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Speed Limitation Based on an Advanced Curve Warning System

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***Abstract*— This paper presents an integrated system to prevent driver from taking a curve with a dangerous speed. The integrated system underlines three functions developed as follows : the first function consists in knowing the geometry characteristics of the coming road; the second function has to compute a safe speed according to the road section, the vehicle and the driver; the last function must impose the speed control of the vehicle in order to achieve a safe speed in the case that the driver does not achieve it[1].**

I. Introduction

On average, roadway curves have five times more accident than on straight roadways and sharper roadway curves have higher accident rates than flatter roadway curves [3]. Then roads authorities tend to prevent those accident risks by deploying an adequate signing policy : the sharper the curve, the stronger the signs. However, despite of the efforts done towards the harmonization of roadway curve signing policies [2], it still happens that drivers are sometimes surprised by a sharp roadway curve that has no warning at all, whereas some over-signed roadway curves may be negotiated at more than 30 km/h over the advisory speed [1]. Furthermore, even with warning signs, drivers are reluctant to reduce their speed on roadway curves until they actually see the need to do so.

Public authorities recently choose a coercive method to decrease the driver speed with the automation of speed radar. After three years of deployment in France, the accident analysis shows a drop in death, from 7742 for the year 2002 to less than 5000 in 2006 [4]. But using an unadapted speed is always one of the largest cause of accident that represents one quarter of the accidents.

We believe that, among many other Advanced Driver Assistance Systems under development, the Curve Warning Systems (CWS) are very promising in terms of safety. In a few words, a CWS uses sensors to determine the vehicle position and velocity. Whenever the vehicle approaches an upcoming curve too fast, the system emits a warning. However, the way the information is delivered to the driver shall limit the effect of the assistance, a limitation of the speed could improve the system.

This paper presents the integrated system providing a safe speed to the driver approaching a curve. The complete system requires the acquisition of the upcoming road geometry in order to compute a safe speed and to regulate the vehicle speed according to the previous computation.

The work is organized as follows : section 2 introduces the ways of gathering the road geometry. Section 3 describes the computation of the safe speed using a vehicle-infrastructure-driver representation, while section 4 develops the speed control. Finally, section 5 presents some simulations and experimental results.

II. The road geometry, beyond the sensor perception

Both sensor limitation and delay required by the driver to analyse a warning prevent us from using sensors like video sensors to detect and use the road geometry. In fact, the computation of the safe speed requires the knowledge of the road on a long range. Common approaches could be based on a digital map. But, the data and their required accuracy (see [8]) could be a problem, both in data gathering and map updating.

Our approach is based on a local map: on a dangerous road section, a local map with accurate data is supposed to be available for the vehicle system.

The way the local map is made available is multiple, it could be for instance the use of the communication with a central. In our application, the local map is uploaded in the vehicle using transponder crimped in the road. In the following we will present the architecture and the data scheme.

A. About transponder

The transponders are one part of a RFID system (Radio Frequency IDentification) which can contain a small amount of data to be transmitted in a memory. One of its advantage is that it is not required for the RFID to have a battery as it is used in many systems, the credit card format is the most known. The system has been tested for automotive applications and presents

[1]We would like to thank SafeSpot European IP project for supporting a part of this research.

Fig. 1. RFID antenna part on a vehicle

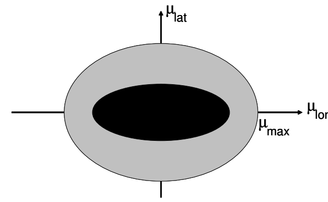

Fig. 2. Global friction domain and driver used friction

good features for an operating frequency of $13.56MHz$ [9]:

- Distance between antenna and tag: $30cm$
- Maximum vehicle speed: $140km/h$
- Data exchanged at maximum speed: $300bits$

Exchanged data increases as the speed decreases. The antenna is presented on the figure 1.

B. About data

The transponder described in the previous subsection is used in order to transmit the geometry of the upcoming curves to the vehicle system. Following the standard in road building, a curve can be entirely described using two kind of geometric forms:

- a circle characterized by its curvature, its superelevation and its slope, supposed constant.
- a clothoid which is a kind of spiral helping drivers to handle the curves. It introduces the curvature in a smoothly way. It is described at its beginning and its end with a curvature, a slope and a superelevation information. These variables are supposed constant varying.

As the goal is to help the driver to handle the curve, only the road geometry part regarding the deceleration phase in the curve will be transmitted to the vehicle. So each curve is coded as follows :

- Distance from the transponder to the beginning of the clothoid, in m
- Length of the clothoid, in m
- Length of the curve, in m
- Curvature at the apex of the curve, in m^{-1}
- Superelevation at the beginning and the end of the clothoid, in rad
- Slope in the curve, in rad

III. Computation of the safe Speed

The first definition of a safe speed in a curve could be directly analyzed from the road conception. In fact, the curvature of the road is restricted given the road category and the speed (V) is directly computed using the following formula:

$$V = \sqrt{\frac{g\mu}{\rho}} \tag{1}$$

where μ is the road friction and ρ is the curvature. Most of the CWS uses this definition. In [6], the definition of the limit speed also takes into account the road superelevation (φ) and the driver's reaction time. The safe speed at the apex of an approaching curve (V_c) can be determined from the equation:

$$V_c = \sqrt{\frac{g}{\rho}\frac{\varphi + \mu}{1 - \mu\varphi}} \tag{2}$$

Moreover, a deceleration γ is defined to reach the speed V_c, from any point prior to the apex (at a distance d):

$$\gamma = -\sqrt{\frac{V^2 - V_c^2}{2d - t_r V}} \tag{3}$$

t_r is the estimated reaction time of the driver.

But these definitions of the safe speed and the deceleration to reach it show some lacks:

- The road geometry is not fully taken into account, and for instance the slope may have a large impact on the safe speed.
- It is not only the incoming curve that may have an impact on the speed, on rural roads the succession of curves shall impact on the safe speed.
- The vehicle dynamic has an impact on the deceleration phase, especially on the mass distribution.

Moreover, driver studies [7] show that each driver has his own limit which remains almost constant. The system can be adapted to a specific driver and will be understood. In [5], we have proposed a computation of a safe speed using the infrastructure geometry stored on a dedicated digital map. We will briefly present the results.

A. Driver consideration

In our model, the driver is described using two sets of parameters. The first one is a time (denoted T) which describes the integration duration of the information by the driver. It is linked with the way of driving: the smoother the speed variation is, the higher this time is. The second set of parameters describes the limit of the driver's dynamic. For safety and comfort matters and under normal weather conditions, the driver remains far away from the dynamic limits of the vehicle. In term of tire road interface, the driver wants to stay in an inner area of the friction ellipse (see figure 2). Let us define the friction part that the driver accepts to mobilize using two parameters λ_{lon} for the longitudinal part of the maximal friction (μ_{max}) and λ_{lat} for the lateral one.

B. Safe Speed for curve negotiation

A safe speed is computed using an accurate definition of the road geometry, including the slope (denoted θ). In order to compute the speed, three simple vehicle dynamic models are used, in order to describe all movements of the vehicle according to the road, to the mass transfer and to the mobilization of friction at the tire road interface. Reversing these three models enables us to compute a safe speed both at the apex of the curve and on the other road segments. The assumption to compute both speed and speed profile, is that the driver mobilizes the whole limited friction and that the vehicle follows the center of the road. The speed is given by the following equations:

$$\begin{aligned} & \theta > 0 : \\ A &= \lambda_{lat}\mu_{max} \\ V^2 &= \tfrac{g}{\rho}\left(\left(1-\tfrac{H}{L_f}\theta\right)\sqrt{1-\left(\tfrac{\theta}{\lambda_{lon}\mu_{max}}\right)^2} * A - \varphi\right) \\ & \theta < 0 : \\ V^2 &= \tfrac{g}{\rho}\left(\left(1+\tfrac{H}{L_r}\theta\right)\sqrt{1-\left(\tfrac{\theta}{\lambda_{lon}\mu_{max}}\right)^2} * A - \varphi\right) \end{aligned} \tag{4}$$

while the speed along the road is directly obtained with the following differential equation:

$$\left\{\begin{aligned} & \text{deceleration phase} \\ 1 &= \left(\frac{1}{\lambda_{lat}\mu_{max}}\frac{\frac{\rho V^2}{g}+\varphi}{1+\frac{H}{L_f}\left(\frac{V}{g}\frac{dV}{ds}-\theta\right)}\right)^2 \\ &+ \left(\frac{1}{\lambda_{lon}\mu_{max}}\left(\frac{V}{g}\frac{dV}{ds}-\theta\right)\right)^2 \\ & \text{acceleration phase} \\ 1 &= \left(\frac{1}{\lambda_{lat}\mu_{max}}\frac{\frac{\rho V^2}{g}+\varphi}{1-\frac{H}{L_r}\left(\frac{V}{g}\frac{dV}{ds}-\theta\right)}\right)^2 \\ &+ \left(\frac{1}{\lambda_{lon}\mu_{max}}\left(\frac{V}{g}\frac{dV}{ds}-\theta\right)\right)^2 \end{aligned}\right. \tag{5}$$

H	Height of center of gravity CG (m)
ρ	Road curvature (m^{-1})
l_f	Distance from front shaft to CG (m)
l_r	Distance from rear shaft to CG (m)
s	curvilinear abscissae (m)

Table 1 : Model parameters

IV. Vehicle speed control in a curve

In order to limit the vehicle speed approaching a curve, one has to use a vehicle model to make a simulation of the system. The notations are described in table 2 below.

A. Vehicle model [10], [14]

The vehicle model used here is a non-linear longitudinal model for control. The longitudinal equation of the drivetrain can be described by :

$$(m+\frac{(J_{wr}+J_{wf})}{h^2})a = \frac{T_s - T_b - M_{rr}}{h} - F_a - mg\sin(\theta) \tag{6}$$

with a non slip assumption like

$$v = R_g h w_e \tag{7}$$

$$T_e = R_g T_s \tag{8}$$

This hypothesis permits to eliminate the term of traction effort in the equations. Equation (6) becomes

$$T_e - R_g(T_b + M_{rr} + hF_a + mgh\sin(\theta)) = I_t a \tag{9}$$

with

$$I_t = \frac{(J_e + R_g^2(J_{wr}+J_{wf}+mh^2))}{R_g h} \tag{10}$$

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 $\mathrm{m.s}^{-2}$)
θ	Road slope angle (deg)
a	acceleration ($\mathrm{m.s}^{-2}$)
J_{wr} J_{wf}	Rear/front wheel inertias (1.2825 $\mathrm{kg.m}^2$)
J_e	Engine/ transmission inertias(0.2630 $\mathrm{kg.m}^2$)
R_g	gear ratio (final gear included)
T_s	Shaft torque (N.m)
v	vehicle speed ($\mathrm{m.s}^{-1}$)
ω_e	Engine speed (rpm)
m	Vehicle mass (kg)

Table 2: Vehicle model parameters

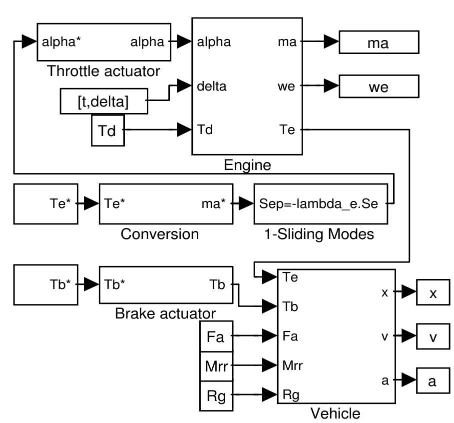

Fig. 3. Global diagram

B. Switching criterion [10]

Switching from throttle to brake is performed using an acceleration threshold a_{th}: if $a^* \geq a_{th}$, the 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. Then, the engine torque can be divided into two parts: T_e which is submitted to control and T_{ct}. The equation (9) can be written

$$T_e - R_g T_b = R_g(M_{rr} + hF_a + mgh\sin(\theta)) + I_t a - T_{ct} \quad (11)$$

In the absence of control inputs, a_{th} can be calculated

$$a_{th} = \frac{1}{I_t}[T_{ct} - R_g(M_{rr} + hF_a + mgh\sin(\theta))] \quad (12)$$

Then, the expressions of the desired engine and brake torques are

$$T_e^* = I_t a^* + R_g(M_{rr} + hF_a + mgh\sin(\theta)) \quad (13)$$

and

$$T_b^* = \frac{T_{ct} - I_t a^*}{R_g} - (M_{rr} + hF_a + mgh\sin(\theta)) \quad (14)$$

T_{ct} is experimentally determined.

The engine torque is generated from the model of an engine [11], [12]. The engine state equations are

$$\dot{m}_a = \dot{m}_{a_{c_i}} - \dot{m}_{a_{c_o}} \quad (15)$$
$$\dot{\omega}_e = k_n(T_e - T_l) \quad (16)$$

where T_l is the load torque at the engine output and k_n a coefficient. The air mass flow rate $\dot{m}_a$ in the intake manifold is obtained by substraction between input $\dot{m}_{a_{c_i}}$ and output $\dot{m}_{a_{c_o}}$ quantities.

V. Synthesis procedure

A sliding mode technique is used for the vehicle speed control. This method is adapted to a nonlinear model and in order to make experimental tests we must choose a technique robust to the sensor noise which is very important for experiments knowing that several sensors are required for longitudinal control.

A. Problem formulation

Let it be $X = [m_a, \omega_e, x, \dot{x}]^t$ the state vector of the system to be controlled where x and $\dot{x}$ are the longitudinal position and speed of the controlled vehicle. The state representation is

$$\dot{X} = f(X, t, u) \quad (17)$$

The system input u is T_e or T_b but in an experimental objective it is easier to use the acceleration input which is easier to be measured and instrumented. Then in order to control the vehicle speed from the road geometry, the desired input of the system is

$$u = a^* = T_e - R_g(T_b + M_{rr} + hF_a + mgh\sin(\theta)) \quad (18)$$

To be able to control the vehicle in acceleration, the vehicle engine must be controlled (see [10], [13]).

B. Control algorithm

The sliding surface chosen for the speed control is of the form

$$S = \dot{x} - V^* \quad (19)$$

where V^* is the desired speed profile imposed by the road geometry.

A sliding mode technique is then applied to the vehicle model to simulate the speed control using the desired speed profile from the transponders. The vehicle acceleration is the control input. The algorithm is

$$u = u_{eq} - k.sign(S) \quad (20)$$

where u_{eq} is the equivalent control satisfying $\dot{S} = \ddot{x} - \dot{V}^* = 0$. After computation, one can write

$$u_{eq} = \dot{V}^* \quad (21)$$

Then, the final control law is

$$u = \dot{V}^* - k.sign(\dot{x} - V^*) \quad (22)$$

The coefficient k is tuned in order to satisfy the condition of convergence in finite time. An analysis of the finite time convergence of the sliding mode algorithm, satisfying the matching condition

$$S\dot{S} \leq -\eta\,|S| \quad (23)$$

where η is strictly positive contant depending on k, show that the control law converges for $k \in \Re^{+*}$.

VI. Simulation results

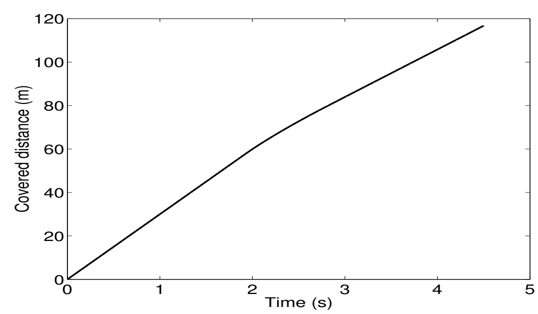

Fig. 4. Covered distance

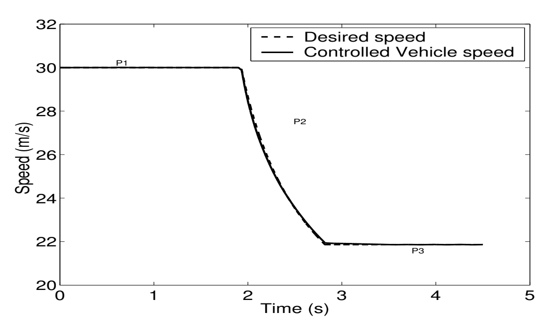

Fig. 5. Speed control with sliding mode technique

Fig. 6. Location of transponders and coded curves on the Satory test track

The algorithm has been simulated with Matlab/Simulink using the model presented in section *4*. The scenario is divided into two phases:

- Phase P1 (see figure 5) : The vehicle covers a straight line at $30m/s$.
- Phase P2 : In the second phase, the vehicle enters in a road section with a clothoid form, it is the beginning of the curve.
- Phase P3 : Then, it enters in a circular road section.

The phase of acceleration at the end of the curve is not simulated.

The results are shown on the figures 4 and 5, where one can see the good performances of the sliding mode control.

VII. Experimentation

The experimentation takes place in Satory, 30km South West of Paris, where we have access to a dedicated test track. This test track represents common curves on countryside road. On the figure 6, the transponder localization has been represented using red bars and coded curves with red ellipses.

The speed control presented in the last section has been experimented on a Peugeot 307 vehicle prototype, equipped with the needed sensors (transponder receiver, antenna, odometer, INS, ...) and a computer in order to compute the safe desired speed for the considered upcoming curve.

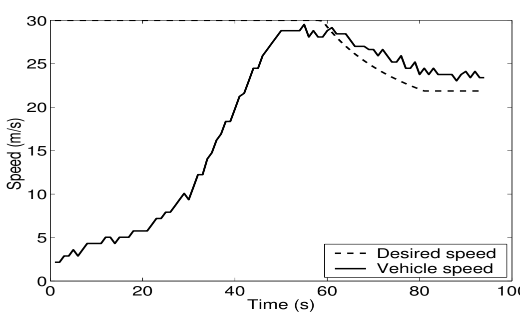

Fig. 7. Vehicle speed control with a PI controller

The sliding mode control was difficult to be tuned, because in simulation, we do not consider the fast vehicle dynamics : the comfort was degraded with some jerk effect. The control gain k was $k = 0.1$. Furthermore, the sliding mode method is generally interesting thanks to its well tracking of the desired input profile. But this is here a problem because the desired speed profile is computed using the road geometry which is built by adding several geometric sections like clothoids, circle. It is too geometric and does not take so much into account the driver's feeling. Then the driver can feel some nuisance like a few fear.

In such a case, an alternative consists in choosing a control method less precise than sliding modes, but that can bring more comfort. We had to do a good compromise.

As the proposed scenario is a speed control in curves, we do not consider that there can be a stopping in the curve like in stop-and-go applications. Then a PID control can be sufficient for this kind of experiment. The PID method will give less precise results, that is to say a small lack of performance regarding to the sliding mode technique, but will permit a smoother progression of the desired speed profile.

A simple PI controller has been implemented and the results are shown on the figure 7 with controller gains *P=20* and *I=10*. The vehicle speed is regulated among the desired speed profile, with smooth variations. Even if the precision is not very well, in a comfort point of view, the driver's feeling is better. Furthermore, the results have been obtained by adding an anticipation of 4 seconds. Otherwise, the driver seems to be afraid while approaching a curve with a dangerous speed because the braking phase occurs too late compared to the beginning of the curve section. The anticipation delay and the PI gains were chosen experimentally. Several drivers have tested this curve warning system and their feeling are relatively encouraging.

VIII. Conclusion

According to a non-linear vehicle model, a sliding mode control is applied for a vehicle speed control in order to approach curves with a safe speed based on the road geometry. The communication of road data are made by transponders. After a simulation phase, experimental results are shown for a given curve. Because of a lack of comfort with sliding modes, a PI controller is defined to increase the comfort. An anticipation of the controller is necessary to avoid a too late braking. Results are illustrated by curves with real data collected during experiments. This curve warning system improves curves approaching by limiting the vehicle speed (Videos of experiments will be shown at the IV2007 conference).

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