DESIGN OF A COUPLED LONGITUDINAL-LATERAL TRAJECTOGRAPHIC DRIVER MODEL

J. Ph. Lauffenburger, M. Basset, G. L. Gissinger

MIPS/MIAM Laboratory – University of Haute-Alsace
12, rue des frères Lumière / F-68093 MULHOUSE Cedex / France
Tel : (33) 3 89 33 69 26 – Fax : (33) 3 89 33 69 49
e-mail : (jean-philippe.lauffenburger, michel.basset, gerard.gissinger)@uha.fr

Abstract: In the field of driver modelling, this paper proposes a new approach to simulation and control applications. The driver is considered as a controller of the closed loop defined by the Driver-Vehicle-Environment system. More precisely, the behaviour model developed describes the driver's activity from the trajectory vector taken, associating the speed and the trajectory itself. The advantage of this model is a unique structure which helps to characterize different drivers' classes. This structure is based on a polar polynomial description and a finite state machine. Two classes — novice drivers and very experienced drivers — were studied to define and validate drivers' models. Results for novice drivers are presented here. In order to validate models with respect to different driver profiles, real experiments were carried out with the instrumented laboratory test car and drivers of different types.

Keywords: driver models, automotive control, trajectory planning, velocity control.

1. INTRODUCTION

In the context of "Driver-Vehicle-Environment" (DVE) system, the driver plays a key role and is more and more the aim of characterizing studies. The different approaches and then, resulting models, are strongly dependant of the objectives to reach and the scientific domains involved. Thus, the driver can be characterized considering the driver himself through the analysis of his predominantly sensorial and mental activities or by the analyse of his driving activity. This developed research work is classified in this second approach via mathematical modelling of his trajectory vector taken.

In the field of simulation and control applications, a great amount of research work on driver modelling has been carried out. The driver is, then, considered as a controller of the closed loop defined by the DVE system (figure 1). Even in this restricted approach, it requires a very large field of competence involving numerous scientific subjects: neurosciences, cognitive sciences, engineering sciences, etc. That represents a real handicap for the synthesis of a unified approach (Basset, 2002).

Here, focus is on the driver's characterization from the trajectory vector followed, using a behaviour model for path planning. Abundant research work (Donges, 1978; Kramer and Rohr, 1982; Afonso, *et al.*, 1993; Majjad, 1998) has been carried out in the literature.

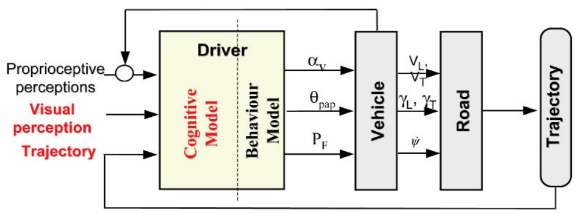

Fig. 1– The driver as a controller in the DVE context

The approach developed here, describes essentially the guidance task (Kiencke and Nielsen, 2000) which represents the set of perceptions, decisions and actions aiming at following a given trajectory. Furthermore, a microscopic point of view (inter-vehicle relationships are not considered – the environment is defined) has been considered.

The main advantage of the model developed is the combined characterization of the longitudinal and the lateral aspects of trajectory taking, considering the driver behaviour analysis discussed in section 2. The principles chosen to model the two aspects – longitudinal and lateral– are detailed in section 3. The results obtained are presented in section 4.

2. DRIVER BEHAVIOUR ANALYSIS

In the literature concerning vehicle control, the longitudinal and lateral aspects are generally considered separately. Thus, on the one hand, the problem of trajectory/steering control is treated assuming a constant speed and, on the other hand, the lateral dynamic is not considered in a speed regulation task. The main aspect of the present study is to provide a solution leading to combined longitudinal and lateral dynamic control.

Even if in a straight line, the longitudinal and lateral dynamics are loosely coupled[1], their interaction becomes primordial when driving in a bend, during overtaking or during obstacles avoidance for instance. In the particular case of curve negotiation, generating a reference trajectory and a driving speed which physically allows the driver to follow this trajectory, is of utter importance. Indeed, in this driving situation, the longitudinal and lateral dynamics are coupled on the basis of the centrifugal force (defining the lateral acceleration as a function of the velocity and the curvature radius of the trajectory). Nevertheless, the trajectory and the associated speed not only depends on function of the geometrical characteristics of the bend, but also on the vehicle and especially on the driver. A driver chooses his trajectory and the associated longitudinal speed based on his capabilities to perceive longitudinal and lateral accelerations (Lechner and Perrin, 1992). Moreover, several driver-dependent parameters such as age, sex, physical and mental capabilities or even his workload, continuously influence the driving task. So, the study of different drivers' profiles in the same driving situations can help to develop a control-oriented driver-dependent model and can lead to driver-adapted assistance systems in a near future.

The driver study described here focuses on the analysis of, on the one hand the vehicle's position and orientation on the road (see section 2.1), and on the other hand, on the associated longitudinal and lateral requests (longitudinal velocity, longitudinal and lateral accelerations) during bend negotiation (cf. section 2.2).

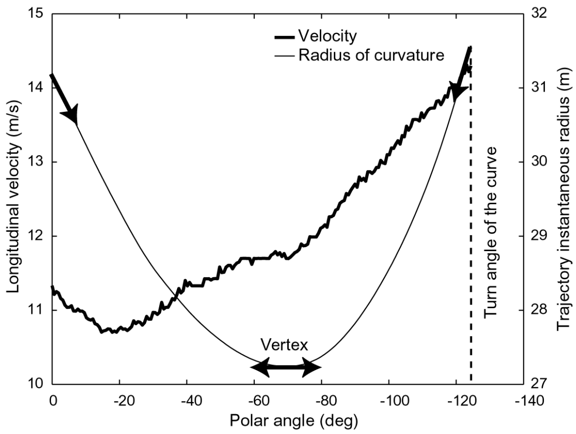

Fig. 2 – ND: radius of curvature and longitudinal velocity

The present results are based on tests carried out with different kinds of drivers in the same conditions: vehicle, turns, etc. The drivers were classified according to their age, driving experience, etc… using the well-defined classification proposed by Rothengatter, *et al.* (1993). The analysis considered two driver profiles representative of opposite driving styles: the "novice driver" (ND) and the "very experienced driver" (VED) (Baujon, *et al.*, 2001) but the description proposed hereafter only concerns the ND.

2.1. Trajectographic analysis

Fig. 2 represents the instantaneous radius of curvature of the ND's trajectory and the associated longitudinal velocity. These curves are plotted in a polar coordinate frame with its centre located on the centre of the turn studied. The representation of these data along the path makes the analysis of the driver's behaviour easier during bend negotiation.

During this particular driving sequence, the ND progressively turns the steering-wheel, increasing the steering angle to a maximum, then smoothly turns it to the initial point, decreasing the steering angle. This driving technique leads to a progressive and smooth trajectory based on a nearly constant lateral acceleration. This path is characterised by a parabolic and symmetric shape (with respect to the vertex) of the radius of curvature (cf. Fig. 2). Different research studies have concluded that the accelerations (and principally the lateral acceleration during bend negotiation) and their variations are linked to the subjective assessment of safety and comfort. Thus, a constant acceleration path like the one described in Fig. 2 shows that drivers focus on this notion to choose their trajectory and the associated requests.

[1] Meaning that speed control is possible without trajectory control and reciprocally.

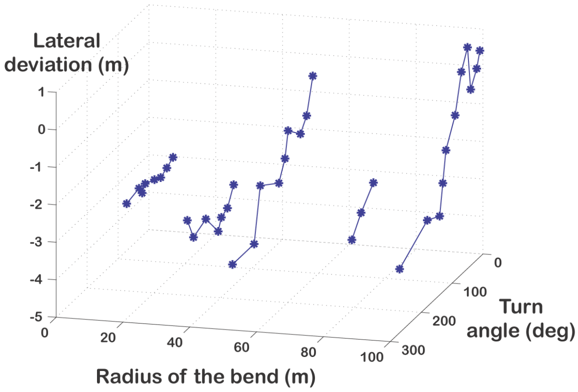

Fig. 3 – ND: Position of the vertex

It is also important to notice that the vehicle's heading (represented by the slope of the radius in Fig. 2) at the beginning and also at the end of the turn is important. This indicates that the driver anticipates the turn (Donges, 1978; Billing, 1977; Kondo, and Ajimine, 1968; Shinar, *et al.*, 1977), thanks to the visual information he perceives of the situation.

Fig. 3 illustrates the influence of the radius of curvature and the turn angle on the lateral position of the ND's vertex. This graph presents the vertex's position with respect to the middle of the road. Thus, a negative (respectively positive) value on the Z-axis indicates that the vehicle is on the internal (respectively external) lane with respect to the bend. This is based on the assumption that during these tests performed on a test track the driver could use the whole road width. From this figure, it can be noticed that:

- In the case of turns with a low radius of curvature (< 50 m), the influence of the turn angle is weak: during the bend negotiation, the vehicle stays in the middle of its driving lane.
- When the radius of curvature is higher than 50 m, the variation of the vehicle's lateral position during the negotiation grows with the augmentation of the turn angle. The driver tends to approach the inner bend when the turn angle grows in order to minimise the effect of the centrifugal force.

2.2. *Longitudinal behaviour analysis*

The speed profile illustrated in Fig. 2 correlated to the accelerations diagram[2] described in Fig. 4 shows that:

- The braking sequence is performed principally before the turn,
- The lateral acceleration and thus the longitudinal speed are nearly constant or slightly increasing during the whole negotiation,

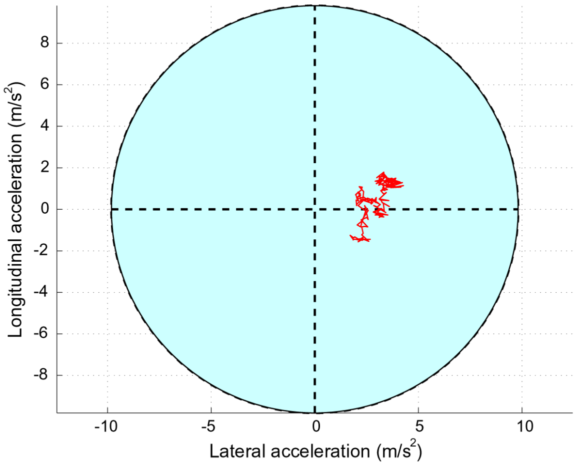

Fig. 4 – ND: accelerations diagram

- The longitudinal excitations are identical during acceleration and deceleration (even if the braking potential of a car is higher than the acceleration potential).

With the same objectives, similar analysis and modelling have been performed for the VED.

3. DRIVER MODELLING

3.1. *Longitudinal behaviour modelling*

The previous section highlighted the fact that in order to negotiate a bend with the appropriate longitudinal velocity, the driver performs different tasks:

- The "braking sequence": to reach an appropriate speed for the curve negotiation,
- The "bend negotiation sequence": nearly with a constant speed,
- The "acceleration sequence": when leaving the bend and depending on the road profile ahead.

Finally, assuming that when driving in a straight line the driver generally maintains a constant velocity, four tasks must be taken into account to model the longitudinal behaviour of a driver. A well suited tool to model a sequential execution like the one described here is the finite state machine.

<u>The finite state machine:</u> Fig. 5 presents the finite state machine implemented for longitudinal behaviour modelling. The overall structure of this state machine has largely been described in (Lauffenburger, *et al.*, 2000a). Nevertheless, the one presented in Fig. 5 has three main improvements concerning state 4:

- The longitudinal controller can switch to state 1 ("Acceleration") before the end of the bend: depending on the visual information the driver perceives of the situation to occur, he can

[2] This representation proposed by (Milliken, and Milliken, 1995) represents the longitudinal acceleration as a function of the lateral acceleration. It particularly shows if these accelerations are coupled (braking/accelerating in turn) or not.

accelerate before reaching the end of the current bend,

- It can also switch to state 1 if the radius of curvature of the bend ahead is greater than the previous one, allowing the driver to accelerate and adapt his speed to the next bend,

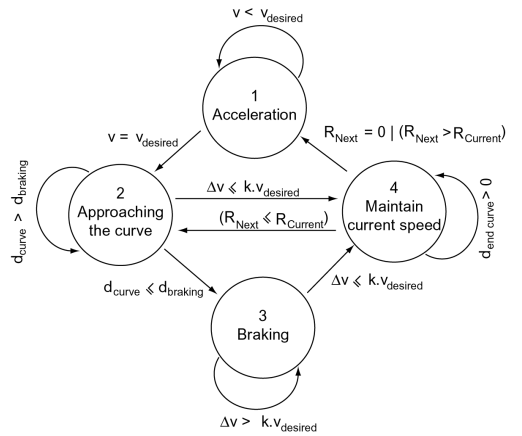

Fig. 5 – State graph of the longitudinal model

- It can change to state 2 if the radius of the bend ahead is lower than or equal to the previous one, requiring a new braking phase.

All these improvements allow a better representation of the driver's behaviour.

Identification of the bend speed: in state 2 ("Approaching the curve"), the state machine determines the reference speed suited for the coming bend according to the bend characteristics, the vehicle's potential and the driver's profile. It has been shown in section 2.1 that the trajectory and the associated speed are based on the subjective notions of comfort and safety. These notions depend on the lateral acceleration or more precisely the centrifugal force the driver is subjected to. It is then natural to determine the reference speed for a bend according to the level of transverse (centrifugal) acceleration admitted by the driver[3]. The reference speed for the curve is determined considering the tolerated lateral acceleration γ_T (depending on the driver and the dynamic potential of the vehicle) and on the instantaneous curvature κ of the trajectory followed (Eq. 1).

$$v^2(t) = \frac{\gamma_T(t)}{\kappa(t)} \quad \text{Eq. 1}$$

The next paragraph shows that the trajectographic model is based on a continuous-curvature curve. This helps to compute, for a given driving situation, a reference path and, with Eq. 1, its associated speed profile. This solution can lead to coupled speed and trajectory control.

3 The level of accepted lateral acceleration is also an indicator of the driver's profile.

3.2. Trajectographic modelling

Based on the analyses presented in section 2.1, an original approach for driver modelling is proposed here. In fact, the solution consists of the trajectographic modelling of different kinds of drivers with the same mathematical model. This model must satisfy two main objectives. On the one hand, the generated trajectory must allow an effective and precise control of the car during path tracking for example. So, steering discontinuities must be avoided. On the other hand, real-time computation capabilities of the identified model are necessary for its implementation.

The necessity of a continuous-curvature model: the solution proposed is derived from the path-planning technique for Autonomous Guided Vehicles (AGV). As steering discontinuities have to be avoided, discontinuous-curvature paths (Dubins, 1957; Reeds and Shepp, 1990) are not suitable for this application. The continuity constraint on curvature induces the continuity of transverse acceleration. This is primordial here because it directly reflects the driver's behaviour whose aim is to minimise the lateral acceleration variations.

Length-dependent continuous-curvature curves such as clothoids (Kanayama and Miyake, 1985) or cubic spirals (Nagy and Kelly, 2001) are subject to mismatching at their end-points. This is due to the numerical integration required for the determination of the points forming the curve. These curves can therefore not be considered.

Finally, the formulation used here concerns polar polynomial curves, representing the trajectory in a polar coordinate frame (radius, polar angle). Initially used to approximate circular arcs, the aim is now to use the flexibility and modularity of the polar curves to precisely and easily model measured trajectories of different kinds of drivers. The shape of the curves can be more or less regular/smooth depending on the conditions imposed. So these curves are well suited for trajectory modelling and for on-line computation because of their simple closed-form expression (cf. Eq. 2).

The polar polynomial curves: This mathematical model has first been introduced by Nelson (1989) and later expanded by Pinchard, *et al.* (1996), adding kinematic and dynamic constraints. The general expression of the polynomial is given by Eq. 2 where the number of parameters a_i defining the polar radius r as a function of the polar angle ϕ depends on the number of continuity constraints imposed.

$$r(\phi) = a_0 + a_1.\phi + a_2.\phi^2 + a_3.\phi^3 + \ldots + a_n.\phi^n \quad \text{Eq. 2}$$

For the trajectory modelling purpose, the polynomial parameters are determined (based on the analysis performed in section 2.1) with respect to the bend characteristics and the driver's profile. The identification of the model has been explained in (Lauffenburger, *et al.*, 2000b; Lauffenburger, *et al.* 2003a) and is thus not illustrated here.

4. EXPERIMENTAL RESULTS

The next section presents the results obtained with the implemented longitudinal and trajectographic models. To validate these models with respect to different driver profiles, real experiments were carried out with the instrumented laboratory test car and drivers of different types (ND and VED). During these tests, the trajectory and the velocity of the vehicle were measured using the test car's embedded architecture and especially the DGPS system and the optical speed sensor. Only the case of the novice driver will be considered here.

4.1. Trajectographic model results

Fig. 6 illustrates, on the one hand, the ND's measured trajectory (solid line) and, on the other hand, the computed polar model (dotted line). Note the precise identification of the end-points and the vertex. Nevertheless, the model deviates from the real path between the beginning of the bend and the vertex.

In order to evaluate this deviation, the relative error (in %) along the path is represented in Fig. 7. As previously mentioned, the continuity constraints at the end-points and the vertex (given by a polar angle of 90°) are precisely computed: the error on these particular points is less than or around 1%. Moreover, the maximum error along the path does not exceed 2.5%. This means that the maximum lateral deviation observed approximately corresponds to 0.9 m. Even if these results are satisfactory, it is obvious that in this case the model must be improved keeping in mind that it is designed for control.

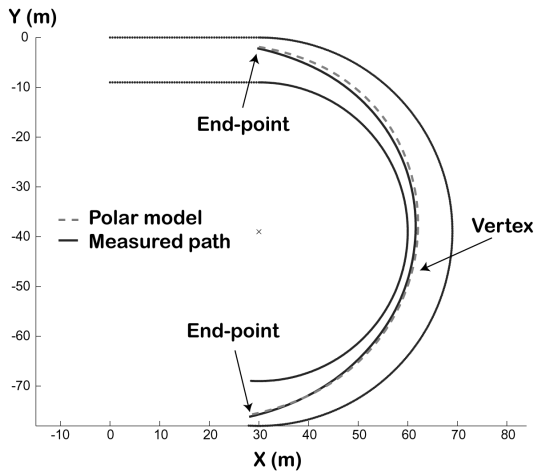

Fig. 6 – ND: polar model and measured trajectory

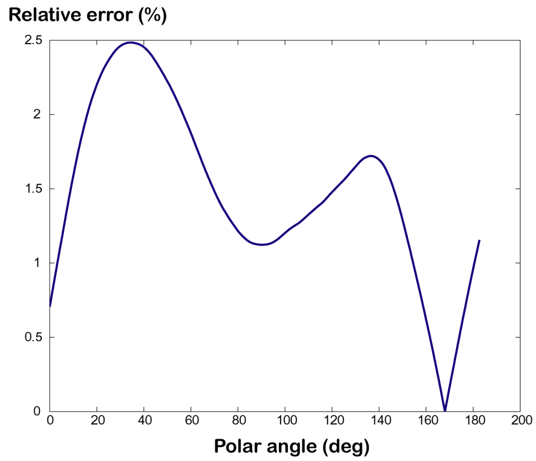

Fig. 7 – ND: Error between the model and the measured trajectory

4.2. Longitudinal modelling results

The validation of the longitudinal model and more precisely the state machine consists of the comparison of the generated speed profile and the measured speed for a given course. These tests are based on 4 assumptions:

- The braking potential is constant and equal to –3 m/s². This reflects the behaviour of a wide range of drivers and especially a ND.
- The acceleration potential is constant and equal to 1.5 m/s².
- The maximum transverse acceleration tolerated by the ND is 2 m/s².
- In a straight line, the speed is maintained constant and equal to 25 m/s.

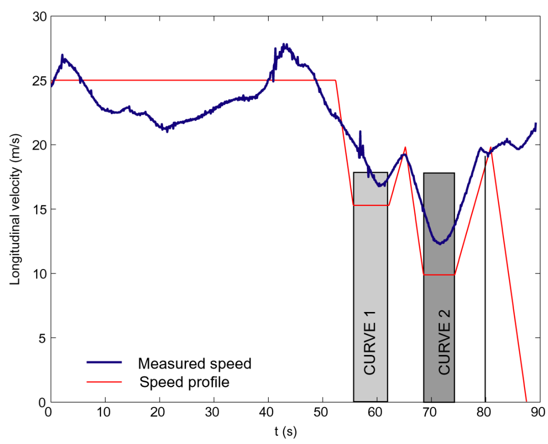

Fig. 8 – ND's speed profile vs. on-line computed speed profile

The results are shown in Fig. 8. The shape of the computed speed profile is close to the measured speed showing that the longitudinal model based on the 4 above presented sequences (see section 3.1) is suitable. However, the braking sequence of the first bend is slightly different. This can be explained by the fact that this curve is preceded by a long straight line allowing the driver to progressively decelerate without braking.

The interest of this test also resides in the comparison of the reference velocity computed for the bends and the measured ones. So, the determination based on the accepted lateral acceleration (cf. Eq. 1) is a satisfactory solution, even if in this case, the transverse acceleration admitted by the ND is higher than 2 m/s^2 assumed for this test. Finally, it can be noticed that the assumed braking and acceleration potentials are higher than the ones noted during this experiment.

5. CONCLUSION

This paper has described a new driver behaviour model which computes a reference path –speed associated with trajectory– appropriate to the negotiation of possible roads. This model essentially describes the guidance task which represents the set of perceptions, decisions and actions aiming at following a given trajectory. Furthermore, a microscopic point of view (inter-vehicle relationships are not considered – the environment is defined) has been considered.

The model developed which associates the characterization of the longitudinal and the lateral aspects of the trajectory taken has been tested and validated through real experiments. Different drivers' categories combined with different representative roads have been used for real testing. Thanks to a unified structure, different models have been identified for the different drivers' classes. This type of model is dedicated to simulation and control applications. Different applications, for instance in the NAICC project (Lauffenburger, et al., 2003a) which involves a driver-aid system, have implied the developed models for path planning. A study is in progress to test other representative drivers' classes.

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