Experimental Vehicle Longitudinal Control using Second Order Sliding Modes

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Abstract

This paper presents the first phase of an experimental implementation of vehicle longitudinal control at low speed. The main objectives are the increase of traffic capacity while improving safety and comfort. Longitudinal control method used is based on second order sliding mode technique. Results are presented either by simulation or by use of an experimental process with a vehicle prototype which is equipped with needed sensors and actuators. The principle is based on the well management of inter-vehicular spacing in relation to vehicle speed. Examples obtained with the automatic system are provided for several traffic situations such as stop-and-go, stop on obstacles, car-following with merging/overtaking. Positive impacts of such a system are given in terms of traffic capacity enhancement and collision gravity reduction.

1 Introduction

Peri-urban networks experience growing daily congestions at peak hours. While in normal steady state driving conditions, traffic capacity of a lane is at around 2200 vehicles per hour on peri-urban motorways, it generally falls to 1200 vehicles per hour [12] in these particular disturbed unsafe traffic conditions. In addition the increase of the spent time and the workload cause drivers' displeasure and irritation.

Thus it is advisable to find solutions to solve such a constant problem. One way is the longitudinal mode automation by regulating vehicle speed and range, considering safety and comfort aspects while ensuring guaranteed travel time.

The adopted approach combines theoretical control apects with functional components that permit sharing with the driver and a gradual achievement of vehicle full automation.

In that way, first step consists in the implementation of a longitudinal shared driving between the driver and the automat. For such a system, the model of inter-vehicular spacing for congested traffic situations can be considered in order to define realistic desired inputs [6]. Besides, this driving assistance needs low cost additional equipment with regard to already existing technological means and driver's workload will be reduced.

In this paper several scenarios of longitudinal control are presented, with recent obtained experimental results. A short example of simulation of a car following control is given. Control law uses a second order sliding mode technique [3, 4, 1] and control input is the vehicle acceleration [2, 5]. A comparison with the driver's reaction time is accomplished and an analysis of experimental results in terms of traffic capacity and collision gravity is carried out [13].

Section 2 presents the considered shared driving modes. Section 3 gives the vehicle model used for control synthesis [2, 7] while sections 4 and 5 provide the control synthesis procedure with some simulation results. Finally section 6 is devoted to the obtained experimental results and their analysis.

2 Control modes for shared driving

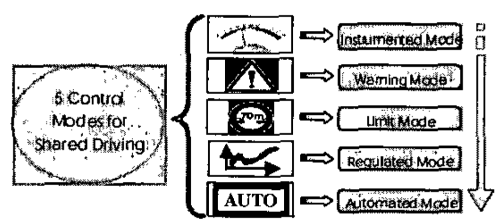

Figure 1: Five control modes for shared driving

Longitudinal control concept at low speed is mainly devoted to the enhancement of traffic conditions and safety while reducing driver's workload in sub-urban congested traffic situations. However, the vehicle can only be in automatic mode under a certain threshold. From realtime observed traffic data, it was established that more than 90% of speeds during daily peak-hours are under 60Km/h. But in such conditions, the traffic can become fluid at certain times, then the

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driver must have the means of taking manual driving again. The primary objective is thus not only to achieve a full automated vehicle but also to provide to the driver a permanent informative or active assistance system. This kind of assistance with vehicle shared control must integrate the priority to the driver to drive in manual mode. Actually, five assistance modes for shared driving have been established:

- *Instrumented mode :* this mode gives an indication of the state or the value of a helpful variable to the driver, as for example the vehicle velocity or actual headway time.
- *Warning mode :* It informs the driver that there is a limit not to overshoot like the maximal authorized speed onto the traffic network or alert him when the minimum safety headway time is reached.
- *Limited mode :* this mode notifies the driver of not overshooting an enforced limit. A typical example is the system of active gas pedal.
- *Regulated mode :* an automated system constrains the controlled vehicle to follow a desired reference signal such as a desired speed or spacing.
- *Automated mode :* the vehicle is completely automated.

The experimental vehicle is designed methodically by adding technical modules. In other words, it is desired to implement and to evaluate several experimental tools including sensors, actuators and HMI that can be used after to gradually conceive more elaborated safety systems. The experimental vehicle is designed in such a way that the driver can always easily override any action performed by the controller.

The following section gives a summary of the vehicle model used for control synthesis.

3 Vehicle model

3.1 Model equations [2]

The vehicle model used for control synthesis is a simplified non-linear model. First of all, the longitudinal equation of the drivetrain is described by

$$(m+\frac{(J_{wr}+J_{wf})}{h^2})a=\frac{T_s-T_b-M_{rr}}{h}-F_a-mg\sin(\theta) \quad (1)$$

with a non slip assumption ($v=R_g h w_e$) and ($T_e=R_g T_s$) one can eliminate the term of traction effort in equation (1) which becomes

$$T_e-R_g(T_b+M_{rr}+hF_a+mgh\sin(\theta))=I_t a \quad (2)$$

with

$$I_t=\frac{(J_e+R_g^2(J_{wr}+J_{wf}+mh^2))}{R_g h} \quad (3)$$

T_b	Brake torque (N.m)
M_{rr}	Rolling resistance torque (N.m)
h	height of the center of the wheel (m)
F_a	aerodynamic force (N)
g	gravity (9.81 m.s^{-2})
θ	Road slope angle (deg)
a	acceleration (m.s^{-2})
J_{wr} J_{wf}	Rear/front wheel inertias (1.2825 kg.m^2)
J_e	Engine/ transmission inertias(0.2630 kg.m^2)
R_g	gear ratio (final gear included)
T_s	Shaft torque (N.m)
v	Vehicle speed (m.s^{-1})
ω_e	Engine speed (rpm)
m	Vehicle mass (kg)

Table 2: Vehicle model parameters

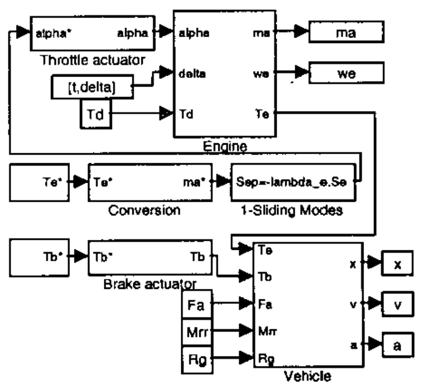


Figure 2: Global diagram

3.2 Switching criterion

Switching from throttle to brake is performed using an acceleration threshold a_{th}: if $a^* \geq a_{th}$, throttle control is activated, and if $a^* < a_{th}$, the system is braking. a^* is the desired acceleration. In this way, a residual engine torque T_{ct} corresponding to a closed throttle must be calculated [2]. Then, the engine torque can be divided into two parts: T_e which is submitted to control and T_{ct}. Equation 2 can be written

$$T_e-R_gT_b=R_g(M_{rr}+hF_a+mgh\sin(\theta))+I_ta-T_{ct} \quad (4)$$

In the absence of control inputs ($T_e=T_b=0$), a_{th} can be calculated

$$a_{th}=\frac{1}{I_t}[T_{ct}-R_g(M_{rr}+hF_a+mgh\sin(\theta))] \quad (5)$$

Then, the expressions of desired engine and brake torques are

$$T_e^*=I_ta^*+R_g(M_{rr}+hF_a+mgh\sin(\theta)) \quad (6)$$

and

$$T_b^*=\frac{T_{ct}-I_ta^*}{R_g}-(M_{rr}+hF_a+mgh\sin(\theta)) \quad (7)$$

T_{ct} is obtained experimentally.

The engine torque is generated from the internal model of the engine [8, 9]. The state equations are

$$\begin{cases} \dot{m}_a = \dot{m}_{ac_i} - \dot{m}_{ac_o} \\ \dot{\omega}_e = k_n(T_e - T_l) \end{cases} \quad (8)$$

where T_l is the load torque at engine output. Air mass flow rate $\dot{m}_a$ in the intake manifold is obtained by subtraction between flow rates at input $\dot{m}_{ac_i}$ and output $\dot{m}_{ac_o}$.

The longitudinal controller is now designed on the basis of the model presented above.

4 Synthesis procedure

A second order sliding mode technique is used for longitudinal control. This method is adapted for non-linear system, and permits a considerable reduction of the inherent chattering phenomenon. This is achieved by applying the algorithm not directly on the control input u but on its derivative. Besides sliding modes are robust to sensor noise which is very important for experiments knowing that several sensors are required for longitudinal control.

4.1 Problem formulation

Let it be $X = [m_a, \omega_e, x, \dot{x}]^t$ the state vector of the system to be controlled. State representation is

$$\dot{X} = f(X, t, u) \quad (9)$$

System input u is T_e or T_b but in an experimental objective it is easier to use acceleration input which is simpler to measure. Then in order to control the vehicle from a leader speed profile, the desired input of the system is

$$u = a^* = T_e - R_g(T_b + M_{rr} + hF_a + mgh\sin(\theta)) \quad (10)$$

To be able to control the vehicle in acceleration, vehicle engine must be controlled [2, 5]. This is performed using a simple first order sliding mode on the throttle angle (figure 2).

4.2 Algorithm

The sliding surface chosen for the control is of the form

$$S = (x - x_l) + (L + h\dot{x}) \quad (11)$$

where x_l is the position of the followed vehicle, L represents the inter-distance while stopping and h is the headway time. This surface S was chosen because of the recent french law that specifies to drivers not to leave a headway time inferior to 2 seconds. When inferior, safety is not assured.

With such a sliding surface, the system has a relative degree equal to 1. The Twisting Algorithm [3, 4, 1] is then applied to the vehicle model to simulate an automatic car-following control. Algorithm is

$$\dot{u} = \begin{cases} -u & if \quad |u| > |u_{eq}| \\ -K_M sign(S) & if \quad S\dot{S} > 0 \; and \; |\dot{u}| \; |u_{eq}| \\ -k_m sign(S) & if \quad S\dot{S} 0 \; and \; |u| \; |u_{eq}| \end{cases} \quad (12)$$

where u_{eq} is the equivalent control satisfying $\dot{S} = 0$. Coefficients k_m and K_M are determined to respect the four conditions of applications of the Twisting Algorithm which is a second order sliding mode algorithm that converges in finite time [4].

5 Simulation results

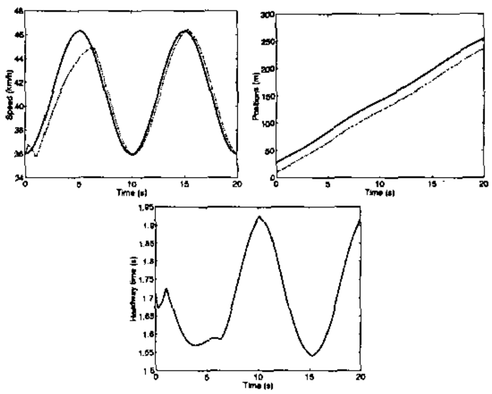


Figure 3: Simulation of a car-following control - (-) leader (...) controlled vehicle - $L = 5m$, $h = 1s$

Congested traffic experimental data analysis shows that 75% of headway times are under 1s. In order to prove the effectiveness of the developed vehicle following controller, a headway time of 1s is chosen in the sliding surface. The controller is implemented with $L = 5\ m$, $h = 1\ s$, $k_m = 30$ and $K_M = 120$. Figure 3 shows results obtained for car following in reaction to speed variations of the preceding vehicle. One can note that the position of the controlled vehicle is well regulated and headway time is always greater than $1\ s$. Furthermore, once the control has converged, the speed of the controlled vehicle follows the imposed speed profile.

6 Experimental tests

Simulation works have lead to satisfactory results for longitudinal control. Then an experimental phase has been carried out with the development of a prototype vehicle. Several tests are proposed in the following in order to analyze the behavior of the controlled vehicle face to a typical scenario. The objectives are thus to evaluate the system and validate it in order to determinate if it can be used as an assistance system sharing with the driver.

At first, a short description of the experimental vehicle is given, both at the equipment level and architectural one.

6.1 Vehicle equipment

The prototype vehicle is a Renault Scenic (figure 4 *a)*), which has been instrumented with several sensors. For the

a) b) c) d)

Figure 4: a) Vehicle prototype - b) Stereovision sensors - c) Braking pedal modified - d) Embedded data processing

developed control strategy, four different measures are necessary at each sample time : inter-vehicular spacing, relative speed, speed and acceleration of the controlled vehicle.

6.1.1 Sensors: According to figure 4 *b)*, the inter-vehicular spacing and relative speed are obtained by a stereovision technique [10, 11]. This system is also used to detect obstacles on the traffic lane, it needs only a calibration test before normal operating. Vehicle speed is obtained by an odometer while an inertial unit returns the longitudinal acceleration of the controlled vehicle.

Sensors previously quoted are for the most of them noisy. Particularly inter-vehicular spacing, vehicle speed and acceleration are filtered numerically so as to obtain data which can be exploited for driver warning or vehicle control.

6.1.2 Control module: The controller block is managed by a dll (Dynamic Link Library) which computes the desired acceleration via the presented Twisting Algorithm and sends a desired algebraic acceleration to the actuator module. The control loop runs at a sample time of 23ms.

6.1.3 Actuators module: Braking pedal is lined by an electrical jack which is controlled in position by a numerical PID controller (see figure 4 *c)*). Throttle angular position is directly controlled by the vehicle integrated electronic control unit.

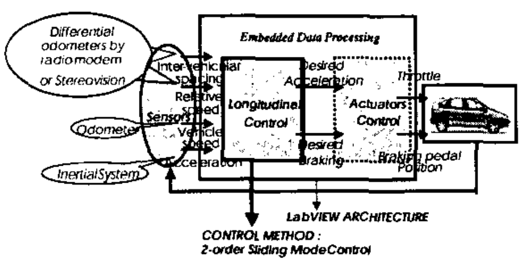


Figure 5: Global system architecture

6.1.4 System architecture: All the previous described modules are managed by a LabVIEW interface which allows process memory management for real-time realization. An embedded data processing has been installed in the vehicle boot (figure 4 *d)*). System architecture is summed up on figure 5.

This vehicle equipment makes possible the experimental evaluation of several scenarios of longitudinal assistance in both warning and shared control modes. However, due to space limitation, only the regulated mode is detailed in this paper.

6.1.5 Switch automatic/manual modes: It was said before that the system considered calls on the shared control with the priority to the driver. Then it is important for such a system that the transition from automatic driving mode to manual driving mode is carried out during a very short time in the case for instance the driver wants to reach the leader faster. That is the reason why as soon as the driver presses on the pedal, a detector orders the system to change of driving mode. This action is immediate and reversible.

6.2 Experimental scenarios

In the following are given the results obtained for some scenarios tested during experimental phase and validated during the IEEE Intelligent Vehicle Symposium IV2002. The desired acceleration is calculated in order to ensure a headway time greater than 2 s with respect to the new french law on headway time. Control law is the one which is presented in 4.2. The derivative of the sliding surface is easily computed using the available sensors.

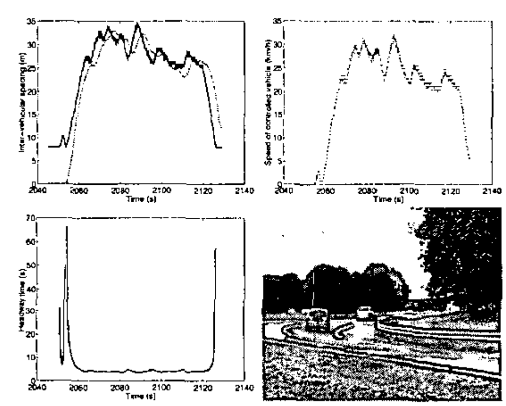


Figure 6: Low speed car-following control - (-) leader (...) controlled vehicle - $L = 8m$, $h = 3s$

6.2.1 Scenario 1 : Low speed car-following control: Figure 6 shows a car-following control with $h = 3s$ and $L = 8m$. One can note that the controlled vehicle follows correctly the preceding vehicle at low speed because measured spacing is near desired spacing. The curve is quite smoother than the desired spacing because of filtered data.

6.2.2 Scenario 2 : Stopping on obstacles: Each stop on obstacle comes after a car-following control.

Fallen motorbike

Stereovison is very useful to detect an obstacle on the lane. In this scenario the controlled vehicle has to stop automatically in front of a fallen motorbike on the road. On figure 7, one can see that the controlled vehicle stops at around 11 m from the motorbike. Headway time indicates that the stopping is carried out safely since headway time is always

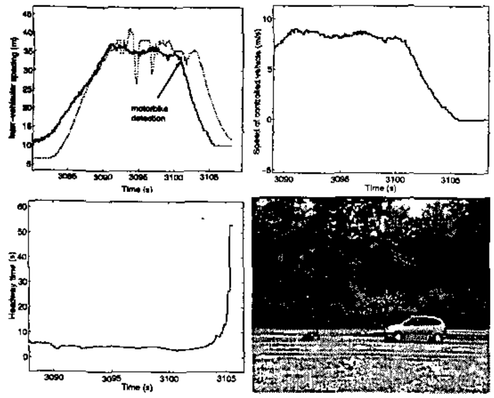


Figure 7: Stop on obstacle - (-) leader (...) controlled vehicle - $L = 10m$, $h = 3s$

greater than 2 seconds.

Pedestrian crossing

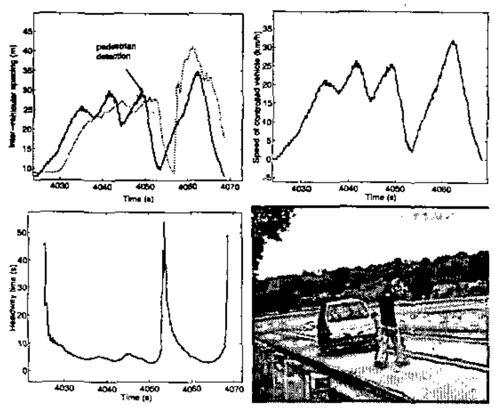


Figure 8: Stop on pedestrian crossing by stereovision - (-) leader (...) controlled vehicle - $L = 8m$, $h = 3s$

This scenario wants to show how the controlled vehicle reacts face to a pedestrian crossing on the lane between both vehicles. Stereovision quickly detects the pedestrian and returns to the system the inter-distance value. The controlled vehicle can automatically determine if it is necessary to stop or only to slow down when the pedestrian walks on the road as it is described on figure 8. For the example, the vehicle stops briefly before restarting as we can see with the measured headway time that is infinite when the pedestrian is in front of the controlled vehicle. The law with respect to headway time is always respected.

6.2.3 Scenario 3 : Stop-and-Go: As the main paper interest is low speed longitudinal control, the third scenario is the realization of a stop-and-go automatic car-following. Figure 9 indicates the reaction of the controlled vehicle when the preceding one carries out successive stopping and restarting. We can note that the evolution of the measured spacing closely follows the desired one. These speed variations are comparable to those of a congested traffic situation

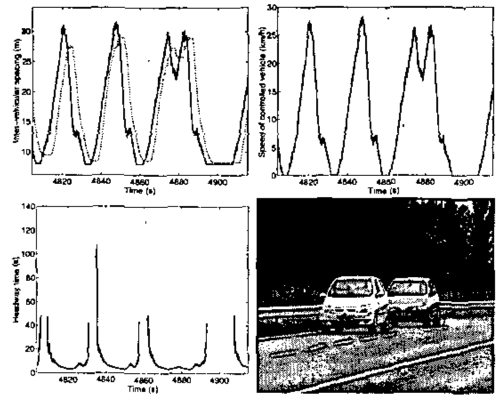


Figure 9: Stop-and-go with stereovision - (-) leader (...) controlled vehicle - $L = 8m$, $h = 3s$

however, the time headway safety criterion is still satisfied.

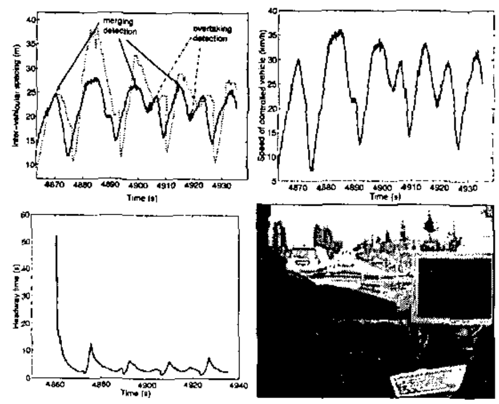
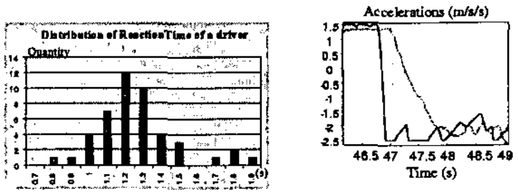


Figure 10: Merging/overtaking influence - (-) leader (...) controlled vehicle - $L = 8m$, $h = 2s$

6.2.4 Scenario 4 : Car-following with merging/overtaking: In congested traffic situations, merging and overtaking are frequent. For example a merging causes a large input disturbance for the controlled vehicle because inter-vehicular spacing is suddenly reduced. Automatic system has to avoid collisions, it reacts well as it is shown on figure 10. Headway time is always greater than 2 seconds.

6.3 Reaction time

One can note that all figures of experimental results present a time delay due to the delay between the measured and the desired accelerations (figure 11 b)). It is mainly a consequence of the time response of the engine, its value is around 0.7 s. Considering that the distribution of drivers' reaction time is centered on 1.2 s (see figure 11 a) and [13]), such a shared control system improves thus this reaction time. The objective in near future is to reduce further this reaction time, knowing that the vehicle engine has actually a time delay of only 0.3 s.



a) b)

Figure 11: a) Distribution of a driver's reaction time - b) Time delay for acceleration - (-) Controller output (...) measured acceleration

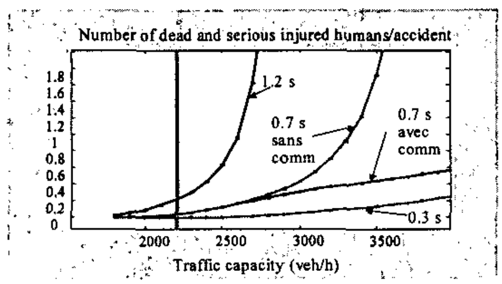


Figure 12: Relation between traffic capacity and gravity

6.4 Capacity/Gravity consequences

The impact of such a system on the traffic capacity and collision gravity is directly linked to the reaction time as it is shown on figure 12. Without automated systems, actual maximum traffic capacity is 2200 $vehicles/hour$ at 50 km/h. The associated accident gravity is of 0.3 dead or serious injured humans per accident. Then at constant capacity, reducing reaction time leads to gravity reduction. At constant gravity, reducing reaction time permits to considerable increase of traffic capacity. As a conclusion, a compromise has to be achieved between safety and capacity.

7 Conclusion

According to a non-linear vehicle model, a second order sliding mode control is applied for longitudinal control of vehicle at low speed. In addition to the automatic mode, several driving assistance modes are declined. After a simulation phase, experimental results are given with different scenarios like car-following control, stop-and-go, stop on obstacles using stereovision detection. Safety aspect is considered by integrating the headway time in the desired spacing. Results are illustrated by real data collected during experiments. It is shown that the developed assistance system improves reaction time. The impact of such a system is then analyzed in terms of traffic capacity and gravity.

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