

## A CONTROL THEORETIC MODEL OF DRIVER STEERING BEHAVIOR

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Abstract

In establishing design criteria for vehicle dynamics which may improve the performance of the driver-vehicle system, a quantitative description of driver steering behavior such as a mathematical model is likely to be helpful.

The steering task can be divided into two levels: (1) the guidance level involving the perception of the instantaneous and future course of the forcing function provided by the forward view of the road, and the response to it in an anticipatory open-loop control mode; (2) the stabilization level whereby any occurring deviations from the forcing function are compensated for in a closed-loop control mode.

This concept of the duality of the driver's steering activity led to a newly developed two-level model of driver steering behavior. Its parameters were identified on the basis of data measured in driving simulator experiments. The parameter estimates of both levels of the model show significant dependence on the experimental situation which can be characterized by variables such as vehicle speed and desired path curvature.

1. Introduction and Conception of a Driver Model

The long term objective of investigating dynamic characteristics of the driver-vehicle system is to establish criteria for the design of vehicle dynamics which may improve the "Active safety" of vehicles. To accomplish this the dynamics of both system elements, i.e., driver and vehicle, have to be known. While the mathematical description of vehicle dynamics is highly developed, there is a considerable lack of such knowledge about the dynamic capabilities and limitations of the driver. In order to help improve the description of driver behavior, the steering activity of drivers measured in an extensive series of driving simulator experiments was investigated. The results are presented in the comprehensive form of a mathematical model.

The basic idea underlying the data analysis and the driver-model concept is the duality of information presented to the driver by the forward view of the road. On the one hand, the visual field of the driver provides information on the instantaneous and future course of the road, so that the driver can extrapolate not only the present but also the future run of the driver-vehicle system's forcing function. This type of visual perception is called anticipation or preview [7], [4], [10], [12]. The information on the forcing function is called "Guidance information", because the driver uses it for guiding the vehicle along its desired path. A physical quantity which seems suitable for the description of the sensory impression about the forcing function, is the curvature of the road (i.e. the reciprocal of the radius of turn), because the central perspective pattern of the road shows a straight or a more or less curved run corresponding to the value of curvature. Therefore the curvature of the vehicle's desired path can be looked at as a measure of the forcing function.

On the other hand, static and dynamic cues in the visual field contain information on the instantaneous deviations between the vehicle's actual path and its desired path (i.e. forcing function). This portion of information is called "Stabilization information", because the driver uses the corresponding visual cues to stabilize vehicle motions with respect to the forcing function. The essential portion of stabilization information can be described by the following quantities (see figure 1):

1. Lateral deviation  $y_{\Delta}$  between the driver's head position and the vehicle's desired path.
2. Angle between the tangents of the desired and the actual path.  
Because in the simulated vehicle dynamics the tangent of the vehicle's actual path is identical with its longitudinal axis, this quantity is called heading angle  $\psi_{\Delta}$ .
3. Difference of the curvatures of the vehicle's actual and desired path, called path curvature error  $K_{\Delta}$ .

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Meckenheim, Germany [9]. This driving simulator consisted of an analogue computer simulation of longitudinal and lateral vehicle dynamics, a mock-up of the driver's seat with speedometer and control elements (steering wheel, gas and brake pedals, automatic gearshift), and special sub-simulators for the generation of driving and engine noise, vehicle motions and the visual out-of-the-window scene (Figure 2).

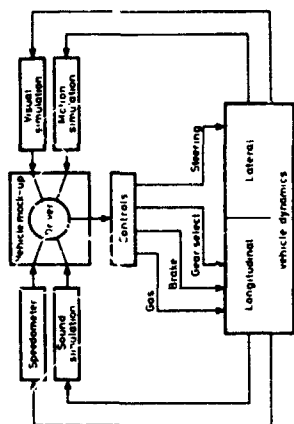


Fig. 2. Topology of the FAT driving simulator

The simulated test course was a winding closed-circuit two-lane road located in a horizontal plane (Fig. 3). The length of the course was 3.2 km. The route consisted of a series of joined road sections of constant curvatures (Figure 3 b).

The visual scene which contained the essential information for the driver was a simulated quasi-natural out-of-the-window forward view of the two-lane test course (Figure 4). This road image was generated according to the instantaneous position and attitude of the vehicle by electronic means and shown to the driver on a 3 m high and 4 m wide screen by a black and white TV projection. The horizontal width of the visual field was about 40°. The angular relations of the lane markings in the simulated visual field as seen by the driver corresponded to an 8 m wide road.

The analogue computer representation of the vehicle dynamics used for this investigation approximately simulated an automobile. The lateral dynamics

The way these three quantities may be perceived by the driver, is discussed in [3] and [4] with reference to [1], [6] and [7].

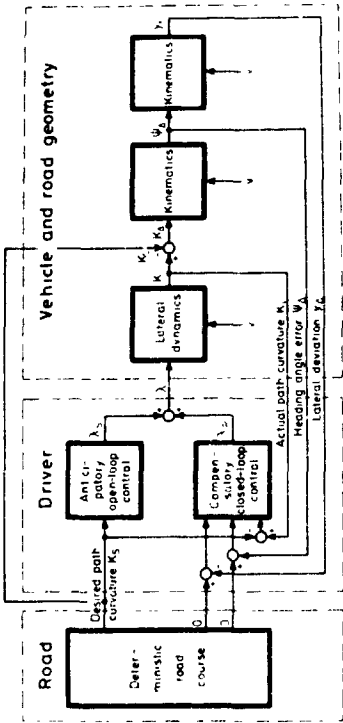


Fig. 1. A structural scheme of human steering behavior in the driver-vehicle-road system

The duality of the driver's visual information is the basis of the two-level structure of the driver model described in this paper (Figure 1). Accordingly, the two levels of the model are called "Guidance level" and "Stabilization level". Instead of a sequential mode of operation as proposed by Crossman and Szostak [2], both levels operate here in parallel. At the guidance level, the anticipation of the forcing function enables the driver to steer in an anticipatory manner when the forcing function changes. Because an anticipatory reaction is always feedforward, such steering behavior can best be explained as an "Anticipatory open-loop control". At the stabilization level, the success of this open-loop control is observed and must be completed by compensation for any occurring deviations. This "Compensatory closed-loop control" stabilizes vehicle motion.

## 2 Driving Simulator and Experimental Procedure

The experiments providing the data for this investigation were carried out in the driving simulator of the Forschungsinstitut fuer Anthropotechnik (FAT) in

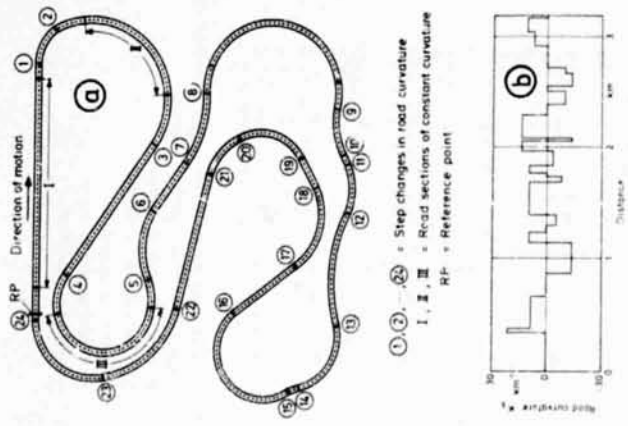


Fig. 3. Test course  
 a) Plan view  
 b) Curvature profile of road centerline

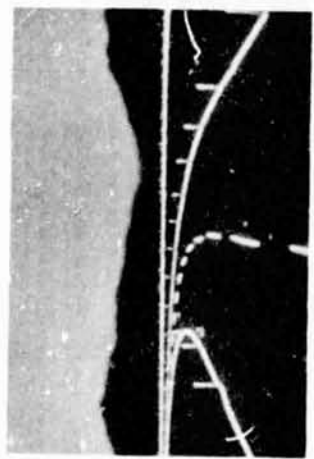


Fig. 4. Quasi-natural visual simulation of a two-lane road

of the vehicle can be defined by the relationship between the steering wheel angle  $\lambda$  and the vehicle's actual path curvature  $K_1$  [5]. In the ranges of lateral acceleration and of steering wheel rotation frequencies covered during the experimental runs, the vehicle's lateral dynamics can be characterized in a first order approximation by a time-delay term:

$$K_1(t) = E_L \lambda(t - T_F) \quad (1)$$

Herein,  $T_F = 0.2$  s is the vehicle's time-delay constant (vehicle-response time) and  $E_L$  is the steady state steering sensitivity ( $E_L = 0.85 \cdot 10^{-3}$  degree  $m^{-1} = 0.049$  rad  $m^{-1}$ ). Since the vehicle is assumed to be neutral steering,  $E_L$  is independent of vehicle speed [8]. It should be mentioned that the value of  $E_L$  used here is about two to three times as high as usually applied in automobiles.

When side slip angle is neglected, the following kinematic equation describes heading angle error  $\psi_\Delta$ , i.e., the angular difference between the desired path's tangent and the vehicle's longitudinal axis:

$$\dot{\psi}_\Delta(t) = \dot{\psi}_\Delta(t_0) + \int_{t_0}^t v(\phi) [K_1(\phi) - K_S(\phi)] d\phi \quad (2)$$

A corresponding equation exists for the kinematic relationship between heading angle error  $\psi_\Delta$  and lateral deviation from the vehicle's desired path  $y_\Delta$ :

$$\dot{y}_\Delta(t) = y_\Delta(t_0) + \int_{t_0}^t v(\phi) \psi_\Delta(\phi) d\phi \quad (3)$$

In equations (2) and (3),  $\psi_\Delta(t_0)$  and  $y_\Delta(t_0)$  are initial conditions,  $v$  is the vehicle's speed and  $K_S$  is the curvature of the vehicle's desired path.

To have a well defined, measurable quantity  $K_S$  as the forcing function of the driver-vehicle system, all subjects were insistently instructed to drive along the centerline of the road as accurately as possible, i.e., while driving, the subjects should make sure that they sit just above the road centerline. During the experiments the simulated road was free of other traffic.

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The data analysis and model identification described in the following chapters is based on data from six subjects measured during experimental runs of three laps on the test course of figure 3.

### 3. Proof of the Driver's Anticipatory Steering Reaction

As shown in figure 3.b, the test course consisted of 24 sections of constant curvatures. At points where two of these sections join together, the road curvature abruptly takes a new value. This change in road geometry is seen by the driver a long time before he passes the joining point, so that he is able to react beforehand. Typical time histories of such steering reaction and of the corresponding output variables are shown in figure 5. The 4th step change of road curvature (see figure 3) is taken as an example. The diagrams show means and standard deviations averaged over 18 individual time histories.

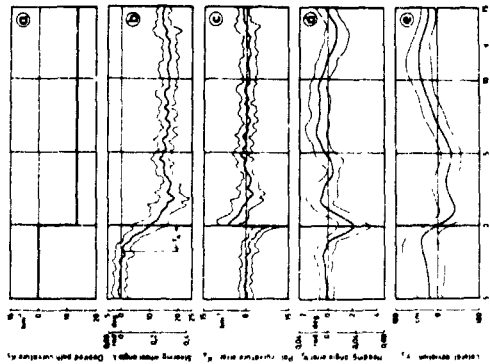


Fig. 5. Typical time histories of system variables at the 4th step change in desired path curvature  
 a. desired path curvature  
 b. steering wheel angle  
 c. path curvature error  
 d. heading angle error  
 e. lateral deviation

The steering wheel reactor starts at a certain time interval, called "anticipation time"  $T_A$ , prior to the step change of road curvature and then shows a lagging transient with a small overshoot (Figure 5.b). The success of this reaction is most clearly demonstrated in the graph of lateral deviation (Figure 5.e): the change in lateral deviation caused by the step change of road curvature is distributed approximately evenly between right and left hand sides of the forcing function.

### 4. Driver Model Structure

The complete structure of the two-level model is shown in figure 6.

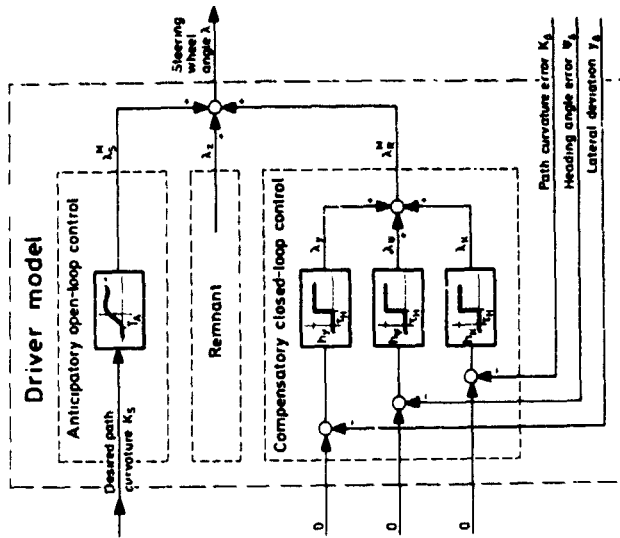


Fig. 6. Block diagram of the two-level model of driver steering behavior

The "Anticipatory open-loop control" submodel representing the guidance level of steering activity simulates the anticipatory response to the deterministic run of desired path curvature. Corresponding to the typical step response of steering wheel angle in figure 5.b, the features of this submodel include anticipation time  $T_A$  and lagged transient response. Because the experimental data were registered in sampled form, the anticipatory submodel is formulated in the discrete time form of a scalar difference equation:

$$\begin{aligned} \lambda_S^M(t_k) + a_n \lambda_S^M(t_{k-n}) + \dots + a_1 \lambda_S^M(t_{k-1}) \\ = b_n K_S(t_{k-n} + T_A) + \dots + b_1 K_S(t_{k-n} + T_A) \end{aligned} \quad (4)$$

where  $\lambda_S^M$  is the steering wheel angle of the anticipatory submodel,  $K_S$  is the desired path curvature,  $t_k$  ( $k = 1, 2, 3, \dots$ ) are the discrete points in time,  $T_A$  is the anticipation time,  $a_i, b_i$  ( $i = 1, 2, \dots, n$ ) are the time-invariant, linear parameters of the difference equation, and  $n$  is the order of the difference equation.

The "Compensatory closed-loop control" submodel corresponding to the stabilization level of steering activity accomplishes the feedback of the output variables. For the mathematical formulation of the compensatory submodel, a very simple approach is used. Each of the three output quantities, i.e., path curvature error  $K_\Delta$ , heading angle error  $\psi_\Delta$ , and lateral deviation  $Y_\Delta$  is delayed by an inherent human time delay and fed back by a single gain factor:

$$\lambda_R^M(t) = -h_K K_\Delta(t-T_H) + h_\psi \psi_\Delta(t-T_H) + h_Y Y_\Delta(t-T_H) \quad (5)$$

where  $\lambda_R^M$  is the steering wheel angle of the compensatory submodel,  $h_K, h_\psi$ , and  $h_Y$  are the gain factors and  $T_H$  is the human time delay.

It has been proved that this simple approach provides the capability of stabilizing the outer loop, i.e., the lateral deviation loop, of the compensatory control process which then shows the features of the crossover model of the human controller [1].

Because both submodels will not completely reproduce the driver's steering wheel angle, a remnant quantity is a third integral part of the model. The remnant comprises driver-induced signals which are not related to the steering task as well as shortcomings of the special structure and features of the model chosen.

At 13 specific sections of the closed-circuit test course, the parameters of the driver model are identified from the experimental data using measurement intervals of 20 s duration [4]. Within this time, vehicle speed is approximately constant, so that a model with piecewise time-invariant parameters is applicable. Ten of the sections contain at least one step change of road curvature which can be utilized for the identification of both model levels. Three sections (I, II, and III in figure 3) have constant curvatures where only compensatory submodel parameters can be identified. Within each section, the experimental data of six subjects with three laps each, i.e., 18 sets of data per section, were evaluated.

## 5. Results and Discussion

In order to provide a qualitative impression of model performance, the steering angles of the driver and the driver model are compared, and the components of the model steering angle shown by way of an example (Figure 7).

Figure 7.a indicates the experimental conditions. The road section under consideration shows three step changes in road curvatures, the vehicle speed is approximately constant. As the comparison of driver and driver model steering angles in figure 7.b shows, the model simulates the driver's steering reactions very well especially as far as the low frequency components are concerned. Figure 7.c presents the contributions of the anticipatory and the compensatory submodels. In figures 7.d to f, the compensatory submodel components are shown. The model remnant in figure 7.g turns out to be a broad band stochastic signal.



time delay is constrained by some lower reaction time limit. Therefore, the relationship indicated by the dotted regression line cannot be extrapolated as in the form of a linear law beyond the speed range covered in the underlying experiments.

The second relationship of the compensatory submodel parameters as illustrated in figure 8.b by path curvature error gain also seems to be reasonable: The velocity vector field [6, 7] of the driver's visual field, which is the basis for the perception of path curvature error [4], becomes more observable as vehicle speed grows. The driver is then able to feed path curvature error back with higher gain.

In addition to the tendencies mentioned which demonstrate the high adaptability of the driver, figure 8.b shows an item which may indicate a human limitation. One of the road sections, the gain factor of heading angle error is significantly higher than in all other sections. This outstanding section is the only straight road section (Section 1 in figure 3). The perception of heading angle error in curved road sections is degraded by the fact that the instantaneous direction of the desired path is not directly depicted in the visual field as it is on straight roads [3, 4]. This degradation causes a decrease in heading angle error gain which is disadvantageous from a control theoretic point of view.

## 6. Conclusions

The results provided by the two-level model of driver steering behavior indicate human adaptability as well as human limitations. The experimental variables in the present investigation which caused variations in human control behavior were vehicle speed and road curvature.

For the initially mentioned long-term objective of improving driver-vehicle-road system performance, the influence of vehicle dynamic parameters such as position of the center of gravity, or tyre features, on human steering activity is of great interest. The two-level model and its identification procedure seem to be suitable for (1) describing human steering behavior, and (2) theoretically evaluating the dynamic interaction within the driver-vehicle control system.

## 7. References

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