Platooning Techniques for the Intelligent Highway : How Close Can We get?

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Abstract

Platoons of vehicles have been advocated for many years in order to increase the throughput of highways. Indeed, this is often presented as the major benefit of the automatic highway with potential gains of 400

1. Introduction

1.1. Background

With the increase in the standards of living in most countries, private means of transportation are constantly increasing leading to well known problems of pollution and congestion. The solution have been up to now to increase the road networks or their capacities. However, we have now reached a point where in many places this increase is not acceptable in economic terms due to the scarcity of land resources or the cost of alternative solutions such as underground roads.The solution of congestion as well as the solution to other problems such as safety, energy usage or speed of road travel has often been seen in the "automatic highway". This concept dates back from the thirties but has been extensively researched only in the last twenty years. Out of these twenty years, only the very last few have seen experiments conducted to demonstrate the feasibility of the concept.The principal idea behind the concept id to "bunch" a number of cars together so that they drive at very short distances to one another. This is made possible at a supposedly high safety by automating the "car-following" task, at least longitudinaly. The first car in the platoon can be either in manual mode or - preferably for safety and liability reasons - in automatic mode.Depending on the number of cars in a platoon and the distance between platoons, throughput increases of a factor of 4 can be envisionned. However, in all instances, this concept can work only if the technology allows us to keep the platoon in a safe configuration under all crcomstances, including of course emergency breaking. This had not been demonstrated up to now. This paper presents a system which demonstrate this capability by using a novel position sensor and sophisticated control technology on an electric vehicle (which probably represents the future drive technology in hybrid vehicles).

1.2. Particular constraints

The first constraint is linked to the performances of the vehicles in speed and acceleration. It is clear that the lead vehicle should impose on itself the least performances of the fleet. Therefore we have decided to limit the acceleration to $2m/s/s$ and the deceleration (in emergency situations) to $5m/s/s$.

the second is linked to the regulation of the platoon. The platoon should be stable asymptotically, that is, without any amplification from one car to the next which would rapidly invalidate the previous constraint.

2. Formulations

The problem can be formulated as the control in acceleration and turning radius of a vehicle with respect to a previous one which it tries to follow as close as possible. We have no a priori knowledge of the behavior of the preceding vehicle which can therefore chose its own path and its own speed profile. In normal driving conditions, the state of each vehicle can be characterized by its location and orientation in the plane (three degrees of freedom constrained) and its longitudinal and angular speeds (linked through its front wheel angle).

The control we want to apply to the following vehicle concerns the acceleration (or deceleration), that is the motor torque (positive or negative) and eventually the brake pressure for emergency situations, and the changes in wheel angle.

This control will receive as input, estimates of the state of the preceding vehicle obtained through sensors in order to follow as closely as possible this preceding vehicle in a safe way. The only assumptions we will make about the behavior of the previous vehicle is that its performances in acceleration and turning radius will never exceed those of the following vehicle.

In order to simplify the problem, we have decided to separate it into two distinct problems : a longitudinal control and a lateral control. We think that these two problems are sufficiently independent in normal driving conditions to validate this assumption.

2.1. Longitudinal Controller

The main constraint in platooning is that you can't allow any amplification from one car to the next and it is well know that without constant and rapid communication of the speed of the first vehicle to all the vehicles in the platoon (which we do not want to assume), it is not possible to maintain a constant distance between the vehicles.

So we have chosen to set a linear relation between the distance and the speed of the vehicles :

$$X_l - X_f = d\min + h \cdot V_f$$

where X_l represent the position of leading vehicle and X_f the position of the following vehicle, or after differentiation :

$$V_l - V_f = h \cdot A_f$$

or in Laplace form :

$$V_f = \frac{V_l}{1 + h.s}$$

So we can see that this choice is equivalent to filter the speed with a low pass constant of h seconds and it is asymptotically stable. We are already experimenting with h=0.35s and dmin=1m and our goal is to reduce these values to h=.2s and dmin=0.5m.

2.1.1. Constant Gain Linear Corrector

For the moment, we have chosen not to take a Jerk saturation into account. This means that we take the acceleration as the command variable and this leads to the following controller:

$$A_{fc} = C_v \Delta V + C_p (\Delta X - hVf - d\min)$$

with $\Delta V = V_l - V_f$ and $\Delta X = X_l - X_f$.Indeed, we want to maintain $\Delta X = hVf + d\min$ as best as we can. The closed loop transmittance with no acceleration saturation is :

$$\frac{X_f(s)}{Xl(s)} = \frac{C_v.s + C_p}{s^2 + (C_v + C_p.h)s + C_p}$$

since we want :

$$\frac{X_f(s)}{Xl(s)} = \frac{1}{1 + h.s}$$

Which leads to the following choices : $C_v = \frac{1}{h}$ and $Cp \leq \frac{1}{h^2}$ .The larger Cp is,the faster the system is. Hence we are tempted to choose $Cp = \frac{1}{h^2}$. This would be optimal if saturations in acceleration are not taken into account. However they are important :$|A_f| < A_{\max} = 2m/s^2$with the electric motor in traction or brake. So we must study the influence of saturations.

2.1.2. Linear corrector with variable coefficients

Let Vo be the initial speed of the vehicle. We can compute the minimal stopping distance D which satisfies the limitations :

$$D(V_0) = \frac{V_0^2}{2.A_{\max}}$$

We can define a safety zone where : $\Delta X \geq D(Vf) - D(Vl)$. An optimal control can be obtained by sliding along the security curve : $\Delta X + D(Vl) - D(Vf) = 0$. After linearization, we obtain : $\Delta X + \frac{\partial D(Vf)}{\partial Vf}\Delta V = 0$. One finds a corrector of the form :

$$\Delta v + Kp.\Delta x = 0 \text{ with } , Kp = \frac{Vf}{A\max}$$

and this gives us a variable gain corrector with :

$$A_{fc} = \frac{1}{h}(\Delta V + K_p(\Delta X - hVf - d\min))$$

with $K_p = \min(\frac{1}{h}, \frac{A\max}{Vf})$.This controller can bear great initial errors since the position gain Kp decreases when the speed increases.

2.1.3. Acceleration control

Now we have to control the vehicle acceleration A_f at the desired value A_{fc}.We have two actuators :

-An electrical motor controlled by a voltage U which provides a force $F = F(U, V_f)$. (You can see the experimental measurements fig1) : its response time is very short.

-Brakes controlled in pressure by a PID with a piston whose response time is long ($\simeq 0.3s$). So we used them only in emergency cases when the required deceleration $A_{fc} \leq -2m/s^2$. In that case we add hydraulic braking to motor deceleration.

-The longitudinal dynamics are described by the following equations:

$$M.A_f = F_t - k(V_f + V_{wind})^2 + Mg\sin(\theta)$$

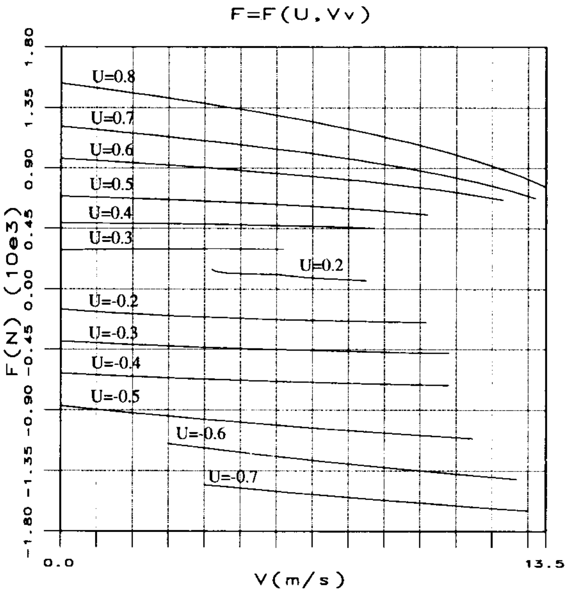

Figure 1. Electrical motor force

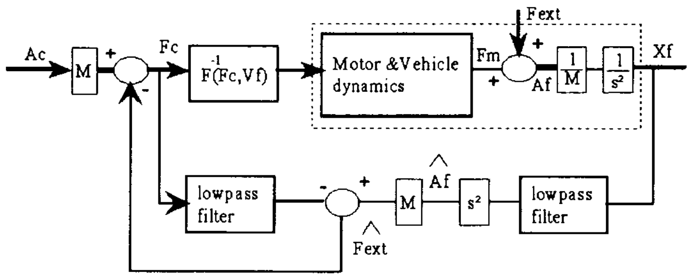

Figure 2. Acceleration controller

$$J\omega_w^{\circ} = r_w\left(F_m - F_b - Ft\right)$$

which gives with a good approximation

$$M.A_f \simeq F_m - F_b + Mg\sin(\theta)$$

the main problem is the estimation of the road gradient θ.

So we designed the acceleration controller with the inverted characteristics of the electrical motor : $U = F^{-1}(F_m, V_f)$ and a gradient estimator, it gives the scheme presented in (fig 2):

2.2. Lateral Controller

At the moment , we are using a simple cinematic model for the lateral part which is in the cartesian

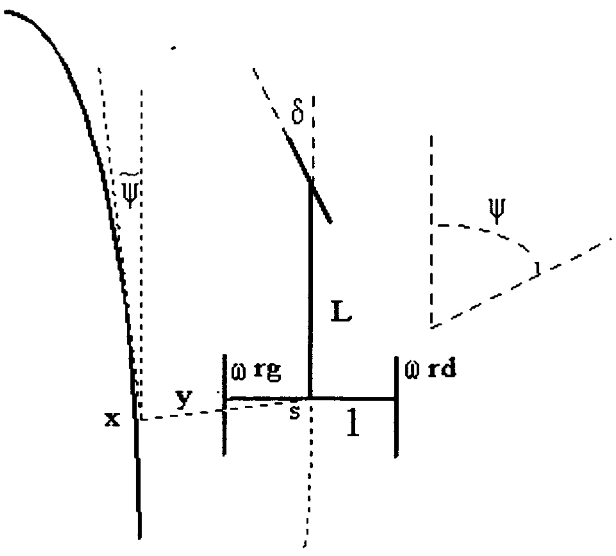

Figure 3. lateral model and errors

space :

$$\begin{pmatrix} \overset{\circ}{X}_0 = V\cos(\Psi_0) \\ \overset{\circ}{Y}_0 = V\sin(\Psi_0) \\ \overset{\circ}{\Psi}_0 = V\frac{\tan(\delta)}{L} \end{pmatrix}$$

We have very precise encoders on the rear wheels which allow us to estimate the speed Vf , the derivative of course $\overset{\circ}{\Psi}_0$ and the path of the car in the cartesian space.

$$\begin{pmatrix} \overset{\circ}{\Psi}_0 = r_w\frac{\omega_{rr}-\omega_{rl}}{l} \\ V = r_w\frac{\omega_{rr}+\omega_{rl}}{2} \end{pmatrix}$$

The simplest control we can think of is to select the wheel angle as equal to the direction of the leading vehicle.

$$\tan(\delta) = \frac{\Delta Y}{\Delta X - L}$$

This is the so-called tractor model and it is very stable although it leads to a following vehicle which cuts corner and this might be a problem with a train of a large number of cars or in sharp turns.

Some more complex lateral control are at the moment in progress, our goal is to be as close as possible to the leader path. We propose two others instantaneous controls with polynomials curves and a method which memorizes the trajectory of the previous vehicle and servos the automated vehicle on this trajectory.

With a third degree polynomial which verify the positions and courses of the two cars we obtain :

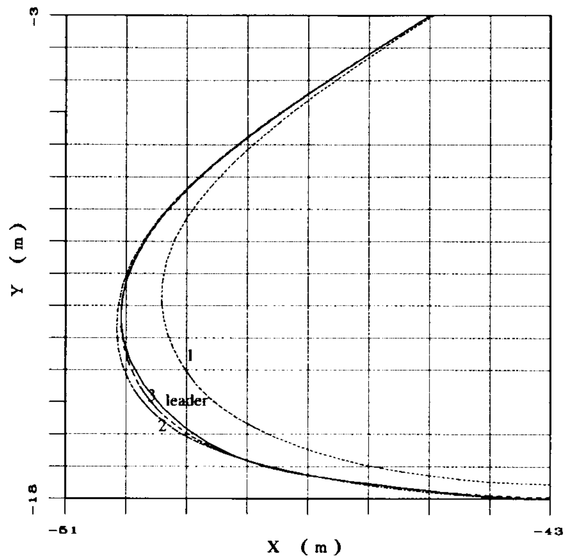

Figure 4. Instantaneous following

$$\tan(\delta) = 2L \cdot \frac{3\Delta Y - \Delta X \cdot \tan(\Delta\Psi)}{(\Delta X)^2}$$

with a fourth degree polynomial which verify the positions and courses of the two cars and the curvature Cf continuity of the follower path we obtain :

$$\overset{\circ}{\delta} = \frac{6V_f \cdot L \cdot b}{1 + \tan^2(\delta)} \text{ with}$$

$$b = \frac{4\Delta Y - \Delta X \cdot \tan(\Delta\Psi) - C_f \cdot (\Delta X)^2}{(\Delta X)^3} \text{ and}$$

$$C_f = \frac{\tan(\delta)}{L}$$

with simulation we can compare this three different methods : the tractor one (1) , the cubic one (2) and the quadric one(3) (fig 4).

The other method is based on the following of a path: the memorized path of the leader car. We want to minimize the distance between the car and the path: y (fig 3). We work in a spatial state and we make the derivative on the curvilign absissa : s. , it gives the new equations relative to the path :

$$\begin{pmatrix} x' = \frac{dx}{ds} = \frac{\cos(\widetilde{\Psi})}{1-C(x)} \\ y' = \sin\left(\widetilde{\Psi}\right) \\ \widetilde{\Psi}' = C_f - x'.C(x) \end{pmatrix}$$

We choose k_1, k_2, k_3 in order to place stable eigen values in the spatial state.

$$y^{(3)} + k_3 \cdot y^{(2)} + (k_1 + k_2) \cdot y' + k_1 \cdot k_3 = 0$$

So the control is :

$$\overset{\circ}{\delta} = \frac{V_f \cdot L \cdot b}{(1 + \tan^2(\delta)) \cos\left(\widetilde{\Psi}\right)}$$

with

$$b = y^{(3)} + C_f^2 \sin\widetilde{\Psi} - 3x' C(x) \cdot \widetilde{\Psi}' \sin\widetilde{\Psi} - \left(x'\right)^3 \frac{dC(x)}{dx}$$

This method is under experiment and we think is the best one to avoid cutting the curves.

3. Experiment

3.1. Sensors

From what we have seen previously, it can be gathered that we need for each vehicle a sensor capable of measuring the distance to the previous vehicle, their relative speed and the angle at which this previous vehicle is located with respect to the automated one. Furthermore, these measurements are needed with a noise and at a rate compatible with the constraints of the servo loop. This rate has been estimated through simulations at about 50 Hz

The sensor which has been developed at INRIA capable of these performances is based on a vision approach with targets located at the rear of each vehicle. The camera we selected is a linear camera with 2048 pixels capable of operating at 1000 Hz equipped with a spherical lens and a cylindrical lens in order to adjust to the changes of the relative angle between the two cars in the vertical plane. We have added an infrared filter and a polarized filter to minimize the influence of ambient light and sun reflections.

The target is made of three sets of LED organized in vertical lines and non co-linear(fig 5). This arrangement allows us to compute the three degrees of freedom of the previous car in the horizontal plane. Given the design parameters f, e and h, simple geometrical considerations (but involving many trigonometric computations), give us the three degrees of freedom that we are looking for : the distances Dx, Dy and the angle $D\psi$. The precision obtained is very high: 5mm at 10 m and through adequate filtering, we can obtain the relative speed that we also need at the desired frequency.

We also have velocity sensors based on encoders for the motor and the rear wheels to know the longitudinal and angular velocity of the vehicle.

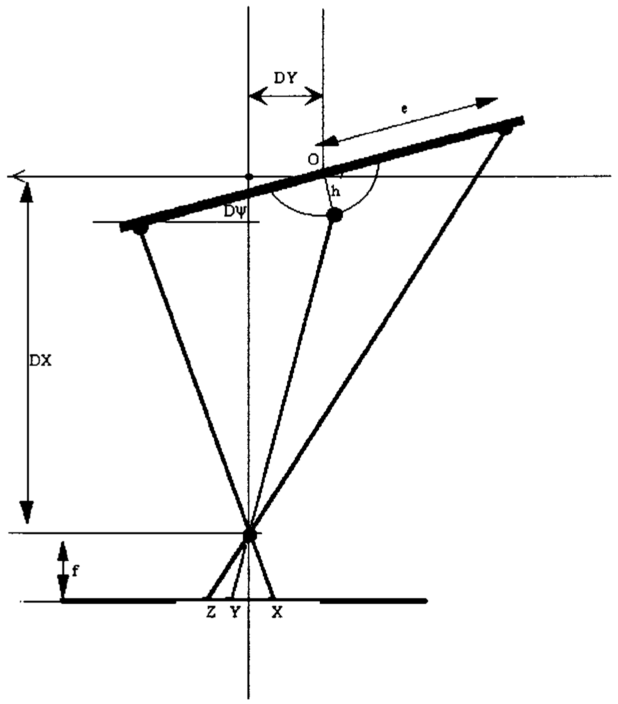

Figure 5. Target and camera scheme

3.2. Experimental Results

In normal case, the hydraulic brakes are not needed ; the motor brake gives a deceleration of $2m/s/s$. As we can see (fig6) the regulated error stays under 30 cm and the distance between the two cars is equal to 4,5m at a 10 m/s speed.

We can notice the regulated error tends towards zero when speed is stabilized which shows that there is no static error.

In emergency case, the hydraulic brake (added to the motor one) gives a deceleration of $5m/s/s$ and the regulated error stays under 50 cm.(fig7) which is correct and guarantees train security.

As we memorize the leader path, we can measure the lateral error y between the two car paths. We verify (fig8) that like-truck following cuts the curves (up to 60 cm).

We are experimenting cubic following : first results are hopeful, indeed the error do not exceed 8 cm but the stability must be reinforced.

4. Conclusion

Using this new vision tool, we have demonstrated that it is possible to implement very close platooning of vehicles. Indeed, we have shown that the headway between the cars can be of the order of 0.3 sec and this can probably be impoved with better brake actuators.

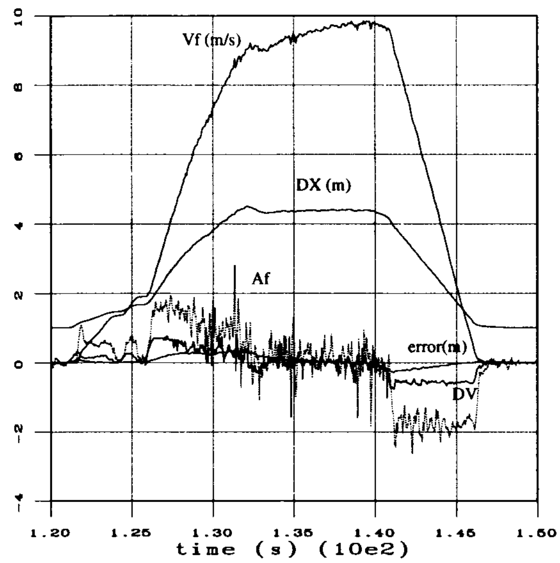

Figure 6. Experiment : normal case

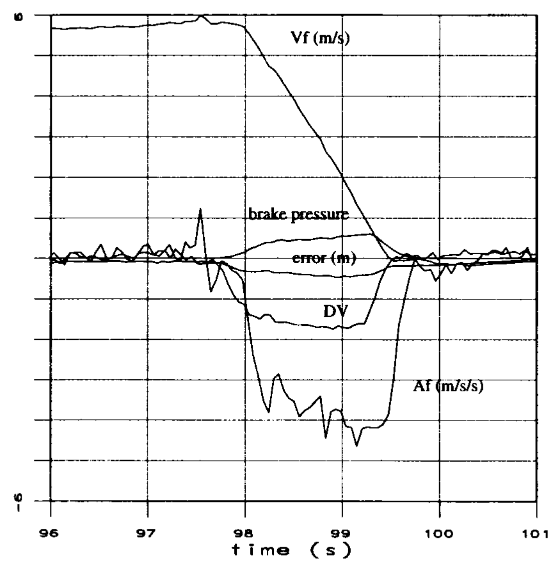

Figure 7. Experiment : emergency case

However, this demonstration has been carried out at the moment at relatively low speeds : up to 40 km/h. Further experiments are now needed to demonstrate the capabilities of the technology although this has already been demonstrated on the paper.

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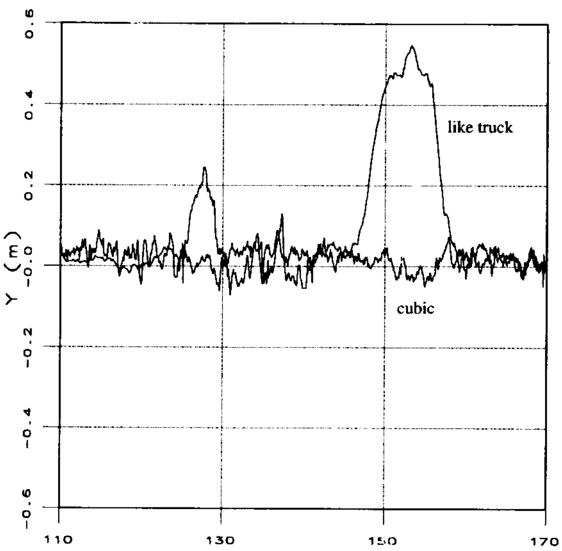

Figure 8. lateral errors

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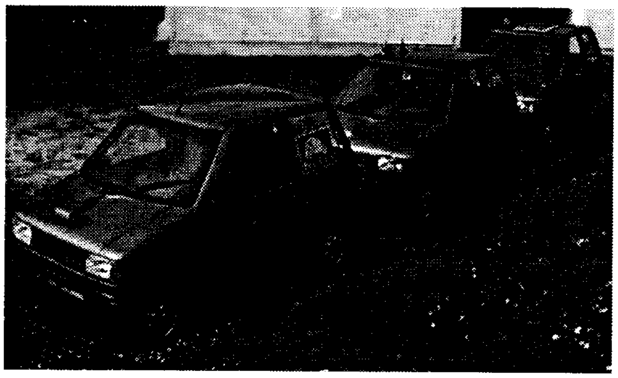

Figure 9. Train of vehicles