following vehicle shows a magnitude less than 1 [17].

Zhou and Peng [18] designed a non-linear speed-dependant range policy inspired by human driving behaviour that they stabilised using the sliding control techniques. Liang and Peng [19] offer an optimal ACC design that is structurally string stable. The notion of string stability margin (SSM) is also introduced in that paper. SSM of an ACC design is an important notion that suits mixed traffic and basically denotes the number of successive standard manual vehicles that instability can be corrected by one ACC vehicle to keep the global string stable. It allows comparison between string stability efficiency of different ACC policies. Unless otherwise specified, the definition of mixed traffic will apply to a traffic that is composed with vehicles controlled from our ACC strategy and vehicles that are manually driven. Manual vehicles will be assumed governed on the basis of the Pipes and Chandler's human driving model [20].

This paper completes the study of the non-linear and second-order longitudinal control strategy introduced in [21]. The strategy is shown to be auto-adaptive and Stop&Go consistent property also demonstrates that the control strategy is string stable and can present high SSM compared to human driving policy. The remainder of the paper is structured as follows: Section 2 presents and analyses the longitudinal control strategy with respect to the model design parameters, the auto-adaptativity and Stop&Go property of the policy are analysed. Section 3 deals with the string stability of the control strategy. The human driving policy is simulated by the Pipes and Chandler's model and compared to the offered strategy as far as string stability is concerned.

2 Control strategy

Fig. 1 illustrates the configuration where the control strategy applies. The host vehicle is assumed to be cruising at initial speed $\dot{x}_1$. A safe interdistance that coincides with the distance to stop is introduced and referred to as d_0. The strategy consists in host vehicle acceleration control when an obstacle has been located close enough to be considered dangerous. The approach considers that at standstill the minimum safe interdistance is non-negative and worth's d_c. During control, the host vehicle is constrained to meet a non-linear acceleration of the form

$$\ddot{x}_1 = -\alpha c \mathrm{e}^{cd}\dot{d} \tag{7}$$

where the penetration distance d worth's 0 at time $t = 0$ and is evaluated then on forth as the difference between the relative distance and the safe interdistance at initial speed; α and c are non-negative parameters.

Integration of (7) yields the following speed control policy:

Reporting in (7) that the following vehicle comes to a complete stop over a distance to stop $d_m = d_0 - d_c$, one obtains

$$\mathrm{e}^{cd_m} = 1 + \frac{\dot{x}_1(0)}{\alpha} \tag{8}$$

Eventually, the strategy yields the following safe interdistance

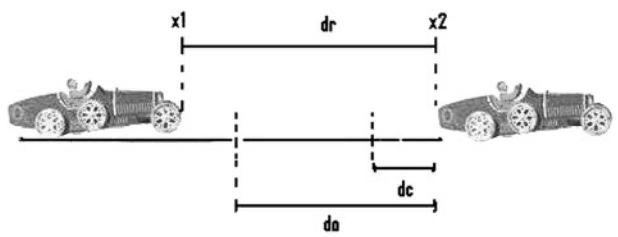

Fig. 1 *Important areas on interdistance*

policy

$$d_0 = d_c + \frac{(\alpha + \dot{x}_1(0))^2}{4B_{max}}, \quad \ln\left(1 + \frac{\dot{x}_1(0)}{\alpha}\right) \tag{9}$$

where B_{max} is the maximum braking rate of host vehicle.

The control strategy is fully presented in [21].

As one can see, the strategy is mainly influenced by parameters α and c.

2.1 Influence of parameters α and c

Parameters α and c play fundamental roles in the control strategy. They imposes the safe interdistance together with B_{max1} and $\dot{x}_1(0)$, they influence comfort throughout acceleration as well as jerk. Simulations show that a greater value of α shorter the required safe interdistance and amplifies the magnitudes of acceleration and jerk. Such identical remarks can be made as well with parameter c. These parameters act as braking reinforcement agents. Fig. 2 shows up the influence of parameter α for a constant value of parameter c which worth's $c = 0.025\ \mathrm{m}^{-1}$. As for Fig. 3, it shows up the influence of parameter c for a constant value of parameter α. In that simulation $\alpha = 10$ m/s. In both simulations, the initial speed of following vehicle is 30 m/s and the leading vehicle is assumed to be stopped.

As the interdistance depends on the model parameters, it is possible, by monitoring them, to impose the value of the interdistance between vehicles and make the control strategy auto-adaptive.

2.2 Auto-adaptive control strategy

As already shown, parameters α and c monitor the safe interdistance. Is there any simple technique that could allow controlling the value of safe interdistance from one or both parameters? The benefit of such a technique would be to enable an auto-adaptation of the control profile according to driver's choices of safe interdistance. Actually, when cruise control systems equip a vehicle, the driver intervention on the braking pedal disables the autonomous cruise control mode and switches to manual driving mode. The problem is that sometimes drivers have the impression that the control system starts acting late. The idea consists in adapting the distance from which the control strategy starts applying so

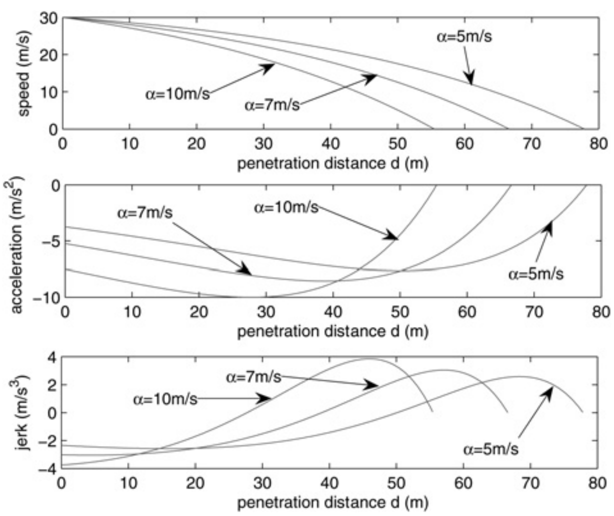

Fig. 2 *Influence of parameter α on the control model*

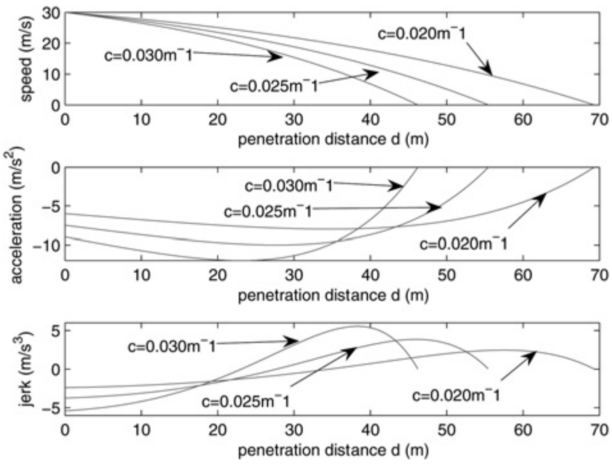

Fig. 3 *Influence of parameter c on the control model*

that it corresponds to the driver will even if in such cases the following policy is no longer optimal as for congestion fighting.

Let us assume a reference vehicle following a leading vehicle at initial speed $\dot{x}_1(0)$. In default strategy, the control system will start braking at the interdistance given by (9) with $\alpha = \alpha_{opt}$. Let us denote by $d_{rmanual}$, the relative interdistance desired by the driver for initial speed $\dot{x}_1(0)$. In the following, we aim to offer a simple algorithm to adapt parameter α to meet the driver-desired safe interdistance. The gap between the optimal interdistance and $d_{rmanual}$ can be expressed as

$$d_{gap} = d_{rmanual} - d_0 \tag{10}$$

We apply a modifier α_{mod} to the optimal value of α, α_{opt} to meet interdistance $d_{rmanual}$. The new acceleration profile is then

$$\ddot{x}_1 = -\alpha_{opt}\alpha_{mod}c\mathrm{e}^{cd}\dot{d} \tag{11}$$

and one gets

$$\dot{x}_1 = -\alpha_{opt}\alpha_{mod}\mathrm{e}^{cd} + \dot{x}_1(0) + \alpha_{opt}\alpha_{mod} \tag{12}$$

If the reference vehicle gets to stop, the new distance to stop is $d_{stop} + d_{gap}$

$$-\alpha_{opt}\alpha_{mod}\mathrm{e}^{c(d_{stop}+d_{gap})} + \dot{x}_1(0) + \alpha_{opt}\alpha_{mod} = 0 \tag{13}$$

hence

$$\alpha_{mod} = \frac{\dot{x}_1(0)}{\alpha_{opt}(\mathrm{e}^{c(d_{stop}+d_{gap})} - 1)} \tag{14}$$

with $d_{stop} = d_0 - d_c$, d_{gap} given by relation (10) and $\alpha = \alpha_{opt}$.

The auto-adaptive control algorithm will rely on (14) to determine the appropriate modifier to apply to α_{opt} in order to meet the driver's style of driving. One has, for the optimal driving policy, $\alpha_{mod} = 1$ and for any other driving policy $\alpha_{mod} < 1$.

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The stationary interdistance in that case changes to the following

$$I_{st2} = d_c + \frac{(\alpha_{opt}\alpha_{mod} + \dot{x}_1(0))^2}{4B_{max1}}, \\ \ln\left(\frac{1 + (\dot{x}_1(0)/\alpha_{opt}\alpha_{mod})}{1 + [(\dot{x}_1(0) - \dot{x}_2)/\alpha_{opt}\alpha_{mod}]}\right) \quad (15)$$

Fig. 4 displays the variation of α_{mod} in function of desired interdistance. In the simulation, the reference vehicle runs at initial speed 30 m/s. One can see how the value of α_{mod} decreases from 1 as the driver-desired interdistance increases.

2.3 Stop&Go consistent strategy

To give an illustration of results achieved with the offered model, a test profile for the leading vehicle has been designed, that includes cruise control, as well as Stop&Go through very hard stop. It is considered that the following vehicle is initially running at the velocity $\dot{x}_1(0) = 30\,\text{m/s}$ and has a maximum braking capacity of value $B_{max1} = 10\,\text{m/s}^2$. The minimum interdistance at stop d_c worths 5 m. Initial configuration is defined by a relative interdistance $d_r = d_0 = 60$ m, initial speed of leading vehicle $\dot{x}_2(0) = 20\,\text{m/s}$. The strategy applied is the infinite braking rate strategy.

The following vehicle decelerates comfortably to match speed of leading vehicle and then remains at the safe stationary interdistance which is worth about 33 m in the simulation. At time $t = 27$ s, the leading vehicle performs a very hard stop with a constant deceleration value (almost B_{max1}) and reaches a jerk magnitude of $20\,\text{m/s}^3$. The controlled vehicle manoeuvres to stop with a deceleration magnitude that hardly attains $8.5\,\text{m/s}^2$ and a jerk magnitude less than $4\,\text{m/s}^3$.

These results are illustrated in Fig. 5 where dynamic characteristics of following vehicle are displayed with continuous lines and those of leading vehicle with dashed lines. They prove that the model, beyond being safe and Stop&Go consistent is also comfortable.

So far, only the dynamics of the controlled vehicle with respect to a single other vehicle has been analysed. One might legitimately question the way the dynamics of the controlled vehicle would be in a traffic of several vehicles.

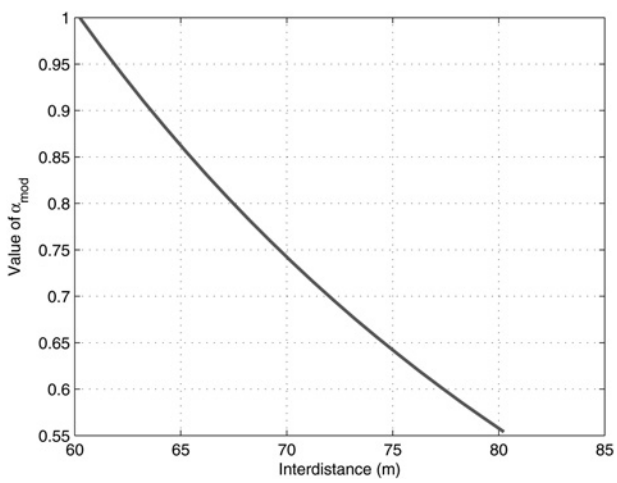

Fig. 4 *Variation of α_{mod} in function of desired interdistance*

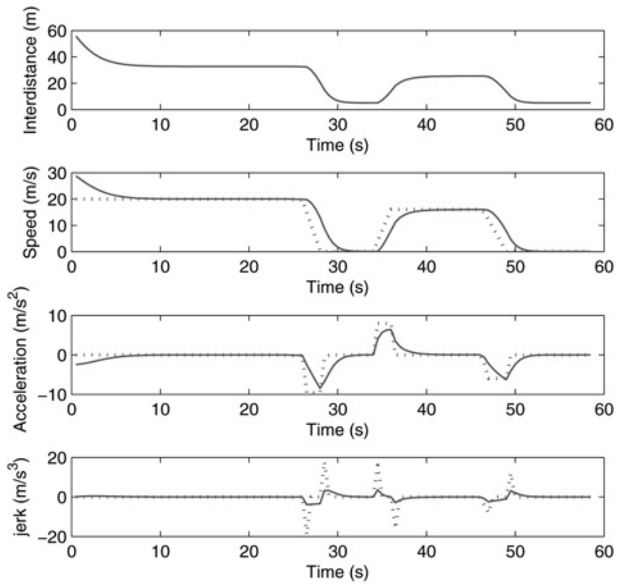

Fig. 5 *Stop&Go illustration*

3 Control strategy string stability

3.1 Human driving vehicles traffic

In order to analyse standard manual vehicle traffic, Chandler's driver model is used to simulate every driver of the traffic. We consider a platoon of n vehicles numbered from 1 to n so that vehicle i follows vehicle $i-1$. Chandler's model can then be written as [19]

$$\dot{v}_i(t) = \frac{\lambda}{M}[v_{i-1}(t-\Delta) - v_i(t-\Delta)] \quad (16)$$

In this expression, λ denotes the sensitivity of the control mechanism, M represents the mass of the vehicle and Δ refers to the human driver time delay. Chandler evaluates the average value of λ/M to worth 0.368 s and the average time delay Δ to 1.55 s. The transfer function of this human driving technique model can then be expressed by the following expression

$$G_H = \frac{v_i}{v_{i-1}} = \frac{0.368\mathrm{e}^{-1.55}}{p + 0.368\mathrm{e}^{-1.55p}} \quad (17)$$

which expression can be approximated [19]

$$G_H = \frac{-0.57p + 0.74}{1.55p^2 + 1.43p + 0.74} \quad (18)$$

To illustrate the string instability of this model, we implemented a platoon of $n = 31$ vehicles in Matlab. The simulations assume that the vehicles follow one the other in a single lane with no passing. In both simulations, all the vehicles drive at an initial speed of 30 m/s and then the leading vehicle accelerates with the constant acceleration rate of $1\,\text{m/s}^2$ to reach the speed of 33 m/s which it keeps for about 10 s before braking at $1\,\text{m/s}^2$ to its initial speed of 30 m/s. The speed profile of leading vehicle is refered to as v_0. Figs. 6 and 7 display the result. In Fig. 6 the average time delay $\Delta = 1.55$ s has been chosen equal for all vehicles. In Fig. 7, time delay of each vehicle is randomly and uniformly chosen between 1 and 2 s. Both simulations

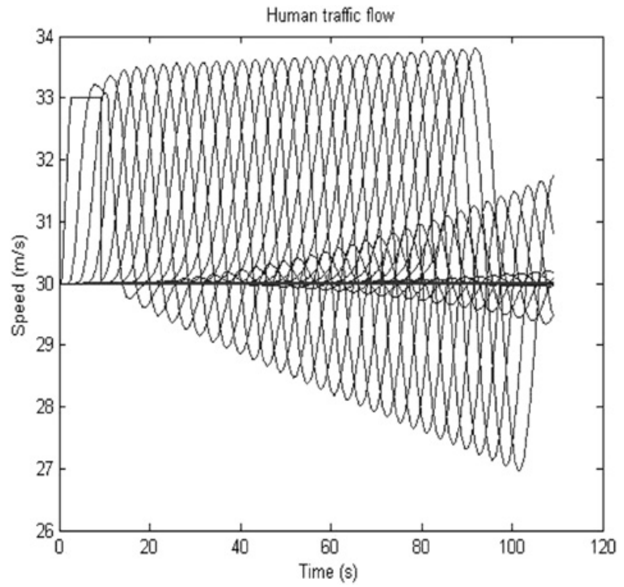

Fig. 6 *Human model traffic instability for constant reaction time*

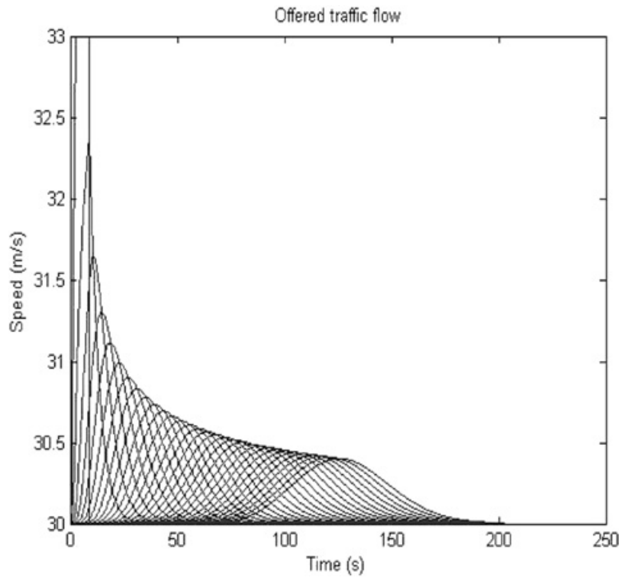

Fig. 8 *String stability with the offered ACC model*

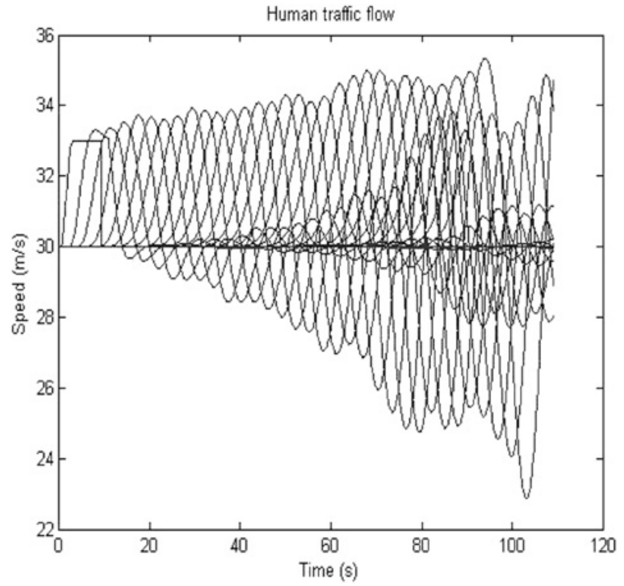

Fig. 7 *Human model traffic instability for random reaction time*

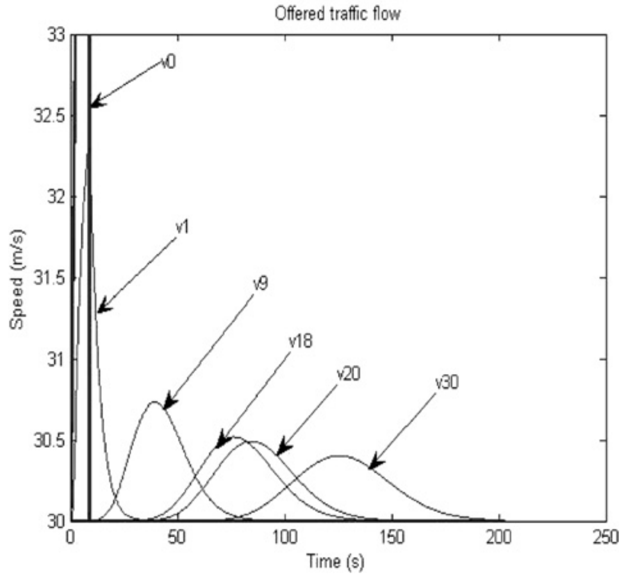

Fig. 9 *No slinky effect with the offered ACC model*

demonstrate that the human driving model is string unstable. The slinky effect is because the model is high.

3.2 Offered ACC model traffic

We performed the same simulation with the offered ACC strategy. The number of vehicles is still $n = 31$ and the leading vehicle has the same velocity profile as in the case of human driving policy. Figs. 8 and 9 show that the slinky effect has disappeared, the string stability has been largely met.

The ACC model provides really satisfactory results as for string stability and slinky effect avoidance. The results presented so far assumed a uniform driving policy for platoon vehicles, an assumption which does not correspond to what happens in today's traffic.

In fact, platoons, nowadays, are likely to be composed by both vehicles running in the manual mode and even different ACC-based vehicles. In the following the term 'mixed' will apply to a traffic where vehicles are either in manual mode or piloted on the basis of the offered ACC strategy.

3.3 Offered ACC model improves mixed platoons stability

The aim in this section is to show that the proposed ACC model has a great benefit on traffic stability enhancement. It is shown here, through simulations that it has a large SSM.

Let us consider a mixed platoon of p vehicles. Each vehicle of the platoon has a car-following policy transfer function G_{human} if the vehicle is in manual mode or G_{acc} if it is monitored with the ACC algorithm. The concerned platoon stability is ensured when one has [19]

$$\| G_{\text{hum}}^{\text{m}}\ G_{\text{acc}}^{p-\text{m}} \| \leq 1 \tag{19}$$

where m denotes the number of manually driven vehicles in

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the platoon. As the manual driving policy is unstable, one has

$$\|G_{\text{hum}}\| > 1 \tag{20}$$

which also yields

$$\|G_{\text{hum}}^{\text{m}}\| > 1 \tag{21}$$

and the module of $\|G_{\text{hum}}^{\text{m}}\|$ amplifies as the number m grows. So ensuring stability in a mixed environment implies that the ACC model has high stability performance and must satisfy the following strict inequality

$$\|G_{\text{acc}}\| < 1 \tag{22}$$

which seems to be the case according to the simulation results in the preceding section.

Figs. 10 and 11 show simulation results for mixed environment. The reaction time for manual vehicles has been randomly and uniformly chosen between 1 and 2 s.

In Fig. 10 show the simulation performed on a vehicle platoon of $n = 101$ vehicles. Here, 25 ACC vehicles were regularly placed in the positions 4, 8, 12, 16, ..., 96, 100 and separated by manual vehicles. In Fig. 11, 101 vehicles were also considered, yet 24 ACC vehicles were randomly positioned in the platoon. The penetration rate in both simulations is therefore about 25%. The results clearly show that the string stability of the whole platoon is ensured. The slinky effect is inexistent (or almost) and the perturbation amplitude decreases with the vehicle position in the platoon.

From the results, one can see that 25% introduction of the ACC model in traffic would stabilise it. It is possible that even a much lower percentage of penetration would ensure mixed traffic stability. The following lines deal with SSM. The goal is to approximate the number of successive manual vehicles that instability can be corrected by only one ACC to make the whole string stable. As mathematical computations seem impossible to lead us to an explicit result because of the model complexity, through simulation we offer to set a lower bound for the ACC model SSM. Yet, this lower bound SSM is quite large even in comparison to the SSM

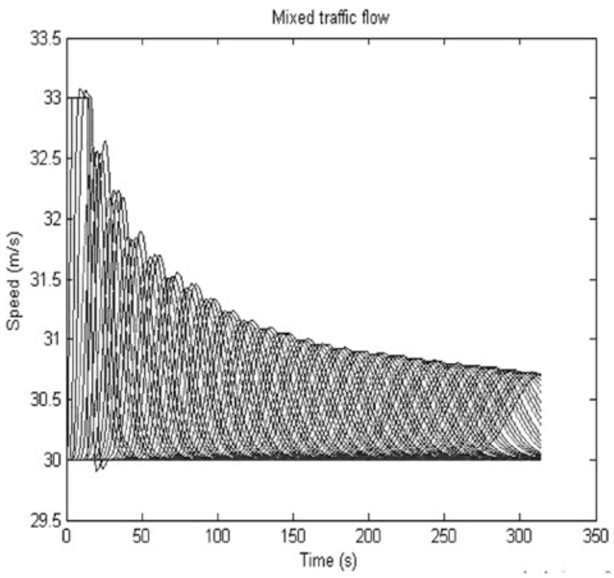

Fig. 10 *Regularly spaced ACC vehicles*
Mixed platoon resists the leader speed perturbation

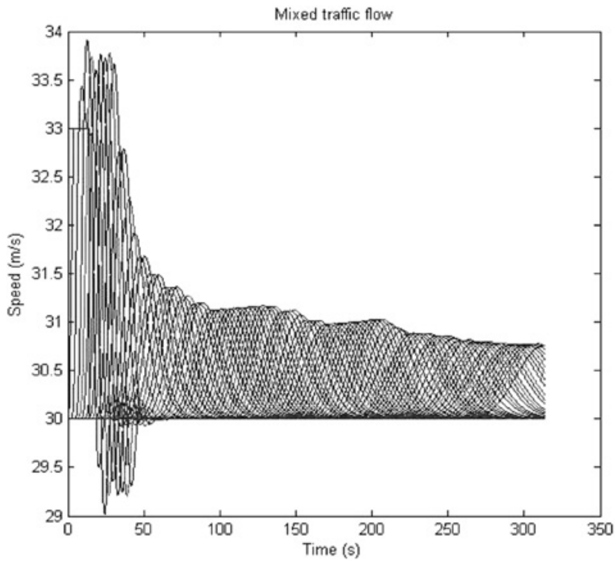

Fig. 11 *Random ACC position*
Mixed platoon resists the leader speed perturbation

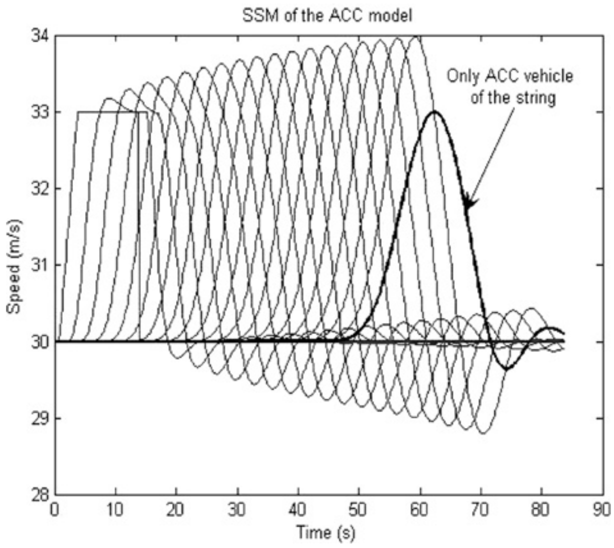

Fig. 12 *SSM for the ACC model*

of the optimal control model introduced in [19] and that has been especially designed in the context of string stability and SSM.

To determine a lower bound for SSM for the scenario, we progressively augmented the number of manual vehicles that precede the only ACC vehicle and stopped when the maximum speed of the ACC velocity profile attains almost 33 m/s. In Fig. 12, 19 manual vehicles controlled on the basis of the Pipes model precede one ACC vehicle which speed reaches the maximum value of 32.99 m/s.

3.4 Discussion

Because the offered control strategy is based on a strongly non-linear model, no transfer function can be evaluated for the control policy. Therefore it is not possible to determine the absolute SSM of the control strategy with respect Chandler's model. The SSM can only be evaluated for given scenarios. It can therefore vary from one configuration to another.

4 Conclusions

In this paper, a non-linear longitudinal control strategy has been studied. The control strategy was shown to be auto-adaptive, that is, the control system can modify the control model parameters to suit the driver's expectation. The strategy is also consistent with ACC as well as Stop&Go applications.

The strategy drastically attenuates speed perturbation through a vehicle convoy and therefore proves a good string stability property. Because of the non-linearity of the control strategy model, no transfer function could be yielded and therefore a global SSM could not be determined with respect to human driving. Nevertheless, the value of SSM determined through simulation of a case study is highly satisfactory.

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