Studies on Vehicle Guidance and Control

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ABSTRACT

For approximately 10 years, part of the research effort of the TNO Institute for Perception has been devoted to the analysis and modeling of driving behavior. In this paper, some of the most relevant research issues in this area will be reviewed. First, an impression is given of some theoretical and experimental studies on course perception and vehicle guidance in preview. Second, two nearly developed methods for describing vehicle control as a supervisory task are discussed. The predictions made with these models were verified in a field experiment in which subjects drove under conditions with temporary occlusion of visual input at different speed levels. Subjects' self-chosen occlusion durations could very well be explained by both models. Suggestions are given of how the proposed methods can be applied to optimize roadway and vehicle characteristics.

For approximately 10 years, part of the research effort of the TNO Institute for Perception has been devoted to the analysis and modeling of driving behavior. In this paper, some of the most relevant research issues in this area will be reviewed. They all start from the basic view that the driver behaves as an information-processing system, looking for relevant input data in order to be able to process the course and speed of his own and other vehicles and, accordingly, to act in the right way. The issues to be discussed concern basic performance while the results of both offer elements in modeling driver behavior.

VEHICLE GUIDANCE

Much of the research into the basic perceptual cues in driving has been concerned with the perception of owner vehicle movements (i.e., the perception of course and speed) for the straight road situation. Instead of starting from a bird's-eye view description, which is the common approach in most of the presently available driver models (1-4), the purpose has been to describe and analyze the situation from a perspective view of the road ahead. Figure 1 shows an impression of the driver's visual scene looking ahead on a straight road marked with continuous lines.

In this figure, a lateral position deviation, Δy, can be optically perceived by the driver as an angular deviation $\Delta\alpha$ (5). The ratio between $\Delta\alpha$ and Δy gives a theoretical estimate of the driver's sensitivity for the perception of lateral position deviations. This ratio changes as a function of (a) the driver's eye height above the delineation, h, and (b) the driver's lateral distance to the delineation, y, according to Equation 1 as follows:

$$\Delta\alpha/\Delta y = h/(h^2 + y^2) \qquad (1)$$

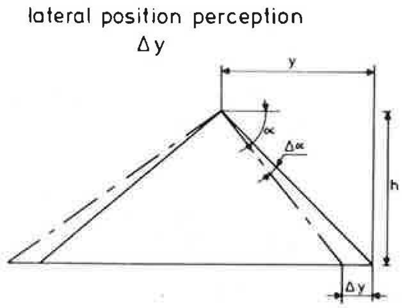

FIGURE 1 View of the road in perspective.

Figure 2 shows a representation of Equation 1, illustrating the effect of four road delineation systems on the driver's theoretical sensitivity for lateral deviations. The four delineation systems are panel-mounted (L_1 and L_2, respectively, with relative eye heights h = -0.10 m and h = 0.40 m), post-mounted (L_3, with h = 0.75 m), and pavement (L_4, with h = 1.25 m).

This analysis turns out to be of great help in understanding and explaining real-world observations, in predicting the kind of difficulties that may arise, for instance, with work-zone delineation systems, and in making recommendations. Schwab and

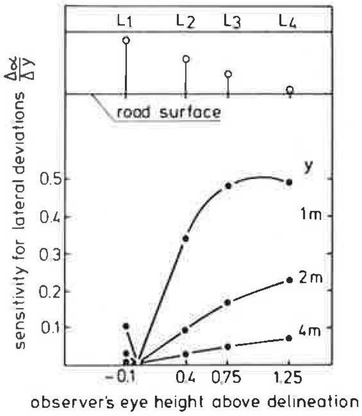

FIGURE 2 Sensitivity of lateral position perception, $\Delta\alpha/\Delta y$, as a function of the observer's eye height above the delineation, h, and different values of lateral distance to delineation, y.

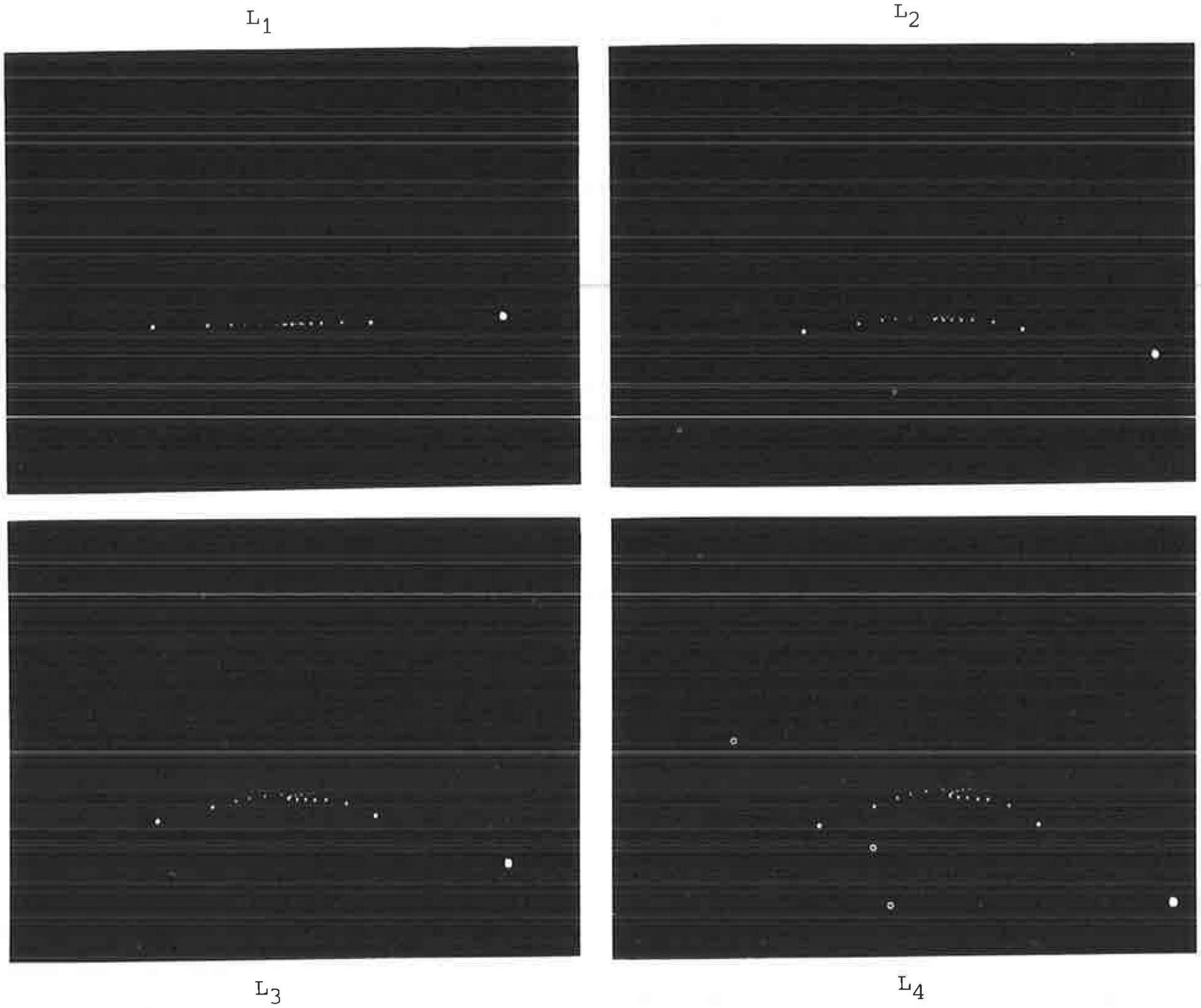

FIGURE 3 Perspective view on the geometry of the road ahead with four systems of delineators of the same geometry.

Capelle (6), for example, found that centerline delineation is highly cost-effective in terms of accident rates and driving performance. In a laboratory experiment, Godthelp and Riemersma (7) showed that there is a large effect of delineation systems varying in height on subjects' error percentages when they judged the simulated work-zone geometries shown in Figure 3. Furthermore, the results, which are presented in Figure 4, show that disturbances such as having some delineators removed from the scene (as is often the case in real situations) may strongly affect the error score. Response times of subjects were also in line with these findings; the higher the eye height above delineation, the shorter the response times in judging work-zone geometry.

The latter findings point to the effect of road delineation on the driver's preview, which is of utmost relevance for anticipation of the road geometry ahead. Early anticipation will allow timely steering performance and so will contribute to traffic safety.

VEHICLE CONTROL

One of the main tasks of the driver when steering his vehicle along the road or through a terrain is to control lateral position. Most of the available steering control models are based on the assumption that the driver acts as an error-correcting mechanism continually allocating attention to the steering task. However, driving cannot simply be considered to be a continuous closed-loop task. First, the driving task does not require permanent error control; second, the driver is sometimes forced to pay attention to aspects other than steering, so that it

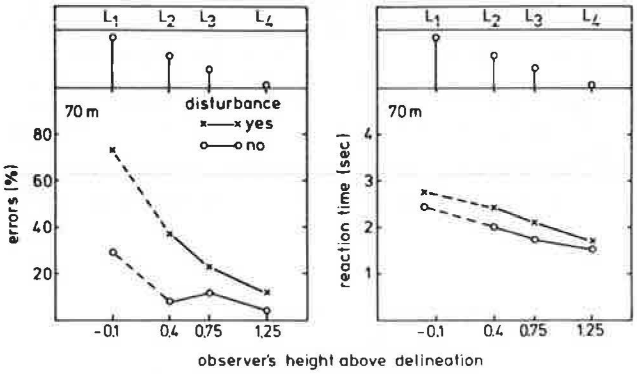

FIGURE 4 Mean error percentages and reaction times for judging the work zone geometries shown in Figure 3.

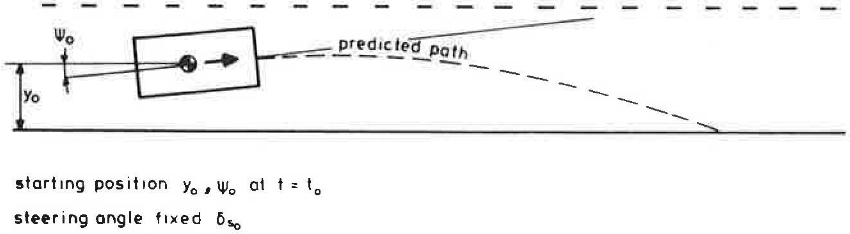

FIGURE 5 Scheme of path predictions in a preview-predictor model.

is even impossible to drive in a continuous closed-loop fashion. Hence, driver models should assume supervisory rather than continuous control. Although several uncertainty models have been developed (8-10), more research in driver modeling is necessary to obtain sufficient insight into the attentional demands of driving and the effects of vehicle and roadway characteristics.

In this paper, two methods will be discussed for the description of driving as a supervisory control task. With both methods, predictions can be made of the driver's spare time beyond the actual steering task. First, with the time-to-line crossing (TLC) approach, predictions can be made on the basis of a preview-predictor model about the time periods during which, for instance, path errors can be neglected. Second, the Optimal Control Model approach (11,12) enables predictions of "free" periods in the observation strategy of drivers during lateral position control.

Time-to-Line Crossing (TLC)

Predictions based on preview-prediction models mostly assume fixed steering control. This is shown in Figure 5. At any moment, the future path of the vehicle is predicted assuming that (a) the vehicle starts from its momentary lateral position, y_o, and heading angle, ψ_o, and (b) the steering wheel remains fixed at its momentary value, δ_{so}.

These path predictions will enable estimates of whether the driver may proceed with, or switch to, a fixed steering strategy. TLC thus defines the time needed by the vehicle to reach either edge of the lane (13). At any moment, TLC can be calculated from the vehicle's lateral position, heading angle, speed, and commanded steering angle. Figure 6 is an example of a time history of these signals together with the TLC measure. TLCs for predictions to the left (centerline) and right (shoulder line) are respectively given above and below the zero axis. Godthelp and Konings (13) argued that TLC may be helpful in describing and evaluating intermittent error-control (or error neglection) and visual open-loop strategies in driving. These strategies can be quantified by using a visual occlusion device that enables subjects to drive with self-chosen occlusion durations.

The Optimal Control Model (OCM)

The OCM describes the driver as a combined observer-predictor, controller, and decision maker (Figure 7), thus enabling the prediction of the observation and control strategy of the driver acting as a multiple-task system supervisor (14).

The driver receives information on the vehicle's position via the display variables, $\underline{y}$, and generates control actions by the vector, $\underline{z}$. The "observation-prediction block" transforms the available input information into estimates of the momentary state of the system including the estimation error (uncertainty). This transformation is made possible with knowledge of the system and display dynamics and compensates for the observation noise $V_{\underline{y}}$ of each display variable, that is, the noise-to-signal ratio for various driving situations (i.e., daytime, nighttime, fog). When no attention is paid to the display variables (e.g., during temporary visual occlusion), the observation noise is defined to be infinite. The control block transforms the internal estimates via an optimization criterion into control actions (e.g., steering wheel movements). With the help of the optimization criterion, the driver is able to evaluate, for instance, variations in lateral position because of lane width.

The supervisory control model found its operationalization by the optimal control model MANMOD (15) and focuses on the prediction of visual "occlusion" times during which no observations are made for refreshing the driver's internal representation.

EMPIRICAL VERIFICATION

Method

Predictions of occlusion times were made with both the TLC and OCM analysis. Model predictions were compared with experimental data of subject's self-chosen occlusion durations as measured during straight road driving with an instrumented car (16). This experiment was conducted on an unused four-lane divided highway over a distance of 2 km and with a lane width of 3.5 m. Half of the runs were performed with normal vision, whereas in the other half, visual occlusion was given by a visor, which could be raised (open) and lowered (closed) on command of the subject. In its normal state, the visor was closed, but on pressing the horn lever, the visor would rise and stay open for 0.55 sec. Measurements were made on steering wheel angle, yaw rate, lateral position, and occlusion times. TLCs were calculated for each sample (4 Hz).

TLC Predictions

Median and 15th-percentile TLC values were calculated together with means and standard deviations of lateral position, lateral speed, and steering wheel angle. Table 1 gives the results of these measures for six different speed conditions. Of main interest,

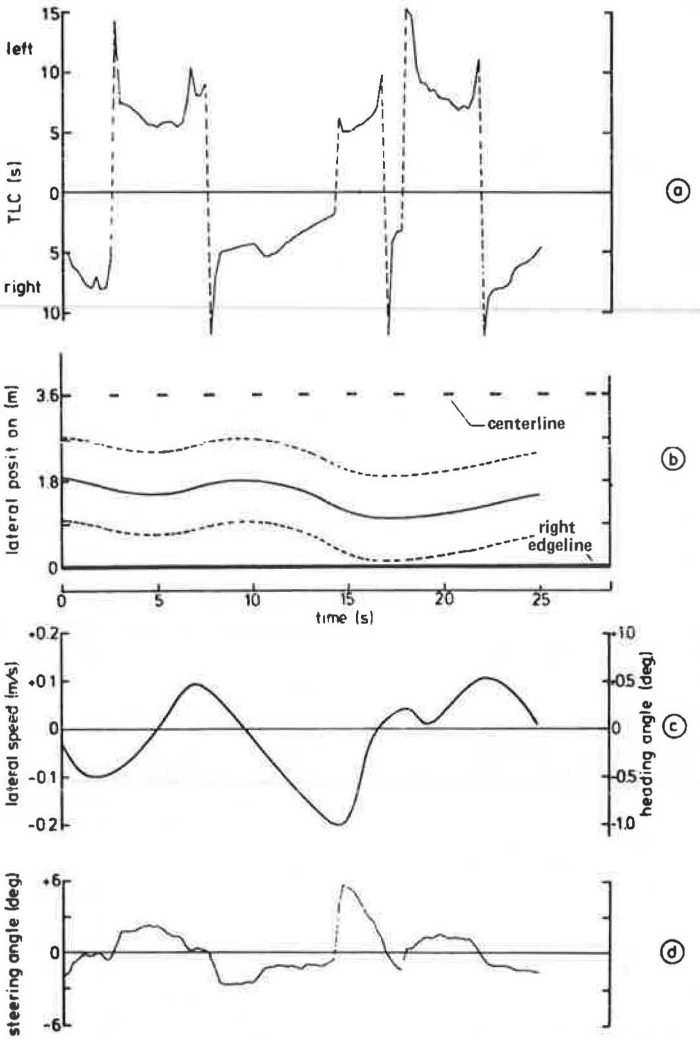

FIGURE 6 Sample time history of TLC (a), resulting from the corresponding lateral position (b), lateral speed (c), and steering-wheel angle (d).

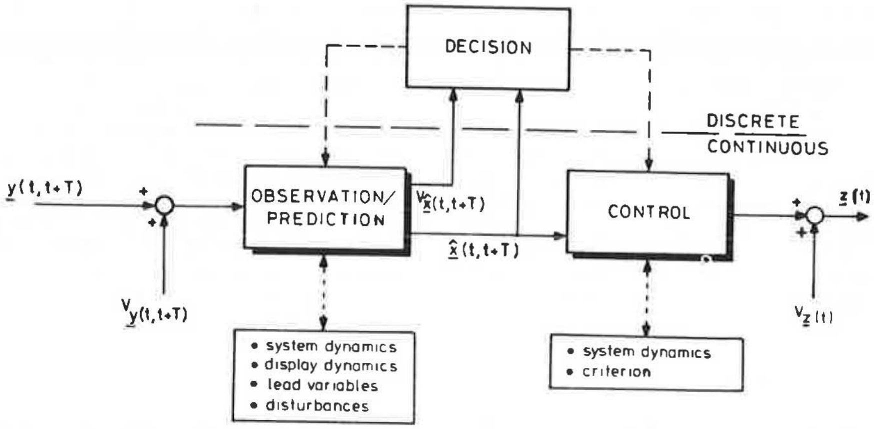

FIGURE 7 Structure of the supervisory driver model *(14)*.

TABLE 1 Lateral Position, Lateral Speed, and Steering Wheel Angle Values as Affected by Vehicle Speed and Visual Occlusion *(15)*

Speed (kph)	20	40	60	80	100	120
Lateral position occlusion (m)						
Mean						
With	1.75	1.78	1.81	1.86	1.94	1.94
Without	1.80	1.78	1.76	1.82	1.77	1.88
Standard deviation (m)						
With	0.26	0.23	0.25	0.23	0.23	0.24
Without	0.12	0.13	0.16	0.15	0.16	0.16
Lateral speed						
Standard deviation (cm/sec)						
With	6.6	7.6	9.4	10.1	11.9	12.5
Without	2.3	3.7	5.1	6.0	6.7	8.0
Steering wheel angle						
Standard deviation (degrees)						
With	3.0	2.0	1.7	1.5	1.5	1.5
Without	1.2	0.9	0.9	1.0	1.1	1.2

Note: kph = kilometers per hour.

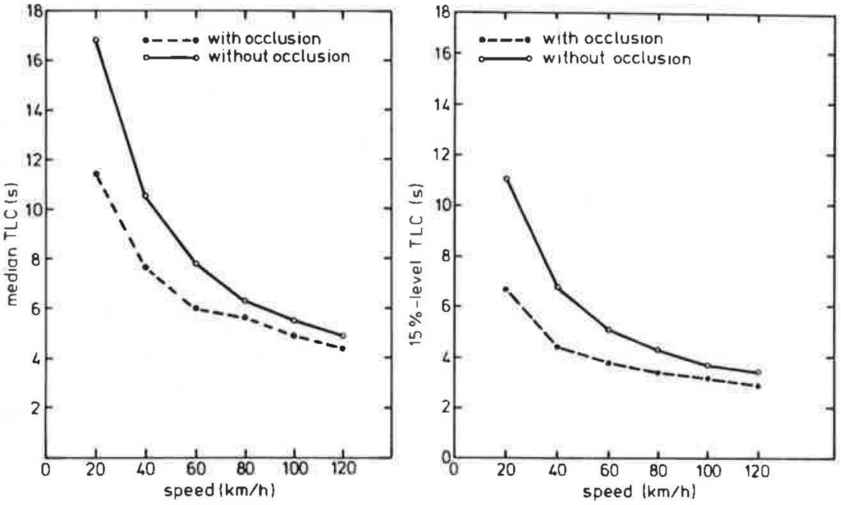

FIGURE 8 Median and 15th-percentile TLC-values as a function of vehicle speed and for runs with and without occlusion.

however, is the relation between the data of Table 1 and the TLC measure by which lateral position, speed, and steering wheel data can be integrally evaluated. Figure 8 shows that TLC is relatively large for low speeds and becoming less dependent on speed when speed increases.

The major reason for developing a time-related measure such as TLC was an interest in the relation between this measure and drivers' open-loop performance (i.e., the duration of the self-chosen occlusion intervals). The relationship between the 15 percent TLC level and the mean of the occlusion times is shown in Figure 9, thus illustrating the potential power of the TLC measure as a predictor of the driver's occlusion strategy.

Figure 10 shows a hypothetical time history of a driver's visual sampling behavior and corresponding TLC. It is clear that, just before the request for a new visual input, there is spare time before which the vehicle would have reached either one of the lane delineations. Hence, this spare time, noted as TLC_e, combined with T_{occ} gives the total time available from the start of the occlusion period until the moment one of the lane boundaries would have been reached.

An interesting finding concerns the ratio between T_{occ} and the sum of T_{occ} and TLC_e, the results of which are given in Table 2. It is evident from the data in Table 2 that this ratio appears to be remarkably constant over a large range of vehicle speeds (no significant differences; $p > 0.20$).

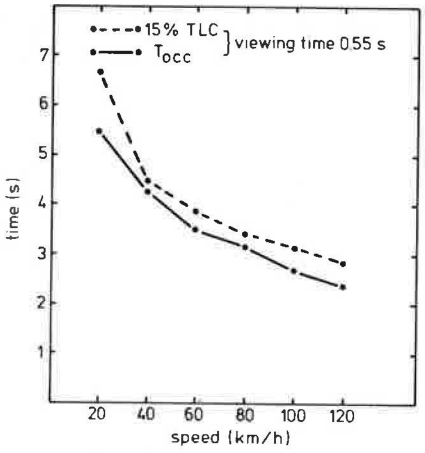

FIGURE 9 Means of occlusion times, T_{occ}, and 15th-percentile TLC-values.

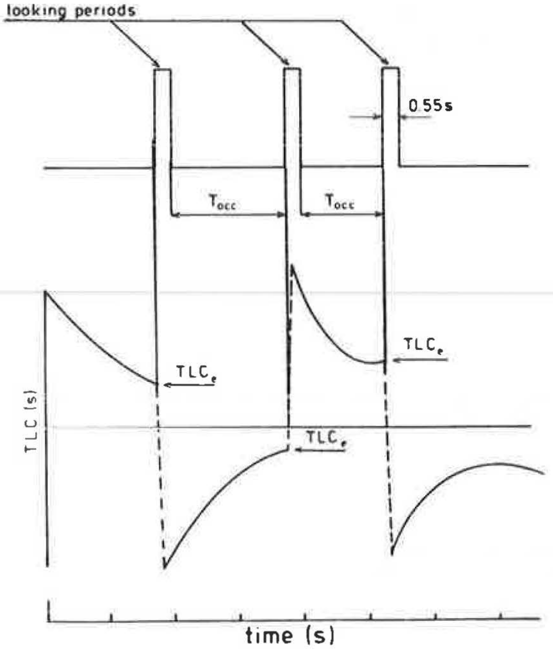

FIGURE 10 Hypothetical time history of a driver's visual sampling behavior and corresponding TLC, illustrating the points at which TLC_e values are determined.

TABLE 2 Median Values of T_{occ}, TLC_e, and Ratio $T_{occ}/(T_{occ} + TLC_e)$

Speed (kph)	T_{occ} (s)	TLC_e (s)	$T_{occ}/(T_{occ} + TLC_e)$
20	5.32	8.88	0.37
40	4.23	6.33	0.40
60	3.45	5.32	0.40
80	3.15	4.77	0.41
100	2.67	4.35	0.39
120	2.38	3.74	0.40

Note: kph = kilometers per hour.

OCM Predictions

All system dynamics for the model predictions were based on the lateral dynamics of the instrumented vehicle (14,16). Combinations were made from the following display variables: lateral position (equals inclination angle α in perspective view of the road--see Figure 1), lateral speed (equals rate of change $\dot{\alpha}$ of inclination angle), yaw rate r, lateral acceleration a_1, and yaw acceleration $\dot{r}$. The model calculations started from the following basic assumptions: no time delays or thresholds, no external disturbances, a perfect internal model of the vehicle dynamics, equal observation noise levels for the various perceptual cues, and weighing coefficients only for display variables and steering wheel rate. The weighing coefficients for the display variables were chosen to be inversely proportional to the square of the corresponding tolerated variations based on the lane boundaries for lateral position or on the measured standard deviations for the other variables (14).

Figure 11 shows the predicted standard deviations of the lateral position of the vehicle as a function of observation noise level, for six combinations of display variables in the observation-prediction block of the model. For all combinations, driving speed was 100 kph. The optimization criterion in the control block was set according to weighing of lateral position (i.e., inclination angle α).

Figure 11 also shows smaller standard deviations of lateral position for lower observation noise levels (i.e., when the state of the vehicle can be estimated more accurately). In comparison with the use of lateral position only (i.e., inclination angle α, as shown in curve 1 of Figure 11), it appears that the addition of yaw rate, r, lateral acceleration, a_1, and yaw acceleration, r, only gives marginal improvements of approximately 1-2 cm in lateral control performance (curves 2 and 3). However, the addition of the lateral speed cue in the observation-prediction block (curve 4) leads to a general improvement of a 10-cm decrease in standard deviation of lateral position. The addition of yaw rate, lateral acceleration, and yaw acceleration again leads to marginal improvements of approximately 1-2 cm (curves 5 and 6).

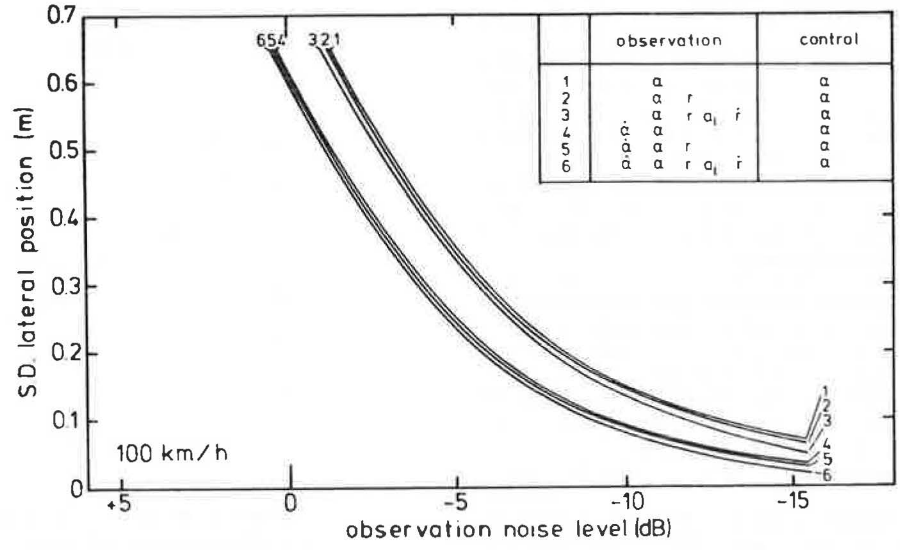

FIGURE 11 Predicted standard deviations of lateral position (via α) as a function of observation noise level for six combinations of display variables.

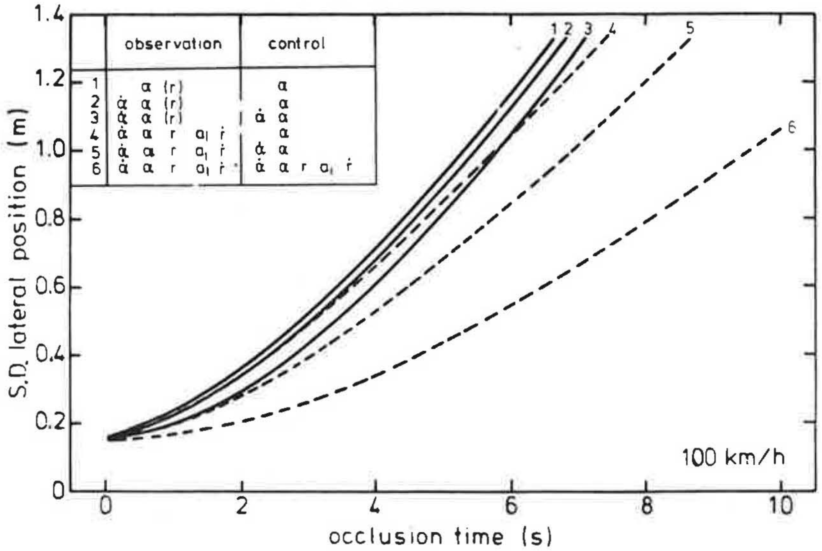

FIGURE 12 Predicted standard deviations of lateral position during visual occlusion, for six combinations of display variables.

It is also clear that more display variables can be weighed according to the optimization criterion in the control block than lateral position alone. Addition of lateral speed only has a marginal effect; yaw rate or both acceleration cues may lead to a 5-10 cm deterioration in standard deviation of lateral position.

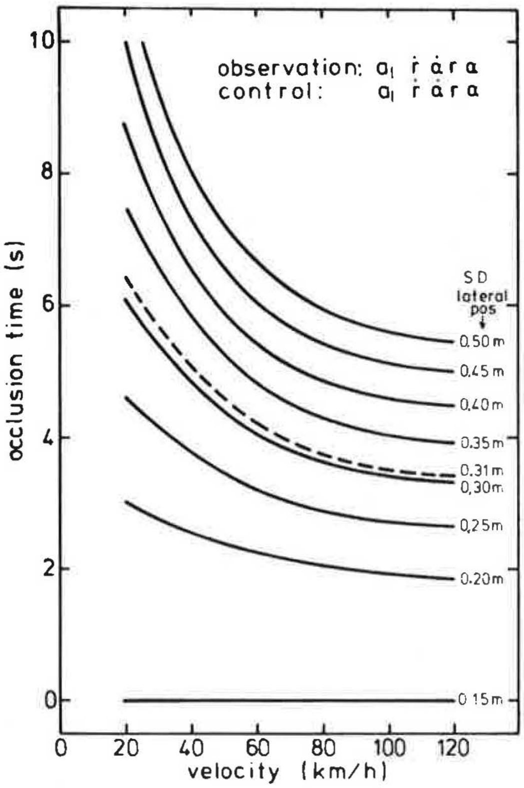

FIGURE 13 Occlusion time as a function of driving speed for constant standard deviation levels of lateral position during observation and control of all five display variables.

The model analysis can be used for the prediction of free periods in the observation strategy while controlling lateral position. Those free periods are reflected by voluntarily chosen visual occlusion durations. During occlusion periods, the driver's estimate of the state of the vehicle has to be based on knowledge of the previously observed display variables and the estimation error will increase as a function of occlusion duration.

Figure 12 gives model predictions for standard deviations of lateral position as a function of occlusion time, for several combinations of display variables.

Larger occlusion durations correspond with larger standard deviations of lateral position. Lateral acceleration, a_1, and yaw acceleration, r, both contribute to much slower deterioration of control performance. Additional weighing of $\dot{\alpha}$ contributes to considerable increase in occlusion durations (curves 5 and 6). Figure 13 shows occlusion time as a function of driving speed for various levels of constant standard deviations of lateral position (i.e., the uncertainty the driver is willing to accept).

The data in Figure 13 are assumed to represent driving behavior of experienced subjects using all available information (i.e., the five display variables) for observation and control. A standard deviation level of 0.15 m reflects nonoccluded observation or an occlusion duration of 0 sec. The 0.31-m level indicates the limit in lateral variation due to a 3.60-m lane width.

The predictions of Figure 13 can be compared with empirically found occlusion durations. It appeared that the OCM enables predictions of empirical occlusion durations within one standard deviation: the correlation between the data of Figure 14 is considerable (r = 0.97). Hence, it is conceivable that experienced drivers indeed use all five display variables for observation and control. (Note that in Figure 14, the field data present mean values and standard deviations of measured occlusion durations of experienced drivers.)

DISCUSSION

Both TLC and OCM analyses appear to be valid methods for the description of automobile driving in terms of a supervisory task.

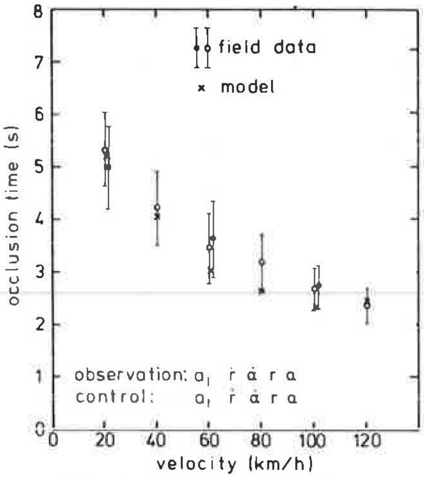

FIGURE 14 OCM predictions of mean occlusion durations as a function of speed when all five display variables are controlled.

TLC enables a quantitative time-related integral measure of driving behavior, predictions on driver's visual sampling strategy related to driving speed, predictions on the probability of lane exceedance, and a description of the relation between self-chosen occlusion durations and the total time available for occlusion. With regard to the latter possibility, it is indeed remarkable that drivers tend to use a constant proportion, approximately 40 percent, of the total available time rather than leave a constant amount of spare time at the end of the occlusion interval.

The OCM analysis enables evaluation of the potential role of various combinations of perceptual cues in driving. Use of the lateral speed cue in the observation-prediction block generally resulted in improved driving performance (i.e., smaller standard deviations in lateral position). Otherwise stated, when using the lateral speed cue drivers have more time to anticipate, while keeping control performance at the same level. Riemersma (<u>17</u>) suggested that the use of the lateral speed cue is an effect of driving experience. This finding was confirmed in a study by Blaauw et al. (<u>14</u>) who compared OCM predictions with field data of experienced and inexperienced drivers. The OCM predictions without lateral speed cue resulted in occlusion durations conforming to those of inexperienced drivers. This result is also in accordance with findings of Smiley et al. (<u>18</u>) who illustrated that inexperienced drivers do not only use the lateral position cue, but also yaw rate and both acceleration cues.

Both TLC and OCM analyses utilize vehicle characteristics as basic elements for predictions. Hence, it seems reasonable to apply these supervision models for the evaluation of vehicle handling properties. The models, in particular, are valuable with regard to the time-related analysis of the driver's attention needed for the driving task as affected by vehicle handling characteristics (i.e., understeering-oversteering) and vehicle dimensions.

In general, the models are applicable to such topics as the effect of various types of road markings on driving performance, the effects of driving practice, the effects of various types of road design, advice speeds, vehicle design, and the evaluation of steering properties.

REFERENCES

1. D.T. McRuer, R.W. Allen, D.H. Weir, and R.H. Klein. New Results in Driver Steering Control Models. Human Factors, Vol. 19, 1977, pp. 381-397.
2. D.H. Weir and D.T. McRuer. Measurement and Interpretation of Driver/Vehicle System Dynamic Response. Human Factors, Vol. 15, 1973, pp. 367-378.
3. C.V. Kroll. Preview-Predictor Model of Driver Behavior in Emergency Situations. <u>In</u> Highway Research Record 364, HRB, National Research Council, Washington, D.C., 1971, pp. 16-26.
4. K. Yoshimoto. Simulation of Man-Automobile Systems by the Driver's Steering Model with Predictability. Bull. Japanese Society of Mechanical Engineers, Vol. 12, 1969, pp. 495-500.
5. J.B.J. Riemersma. The Perception of Course and Speed During Locomotion, A Review of Theoretical Formulations. Report 1979-C4. TNO Institute for Perception, Soesterberg, The Netherlands, 1979.
6. R.N. Schwab and D.G. Capelle. Is Delineation Needed? ITE Journal, Vol. 50, No. 5, 1980.
7. J. Godthelp and J.B.J. Riemersma. Perception of Delineation Devices in Road Work Zones During Nighttime. Technical Paper Series 820413. SAE, Warrendale, Pa., 1982.
8. J.W. Senders, A.B. Kristofferson, W.H. Levison, C.W. Dietrich, and J.L. Ward. The Attentional Demand of Automobile Driving. <u>In</u> Highway Research Record 195, HRB, National Research Council, Washington, D.C., 1967, pp. 15-33.
9. H.T. Zwahlen and K.N. Balasubramanian. A Theoretical and Experimental Investigation of Automobile Path Deviations When Driver Steers with No Visual Input. <u>In</u> Transportation Research Record 520, TRB, National Research Council, Washington, D.C., 1974, pp. 25-37.
10. P. Milgram, J. Godthelp, and G.J. Blaauw. An Investigation of Decision Making Criteria Adopted by Drivers While Monitoring Vehicle State in the Temporary Absence of Visual Input. Proc., Second European Annual Conference on Human Decision Making and Manual Control, Bonn, Federal Republic of Germany, 1982, pp. 104-117.
11. S. Baron and D.L. Kleinman. The Human as an Optimal Controller and Information Processor. IEEE Transactions on Man-Machine Systems, Vol. MMS-10, No. 1, 1969, pp. 9-17.
12. D.L. Kleinman, S. Baron, and W.H. Levison. A Control Theoretic Approach to Manned-Vehicle Systems Analysis. IEEE Transactions on Automatic Control, Vol. AC-16, No. 6, 1971, pp. 824-832.
13. J. Godthelp and H. Konings. Levels of Steering Control: Some Notes on the Time-To-Line Crossing Concept as Related to Driving Strategy. Proc., First European Annual Conference on Human Decision Making and Manual Control, Delft, The Netherlands, 1981, pp. 343-356.
14. G.J. Blaauw, J. Godthelp, and P. Milgram. Optimal Control Applications and Field Measurements with Respect to Automobile Driving. Proc., Third European Annual Conference on Human Decision Making and Manual Control, Roskilde, Denmark, 1983, pp. 371-388.
15. S. Baron and J.E. Berliner. MANMOD, A Computer Program for Statistical Analysis of Dynamical Systems Involving Man as a Controller. Report 2704. Bolt, Beranek and Newman, Inc., Cambridge, Mass., 1974.

16. J. Godthelp, G.J. Blaauw, and P. Milgram. Supervisory Behaviour in Automobile Driving: New Approaches in Modeling Vehicle Control. Proc., 20th Fisita Congress, Vienna, Austria, 1984, pp. 3.255-3.265.
17. J.B.J. Riemersma. Perception and Control of Deviations from a Straight Course: A Field Experiment. Report 1982 C-20. TNO Institute for Perception, Soesterberg, The Netherlands, 1982.
18. A. Smiley, L. Reid, and M. Fraser. Changes in Driver Steering Control with Learning. Human Factors, Vol. 22, No. 4, 1980, pp. 401-415.

Publication of this paper sponsored by Committee on Vehicle User Characteristics.

Abridgment

Impact of Drunk Driving Legislation in the State of Alabama

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ABSTRACT

On May 19, 1980, a major revision in the Alabama driving-under-the-influence (DUI) laws went into effect, which gave judges greater discretion in sentencing. In this paper, the period before the revision of the law, in which a DUI conviction automatically resulted in revocation of the driver's license, is compared with the period after the revision. A significant increase was found in the number of DUI convictions of the after period, showing that the new law was being observed. This was accompanied by significant reductions in the number of DUI citations reduced to reckless driving, the proportion acquitted and/or dismissed, and the proportion of revocations. The law required court referral to an education program on the first offense, and these referrals significantly increased in the after period. However, the corresponding change in accidents was not favorable because there was a significant increase in the proportion of alcohol-related accidents in the after period.

On May 19, 1980, a revision of Alabama laws with regard to driving under the influence (DUI) of intoxicating liquor or narcotic drugs became effective. The basic change in the law would appear to weaken its effectiveness in that the former mandatory revocation provision was removed. The former law stated that "The director of public safety shall forthwith revoke the license of any driver upon receiving a record of such driver's conviction (of)...driving a motor vehicle...while intoxicated." This provision was modified to read as follows:

> The director of public safety shall forthwith revoke the license of any driver upon receiving a record of such driver's conviction (of)...driving...while under the influence of intoxicating liquor; providing, however, that on a first conviction such revocation shall take place only when ordered by the court rendering such conviction.

In addition to these changes, first-time offenders were required to complete a DUI court-referral educational program approved by the State Administrative Office of Courts. In addition, the law specifically states that charges cannot be reduced to reckless driving or any other offense. (The consistent use of either of the terms "DWI" or "DUI" throughout this paper would be technically incorrect because Alabama used DWI before the law change and DUI after. However, in the remainder of this paper, DUI will be used.)

Although this change might be considered a weakening of the punitive measures related to DUI, the previous circumvention of the mandatory revocation by a large number of judges in Alabama made conviction of DUI on the first offense unlikely. The resulting inaccuracy in the records made recidivism impossible to measure and, thus, multiple offenders were not being consistently punished. In fact, under the situation prior to May 1980, most offenders were