STUDIES ON HUMAN VEHICLE CONTROL

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C O N T E N T S

CHAPTER 1

1. INTRODUCTION

1.1 The purpose of this study

In today's society the role of man in controlling industrial processes is changing rapidly. Originally man mainly played the role of an active, manual controller, whereas this function nowadays has largely been transformed to that of a supervisor who is just watching the process as it is controlled by an automate. A similar trend can also be noted in vehicle control processes: Autopilots have partly taken over the role of aircraft pilots and the same can be said for ship helmsmen.

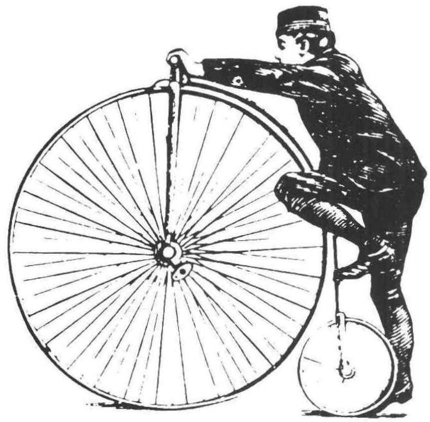
More or less in contrary with this tendency towards automated control, the functioning of man as the controller of wheeled and tracked vehicles has almost remained unchanged. Several systems for automated automobile guidance have been proposed, but none of these has been generally accepted until now, and it seems justified to assume that this will also not be the case in the near future. Therefore, in both civilian and military ground traffic, the direct influence of human limitations will remain relatively large and it is this situation where the present study starts from.

Traffic unsafety is an important aspect of this human reliability problem, yearly resulting in a large number of casualties and an enormous loss of money. More than 75,000 people were killed in road traffic in The Netherlands since World War II. An analysis of these accident figures shows that in most cases the automobile was involved. Regarding the financial losses, the 1981 Annual Accident Report of the Royal Dutch Army indicated a yearly cost of six and a half million Dutch guilders (about 2.2 million U.S. dollars) as a result of traffic accidents with military vehicles.

Despite these figures it can be argued that traffic research and vehicle engineering have resulted in a traffic system of a highly developed technological level. The central role of man, however, makes the system vulnerable and further improvements of safety will largely depend on our understanding of human capabilities in driving. Regarding this issue, the present study focusses on the most elementary aspect of driving, i.e the vehicle steering control task. By far the most steering control descriptions as they are available nowadays are based on the fundamental assumption that drivers steer their vehicle in a continuous error-correction mode with permanent visual feedback i.e. closed loop. However, as is commonly accepted, driving cannot simply be considered as such a continuous closed loop task. On the one hand, it can be argued that under many circumstances driving does not require permanent path error control, whereas on the other hand, the driver may be forced, temporarily, to pay (visual) attention to other driving task aspects which, by definition, makes it impossible to steer the vehicle with permanent visual feedback. The literature shows very few quantitative descriptions about the role of error-neglection and visually open loop steering strategies in driving. Yet such descriptions are needed if one wants to understand the attention needed for vehicle steering and its dependency on factors like speed, type of manoeuvre, roadway and vehicle characteristics, etc. The present study focusses on this issue. Its main purpose is to enlarge our understanding about the potential role of visually open loop strategies and error-neglection in vehicle control.

1.2 Outline

How can the driving task be divided into a series of subtasks? In answering this question Chapter 2 gives a short analysis of the driving task, in which it is argued that steering control is to be considered as the most essential subtask in driving. In a subsequent analysis on steering strategies it is illustrated that, although we know a lot about error-correction strategies, very few quantitative data are available on error-neglection and visually open loop strategies. It is mentioned specially that a time-domain analysis of driving is lacking which allows for a description of vehicle control as a time-serial process with alternation between error-correction and error-neglection strategies. Furthermore, it is hypothesised that the degree to which drivers temporarily may use visually open loop strategies will depend on a) their skill to generate the correct steering actions during periods without visual feedback and b) the opportunity for error-neglection. Chapter 2 ends with a paragraph, in which the consequences of the analysis on steering strategies are transformed into a number of research questions. The experiments, conducted to answer these questions are described in Chapters 4 to 8, whereas Chapter 3 will give some details about the instrumentation used, the vehicle dynamics and the proposed time-domain data analysis. A general discussion of the results, a summary of the conclusions and some examples of applications are given in Chapter 9. Finally the mathematical vehicle model which is used to describe the instrumented car and driving simulator characteristics is presented in an Appendix.



CHAPTER 2

2. BACKGROUND AND FRAMEWORK

2.1 The driving task

When guiding a vehicle along the road or through a terrain the driver's primary task is to control the vehicle. The overall driving task, however, is to be considered as a combination of subtasks, the most essential of which is vehicle control. In an extensive driving task analysis, McKnight and Adams (1970) distinguish as much as 65 subtasks. A more global analysis is presented by Allen et al. (1971), who describe three hierarchically ordered task levels, strategic level, manoeuvre level and vehicle control level. Tasks at the strategic level are those dealing with route planning and choice, i.e. processes covering a relatively long period of time. The interaction with other road users (e.g. overtaking), signs, traffic signals, etc. defines the manoeuvre level, which includes processes of about 5 to 10 seconds. Finally, the actual motion of the vehicle is regulated at the vehicle control level, where speed and lateral position are controlled and the updating time of the processes involved may reach low values, ultimately resulting in a task with almost continuous error-correction.

The hierarchical ordering of the levels is reflected by the fact that performance at each level serves as a starting point for the nearest lower level. In this ordering the lowest level, i.e. vehicle control, is to be considered as the basic task in driving. The attention needed for vehicle control may strongly effect the quality of performance at the strategic and manoeuvre level. Driving at a moderate speed on a quiet freeway can be considered as an example of a relatively easy task which even may permit the driver, temporarily, to neglect vehicle path errors. Interference between task levels will hardly occur in such a task. However, the demands of driving may also be considerably higher: Driving on a crowded intersection may lead to a situation in which these interference effects are very likely to occur; looking for route signs and the observation of other vehicle motions may require a visual sampling pattern resulting in a temporary loss of immediate visual feedback about the own vehicle motion. Furthermore, the manual operation of controls, such as turn-indicator and gear-lever, may interfere with the steering-wheel actions. In an analysis on tracking performance, Wickens and Gopher (1977) indicated that during periods of task overload the tracking data contain "holds", i.e. periods with no steering control at all. Whether the interference effects as described here actually will result in unsafe driving performance largely will depend on their consequences in terms of vehicle motion errors. The present study starts from this question and analyses steering control in a way which allows us to understand why a driver may temporarily neglect vehicle motion errors and/or behave in a visually open loop mode.

The research program chosen for this study will be described in Section 2.3. In advance a short review of the literature on steering strategies will be presented in Section 2.2.

2.2 Steering strategies

As argued before automobile steering cannot simply be considered as a continuous, closed loop task. Instead of performing in a closed loop mode drivers may temporarily switch to open loop control. Furthermore, the error-correction mode may alternate with periods of error-neglection. Both these aspects, i.e. open versus closed loop control and error-neglection versus error-correction, will be defined now in more detail.

Open loop versus closed loop control

From a straightforward servo-theoretical point of view, a system operates in an open loop mode whenever information about actual system behavior is unavailable. However, in case of human vehicle control this definition needs some clarification. The question can be raised, for instance, under which conditions path error information is "unavailable". Even during complete visual occlusion one can hardly say so, because this would only be true if the driver just relies on immediate visual feedback. In reality this is not the case, as the driver also receives feedback through non-visual modalities, e.g. proprioceptive and vestibular feedback. Furthermore, the experienced driver may have a fairly developed internal representation of the expected vehicle performance in relation to the roadway, which can be used to estimate the difference between desired and actual system behavior during periods without visual feedback. In the present study we will use the terms open and closed loop in relation with the availability of visual feedback: Steering during the absence of visual information will be referred to as open loop control, whereas the term closed loop will be used for steering with visual feedback.

Error-neglection versus error-correction

During certain periods of time the driver will not act upon momentaneous path errors. On the one hand, this strategy may be the result of a voluntary decision to ignore path errors, whereas on the other hand, the complexity of the driving task may force the driver to do so. Both situations will result in passive, no-steering periods. In the present study driver's not acting upon path errors will be referred to as error-neglection, whereas the strategy to minimize path errors will be noted as error-correction.

In the Sections 2.2.1 and 2.2.2 a brief overview will be given of the literature on various steering strategies. Regarding the "closed loop, error-correction" literature this overview will focus particularly on those studies which are considered to be also useful in an analysis on open loop and/or error-neglection strategies.

2.2.1 Closed loop steering with continuous error-correction

Most of the available steering control models are based on the assumption that the automobile driver acts as an error-correcting mechanism with continuous attention allocated to the steering task. These model descriptions can roughly be divided into two categories:

1. Describing function models, based on a frequency-domain analysis and presented by Weir and McRuer (1973), McRuer et al (1977) and others.
2. Preview-predictor models, based on a time-domain analysis and proposed by Sheridan (1966), Yoshimoto (1969), and Kroll (1971).

Apart from the methodological difference, i.e. frequency-domain versus time-domain analysis, both models differ also with respect to their underlying assumptions about the nature of driver's error control. Describing function models are principally based on the assumption that a driver reacts on momentaneous path errors, whereas a preview-predictor model assumes that the driver uses a weighed sum of predicted path errors. Predicted path errors are calculated by comparing the previewed roadway geometry with vehicle path predictions, which are usually based on the assumption of no-steering control during the time span of the prediction process.

Garrott et al. (1982a, 1982b) compared the two classes of models and concluded that the describing function model should be considered as preferable for future research purposes. This conclusion is drawn because of parameter identification problems, which are most pronounced with the preview-predictor model. For mathematical simulation of closed loop, error-correction tasks this conclusion seems justified. However, when describing driving as a task in which closed and open loop as well as error-correction and error-neglection strategies alternate, the preview-predictor approach may be attractive, in that it uses vehicle path predictions, which reflect anticipation processes as these may occur during error-neglection and open loop control. Therefore, the role of anticipation in describing function models and preview predictor models will now be considered in more detail.

Krendel and McRuer (1968) and Pew (1974) analysed the steering task in terms of levels of control. In their description a distinction is made between three control levels: i.e. precognitive, pursuit and compensatory control. The degree by which a driver anticipates varies for each of the levels. On the precognitive level the driver uses motor programs, which are available to him through overlearning of certain manoeuvres. Acting on the pursuit level the driver uses his knowledge about the vehicle's input-output characteristics to guide the vehicle in a sort of preview mode, along an intended trajectory. Finally, the compensatory level describes a driving situation in which the driver just reacts to unpredictable, momentaneous path errors.

For each of these levels describing function models have been proposed. Weir and McRuer (1973) presented the cross-over model application for driving tasks at the compensatory level. Allen and McRuer (1977) and Donges (1978) have given models in which a pursuit or preview mode acts in parallel with error correction. Finally Allen (1982) presented a "precognitive driver model with continuous closed loop operations". Each of these models offers a good mathematical simulation of drivers' steering performance, while they also contain meaningful parameters, representing for example drivers' time delay or anticipation time. Actually, the functioning of anticipation is reflected in the latter parameters: Time delays are reduced and may be transformed into an anticipation time. However, a description of how a driver may use the benefits of anticipation in error-neglection or open loop control is not possible in terms of the describing function model, since the model is principally based on the assumption that the driver behaves in a closed loop, error-correction mode.

The strategies described in the levels of control reflect primarily anticipatory performance with respect to the system input, i.e. the perceived roadway geometry. Anticipation processes dealing with the expected system output, i.e. the vehicle path are only indirectly involved. This leads us to the characteristics of the preview-predictor model. Despite its intuitively attracting properties, this model has never been accepted as a fruitful way of describing automobile steering. One explanation for this can be found in the aforementioned parameter identification problems. Another, more essential reason may be that, until now, preview-predictor models have only been used to simulate error-correction performance. Ultimately, however, this is in contradiction with the nature of this type of model, which uses path predictions that are based on an assumption of no-steering control i.e. error-neglection. In the present study it will be illustrated, therefore, that the time-domain analysis used in the preview-predictor description can also (or even better) be used in a way which is more directly related to this fixed steering assumption. The path predictions made in the model can be used in that case to quantify the potential role of error-neglection and open loop control strategies in driving.

2.2.2 Open loop steering and error-neglection

Descriptions of open loop automobile driving have been developed earlier to quantify driving task demands in terms of a driver's self chosen occlusion times, i.e. the period of time during which a driver is willing to control the vehicle without visual feedback. Senders et al. (1967) and Zwahlen and Balasubramanian (1974) proposed mathematical uncertainty models, in which it is assumed that the driver uses an estimate of the vehicle's lateral position to choose the (average) length of the occlusion interval. This estimate is based on the vehicle motion spectral characteristics. Milgram, Godthelp and Blaauw (1982) extended this approach by arguing that driver's estimate of the vehicle path will not solely be based on lateral position input but also on heading angle information. They developed a time-series model in which both these inputs were used to quantify driver's uncertainty about the vehicle path and applied it to explain drivers self-chosen occlusion times.

All of the models on open loop behavior mentioned here were developed to describe and predict driver's voluntary chosen occlusion times, while neither of the models gave a quantification of the time which was actually available for occlusion. Yet it may be expected that drivers will choose the duration of occlusion periods somehow in relation with the time available, which ultimately will be restricted by the vehicle trajectory reaching the edge of the lane. This trajectory will largely be governed by drivers' steering actions generated during the occlusion period. During this period drivers may apply either a passive, no steering strategy, in a sort of error-neglection mode, or an active steering strategy with steering actions generated on the basis of the estimated vehicle path in relation to the roadway.

Assuming that no external disturbances are acting on the driver-vehicle system, it may be expected then that the time available for occlusion, i.e. for open loop control, will depend on:

a. The accuracy of the open loop generated steering actions,
b. the time available for error-neglection.

Regarding open loop steering it can be assumed that accuracy will depend on the predictability of the steering task. A reference can be made here to the "levels of control" as described by Krendel and McRuer (1968) and Pew (1974): When controlling a vehicle at the precognitive level, drivers will have a rather good estimate of the control actions to be taken and the preprogrammed nature of such tasks may be particularly useful during periods without visual feedback. In preview tasks drivers cannot rely on preprogrammed steering-wheel commands; however, predictions about the vehicle trajectory in relation to the roadway can still be made and this process also permits the driver to generate steering actions during periods without external feedback. Open loop steering will become most inaccurate in compensatory tasks with a low level of predictability, e.g. when compensating windgusts under no-preview conditions. This reasoning makes clear that a fruitful analysis of open loop steering accuracy has to be done in relation with the various levels of control.

One of the first authors who described an error-neglection strategy was Rashevsky (1964, 1970). In a series of papers he presented a theoretical model of automobile steering control and one of the essential features of this model was a threshold for lateral position errors. As long as the lateral car position remained within this "dead zone" the "driver" would generate no steering actions. Although the model proposed suffered from some shortcomings, e.g. the no-steering strategy was only possible with the steering-wheel in the central position, the approach was intuitively appealing in that it showed how non-linear driver characteristics might be implemented in a mathematical description of driving. Experimentally Rashevsky's model was not verified. Carson and Wierwille (1978) extended this approach by developing a non-linear model in which two vehicle motion characteristics served as the driver's input, i.e. the lateral position, y, and the heading angle, ψ, this last angle being proportional to lateral speed, $\dot{y}$. For each of the driver inputs a threshold was implemented in the model. Fig. 2.1 gives an illustration. This model was verified in an experiment on straight road keeping of a highly unpredictable nature (random windgusts). The authors claim that their model describes the experimental data better than "previous linear models", although a quantitative comparison between the two is not given. Mean values of the thresholds as derived from the Carson and Wierwille (1978) data are $y_0 = 0.15$ m and $\psi_0 = 0.27^o$, the latter heading angle level being equivalent to a lateral speed threshold $\dot{y} = 0.11$ m/s. These values indicate that the non-linearity of the model mainly represents perceptual thresholds.

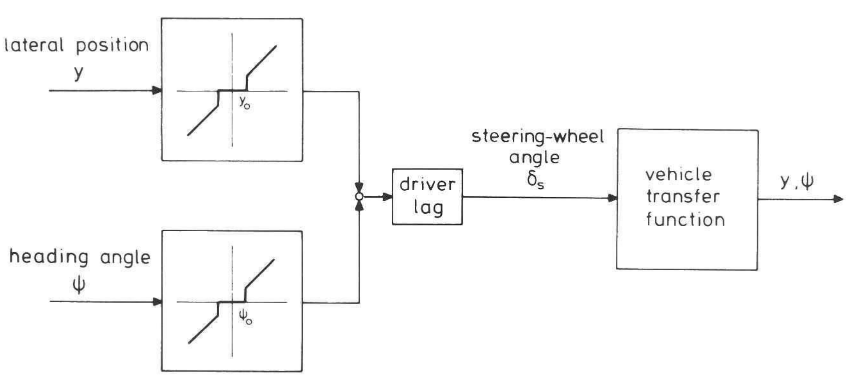


Fig. 2.1 The non-linear driving model as proposed by Carson and Wierwille (1978).

Baxter and Harrison (1979) introduced a new element in this type of non-linear models. On the one hand they agreed that "visual sensitivity" thresholds play an important role in driving. On the other hand they argued that in relaxed driving the driver may also maintain the steering-wheel in its momentary position, in cases the "aimpoint error input" is tending towards zero. (The aimpoint error, ψ_a, represents a weighed sum of lateral position and heading angle, $\psi_a = \psi + y/d$, where d represents the distance between vehicle and aimpoint.) Fig. 2.2 gives an illustration of the Baxter and Harrison model in which a hysteresis loop is used to simulate both the perceptual threshold and the fixed steering strategy for periods with the aimpoint error becoming smaller. The experimental verification of this model was performed in a "relaxed" straight road keeping task and a comparison with the linear model indicated the hysteresis model to be "significantly" better. Despite this result one should be aware of the parameter identification problems associated with the non-linear models as discussed now. Regarding this point it can be argued that the validity of such a model will be strongly related to the driving task considered.

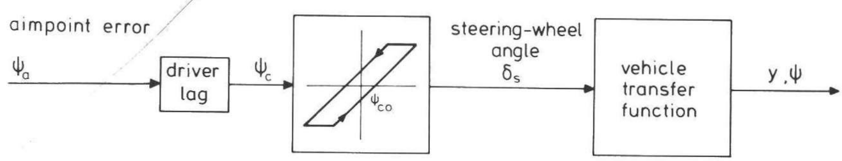


Fig. 2.2 Hysteresis-model of driving as proposed by Baxter and Harrison (1979).

Although the Baxter and Harrison model considers two types of fixed steering strategy, none of these can be regarded to as actual error-neglection. The perceptual threshold is related to driver's psychophysical limitations, whereas the strategy to maintain the steering wheel fixed when the vehicle path error is becoming smaller, cannot either be described as an error-neglection strategy. Actually, the literature does not show any error-neglection descriptions of driving. Such a description should meet two major requirements, 1) it should give insight into the opportunity for error-neglection at each moment of a run, i.e. independent of the momentaneous vehicle position, and 2) it should allow for a description of the actual limitations of error-neglection, i.e. drivers' decision making process in switching from error-neglection to error-correction, when approaching the edge of the driving lane. A description of the steering process as suggested here was developed in the present study and will be presented as a time-domain analysis of driving in Section 3.4.

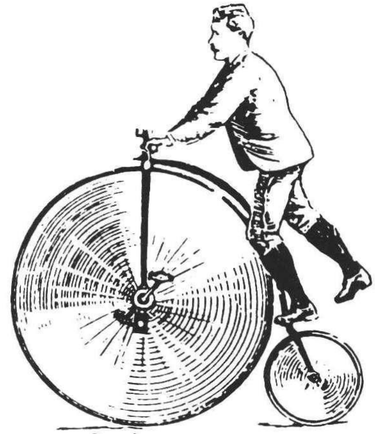
2.3 Conclusions and research plan

In summary the following major conclusions can be drawn from the analysis on steering strategies:

1. The time available for open loop control in a driving task without external disturbances on the driver-vehicle system depends on:
   a. The accuracy of the open loop generated steering actions,
   b. the time available for error-neglection.
2. The literature does not present quantitative data about open loop vehicle steering. An analysis on open loop steering accuracy should be made in relation with the levels of control description given by Krendel and McRuer (1968) and Pew (1974).
3. The literature does not present quantitative data about the potential role of error-neglection in vehicle steering. The path predictions made in a preview-predictor model may be fruitfully applied to develop a description of error-neglection. Such a description should meet two major requirements:
   a. It should give insight into the opportunity for error-neglection at each moment of a run,
   b. it should allow for a description of a driver's decision making process in switching from error-neglection to error-correction, when approaching the edge of the driving lane.

The purpose of the present study, which was given in general terms in Section 1.1, can now be specified as follows:

a. Quantify the factors determining the accuracy of open loop generated steering actions in a laboratory task (Chapter 4, Experiment I and II).
b. Replicate the steering accuracy data from a) in actual open loop driving tasks, both on a precognitive and a preview level of control (Chapter 5 and 6, Experiments III to VI).
c. Develop a time-domain analysis of driving, with which the potential role of error-neglection strategies in driving can be described (Section 3.4).
d. Apply the error-neglection analysis and the steering accuracy data in a combined model to predict the occlusion times in a driving task with self-paced occlusion (Chapter 7, Experiments VII and VIII).
e. Quantify the extremes of error-neglection in terms of the analysis developed under c) by means of analysing drivers' decision making process in switching from error-neglection to error-correction, when approaching the edge of the driving lane (Chapter 8, Experiment IX).



CHAPTER 3

3. GENERAL ASPECTS OF THE METHODOLOGY

3.1 Introduction

Although the experiments described in this thesis are varying in nature, some general aspects of the methodology will be presented in this chapter. The majority of the experiments was conducted with the instrumented car and the driving simulator, both belonging to the standard equipment of the Institute for Perception TNO. Section 3.2.1 and 3.2.2 will give a rough description of these instruments, whereas Section 3.3 will present an impression about the properties of these instruments in terms of vehicle dynamics. A more complete description of the mathematical model used to describe the instrumented car properties and to calculate the relation between steering-wheel actions and vehicle motions in the driving simulator is presented in Appendix A. The method proposed for the time-domain analysis of driving is presented in Section 3.4.

Further details about the methodology, e.g. the experimental procedures, data analysis, etc., will be given in the chapters describing the experiments.

3.2.1 Instrumented car

The instrumented car used for the Experiments IV, VI, VII, VIII and IX is a Volvo 145 E. This car is provided with an additional power supply unit of 1 kW, which permits the use of a variety of sensors and other experimental equipment, most of which are shown in Fig. 3.1. The sensors allow for the measurement of a set of vehicle motion and driver response signals, while a

PDP 11/02 computer with floppy disk is used for experimental control, data monitoring and storage. For an extensive description of the instrumented car see Blaauw and Burry (1980).

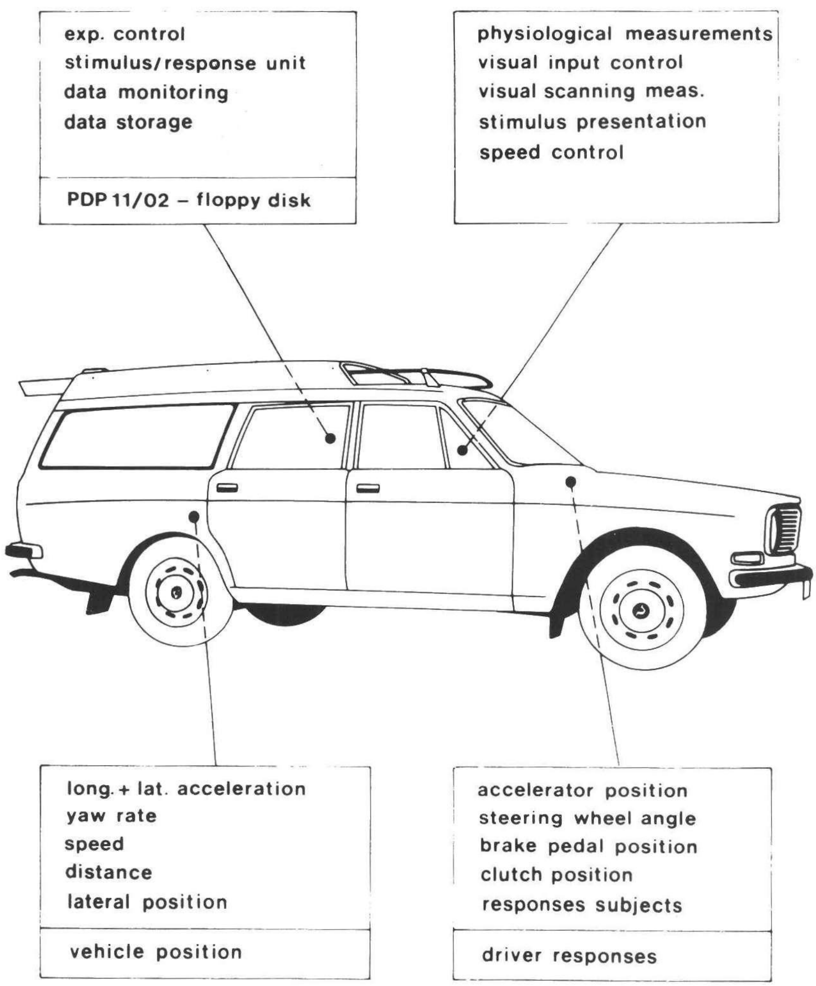


Fig. 3.1 Schematic representation of the instrumented car.

In particular for the present experiments two additional instruments were designed, i.e. a visual occlusion device and a speed control unit. The occlusion decive, used in the Experiments IV, VII and VIII, consisted of an electromagnetically driven visor mounted on a lightweight bicycle helmet. The visual field was occluded by a sheet of translucent drawing paper mounted on a frame, which could be raised or lowered on command by the experimenter or the subject, depending on the type of experiment, i.e. whether the occlusion task was paced or self-paced.

In Experiment VI, which was actually performed after the other occlusion experiments, subjects wore a newly developed occlusion device, consisting of a pair of safety goggles, of which the glasses were provided with a liquid crystal layer. By using the electric field dependency of this material, the goggles could be switched from a transparant mode (ON) to a translucent mode (OFF). A complete description of this elegant occlusion technique is given by Milgram and Van der Horst (1984).

In each of the instrumented car experiments with occlusion a number of safety measures was maintained, including fail-safe circuitry and a master dead-man's switch. Furthermore, subjects did not have to concern themselves with maintaining a constant vehicle speed, as this was held fixed by a speed control unit, which consisted of a servo-regulated, mechanical device, mounted underneath the gas-pedal. In the normal state this device was in a "down" position. Only when the car accelerated and speed reached a value close to the speed set by the experimenter, the unit was activated, moved upwards and served as a mechanical stop of the pedal. The advantage of this system, as compared to cruise controls mounted closer to the engine, is that subjects get the correct "feeling" of how the speed control unit is effecting the movement of the pedal. Furthermore the car can be decelerated just by releasing the pedal, whereas most cruise control systems require a brake action to do so. Subjects were instructed just to maintain a reasonably constant pressure on the gaspedal. In this way speed was held constant to within deviations of about 1 km/h.

3.2.2 Driving simulator

The driving simulator used in Experiments III and V consists of five major components: mock-up, computer system, camera drive units, TV recording and projection systems and a scale model. The driving simulator has a fixed base, Volvo 145 mock up, of which the interior is similar to that of the

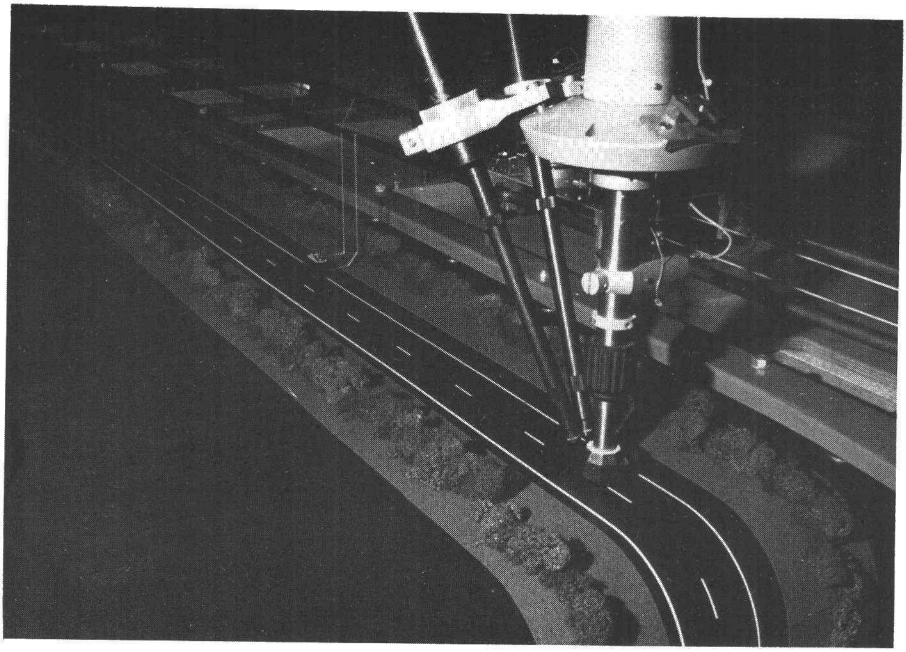


Fig. 3.2 The TV recording system and the projected picture in front of the mock up.

instrumented car. The visual scene is TV recorded in the scale model and projected on screens in front of the mock-up with an horizontal field of view of 120°. Subjects control the TV recording element to move in the scale model, which may be either a fixed model or a moving belt system. Fig. 3.2 gives an illustration.

Driver's control actions are fed into a hybrid computer system which calculates the actual vehicle motions and the subsequent motions of the camera drive units. At the time of the experiments the computer system consisted of a PDP 15 system which controlled the motion of the camera drive units and also served as a data storage device. Vehicle dynamics were simulated on an analog computer, i.e. a Hitachi 220/240. The dynamics of the vehicle model used in this simulation are given in Section 3.3 and Appendix A.

The mathematical simulation also involves the dynamics of the steering system. Special attention is given to this part of the vehicle dynamics, because steering torque served as an important variable in the Experiments III and V. Mechanically, the steering torque was simulated by an electric torque motor mounted on the steering axis in the mock up. The torque motor used is an Axem MV 19.

3.3 Vehicle dynamics

The lateral dynamics of the instrumented car and the driving simulator can be described in terms of the yaw rate to steering-wheel angle transfer function[1]:

$$\frac{r}{\delta_s} = \frac{G_r(T_r s + 1)}{\frac{1}{\omega_r^2} s^2 + \frac{2\beta_r}{\omega_r} s + 1} \qquad (1)$$

with: G_r = yaw rate gain 1/s

r = yaw rate rad/s

s = La Place operator 1/s

T_r = yaw rate time constant s

[1]The nomenclature is given on page 146.

β_r	= yaw rate damping coefficient	-
δ_s	= steering-wheel angle	rad
ω_r	= yaw rate natural frequency	rad/s.

A series of tests was performed to measure the stationary and dynamic characteristics of the instrumented car (Godthelp et al., 1982). The results of these measurements, i.e. the vehicle parameters, were implemented in the mathematical vehicle model as applied in the driving simulator. Therefore, the dynamic proporties of both instruments can be considered as identical.

Table 3.I gives the transfer function parameters for a range of speeds, covering the speeds applied in the various experiments. A complete description of the mathematics of the instrumented car and driving simulator is given in Appendix A.

Table 3.I Yaw rate to steering-wheel angle transfer function parameters for different speeds.

speed (km/h)	G_r (1/s)	T_r (s)	ω_r (rad/s)	β_r (-)
20	0.100	0.042	18.39	1.01
40	0.172	0.084	9.96	0.93
60	0.207	0.126	7.40	0.84
80	0.216	0.167	6.26	0.74
100	0.212	0.209	5.66	0.66
120	0.201	0.251	5.30	0.58

The steering torque to steering-wheel angle transfer function can mainly be characterised by its steady state relationship, i.e. the steering torque gradient:

$$\left(\frac{M_t}{\delta_s}\right)_{ss} = G_t \frac{m\, b\, t\, u^2}{G^2\, l^2 (1 + K u^2)} \qquad (2)$$

with: b	= distance between vehicle c.q. and rear axis	1.0 m
G	= steering system gear ratio	19.8
G_t	= steering torque coefficient	-
K	= stability factor	0.001946 s^2/m^2
l	= wheel base	2.62 m
m	= vehicle mass	1924 kg
M_t	= steering-wheel torque	Nm
t	= front wheel trail (mechanical + pneumatic)	0.034 m
u	= vehicle forward speed	m/s
δ_s	= steering-wheel angle	rad.

The steering torque coefficient G_t was used in the Experiments I, II, III and V to vary the steering torque level.

3.4 A time-domain analysis of driving

In order to clarify the potential role of error-neglection strategies in driving a time-domain analysis was developed, which allows for the calculation of the time which is actually available for such a strategy and which illustrates the effects of driving speed, road width and vehicle characteristics. It was indicated that the fixed steering assumption underlying a preview-predictor model may be fruitfully applied to develop this analysis.

Godthelp and Konings (1981) gave the first example of using a preview-predictor model in this way. They presented a theoretical formula describing the time available for fixed steering and illustrating the effects of some vehicle and road related factors. Fig. 3.3 gives an illustration of this approach. Given an initial lateral position $y = w_r/2$ at the centre of the lane, a heading angle $\psi = 0$, a vehicle speed u and a path curvature, corresponding with a steering-wheel angle error δ_{se}, the Time-to-Line-Crossing or TLC, i.e. the time necessary for any part of the vehicle to reach the edgeline, can be described as:

$$TLC = \frac{Gl(1 + Ku^2)\arccos\left\{1 - \frac{(\frac{w_r}{2} - w_{ve})\delta_{se}}{Gl(1 + Ku^2)}\right\}}{u\,\delta_{se}} . \qquad (3)$$

The steering-wheel angle δ_{se} represents the steering-wheel error, i.e. the difference between the required mean and the actual steering-wheel angle.

The required, mean steering-wheel angle for a particular road section can be described with the following formula:

$$\delta_s = Gl(1 + Ku^2)\, c_r \, . \, 10^{-3} \, . \tag{4}$$

Furthermore, the effective vehicle width w_{ve} can be described as:

$$w_{ve} = \frac{w_v}{2} \cos\psi + l_f \sin\psi \tag{5}$$

with: c_r	= road curvature	km^{-1}
l_f	= distance between vehicle c.q. and vehicle front	m
TLC	= time-to-line crossing	s
w_r	= road width	m
w_v	= vehicle width	m
w_{ve}	= effective vehicle width (see Fig. 3.3)	m
δ_{se}	= steering-wheel angle error	rad
ψ	= heading angle	rad.

By combining the formulae (3), (4) and (5) the TLC can be calculated. Fig. 3.4 gives two results of such a calculation, showing the effects of the vehicle understeer/oversteer factor K, road width and vehicle width. The parameter values taken as constants for these illustrations correspond with those of the instrumented car and are given in Fig. 3.4. The steering-wheel angle error was given the arbitrary value $\delta_{se} = 1°$. In a similar theoretical analysis it was also shown that TLC is independent of road curvature. In other words: a 1 degree steering-wheel angle error in a curve results into the same TLC as a 1 degree error on a straight road.

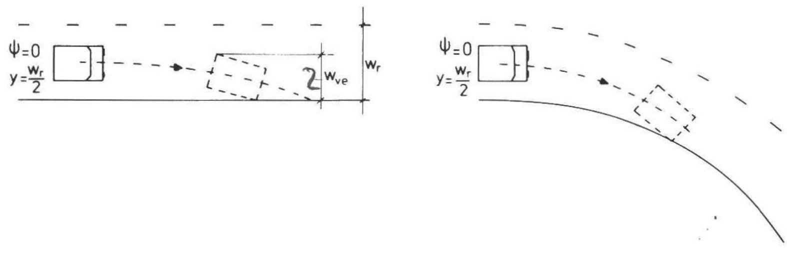


Fig. 3.3 Schematic presentation of a path prediction under a fixed steering assumption. The figure also illustrates the effective vehicle width at the moment of line crossing.

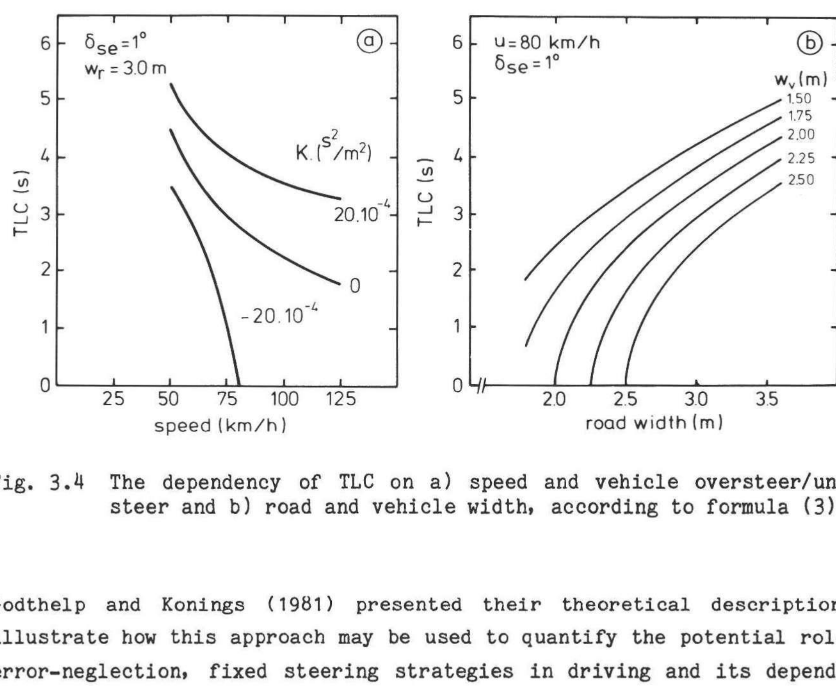


Fig. 3.4 The dependency of TLC on a) speed and vehicle oversteer/understeer and b) road and vehicle width, according to formula (3).

Godthelp and Konings (1981) presented their theoretical description to illustrate how this approach may be used to quantify the potential role of error-neglection, fixed steering strategies in driving and its dependency on road and vehicle related parameters.

In a further analysis the TLC-concept was developed to be also used in relation with actual field data. During experiments with the instrumented car or driving simulator sampled measurements are made on vehicle speed, lateral position, heading angle and steering-wheel angle, whereas data about the car and road width are also known.

Fig. 3.5 shows the position of the car as measured at a particular moment. Based on the preview-predictor approach a TLC-value can now be determined, representing the time necessary for the vehicle to reach either the left or the right edge of the lane, assuming a fixed steering strategy, after the sample considered. TLC's can be calculated in this way for each sample of a run. Actually these TLC's represent an estimate, for each moment in time, whether the driver may proceed with, or switch over to, an error-neglection strategy.

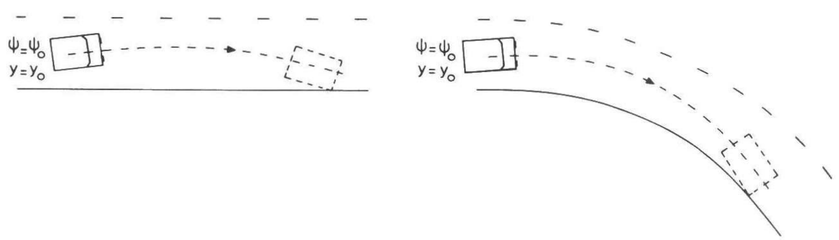


Fig. 3.5 Schematic presentation of the path prediction, made on the basis of sampled data.

Fig. 3.6 shows an example of time histories of sampled measurements on lateral position, lateral speed/heading angle and steering-wheel angle. Fig. 3.6a gives the TLC measure as derived from these signals. TLC's for predictions to the left (centreline) and right (edgeline) are given above and below the zero-axis respectively. Actually, the software package which was developed to calculate TLC's from sampled data used the lateral position y, the steering wheel angle δ_S and vehicle speed u as main input data. Heading angle ψ was derived from lateral speed $\dot{y}$, which on its turn was calculated by way of differentiating y. Data about road width, vehicle dimensions, steering ratio and stability factor can be changed optionally. The future, circular path of the car was predicted on the basis of the steering-wheel angle, which was assumed to remain fixed. The actual curv-

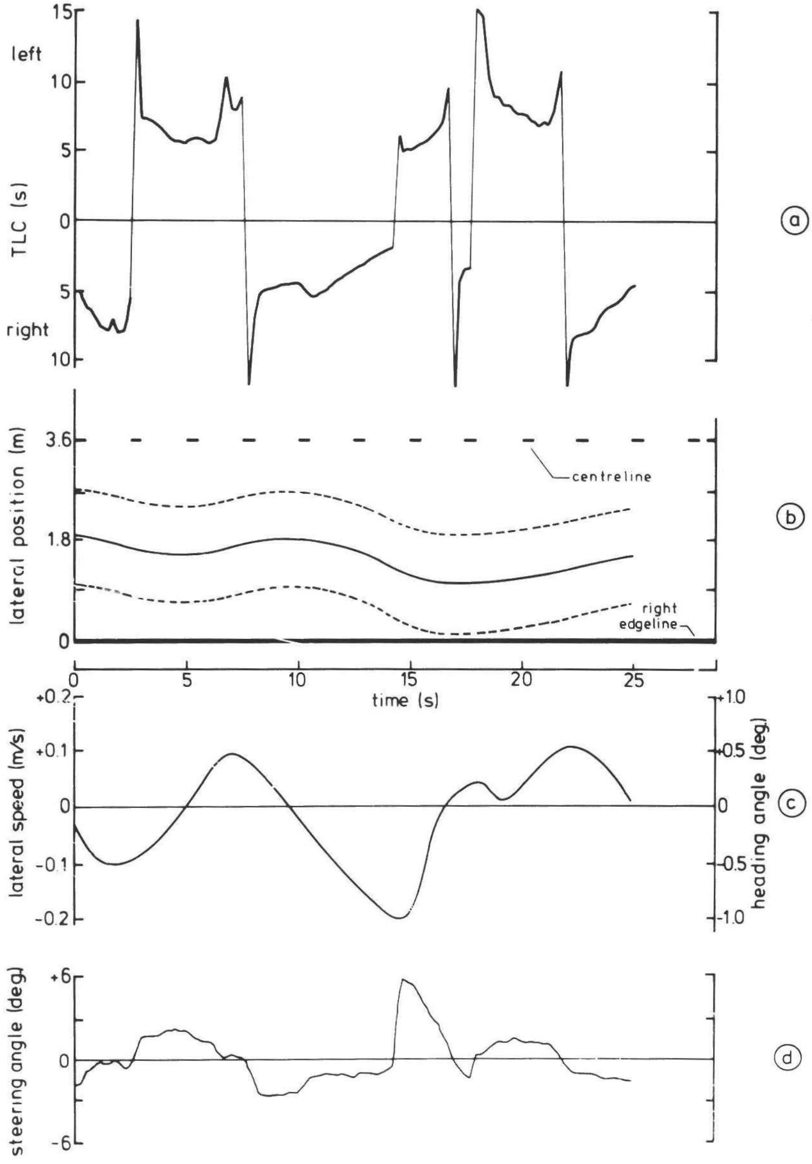


Fig. 3.6 Sampled time history for a TLC signal (a), resulting from the corresponding lateral position (b), heading angle (c), and steering-wheel angle (d) data.

ature of the predicted path was calculated using the following steady state (ss) relationship between vehicle path curvature c_v and steering-wheel angle as intermediate factor:

$$\left(\frac{c_v}{\delta_{se}}\right)_{ss} = \frac{G_r}{u} . \quad (6)$$

Again, δ_{se} represents the steering-wheel angle error, i.e. the difference between the required and actual steering-wheel angle. For each sample of vehicle position a stepwise path prediction was made with a step-duration of 0.1 s. The prediction process was stopped as soon as any part of the vehicle reached either of the two lane markings.

CHAPTER 4

4. THE ACCURACY LIMITATIONS OF CLOSED AND OPEN LOOP STEERING, AS MEASURED IN A REPRODUCTION TASK

4.1 Introduction

The time available for a driver to control his vehicle without immediate visual feedback, will partly depend on the accuracy of the open loop steering actions. It was argued in Section 2.2 that anticipation strategies based on preprogramming and/or preview may give the driver an almost perfect knowledge of the steering actions to be made in a particular manoeuvre, even during periods without immediate, visual feedback. The ultimate accuracy of open loop steering actions, however, will be limited because of inaccuracies in the motor system i.e. a driver's limitations to transform desired into actual steering-wheel movements. For closed loop tasks this motor inaccuracy will probably be insignificant as compared to observation noise levels (Pew and Baron, 1978). In case of open loop steering the motor system operates more independently, so that its accuracy limitations will play a more pronounced role. The reproduction experiments described in this chapter (Godthelp, 1980) were designed to analyse these limitations and to provide quantitative data about a driver's motor "acuity" under open loop steering conditions.

Vehicle steering tasks may be of a quite varying nature: They may be discrete or continuous, with or without time-constraints, amplitudes may be small or large, with low or high steering-wheel movement velocity, etc. Each of these factors may strongly effect steering accuracy. A literature review indicated that most studies on open loop movement accuracy are concerned with the reproduction of step movements without time-constraints (Marteniuk, 1973; Kelso and Wallace, 1978). The results of these studies show that reproduction accuracy is dependent on the preselection effect: When a blindfolded subject makes a movement of a self-chosen (preselected) length and later is asked to reproduce this movement, considerable improvement occurs as compared to conditions, in which the subject moves to an experimenter-defined, spatially constrained location. Marteniuk, Shields and Campbell (1972) illustrated that reproduction accuracy of movements with a voluntary chosen movement time is independent on movement amplitude. They also found a tendency to reproduce short movements with a too large amplitude (overshoot), while large movements were reproduced too short (undershoot). Adams, Gopher and Lintern (1977) showed that the accuracy of open loop movements may improve through proprioceptive force feedback added by means of spring resistance.

In each of the aforementioned reproduction studies movement time was free, so that effects of time-constraints did not become visible. Nevertheless, such effects are very likely to occur: For closed loop, step movements Fitts (1954) proposed a relationship - known as Fitts' law - between movement time, movement amplitude and movement accuracy, which largely can be explained as a speed/accuracy trade-off. Schmidt, Zelaznik and Frank (1978) modified Fitts' law by argueing that accuracy in terms of endpoint variability will be directly proportional to movement amplitude and inversely proportional to movement time, which implies accuracy to be linearly related to movement velocity. Fig. 4.1 shows the Schmidt et al. data, illustrating the linear relationship between the standard deviations of the movement endpoints and movement velocity. Actually these data are not fully in correspondance with what Schmidt et al. expected, because the function should pass the origin in case of proportionality. Further discussions about the theoretical evidence of these data are therefore still going on (Newell, Carlton and Carlton, 1982). Nevertheless, it seems justified to consider the linear relationship between (closed loop) movement accuracy and velocity as a powerful law, for which it can be assumed that it is valid not only for step movements but also for continuous tasks: In experiments on closed loop sine-wave (pursuit) tracking Poulton (1950, 1952) and Hartmann and Fitts (1955) indeed found similar results. Doubling the amplitude of the sine-wave - and thus doubling the velocity of the control movements - results in an increase in tracking error which can quite well be explained from the Schmidt et al. (1978) data.

It is remarkable that the analysis of factors, influencing closed loop movement accuracy, has hardly ever been discussed in terms of its implications for open loop movements. Yet such an analysis seems of particular interest for conditions in which subjects have no opportunity for immediate movement corrections. The question can be raised, for example, whether the linear relationship between steering accuracy and movement velocity is also

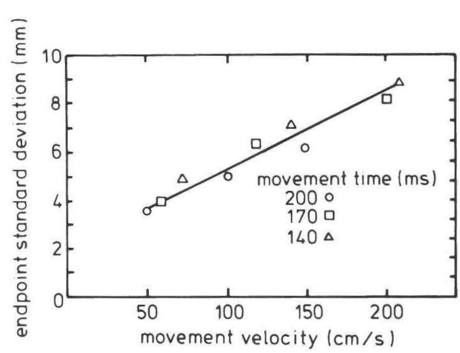


Fig. 4.1 The relation between endpoint standard deviations and movement velocity for different movement times (Schmidt et al., 1978).

valid for open loop conditions. Actually Schmidt et al. (1978) suggest this to be true, by argueing that "the law defining the accuracy of such (open loop) programs could be approximated by the expressions described here i.e. the accuracy is proportional to the average velocity". Studies on mathematical modeling of open and closed loop step movements by Eland (1981), Sparreboom et al. (1983) and Ruitenbeek (1984) indicated that the widthdrawal of visual feedback does not strongly effect the model parameters, describing the movement control strategy. However, movement accuracy appeared to be less in case of the open loop movements.

In the present study Experiment I was chosen in close correspondance with the Marteniuk et al. (1972) study and aimed to quantify open loop steering accuracy in a discrete task: Subjects reproduced step steering-wheel movements of different amplitudes under self-chosen timing conditions. The effect of additional proprioceptive feedback was analysed by varying the steering force.

In Experiment II subjects reproduced a time-constrained movement pattern, which can roughly be characterised as an isolated sine-wave. Steering-wheel angle amplitude and frequency were varied to permit the analysis of movement velocity effects. The questions to answer in this experiment were, 1) whether the linear relationship between movement velocity and accuracy as proposed by Schmidt et al. (1978) would also be reflected in a continuous task, and 2) how this relation holds for open loop conditions. Steering force was again varied to quantify the role of additional proprioceptive feedback. Actually the isolated sine-wave was chosen because such a steering-wheel movement is needed to perform a lane change manoeuvre in automobile driving. Vehicle speed and desired lateral path deviation may affect the amplitude of the sine-wave steering-wheel movement in such a manoeuvre, whereas the available manoeuvre time may affect its frequency. A comfortable manoeuvre may take about 5 seconds (0.2 Hz sine-wave), while the time available for obstacle avoidance may be as short as 2 seconds (0.5 Hz sine-wave). Furthermore the lane change manoeuvre seems of particular interest since this manoeuvre is often referred to as an example of precognitive steering, for which the dependency on instantaneous visual feedback is relatively low (see also Chapter 5).

4.2 Experiment I: Reproduction of discrete steering-wheel movements

4.2.1 Method

Apparatus

The experiment was carried out in the mock-up of the driving simulator, of which the steering-wheel has a 0.22 m radius with spokes mounted in the wheel at 56.5 degrees to the left and to the right from the axis connecting the most upper and lower points of the wheel. The angle between the steering-wheel plane and the vertical axis through the centre of the wheel is 15 degrees. The steering-wheel axis is connected with a potentiometer which measures the steering-wheel angle. Steering force is generated by means of an electric torque motor, which is connected with the steering-wheel axis by a gearbelt drive.

Subjects

Twelve male subjects (Ss) participated in the experiment, all of them university students. Ss ranged in age from 20 to 34 years. Ss had their driving license for at least two years. All Ss were right-handed.

Experimental conditions

In a within-subjects design, Ss reproduced four steering-wheel positions. The positions were 30° to the left (δ_S = -30°) and 10°, 30° and 50° to the right (δ_S = 10°, 30°, 50°). The movements had to be reproduced in combination with three steering-wheel rim force levels i.e. 0 N, 7.5 N and 15 N, giving a total number of 12 movement conditions. For the steering-force conditions the relation between steering-wheel angle and steering force was linear, i.e. the wheel was spring-centered.

Procedure

Subjects were blindfolded during the experiment. The seat was adjusted so that Ss comfortably could hold the steering-wheel with their arms slightly bent. Ss were instructed to hold the steering-wheel with their thumbs resting on the upper left and right spokes. Each subject participated during one day, on which he made 12 blocks of movement trials, i.e. one for each of the movement conditions. In a block the same movement was presented and reproduced for 40 consecutive trials. In all conditions the centre position of the steering-wheel ($\delta_S = 0°$) served as the starting point. In a trial Ss actively moved the steering-wheel to a stimulus position marked by an auditory signal. Actually, the signal marked an area of plus and minus 1/4° around the stimulus angle. Then, the experimenter moved the steering-wheel back to the starting position which was marked by a stop. Next to this stimulus presentation Ss were required to reproduce the movement as accurately as possible without the aid of the warning signal. Thus one trial consisted of a criterion or stimulus movement followed by a reproduction movement. A block of 40 trials of a particular movement condition lasted about 15 min. Sequence of movement conditions was randomized over Ss. Time between blocks was at least 20 min.

Data analysis

Both stimulus and reproduction steering-wheel angle were recorded. The difference between reproduction and stimulus angle within a trial was taken as algebraic error. Positive algebraic errors, i.e. reproduction steering-wheel angle larger than stimulus angle, will be noted as "overshoot", while negative algebraic errors are described as "undershoot". Performance on the first 15 trials was not taken into the final analysis in order to overcome habituation and/or transfer effects and for the sake of correspondence with the data analysis of Experiment II. Standard deviations for the stimulus and reproduction angles were calculated over the last 25 trials of each block. Differences between conditions were tested by analysis of variance

(ANOVA) with main factors stimulus/reproduction (SR), steering-wheel angle amplitude (SA) and steering force (SF)[1]. Trials were considered as replica in the ANOVA on the algebraic errors.

4.2.2 Results

Results showed no differences between the 30° movement to the left and the right. Therefore, only the results for the rightward movements will be presented. Fig. 4.2 presents the algebraic errors and shows a general overshoot effect which appears to be significant ($p < 0.01$). An additional Newman-Keuls test revealed this effect to be equal for the 30° and 50° movements and less for the 10° movements. The SA x SF interaction was not significant. However, when only the 10° movement was taken in the analysis, a main effect of SF ($p < 0.05$) indicated the strongest overshoot tendency for the highest SF levels. Results about endpoint variability are given in the right part of Fig. 4.2. A significant SA x SR interaction ($p < 0.01$) clearly illustrates the increase of the reproduction standard deviations with larger steering-wheel angles. Furthermore, a SF x SR interaction ($p < 0.01$) indicates that this standard deviations are smallest with steering force available.

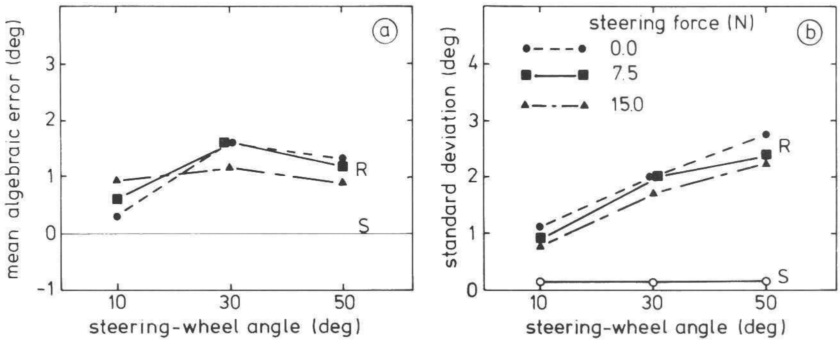


Fig. 4.2 Algebraic error and standard deviations of the stimulus (S) and reproduction (R) steering-wheel movements for the conditions in Experiment I.

[1]A list of abbreviations is given on page 150.

4.3 Experiment II: Reproduction of continuous steering-wheel movements

4.3.1 Method

Instrumentation

Experiment II was conducted in the same mock-up as used in Experiment I. A visual pursuit tracking task was used to present the stimulus movement. Visual presentations were made with the aid of a TV projector which was situated above the mock-up. Two vertical lines were projected on a screen, situated at 2.90 m in front of Ss' head position. The upper vertical line served as the target while the lower was controlled by the Ss. The lines moved horizontally and were projected at about eye level height, see Fig. 4.3. The height of the lines was 19 cm with a vertical interspace of 2 cm. Line width was 3.5 cm. The gain between Ss' cursor and steering-wheel angle was 1.12 cm lateral displacement (0.22 degrees of visual angle) per degree of steering-wheel angle.

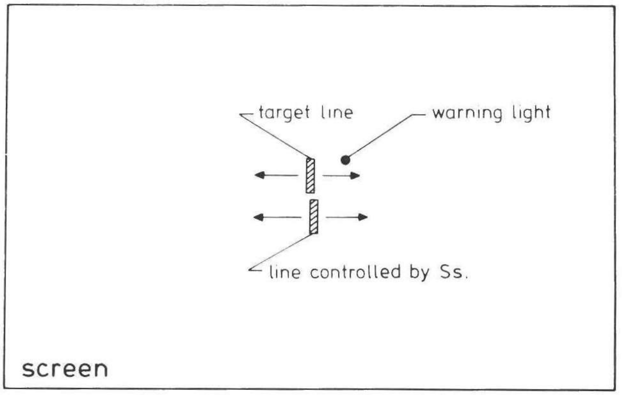


Fig. 4.3 The visual presentation given in Experiment II.

Subjects

Twenty-four male Ss participated in the experiment. All of them were university students. Ss ranged in age from 20 to 30 years. All Ss had their driving license for at least two years. None of them took part in Experiment I. All Ss were right-handed.

Experimental conditions

In a partly within - partly between - subjects design Ss reproduced six steering-wheel movement patterns. This pattern was based on a sine wave with a modification at the start and end of the movement, in order to guarantee a smooth movement. Fig. 4.4 shows the target pattern as described in terms of Steering-wheel angle Amplitude SA and Frequency F. The first part of the movement was to the left. Three amplitudes, 10°, 30° and 50° and two frequencies, 0.2 Hz (0.4 π rad/s) and 0.5 Hz (π rad/s) were considered, giving a total number of six steering-wheel movement patterns. (The relation between these movement conditions and a lane change steering-wheel movement is described in Section 4.1.) Durations of the 0.2 Hz and 0.5 Hz movements were $5^5/6$ sec and $2^1/3$ sec respectively. Frequency served as the between-subjects variable so that 12 Ss reproduced the 0.2 Hz movements, while the other 12 Ss reproduced the 0.5 Hz movements. All of the movement patterns were reproduced at each of three steering-wheel rim force levels i.e. 0 N, 7.5 N and 15 N. As in Experiment I, the relation between steering force and steering-wheel angle was linear. Steering-wheel angle amplitude and steering force were used as the within-subject variables.

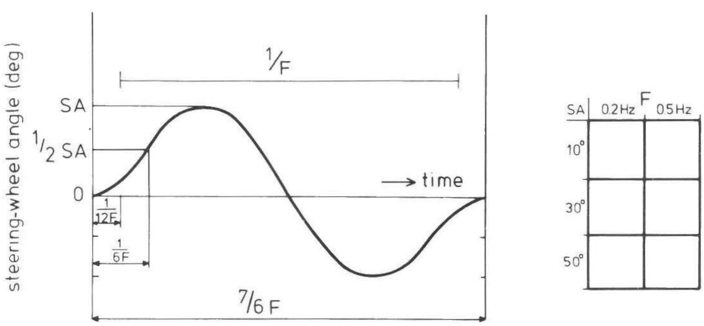


Fig. 4.4 Steering-wheel angle target pattern for the movements in Experiment II.

with: SA = steering-wheel angle amplitude deg
F = frequency Hz
ω = radial frequency rad/s

The stimulus pattern can be described as:

$0 < t < 1/6F : \delta_s = SA\,(1 - \cos \omega t)$

$1/6F < t < 1/F : \delta_s = SA \sin(\omega t - \pi/6)$

$1/F < t < 7/6F : \delta_s = SA\,\{\cos(\omega t - \pi/3) - 1\}$

Procedure

Ss' seat and handgrip were adjusted as in Experiment I. The experiment took 12 days with the 0.2 Hz movements carried out in the first six days and the 0.5 Hz movements on the last six days. Each S participated during one day, on which he made 9 blocks of movement trials, i.e. one for each movement condition. In a block the same movement was presented and reproduced for 40 consecutive trials. Pursuit tracking of the target pattern served as the stimulus phase of each trial. The starting position of both the target line and Ss' cursor corresponded with the centre position of the steering-wheel. The starting moment of the target movement could be anticipated with the aid of a warning signal. This signal was a light spot projected on the screen at 20 cm to the right of the target line, see Fig. 4.3. Before the start of the target movement this spot moved to the left (20 cm/sec). The target movement started as soon as the light spot touched the target line. After tracking the stimulus movement Ss had to close their eyes and reproduce the movement as accurately as possible without the aid of visual feedback. After this reproduction movement Ss released the steering-wheel. Then the experimenter placed the steering-wheel in the starting position. Thus, Ss did not get feedback about the terminal position of the reproduction movement. A block of 40 trials was carried out in about 15 min and 10 min respectively for the 0.2 Hz and 0.5 Hz movements. Sequence of movement conditions was randomized over Ss for the within-subjects part of the experimental design. Time between blocks was at least 20 min.

Data analysis

Both stimulus and reproduction steering-wheel movements were recorded with a sample rate of 105 samples for each movement. Learning effects were analysed in terms of the integrated absolute error score during pursuit tracking with visual feedback. An evaluation of these data indicated that all of the habituating, learning and/or transfer effects occurred during the first 15 trials of each block. For that reason data analysis was restricted to the last 25 trials of each block.

The difference between Ss' movement amplitude (δ_{sl}, δ_{sr}, see Fig. 4.5) and target movement amplitude (10°, 30° or 50°) within a trial was taken as algebraic error. Positive algebraic errors, i.e. Ss' movement amplitude larger than the target movement amplitude, will be noted as "overshoot", whereas negative algebraic errors are described as "undershoot". Timing accuracy was measured by determining the movement time T_m, for which the start and end of each movement were calculated by way of a least square fit, thereby constructing a regression line through the eight data points surrounding the point $\delta_s = 0.5\ \delta_{sl}$ (start) and $\delta_s = 0.5\ \delta_{sr}$ (end), see Fig. 4.5. Timing accuracy was calculated in relation with the same type of movement time of the target movement. Therefore timing accuracy is presented in terms of percents too slow or too fast. Standard deviations were calculated over the last 25 trials in a block for the movement amplitude to the left (δ_{sl}) and the right (δ_{sr}) and for the timing accuracy data. Differences between conditions were tested for statistical significance by ANOVA with main factors stimulus/reproduction (SR), steering-wheel angle amplitude (SA), steering force (SF), and frequency (F). Trials were considered as replica in the ANOVA on the algebraic amplitude errors and on timing errors.

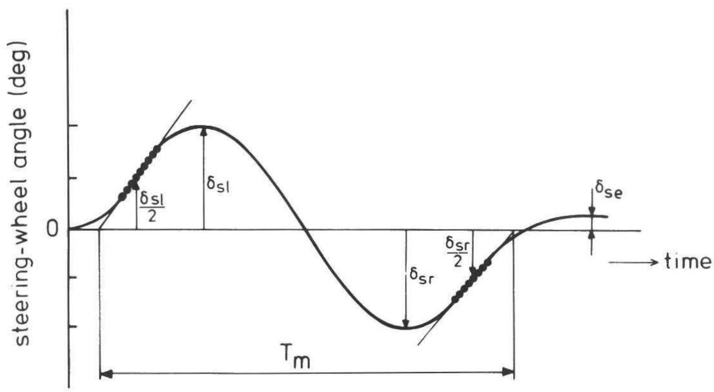


Fig. 4.5 Analysis of the stimulus and reproduction movements in Experiment II.

4.3.2 Results

As shown in Table 4.I the primary part of the movement (to the left) has a remarkable overshoot tendency ($p < 0.01$) An SR x SA interaction ($p < 0.05$) points to the fact that the overshoot effect is least pronounced for the 10° movement conditions. In the second part of the movement (to the right) the overshoot effect is less (0.2 Hz condition) or even disappeared (0.5 Hz condition). In the latter condition an undershoot effect can even be noted for the 50° movement condition. Steering force does not heavily influence the overshoot/undershoot effect. Only in the 0.2 Hz condition the steering force level of 15 N tends to result in less overshoot as compared with the 0 N condition.

The standard deviations of the movement amplitudes show about the same effects for the movement parts to the left (δ_{sl}) and the right (δ_{sr}), see Fig. 4.6. Amplitude variability appears to be highly dependent on movement amplitude ($p < 0.01$) with the largest deviations for the largest amplitudes. Furthermore, an F x SA x SR interaction ($p < 0.01$) indicates that for the 0.2 Hz condition the slopes of the S and R curves differ significantly, whereas these slopes are rather parallel for the 0.5 Hz condition. Steering force decreases amplitude standard deviations ($p < 0.01$). Actually this SF effect holds for both the stimulus and reproduction movement in case of the movement part to the left. For the movement part to the right SF mainly effects the variability of the reproduction movement (SF x SR interaction, $p < 0.01$).

Table 4.I Mean algebraic errors (degrees) for the steering-wheel angle amplitudes in Experiment II. Algebraic errors are given positive in case of amplitude overshoot (S = stimulus, R = reproduction).

movement amplitude (deg)	steering force (N)	0.2 Hz				0.5 Hz			
		δ_{sl}		δ_{sr}		δ_{sl}		δ_{sr}	
		S	R	S	R	S	R	S	R
	0	0.45	3.06	0.27	1.69	0.32	2.80	0.33	0.96
10°	7.5	0.29	4.13	0.19	2.95	0.11	3.04	0.07	1.61
	15	0.14	2.89	-0.03	1.37	0.42	4.16	0.06	1.53
	0	0.22	6.06	0.11	3.22	-0.02	4.30	0.01	-0.60
30°	7.5	0.02	5.83	-0.19	1.57	-0.63	4.15	-0.43	0.57
	15	-0.05	5.21	-0.20	1.50	-0.46	4.70	-0.36	1.05
	0	-0.43	7.82	0.09	5.65	-1.17	4.16	-0.40	-0.86
50°	7.5	-0.44	5.86	-0.11	3.87	-1.38	1.94	-0.88	-4.76
	15	-0.39	3.72	-0.40	2.27	-1.61	2.16	-0.85	-0.53

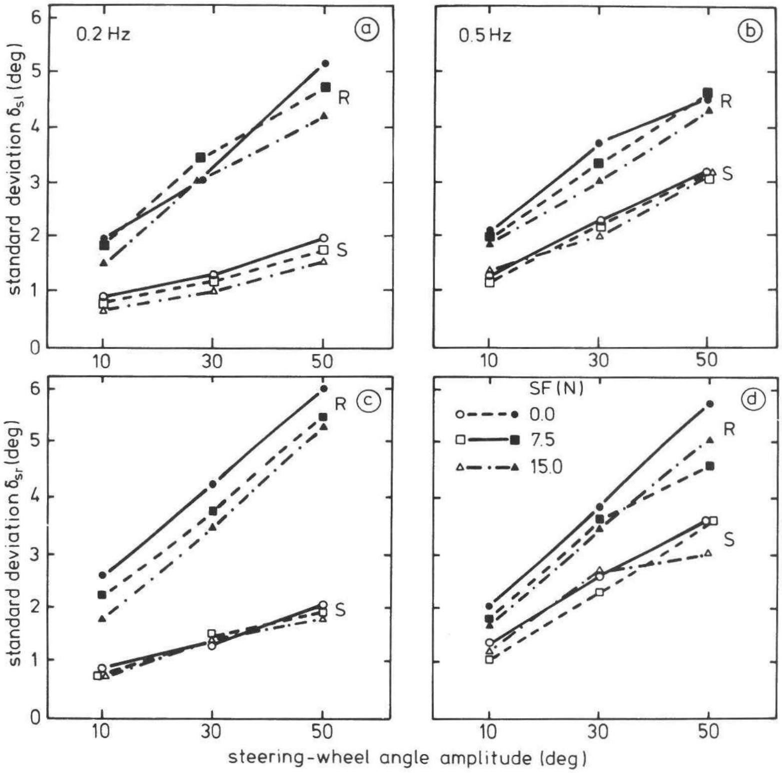


Fig. 4.6 Standard deviations of the steering-wheel angle amplitude for the movement conditions in Experiment II (S = stimulus, R = reproduction).

Means and standard deviations of the relative errors in timing are shown in Table 4.II. Regarding the means the ANOVA showed two significant ($p < 0.01$) interactions, i.e. SA x SR and SF x SR, indicating that movement amplitude and steering force influence mean timing accuracy in reproduction. In most conditions reproduction times are too long, especially with the 30° and 50° amplitudes. Only in the movement with the lowest velocity levels (0.2 Hz, small amplitudes) and with steering force available the tendency to reproduce movement times too long disappears. The effect of steering force on shortening of movement times in reproduction is quite general and influences all of the movement conditions.

The ANOVA on the timing error standard deviations revealed a F x SR interaction ($p < 0.01$), which shows the variability differences between stimulus and reproduction movements to be smaller in the 0.5 Hz condition as compared with the 0.2 Hz movements. Steering force did not effect timing variability.

Table 4.II Means (η) and standard deviations (SD) for the relative errors (%) in timing in Experiment II. Means are given positive when movements are made too slow (S = stimulus, R = reproduction).

movement amplitude (deg)	steering force (N)	0.2 Hz				0.5 Hz			
		η		SD		η		SD	
		S	R	S	R	S	R	S	R
	0	2.78	2.28	3.2	9.2	3.41	7.56	5.5	8.2
10°	7.5	1.53	0.24	3.7	9.1	1.53	6.32	5.8	7.3
	15	1.41	-5.31	3.7	7.1	0.99	5.87	7.0	7.8
	0	0.58	7.51	2.2	7.3	1.69	13.90	4.6	6.9
30°	7.5	0.87	-1.98	2.4	7.5	2.75	12.14	4.8	6.8
	15	0.81	3.61	2.5	7.7	1.35	9.87	4.8	7.3
	0	1.08	9.15	2.1	7.1	2.73	14.50	4.6	7.2
50°	7.5	1.01	8.84	2.0	6.3	3.00	10.45	9.3	6.8
	15	1.22	6.74	2.0	7.0	3.45	9.58	10.5	7.2

4.4 Discussion and conclusions

In most studies on movement reproduction a tendency to amplitude overshoot is found for relatively small movements, while undershoot often occurs for large amplitudes. This effect is not fully confirmed in the present data. Both for the discrete and the continuous reproduction task an overshoot effect was found for each of the amplitudes. One explanation for this may be that in the present experiment even the largest amplitude (50°) was relatively small. Another reason can be found in the results of Buck (1976, 1978), who illustrated that undershoot tendencies for larger movements most probably are caused by boundary effects. Buck showed overshoot/undershoot effects to be dependent on boundary distance rather than on movement length. Boundary distance is the distance between desired movement endpoint and the furthest limit of the movement. This limit may be either the edge of the display in case of visually guided movements or the physical stop of the control lever or steering-wheel. Undershoot is likely to occur with short boundary distances. Because these distances were very large in the present experiment, similar effects will not have played a role. The general overshoot tendency is also in line with findings of Poulton (1974), who reported amplitudes to become too large in tracking tasks, in which visual feedback was temporarily withdrawn. The timing overshoot tendency as found in Experiment II was also found earlier (Vossius, 1965): In a pursuit tracking task subjects learned a periodic movement pattern, which they were asked to reproduce after withdrawal of the visual input. The reproduction movements appeared to be about 10% too slow, this percentage being in close correspondence with the present data. The question remains here, whether and how, sharper defined time boundaries will influence timing overshoot effects. This question seems of particular interest when translating the amplitude and timing overshoot data to the vehicle control task. When steering a vehicle under temporary absence of visual feedback the driver will mostly be aware of the task boundaries in terms of both space and time. An actual driving experiment seems necessary to analyse whether and how these overshoot effects will play a role in open loop vehicle control. The lane change experiment to be presented in Chapter 5 was designed to answer this question.

A major reason to perform the present experiments was to quantify a subjects motor "acuity" under open and closed loop conditions both in a discrete and a continuous steering task. The data on amplitude variability can be considered as a measure for this acuity. The suggestion that steering force may serve as an additional cue, which may help to reduce this variability, was confirmed in the present analysis. Another question to answer was whether the linear relationship between amplitude standard deviations and movement velocity, as suggested by Schmidt et al. (1978) would also be valid for continuous steering tasks and under open loop conditions.

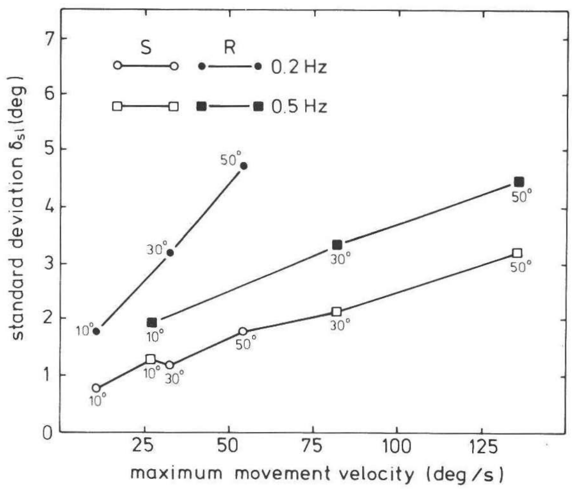


Fig. 4.7 Standard deviation of the amplitude δ_{Sl} as a function of maximum movement velocity in Experiment II. The data were averaged over steering force levels (S = stimulus, R = reproduction).

Regarding this question, Fig. 4.7 gives the amplitude standard deviations of the primary part of the movement (to the left) as a function of movement velocity as found in Experiment II. For this purpose the data are averaged over steering force levels. Maximum movement velocity during the primary movement part is given on the horizontal axis. The open and filled symbols represent the amplitude variability for the stimulus and reproduction movements, respectively. This way of presenting the data shows two remarkable results: 1) the relationship between standard deviations and velocity is almost perfectly linear for the stimulus movements and 2) amplitude variability of the reproduction movements is dependent on amplitude rather than on velocity. The latter result was also clearly visible in Fig. 4.6: For the reproduction trials amplitude standard deviations appeared to be independent of movement frequency and thus independent of velocity. The amplitude effect was about equal for the 0.2 Hz and 0.5 Hz movements as is also shown in Fig. 4.7. It can be concluded now that the stimulus results fit quite well with the proposed linear relationship between accuracy and velocity. However, Schmidt et al. (1978) expected this proportionality to be also valid for not visually monitored, preprogrammed movements and this appears not to be true. Rather it appears that movement amplitude is the major factor determining open loop steering accuracy. Furthermore, the suggestion that steering force may serve as an additional cue, which can help to reduce movement variability, was confirmed in the present experiments.

In summary the following conclusions can now be drawn from the present data of Experiment I and II:

1. When reproducing simple discrete and continuous movements under conditions without visual feedback a general tendency exist to overshoot both movement amplitude and movement time.
2. Amplitude variability under visually open loop conditions is linearly related to movement amplitude. The proportionality between accuracy and movement velocity seems only valid for visually guided movements.
3. Steering force improves movement accuracy in terms of amplitude variability.

CHAPTER 5

5. PRECOGNITIVE CONTROL: OPEN AND CLOSED LOOP STEERING IN A LANE CHANGE MANOEUVRE

5.1 Introduction

In this chapter, two experiments will be presented, in which steering performance in a lane change manoeuvre was analysed under both open and closed loop driving conditions (Godthelp, 1984). Steering in such a manoeuvre is often referred to as an example of precognitive control being relatively independent of immediate visual feedback. Allen (1982) presents "a precognitive driver model with continuous closed loop operations", which gives a rather good mathematical simulation of driver's steering performance in a lane change. However, few data are available about how a driver may use the benefits of his precognition to behave in a visually open loop mode.

Fig. 5.1 gives an impression of the steering-wheel angle, heading angle and lateral position time histories, occurring in a lane change manoeuvre. The steering-wheel movement roughly can be described as a sine-wave, i.e. a simple, continuous movement assumed to be carried out at a precognitive level after a relatively short learning period. Despite the continuous character of the steering-wheel movement, it will appear to be useful to recognise four phases, noted 1 to 4, in the steering-wheel angle time history (Fig. 5.1). Phase 1 refers to the initial steering action δ_{sl} to the left ($t_o \rightarrow t_{sl}$), whereas during phase 2 the steering-wheel is returned to the central position which is reached at about the moment of maximum heading angle ψ_m ($t_{sl} \rightarrow t_\psi$). In phase 3 the steering-wheel is turned to the right to δ_{sr} ($t_\psi \rightarrow t_{sr}$) and, finally, phase 4 describes the centralising part of the steering-wheel movement at the end of the manoeuvre ($t_{sr} \rightarrow t_{se}$).

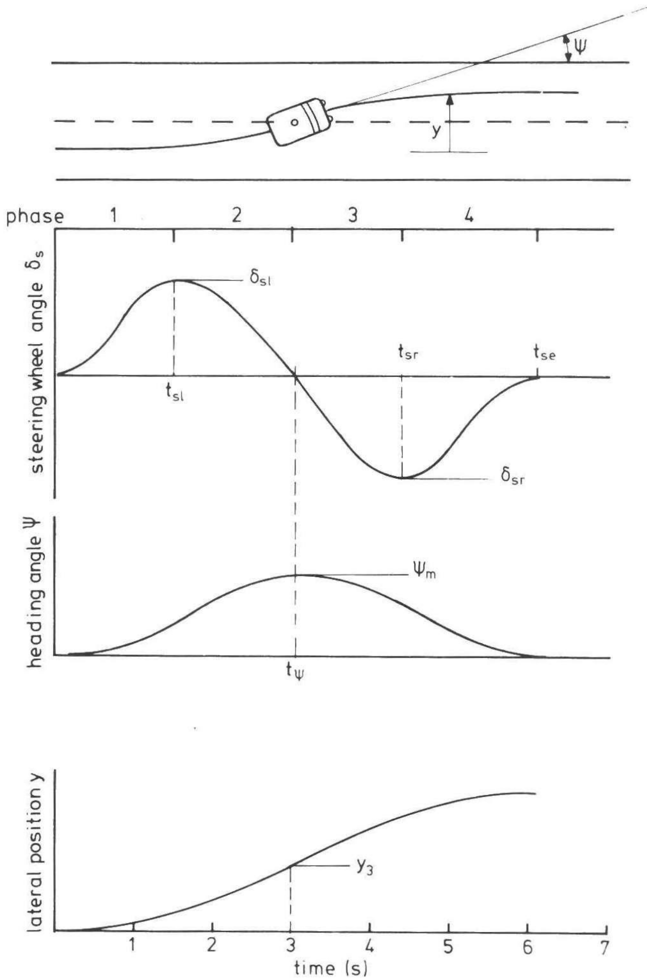


Fig. 5.1 Time histories for the steering-wheel angle, heading angle and lateral position signal in a lane change manoeuvre.

The purpose of the experiments reported here was, 1) to verify, whether the results on steering accuracy as found in the reproduction experiment (Exp. II) could be replicated in a real, open loop driving task, and 2) to analyse these data in terms of their implications for vehicle motion. Regarding this last point, it is important to notice that, ultimately, the time available for visually open loop control will depend on the vehicle trajectory in relation to the roadway boundaries during the occlusion period. In case of a lane change it can be derived from a simple, mathematical vehicle model that the maximum heading angle, ψ_m, will be about proportional to steering-wheel angle amplitude, δ_{s1}, and the time, t_ψ. In other words: Errors in δ_{s1} and/or in t_ψ will be proportionally reflected in ψ_m. In view of this, it should be noticed that the actual vehicle motion depends on the integrated steering-wheel movement. Hence, the driver may use a sort of compensation strategy, i.e. the steering-wheel amplitude δ_{s1} and the time t_ψ may be mutually dependent: large amplitudes may, for example, be connected to fast movements. Ultimately, this process will determine how steering amplitude and timing errors will effect vehicle motion errors.

The conditions chosen for the experiments to be presented here, were in close correspondance with those of the reproduction experiment. Subjects made a series of identical manoeuvres, half of which were performed under closed loop conditions, i.e. with normal visual feedback, whereas the other half were carried out during temporary visual occlusion, i.e. open loop. In Experiment III steering force served as the main independent variable, whereas the effect of steering-wheel movement amplitude was analysed in Experiment IV.

5.2 Experiment III: The effect of steering force

5.2.1 Background

The results of the reproduction experiment showed that steering force might improve accuracy in reproducing steering-wheel movements. Experiment III was designed to analyse whether this effect could also be found in a lane change manoeuvre. The timing and geometry of this manoeuvre were chosen such that the required steering-wheel movement corresponded closely with the 0.2 Hz, 10^o steering-wheel movement condition of Experiment II. A second reason to choose this movement was that the reproduction data suggest the sensitivity for changes in steering force to be relatively high in this condition. The experiment was conducted in a driving simulator. All subjects made a series of overtaking manoeuvres the first part of which, i.e. the lane change to the left, was analysed. Occlusion was implemented by a blink in the visual scene during phase 1 (see Fig. 5.1) of the steering action. Steering force served as the main independent variable.

5.2.2 Method

Driving simulator

The experiment was carried out in the driving simulator which was described in Section 3.2.2 and Appendix A. The steering torque coefficient G_t was used in this experiment to vary the steering torque gradient without effecting the other steering system dynamics.

Subjects

Three groups of nine subjects (Ss) each, participated in the experiment. All Ss were university students and had their driving license for at least two years. Ss ranged in age between 20 and 36 years. They were paid for their services.

Procedure

Each S took part in the experiment on two consecutive days, which will be noted as day 1 and day 2. On each day S made a 50 minutes run on a simulated straight motorway with a lanewidth of 3.60 m. After a short instruction S took place in the mock-up. At that moment the car was parked on the paved shoulder. First S was given instructions about the procedure during the run. Then, S started and accelerated to a speed of 24 m/s (86.4 km/h). Speed was automatically limited to this level and S just had to push the accelerator beyond the required position. The general instruction was to drive "normally" in the right lane. After a five minutes period of driving S was asked to make a training series of five passing manoeuvres without any other vehicle being involved. Then, the first experimental run was started. In this run S made 40 consecutive overtaking manoeuvres, with a time interval between manoeuvres of about 1 minute. The vehicle to be overtaken drove with a speed of 17 m/s (61.2 km/h). An illustration of the visual scene is given in Fig. 3.2, page 24. Ss were instructed to make all the manoeuvres in the same way and to start each manoeuvre from the middle position of the right lane with the car in the straight ahead position. Furthermore, S was told to start the manoeuvres at the moment of a short blink in the 40^o central part of the visual scene. This blink was always given at an intervehicle distance of 56 m, which corresponds with an intervehicle time distance of 8 s. The duration of the blink was either 0.1 or 1.0 s. The 0.1 s blink just served as a warning signal for S to start his manoeuvre, while the 1 s blink was given as temporary occlusion, covering phase 1 of the steering action. In case of the 1 s blink S was instructed to interpret the onset of the blink as the start signal and to make the first steering wheel movement to the left during the blink. On day 1 the first 10 manoeuvres were all made with the 0.1 s blink. For the next 30 manoeuvres of day 1 and the 40 manoeuvres of day 2 the 0.1 s and 1.0 s blink were given in alternation. The manoeuvres with 0.1 s and 1.0 s blink will be considered as the conditions without and with occlusion respectively. Three steering torque coefficients were considered: $G_t = 0$, $G_t = 1.43$ and $G_t = 2.86$, giving steering-wheel rim forces of 0 N, 7.5 N and 15 N at a steering-wheel angle of 10^o with a driving speed of 24 m/s. These steering-wheel rim force levels corresponded to the conditions in the reproduction experiment as previously described. At a speed of 24 m/s the three G_t levels led to steering torque gradients of 0 Nm/rad, 9.5 Nm/rad and 18.9 Nm/rad, respectively. Each of the steering torque gradients served as an experimental condition for a group of Ss, giving three groups of nine Ss in a between-subjects design.

Data analysis

From the start of each manoeuvre (t = 0) the following signals were registrated:

δ_s	steering-wheel angle
ψ	heading angle
y	lateral position

The sample period was 10 s and the sample rate 16 Hz, this rate being high enough to analyse lane change steering-wheel signals of which signal frequency is below 2 Hz. The following steering-wheel angle and vehicle motion characteristics were determined for each manoeuvre (see Fig. 5.1):

δ_{sl}	= maximum steering-wheel angle, left	deg
t_{sl}	= time of δ_{sl}	s
δ_{sr}	= maximum steering-wheel angle, right	deg
t_{sr}	= time of δ_{sr}	s
ψ_m	= maximum heading angle	deg

t_ψ = time of ψ_m s

$y_{1,2,3--}$ = lateral position at t = 1,2,3 -- s m

$\psi_{1,2,3--}$ = heading angle at t = 1,2,3 -- s deg

A primary question was whether and how steering performance was effected by learning. In order to localize learning effects, the total set of 80 manoeuvres was subdivided for each subject into four sets (I, II, III, IV) of 20 manoeuvres each. Fig. 5.2 presents the standard deviations of δ_{sl} for the different sets. SD's were calculated for each subject over the 10 manoeuvres with and without occlusion in a particular set, respectively. Each data point in Fig. 5.2 represents the mean SD over nine Ss. The data for the manoeuvres with occlusion in set I were not available, because of the training procedure in this set. The SD's for the manoeuvres without occlusion in set I were calculated over the 10 odd numbered manoeuvres. An

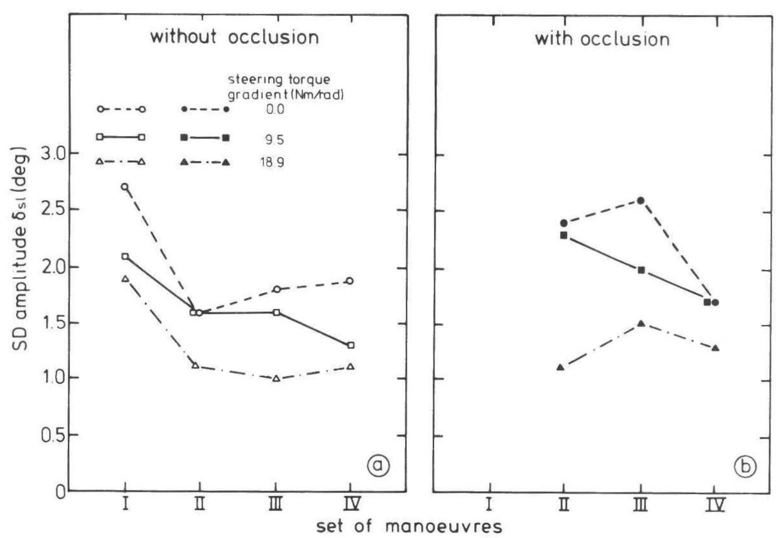


Fig. 5.2 Standard deviations (SD) of the amplitude of the initial steering-wheel movement to the left for the four sets of manoeuvres. Each data point represents the mean SD of 9 Ss for a particular set. For each set the SD's were calculated both for the 10 manoeuvres with and without occlusion, which are given in the right and left part of the Figure, respectively.

ANOVA on the "without-occlusion" data indicated a main effect of sets ($p < 0.01$). A Newman-Keuls test on the same data showed no differences between the sets II, III and IV, whereas set I differed from all these. Furthermore, ANOVA on the total set II, III and IV data (with and without occlusion) indicated no set effect. To exclude learning effects it was decided for further analysis to focus on this homogeneous part of the data and to calculate means and SD's over the 30 manoeuvres with and without occlusion in this group of data. Differences between conditions were tested for statistical significance by way of ANOVA with main factors: Subjects (Ss), steering torque gradient (SF) and occlusion (OCC).

5.2.3 Results and discussion

The circular dots in Fig. 5.3 represent means and standard deviations for δ_{sl} and δ_{sr}. For the means the ANOVA revealed a main effect of OCC ($p < 0.01$), indicating an "overshoot" tendency for the manoeuvres with occlusion. For the mean δ_{sl} the ANOVA also yielded a main effect of SF. A Newman-Keuls test showed that the mean δ_{sl} for the steering torque gradients 9.5 and 18.9 Nm/rad differed significantly ($p < 0.05$). The tendency towards relatively large amplitudes with the medium torque gradient can also be seen in the δ_{sr} data. However, the ANOVA did not show a significant effect here.

Regarding steering amplitude variability, the ANOVA on the δ_{sl} and δ_{sr} standard deviations resulted in a tendency ($p < 0.10$) and a main effect ($p < 0.05$) of SF, respectively. In both cases amplitude variability is smallest with the higher torque gradients. For the SD's of δ_{sl} the ANOVA also showed a main effect of OCC ($p < 0.01$): variations are largest for the condition with occlusion. For the δ_{sr} variations this effect is absent, which can largely be explained by the relative shortness of the occlusion period.The square dots in Fig. 5.3 represent the same data for the sine-wave reproduction experiment (Experiment II) described in Chapter 4 and it appears that - although some differences can be noticed in the absolute level of the variables - the correspondence of the steering force and occlusion effects is remarkable for both sets of data. Regarding the means the difference is simply the result of the fact that the present lane change task required a smaller steering-wheel movement as compared to the 10^{o} reproduction task. Despite this difference, the OCC effect (overshoot) as well as the SF effect (relatively large amplitudes in the median torque area) are similar in both experiments. With respect to the SD results, the reproduction data showed a rather pronounced effect of occlusion, which was mainly the result of the accurate visual guidance in that experiment. In the present experiment the OCC effect is less (δ_{sl}) or even absent (δ_{sr}). Nevertheless, the SD's for the reproduction data (square, closed dots) are close to the present lane change data. Furthermore, the similar steering force effect confirms the hypothesis set on the basis of the reproduction experiment, that steering force reduces steering variability in precognitive steering tasks as considered in this experiment.

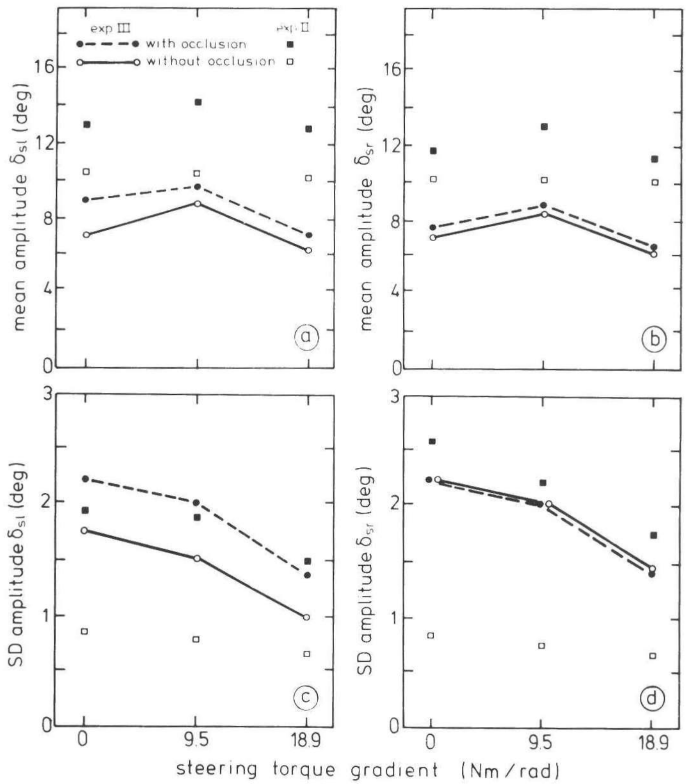


Fig. 5.3 Means and standard deviations of δ_{sl} and δ_{sr} for different steering torque gradients and for the manoeuvres with and without occlusion. The square dots represent the analogue results from Experiment II.

Table 5.I presents the means and SD's for t_{sl}, t_{ψ} and t_{sr}. Regarding the SD's of t_{sl}, the ANOVA showed an OCC effect ($p < 0.05$) indicating that timing variability is smallest for the runs with occlusion. This remarkable result is probably caused by the fact that the end of the 1 second occlusion period may have served as a timing aid during the initial steering action to the left. Furthermore, the tendency to relatively slow steering actions under conditions without visual feedback - as found in the reproduction experiment - is not replicated in the present data. For the t_{ψ} and t_{sr} means, a slight tendency can even be noticed for faster steering actions under occlusion as compared to the manoeuvres with visual feedback.

The question remains how the present steering-wheel movement data are reflected in the vehicle motion. Fig. 5.4 presents means and SD's of the maximum heading angle ψ_m and the ANOVA showed similar effects as found for the δ_{sl} data, i.e. larger mean heading angles for manoeuvres with occlusion

Table 5.I Means and standard deviations of t_{sl}, t_{ψ} and t_{sr} (in seconds) for different steering torque gradients and for the manoeuvres with and without occlusion.

		t_{sl}		t_{ψ}		t_{sr}	
	steering torque gradient	occlusion without	occlusion with	occlusion without	occlusion with	occlusion without	occlusion with
means	0	1.57	1.46	3.18	2.99	4.70	4.36
	9.5	1.39	1.35	3.13	2.87	4.35	4.06
	18.9	1.46	1.40	3.47	3.22	5.09	4.80
SD	0	0.46	0.36	0.41	0.38	0.74	0.73
	9.5	0.26	0.17	0.19	0.29	0.59	0.64
	18.9	0.32	0.24	0.43	0.33	0.69	0.62

($p < 0.01$) and a tendency for smaller heading angle variability with steering force available ($p < 0.10$). The y_3 data, i.e. the lateral position at about t_{ψ}, also showed these tendencies. However, the ANOVA did not reveal significant effects here. Nevertheless, it can be concluded that the effects of OCC and SF as found for the steering-wheel action δ_{sl} at about $t = 1.45$ s are still reflected in the vehicle motion data at $t = 3.30$ s. It seems of importance also that the ANOVA did not show a significant OCC x SF interaction. Hence, regarding the present precognitive steering task it can be concluded that the SF effect is of about equal importance for manoeuvres both with and without occlusion.

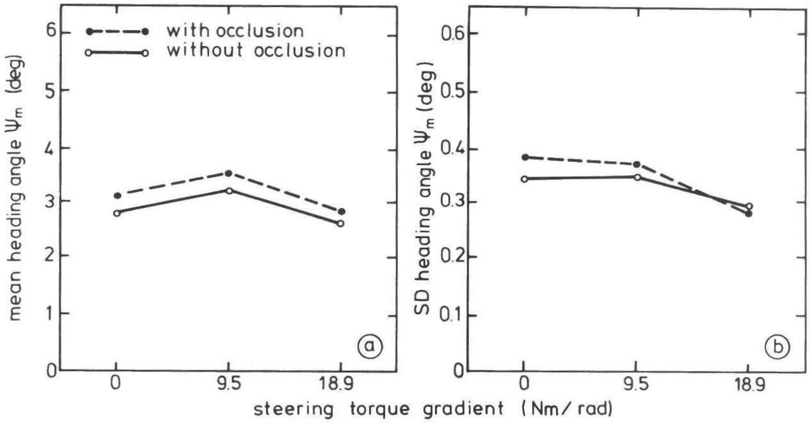


Fig. 5.4 Means and standard deviations of ψ_m for different steering torque gradients and for the manoeuvres with and without occlusion.

5.2.4 Conclusions

In summary, the following conclusions can be drawn about the effect of steering force and a 1 s occlusion period on steering performance in the simulated lane change manoeuvre.

1. Steering force reduces steering-wheel amplitude variability, this effect being also reflected in the vehicle motion data. This result is in correspondance with the conclusions of the reproduction experiments.
2. A one second occlusion period during the initial, pull-out phase of the steering-wheel movement leads to relatively large steering-wheel angle amplitudes, i.e. an overshoot tendency. This result is also in correspondance with the reproduction data.
3. The tendency to relatively slow steering-wheel movements under conditions without visual feedback, as found in Experiment II, is not replicated in the present data.

4. Steering force tends to result in relatively large steering-wheel angle amplitudes in the median steering torque area.
5. The one second occlusion period results into larger amplitude variability of the pull-out steering action.

5.3 Experiment IV: The effect of steering-wheel movement amplitude

5.3.1 Background

The results of the reproduction experiment indicated that steering variability strongly increases with larger steering-wheel movement amplitudes (Fig. 4.6). The main purpose of Experiment IV was to verify this effect in a lane change task. The procedure in this experiment was again chosen such that steering had to be performed on a precognitive or well-learned level of control. However, there were some marked differences with Experiment III. Firstly, Experiment IV was carried out in a field situation, i.e. with an instrumented car. This was done to obtain further insight into the absolute validity of the reproduction data and the simulator lane change results. Secondly, the occlusion period at the start of the manoeuvre was taken longer now, i.e. 3 s instead of 1 s. The longer occlusion was chosen to quantify steering under occluded conditions over a longer period of time, i.e. not only during the initial pull out steering action (phase 1; Fig. 5.1), but also in the period shortly after this action. The 3 s period was meant to cover both phase 1 and 2 of the sine-wave shaped steering-wheel movement. Furthermore, the lane change task was presented now as a path through a series of cones, instead of being part of an overtaking manoeuvre. The main independent variable, steering-wheel movement amplitude, was varied by changing the geometry of the path through the cones and by driving speed.

5.3.2 Method

Instrumented car

The experiment was conducted with the instrumented car as described in Section 3.2.1 and Appendix A. Measurements were made on steering-wheel angle, yaw rate and lateral position. The latter two signals were combined afterwards to calculate the heading angle signal. During the runs with an occlusion period, Ss wore an electromagnetically driven, visual occlusion device mounted on a lightweight bicycle helmet. The visual field was occluded by a sheet of translucent drawing paper mounted on a frame, which could be raised or lowered on command with a transition time of ca. 30 ms. In its normal state the visor was open. At the begin of a lane change manoeuvre with occlusion the visor was lowered and remained closed for a fixed period of 3 s, after which the visor opened automatically.

Subjects

Seven male Ss, ranging in age from 24 to 35, participated in the experiment. All had at least three years and 30,000 km·driving experience. They were paid for their services.

Procedure

Ss made three series of 60 lane change manoeuvres each. The series differed with regard to speed and geometry of the lane change. Fig. 5.5 shows how this manoeuvre path was situated and Table 5.II presents the speeds and geometries for the different series, which will be noted as M80, M40 and M24. The lane change characteristics were chosen such that the series covered a range of steering-wheel angle amplitudes, which was about equivalent to those of the 0.2 Hz condition in Experiment II. Each series consisted of three consecutive sets (I, II and III) of 12, 36 and 12 manoeuvres respectively. The manoeuvres in set I and III were made with the

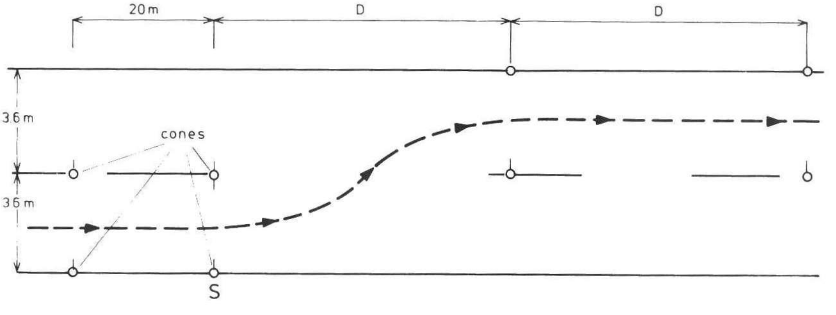


Fig. 5.5 Geometry of the manoeuvre path, as it was marked by cones on the two-lane highway.

Table 5.II Speeds and geometries for the three series of manoeuvres (see Fig. 5.5).

Manoeuvre code	Manoeuvre distance (m)	Speed (km/h)
M24	30	24
M40	50	40
M80	100	80

3 s occlusion period, while set II of 36 manoeuvres was made with normal vision. The experiment took place at a 3.5 m wide, straight section of a still unused two-lane motorway. Four lane change paths were placed on this section with an intermanoeuvre time distance of about 10 s. Therefore, S actually made four consecutive manoeuvres, then turned the car and drove back to the starting position, where he started for the next four manoeuvres of a particular set.

S was instructed to make all the manoeuvres of a series in the same way, to start each manoeuvre from the centre position of the right lane and to end it in the middle of the left lane. Furthermore, S was instructed to start the manoeuvre immediately after the closure of the visor, whereas in the runs with normal vision an auditory warning signal was given at the same place, i.e. point S, see Fig. 5.5.

Data analysis

From the start of each manoeuvre ($t = 0$) the following signals were recorded:

δ_s	steering-wheel angle
y	lateral position
r	yaw rate

The sample period was 10 s and the sample rate 10 Hz. Sample rate was slightly lower as compared to Experiment III, because of limited storage possibilities in the instrumented car. The yaw rate and lateral position signals were combined afterwards to calculate the heading angle signal and to reconstruct some missing parts of the lateral position signal. For each manoeuvre the same steering-wheel angle and vehicle motion characteristics were determined as in Experiment III.

The first question to answer in the present analysis was, again, whether and if how, performance was effected by learning. For the sake of this analysis set II was subdivided into three sets of 12 manoeuvres each, i.e. IIa, IIb and IIc. For each type of manoeuvre this gives a total of 5 sets of 12 manoeuvres (I, IIa, IIb, IIc and III). An analysis on the means of the dependent variables (not presented here) showed that performance, as averaged over each set was quite constant in a series. The only significant effect dealt with a small trend in the timing of the steering-wheel movement in the 80 km/h series, which indicated that this movement shifted a little back for the sets IIc and III as compared to the sets I and IIa. This effect was rather small and it seems justified to conclude that mean performance did hardly change during the learning process. However, an analysis on performance variability did show some marked learning effects. The standard deviations of the lateral position y_3, as shown in Fig. 5.6,

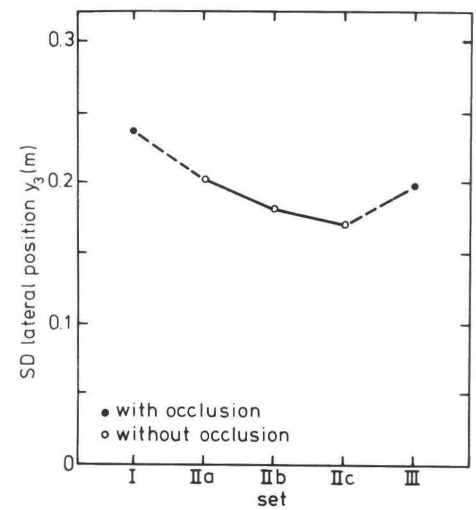


Fig. 5.6 Standard deviation of y_3 for the different sets and averaged over the different manoeuvres.

may be considered as a representative illustration. Variability in performance was always largest in set I, i.e. the manoeuvres with occlusion and without previous experience with the manoeuvre task. Furthermore, it appeared that the SD's are still quite large in the first set with normal visual feedback (set IIa), and that variability decreases in the next sets IIb and IIc. For the final set III (with occlusion) the standard deviations are again somewhat larger, but it is evident that variability in this set is relatively small as compared to the set I, which shows clearly that the learning process over the sets II is reflected in performance during set III.

An ANOVA on the combined data of set I and III (with occlusion) and IIa and IIc (without occlusion) did not show a significant OCC x set interaction, which indicates that the manoeuvres with and without occlusion benefited about equally of the learning process. To exclude learning effects it was decided to focus on the IIc and III data, i.e. the manoeuvres with and without visual feedback at the end of a series. Differences between experimental conditions were tested on their statistical significance by ANOVA with the following main factors: Subjects (Ss), occlusion (OCC) and manoeuvre (SA). This last factor was coded SA because of its relationship with the Steering-wheel angle Amplitude.

5.3.3 Results and discussion

Table 5.III presents the means of the steering-wheel angle amplitude δ_{sl}. The ANOVA showed an OCC x SA interaction ($p < 0.05$) for these data; with small amplitudes (M80), occlusion leads to a slight overshoot tendency, whereas this effect is reversed for the M40 and M24 amplitudes. The overshoot tendency for the M80 data confirms the Experiment III and reproduction data. However, the <u>general</u> tendency to overshoot during occlusion, which was found in the reproduction experiment for all amplitudes, is not confirmed for the larger amplitudes.

Fig. 5.7 shows the means and the SD's of the steering-wheel amplitudes δ_{sl} and δ_{sr} on the horizontal and vertical axis, respectively. Actually, this figure presents the data of three experiments. The circular dots refer to the present lane change Experiment IV, the square dots represent the 0.2 Hz data of Experiment II, while the triangular dots are those for the 9.5 Nm/rad torque gradient condition in Experiment III. This particular torque gradient corresponds quite well with that of the instrumented car.

Table 5.III Means (deg.) of the steering-wheel angle amplitude δ_{sl}.

	occlusion	
manoeuvre	without	with
M80	13.2	13.9
M40	30.8	28.5
M24	69.4	64.4

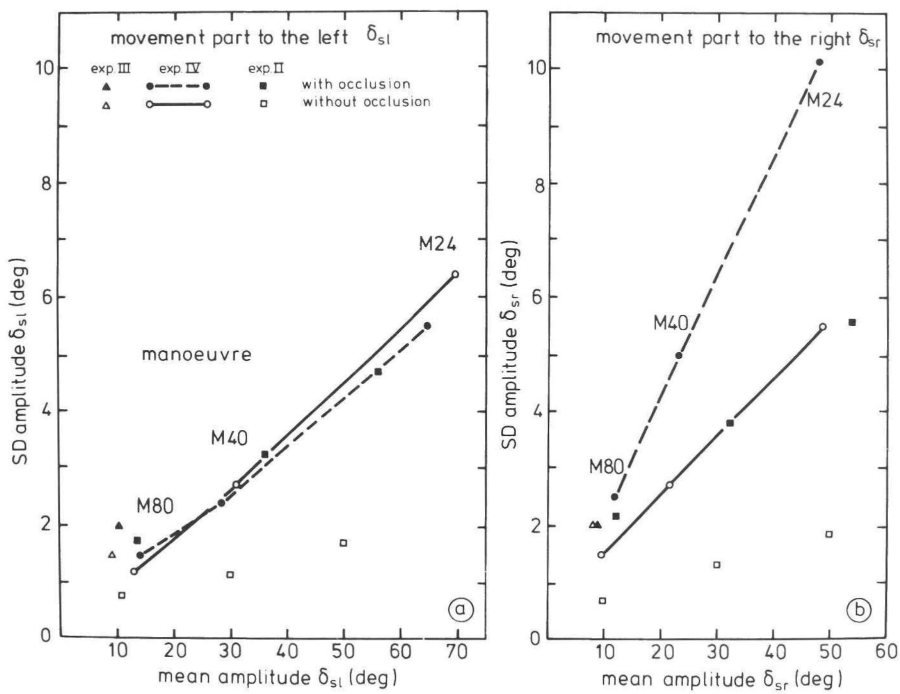


Fig. 5.7 Means (abcis) and standard deviations (ordinate) of δ_{sl} and δ_{sr} for the manoeuvres with and without occlusion.

Regarding the δ_{sl} standard deviations the ANOVA showed a tendency ($p < 0.10$) for the interaction OCC x SA: for the M80, small amplitude movements, the SD's are larger with occlusion, whereas this effect is reversed for the M40 and M24 steering-wheel movements. Together, the ANOVA on the present δ_{sl} data indicates that the main effect of OCC as found in the reproduction experiment (overshoot, larger variability) is only valid for the small amplitude manoeuvres. Most high speed lane changes will be performed at small steering-wheel angle amplitudes. The ANOVA on the SD's of the δ_{sl} also showed a strong SA effect ($p < 0.01$), indicating larger variability with the larger amplitudes. As such, this effect is not surprising. However, the close, absolute correspondence with the reproduction results justifies the conclusion that in the present task condition the SD's in the steering-wheel movement amplitude are about linearly dependent on the amplitude. In quantitative terms, the data for this relationship show that the SD's are about 9% of the amplitude.

For the steering-wheel movement to the right the ANOVA on the means did not show any OCC effect. The ANOVA on the SD's, however, revealed main effects of SA ($p < 0.01$) and OCC ($p < 0.05$). This SA dependency again can be explained by a linear relationship between SD and amplitude. The OCC effect in the SD's of δ_{sr} is a result of the larger variability in the vehicle position at $t = 3$ s in the runs with occlusion, leading to relatively large steering corrections in phase 3 of the steering-wheel movement. Before discussing these vehicle position data in more detail we will focus on the timing data, as presented in Table 5.IV. For the means of these data the

Table 5.IV Means and SD's of t_{sl}, t_{ψ} and t_{sr} for the different manoeuvres in Experiment IV.

		t_{sl}		t_{ψ}		t_{sr}	
	manoeuvre	occlusion without	occlusion with	occlusion without	occlusion with	occlusion without	occlusion with
means	M24	1.41	1.48	2.90	3.03	3.94	3.90
	M40	1.26	1.26	2.73	2.83	3.73	3.78
	M80	0.99	1.02	2.50	2.49	3.35	3.40
SD	M24	0.12	0.16	0.15	0.17	0.27	0.55
	M40	0.14	0.14	0.15	0.16	0.34	0.30
	M80	0.14	0.15	0.17	0.21	0.36	0.35

ANOVA does not reveal an OCC effect, whereas a main effect of SA ($p < 0.01$) shows that the t_{sl}, t_{ψ} and t_{sr} values are shortest for the smallest amplitudes. The ANOVA on the SD's did not reveal any significant effects. SD's as averaged over conditions were 0.14 s and 0.36 s for t_{sl} and t_{sr}, respectively. Both these values can roughly be quantified as 10% of the mean t_{sl} or t_{sr}.

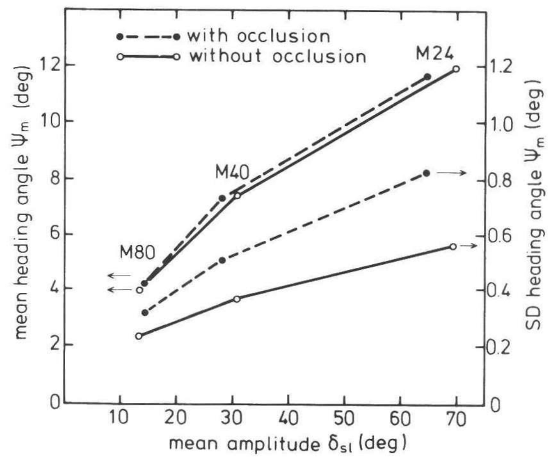


Fig. 5.8 Means and standard deviations of ψ_m for the different manoeuvres, with and without occlusion.

The relatively small effect of OCC on the SD's of δ_{sl} and the absence of such an effect on the SD's of t_{sl} might suggest that the variability in vehicle position at the end of the occlusion period will be largely independent of occlusion. However, the ψ_m, ψ_3 and y_3 data do not confirm this suggestion. For all of these variables the ANOVA on the SD's showed a main effect of OCC ($p < 0.05$). The ψ_m data in Fig. 5.8 give an illustration, showing that SD's are larger for the manoeuvres with occlusion. Furthermore, a significant OCC x SA interaction ($p < 0.01$) indicates these differences to be largest for the M24 manoeuvre i.e. the manoeuvre with the largest heading angle. However, this interaction largely can be explained by the fact that the SD's are about a constant percentage of the mean ψ_m, i.e. about 5% and 7% for the manoeuvres with normal vision and occlusion, respectively. These percentages are small as compared to the SD's of δ_{sl} (9% of mean δ_{sl}) and t_{sl}(10% of mean t_{sl}). As was argued in the introduction, a linear vehicle model predicts proportionality between heading angle variability and steering-wheel amplitude variability, and on the basis of this reasoning the percentages mentioned were expected to be equal. An explanation for these apparently conflicting results can be found in the mutual dependency of the steering-wheel movement amplitude and timing characteristics. A correlation analysis on the δ_{sl} and t_ψ data clearly illustrated this dependency: Table 5.V presents the correlation coefficients and Fig. 5.9 gives a representative example which shows how large amplitudes δ_{sl} are combined with small values of t_ψ for the manoeuvres with normal visual feedback, whereas this relationship does not exist for the manoeuvres with occlusion.

Table 5.V Product-moment correlation coefficients for the relation between δ_{sl} and t_ψ, as averaged over subjects.

	occlusion	
	with	without
M24	0.45	0.68
M40	0.45	0.61
M80	0.52	0.56

An ANOVA on the correlation coefficients (after a Fisher r to Z transformation, Hays (1966)) revealed the same interaction OCC x SA ($p < 0.05$) as for the SD's of ψ_m. In total the present analysis leads to the following conclusion on the effect of occlusion: more than affecting the variability in δ_{sl} and t_ψ separately, the withdrawal of visual feedback deteriorates the mutual tuning of these quantities.

The ultimate effect of occlusion on the lateral position variability is illustrated in Fig. 5.10. For each of the manoeuvres M24, M40 and M80, the mean lateral position time history is presented in combination with the SD's for the manoeuvres with and without occlusion. The effect of occlusion is most pronounced during phase 3 of the manoeuvre, which also explains the SD's of δ_{sr} in Fig. 5.7b.

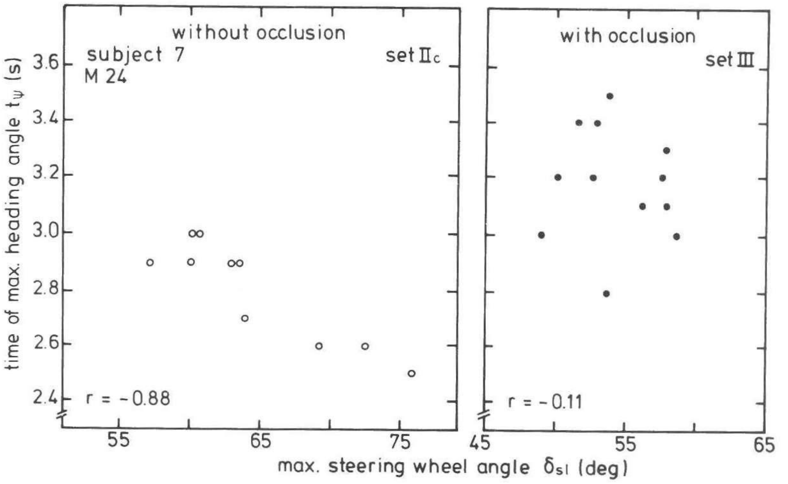


Fig. 5.9 Relationship between δ_{sl} and t_{ψ} for the set IIc and III manoeuvres; subject 7, M24.

5.3.4 Conclusions

In summary, the following conclusions can be drawn about the effect of steering-wheel movement amplitude and a 3 s occlusion period on steering performance in the lane change manoeuvres:

1. Variability in steering wheel-movement amplitude increases about linearly with movement amplitude. Standard deviations are about 9% of the amplitude. This result corresponds very well with the data from Experiment II.
2. The linear relationship between steering-wheel angle variability and amplitude as stated by conclusion 1, is about equal for the manoeuvres with and without occlusion.
3. The tendency to overshoot the steering-wheel movement amplitudes in manoeuvres without visual feedback as found in the reproduction experiment is not completely confirmed. Regarding also the results of Experiment III, the conclusion can be drawn that this overshoot effect is only valid for manoeuvres with small steering-wheel movement amplitudes.
4. The tendency to relatively slow steering-wheel movements under conditions without visual feedback, as found in Experiment II, was again not confirmed in the present analysis.

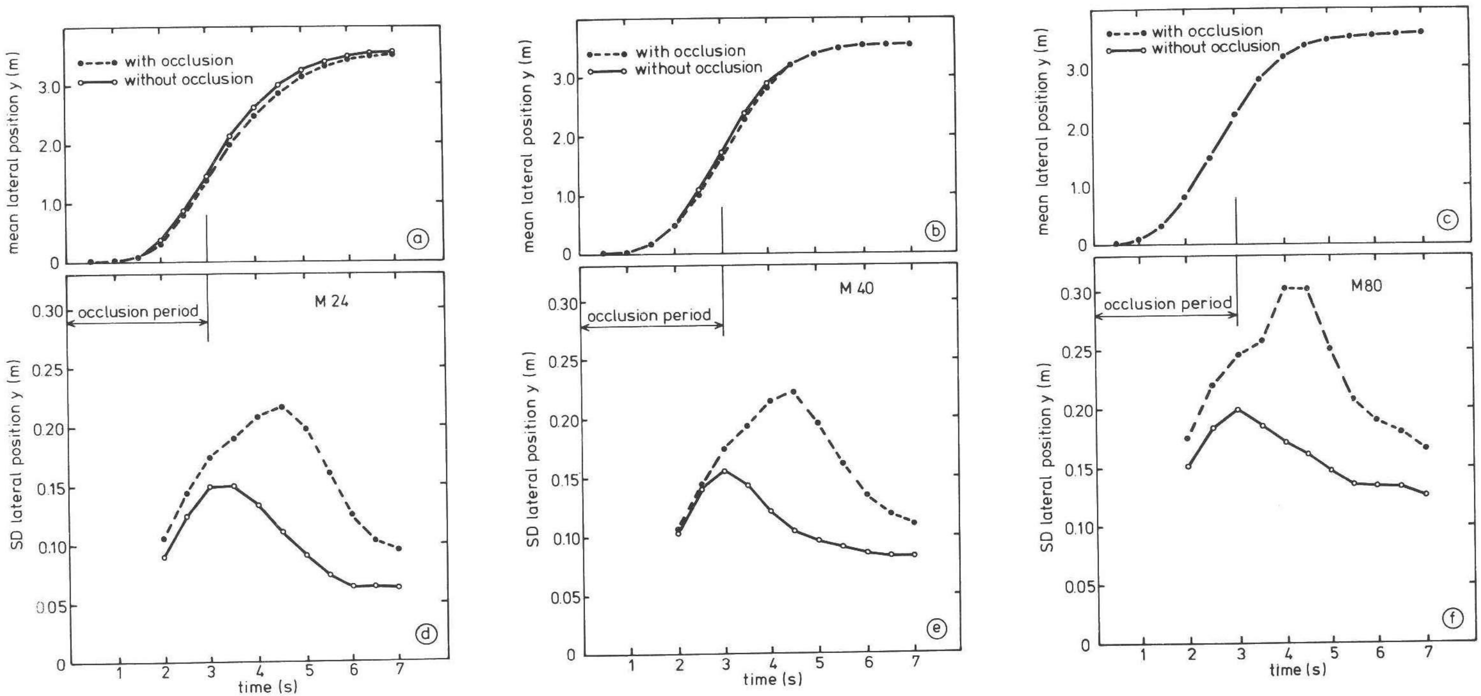


Fig. 5.10 Means and standard deviations of y during the successive phases of a manoeuvre.

5. Regarding the influence of visual feedback it can be concluded that the withdrawal of this feedback deteriorates the mutual tuning of steering-wheel amplitude and timing, rather than affecting the variability of these quantities separately.

5.4 General discussion

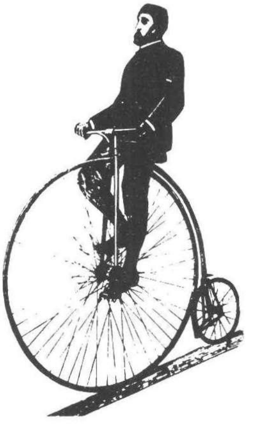
The analysis of vehicle steering under temporary absence of visual feedback as presented in this chapter was performed to verify earlier findings on steering accuracy as found in a sine-wave reproduction task (Experiment II). In the latter experiment, steering accuracy in terms of amplitude variability improved with additional steering force feedback, whereas this variability appeared to be linearly related to movement amplitude. Furthermore, the reproduction experiment indicated overshoot effects for both amplitude and timing, i.e. a tendency to reproduce amplitudes too large and movement times too long under conditions without visual feedback.

The overshoot effects as noted here were not found in the present lane change experiments: steering-wheel movement times for open loop manoeuvres corresponded quite well with those during closed loop driving, while amplitude overshoot was only found for the manoeuvres, requiring a small steering-wheel amplitude. It can be assumed that the consequences of overshoot in a lane change task, i.e. reaching the boundary of the left lane, did play a role here. As mentioned earlier, Buck (1976, 1978) also illustrated that boundary effects may strongly influence overshoot-undershoot tendencies. The present results therefore show that in a well-learned task, drivers are quite well able to generate the correct (mean) steering-wheel amplitude and movement time.

The results on steering accuracy in terms of amplitude variability as found in the reproduction experiment are completely confirmed in the present data: variability is smaller with steering force available and increases about linearly with movement amplitude. Both these results are of vital importance for a description of open loop steering performance. Actually, a driver's ultimate accuracy in generating open loop steering-wheel can be quantified by a linear relationship with movement amplitude: amplitude standard deviations are about 9% of the amplitude.

The question remains how these results can be interpreted in terms of their consequences for driving strategy. With respect to this question the steering force effect should be considered as an important result. The literature shows very few quantitative data about effects of steering "feel" on driving. The reason is probably that most studies on this topic have focussed on closed loop, unpredictable tasks. The present results show that steering force may help to reduce steering errors under conditions without immediate visual feedback, this effect being of particular importance in tasks of a precognitive nature as considered in this chapter. Furthermore, the linear relationship between amplitude standard deviations and movement amplitude as quantified in this paper should be regarded as particular useful in driver modeling. For the development of steering as well as observation strategy models, it is important to know that even in well-learned tasks, drivers generate control actions with a variability of about 9% of the amplitude. A reference can be made here to Blaauw, Godthelp and Milgram (1983), who implemented this quantity as a motor noise component in an optimal control model which was applied to describe a driver's observation strategy.

Finally, it is important to notice that even after a 3 second occlusion period in a lane change manoeuvre, the path variations remained quite well within the lane boundaries. Actually Fig. 5.10 showed that the largest path deviations occured in the second part of the manoeuvre i.e. at about 1 second after the end of the occlusion period, the largest standard deviation being 0.30 m in case of the high speed manoeuvre. It is evident, of course, that these variations will become unacceptable in tasks with closer lane boundaries and/or for longer occlusion periods. The relation between the present steering accuracy data and the duration of drivers' self chosen occlusion periods was analysed in Experiment VII and VIII which will be presented in Chapter 7.



C H A P T E R 6

6. PREVIEW CONTROL: OPEN AND CLOSED LOOP STEERING AT CURVE ENTRANCE

6.1 Introduction

As indicated in Section 2.2 the time available for open loop driving will partly depend on the accuracy of the steering actions as generated during the open loop period. This accuracy will largely be affected by a driver's ability to predict the vehicle path as needed to follow the roadway. Therefore predictability was considered to vary between the precognitive, preview (or pursuit) and compensatory control mode. After the analysis on open loop steering accuracy for a precognitive task, as presented in the Chapter 5, we will now focus on the question of how well a driver can generate open loop steering actions in a preview task. As such curve entrance was analysed in the experiments to be discussed in this chapter.

Fig. 6.1 gives a schematic impression of steering control during curve negotiation. For a curve with constant curvature c_1 the driver will start his steering action at an anticipation time T_a before the actual curve begins (t_b). This anticipatory steering-wheel action will be finished at a short period after t_b. Then a period of stationary curve driving begins, during which the driver may generate correcting steering-wheel movements. Finally, the steering-wheel is returned to the central position in a period surrounding the endpoint of the curve (t_e). The different phases of this steering control process are numbered as phase 1, 2 and 3 in Fig. 6.1.

The steering-wheel angle needed for a particular curvature can roughly be characterised by the following relationship:

$$\delta_s = Gl(1 + Ku^2)\, c_r \,.\, 10^{-3} \qquad (4)$$

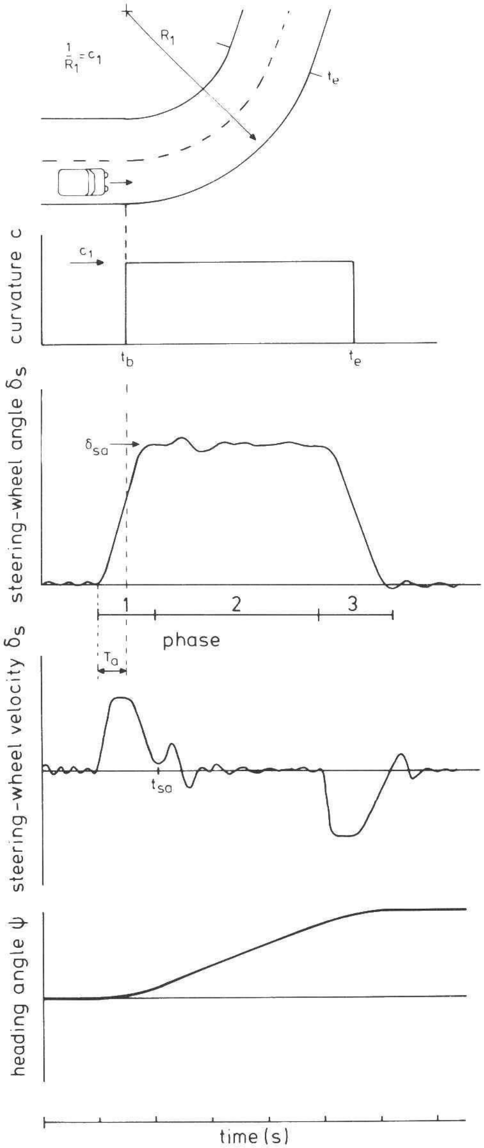


Fig. 6.1 Time histories for the steering-wheel angle, steering-wheel velocity and heading angle signal in a curve negotiation task.

with: c_r = road curvature km^{-1}

G = steering system gear ratio

K = stability factor s^2/m^2

l = wheel base m

u = vehicle forward speed m/s

δ_s = steering-wheel angle rad.

Fig. 6.2a and b give graphical representations of this formula, in which it is shown how the steering-wheel angle needed for a particular curve depends on path curvature and driving speed. The constants taken in this figure are those for the instrumented car described in Section 3.2.1 and Appendix A.

The available steering control models for curved road driving (Donges, 1978; Allen and McRuer, 1977) always assume an error-correction mode to function in parallel with an anticipation mode. Fig. 6.3 gives a schematic diagram of such a model. The anticipation mode generates steering actions, δ_{sa}, using the previewed road curvature, c_r, as major input and a weighting quantity, A, to translate this curvature into a steering-wheel movement. Actually A represents driver's knowledge about the relation between steering-wheel angle and vehicle path curvature, as this was also illustrated in Fig. 6.2. On the basis of momentaneous perceived path errors, the compensatory mode generates correcting steering-wheel movements, δ_{sc}, which, taken together with δ_{sa}, result in an overall steering action, δ_s. Contrary to the assumption underlying the model shown in Fig. 6.2, Crossman and Szostak (1968) already indicated that the anticipatory and compensatory mode should be considered as acting in serial order rather than in parallel. They argued that, particularly at curve entrance, steering primarily will be based on the anticipatory mode, while compensatory control comes into operation only after this initial steering action. Although intuitively this reasoning seems correct, the closed loop situation hardly permits any verifyable distinction between these modes. In the present analysis on open loop curve entrance, however, this distinction seems meaningful, since the temporary withdrawal of visual feedback, will force the driver to rely only on the anticipatory mode during a particular period of time. In that case the accuracy of the anticipatory steering action will ultimately determine the opportunity for open loop control in this driving task.

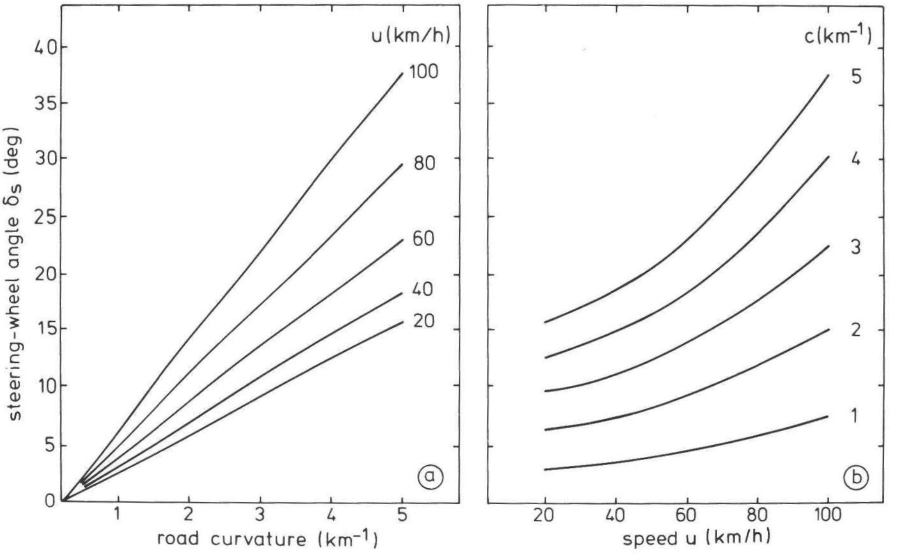


Fig. 6.2 The steering-wheel angle needed to negotiate a curve as a function of road curvature (a) and driving speed (b), according to formula (4).

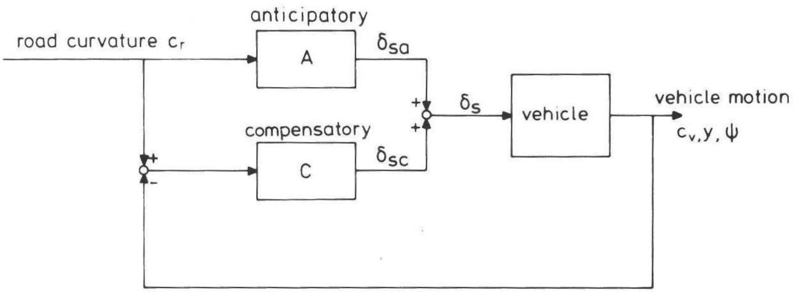


Fig. 6.3 Schematic diagram of the two-level model as proposed by Donges (1978).

The anticipatory steering action can be regarded as the outcome of an information processing chain, which contains three major stages:

a. perception of the curve, resulting into an estimated curvature;
b. translation from estimated curvature into a desired steering-wheel position;
c. motor control process to transform the desired steering action into an actual action.

Drivers' steering performance will be affected by inaccuracies in each of these stages. A reference can be made here to the accuracy data for precognitive control as presented in Chapter 5, for which it is assumed that they originated mainly from stage c. In a preview control task as considered now, the inaccuracies of the subprocesses a) and b) will be added to those of the motor control process. This leads to hypothesis 1, saying that -in total - the inaccuracies will be larger as those found in experiments II and IV. Furthermore, the tendency towards larger steering inaccuracies with larger amplitudes as found in Experiment IV leads to hypothesis 2, saying that the necessity for compensatory control after the anticipatory steering action will be strongest for sharp curves, i.e. those requiring large steering-wheel angle amplitudes. The experiments described in this chapter were conducted to verify these hypothesis and to analyse a driver's ability to generate the correct anticipatory steering-wheel angle as it depends on road curvature and driving speed as shown in Fig. 6.2.

In Experiment V this ability will be described in terms of a subject's accuracy in generating the correct δ_{sa}, i.e. the anticipatory steering-wheel angle required for a particular road curvature, c_r, in accordance with the mathematical relation (4). In Experiment VI the efficiency of the open loop steering action will be characterised in terms of the TLC analysis given in Chapter 3; the TLC at the end of the anticipatory, open loop steering action represents the time available for error-neglection after this action and thus serves as a useful quantification of its correctness. In each of these experiments subjects entered curves of different (constant) curvatures, which were presented to them in a quasi-random order, thus preventing the task to reach the same level of predictability as in Experiments III and IV. Half of the manoeuvres again were performed under closed loop conditions, i.e. with normal visual feedback, whereas the other half were carried out during temporary visual occlusion, i.e. open loop.

In Experiment V road curvature and steering force served as the main independent variables, whereas the effects of driving speed and, again, road curvature were analysed in Experiment VI.

6.2 Experiment V: Effects of road curvature and steering force

6.2.1 Background

The main purpose of this experiment was to measure a driver's ability to generate the steering-wheel angle, δ_{sa}, in an open loop curve entrance task. In relation with the results found in Experiments I to IV, it was expected that this ability would be dependent on the absolute level of the steering-wheel angle δ_{sa}, needed for a particular curve. Therefore, road curvature, being linearly related to δ_{sa}, was chosen as the main independent variable. The suggestion that the steering-wheel errors would be largest for the manoeuvres with the largest steering-wheel angle, i.e. for the sharpest curves, also implies that the corrections needed after the anticipatory steering action will be strongest for these curves. The steering-wheel movement in phase 2 of the manoeuvre was analysed to find more evidence for this reasoning.

Although the literature on car driving does not show any data about steering force effects in preview tasks, it was decided to analyse the effect of this variable in the present experiments as well, thus permitting a later comparison with the results of the precognitive steering task as considered in Experiment III.

6.2.2 Method

Driving simulator

The experiment was carried out in the driving simulator as described in Section 3.2.2 and Appendix A. The winding road simulated on the moving belt consisted of a series of straight and curved road sections with a total length of 1.82 km. The roadway geometry is that of a two-lane rural road without paved shoulder, lane width being 3.60 m and without other traffic. Fig. 6.4 gives the sequence, length and direction of the curves, each of these having a constant curvature. Five different curvatures actually occured: c_r = 1, 2, 3, 4 and 5 (km^{-1}), representing curve radii of 1000, 500, 333, 250 and 200 m respectively. The connection between curves is always made by a straight road section.

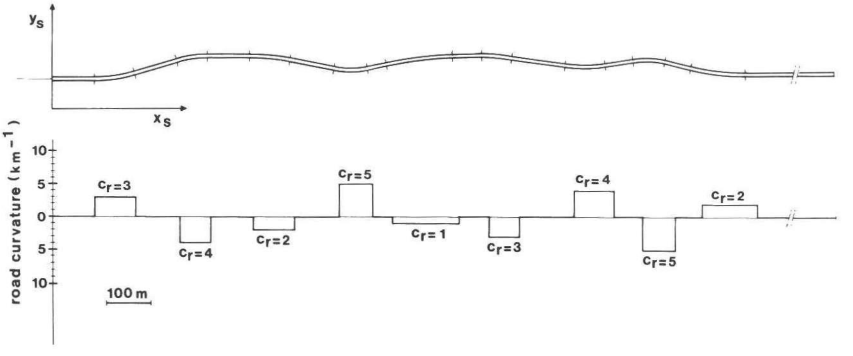


Fig. 6.4 Sequence, length and direction of the straight and curved road sections of the winding road in the simulator.

Subjects

Three groups of six subjects (Ss) each, participated in the experiments. Ss ranged in age from 22 to 34 and all had at least three years and 30.000 km driving experience. They were paid for participating in the experiment.

Procedure

Each S participated in the experiment on one day, during which he made three sets of runs of about 45 min, which will be noted as set I, II and III. A set consisted of 30 runs, each run covering once the route shown in Fig. 6.4. Time between sets was at least 1 hr. Before the first set started, S was given a written instruction about the nature and procedure of the experiment. Then S took place in the mock up and accelerated the car to a speed of 24 km/h (86.4 km/h). Speed was automatically kept constant on this level, just by pushing the accelerator pedal beyond the required position. The general instruction was to drive "normally" in the right lane. The first 14 runs of set I were made with normal visual feedback in order to make S familiar with the simulator. During this period S was told to start each curve entrance manoeuvre at about the middle position of the right lane with the car in the straight ahead position. Furthermore, the experimenter, who was also seated in the mock up, informed S about the place and duration of the occlusion period, which was to be expected in the last 16 runs of set I and in sets II and III. Starting with run 15 of set I, occlusion of the complete visual scene was given every other curve, i.e. curve 1, 3, 5, 7 and 9 for the odd-numbered runs and curve 2, 4, 6 and 8 for the even-numbered runs. Occlusion started at 0.5 s before the beginning of the actual curve (t_b, Fig. 6.1) and lasted 1.2 s. The 0.5 s advance period was chosen to be shorter than the anticipation time T_a, for which Donges (1978) presented a value of 1.0 s. By consequence, S always initiated his steering action before the beginning of the occlusion period, i.e. similar to the manoeuvres without occlusion. The 1.2 s duration permitted S to finish the required steering-wheel angle during the occlusion period according to the instruction given.

Three steering torque coefficients were considered: $G_t = 0$, $G_t = 0.45$ and $G_t = 0.91$, giving steering-wheel rim forces of 0 N, 7.5 N and 15 N in a curve with $c_r = 5\ km^{-1}$ and a driving speed of 24 m/s. These steering forces again corresponded with those in the Experiments I and II. The G_t levels as mentioned correspond with steering torque gradients of 0 Nm/rad, 3.0 Nm/rad and 6.0 Nm/rad, respectively. Each of the steering torque gradients served as an experimental condition for a group of Ss, giving three groups of six Ss in a between-subject design.

Data analysis

Data storage started 1.2 s before the beginning of the curve and continued to 1.2 s after the end of the curve. Sampling rate was 10 Hz. The following signals were recorded:

δ_s steering-wheel angle

ψ heading angle

x_s moving-belt longitudinal position

y_s lateral camera position

OCC occlusion

The x_s and y_s signals (see Fig. 6.4) were measured to allow a later calculation of the vehicle lateral position, i.e. perpendicular to the roadway. However, this analysis appeared to be too inaccurate and it was decided therefore to focus on the steering-wheel movement analysis in this experiment. Furthermore, the data analysis was performed only for the manoeuvres with an heading angle error of less than 0.5° at the moment 0.5 s before the beginning of the curve. This was done in order to minimize the effects of vehicle motion errors at the begin of the curve. This restriction resulted in a loss of 41% of the data for the $c_r = 1\ km^{-1}$ curve. Therefore, it was decided to withdraw this curve from the further analysis. For the other curves, this restriction resulted in a loss of 19% of the manoeuvres which were coded as missing data in the final analysis.

Note: The occurance of heading angle errors at the beginning of the curves can be explained as an after-effect of the preceding curve, due to the relatively short straight road sections between the curves.

Steering-wheel movement velocity was calculated from the original steering-wheel signal for each manoeuvre. The extent of the anticipatory steering action δ_{sa} (see Fig. 6.1) was determined by localizing the first moment in time (t_{sa}) with minimum steering-wheel velocity during the second half of the occlusion period (or during the equivalent period in the runs without occlusion). When this minimum was larger than 3°/s, the manoeuvre was coded as missing data. This criterion value was derived from a preliminary analysis, which indicated that in many cases the steering-wheel velocity keeps a small value, even after the anticipatory steering action has been generated. Fig. 6.1 gives a representative example, illustrating that, although the anticipatory action can be recognised quite easily, the steering-wheel velocity does not reach the $\dot{\delta}_s = 0$ level at t_{sa}.

Driver's steering correction after t_{sa} was characterised by way of determining:

a. Mean absolute steering-wheel velocity:

$$\dot{\delta}_{sm} = \frac{1}{T} \int_{t_{sa}}^{t_{sa}+2} |\dot{\delta}_s| \, dt \; . \tag{7}$$

b. Total time T_f with steering-wheel fixation, i.e. steering-wheel velocity $\dot{\delta}_s$ less than 1°/s, the latter value again being derived from a preliminary analysis.

Both quantities a) and b) were calculated for each manoeuvre over a period of 2 s after t_{sa}. Means and standard deviations (SD's) were calculated for δ_{sa}, $\dot{\delta}_{sm}$ and T_f. Because set I mainly served as a training period, the data of this set were not implemented in the analysis. Furthermore, a preliminary ANOVA indicated no differences between sets II and III and, therefore, it was decided to consider the results of these sets as one integrated block of data in the final analysis. Differences between conditions were tested on their statistical siginificance by way of an ANOVA, which contained the following main factors: subjects (Ss), steering force (SF), occlusion (OCC), road curvature (CU), and curvature direction (DI).

6.2.3 Results and discussion

The ANOVA indicated no effects of SF and DI and, therefore, the data will be presented as averaged over these factors. Fig. 6.5a presents means of δ_{sa} for different curvatures and manoeuvres with and without occlusion. The ANOVA revealed a main effect of CU ($p < 0.01$), while effects of OCC appeared to be absent. A comparison can be made here with the theoretically required steering-wheel angle as represented in formula (4). This theoretically desired δ_{sa} level is also shown in Fig. 6.5a and it is evident from this comparison that the differences between required and actual behavior are only small: The anticipatory steering-wheel angle is slightly below the theoretically required level and the curvature dependency is almost per-

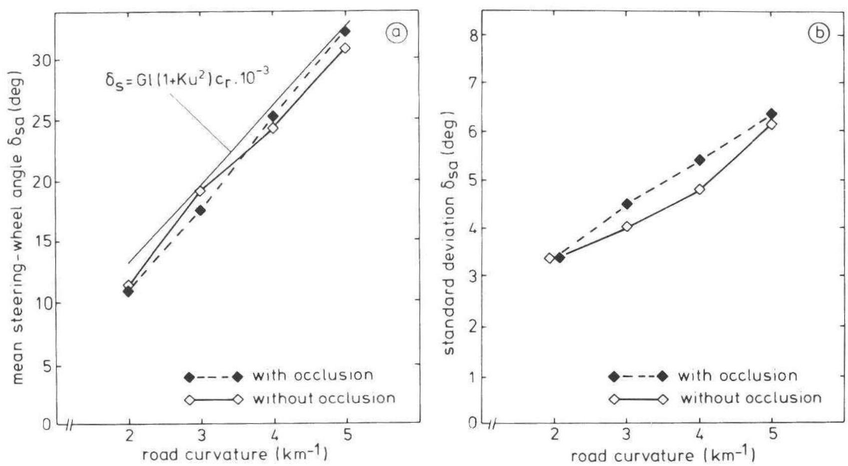


Fig. 6.5 Means and standard deviations of δ_{sa} as a function of road curvature.

fect. It seems justified to conclude, therefore, that drivers are quite well able to generate the correct (average) steering-wheel angle δ_{sa} for a particular curvature.

The accuracy of the anticipatory steering-wheel action δ_{sa} can be described in terms of its standard deviations, for which the curvature dependency is given in Fig. 6.5b. The ANOVA on these data revealed main effects of CU and OCC. Variability increases strongly and about linearly with curvature and is slightly larger with occlusion as compared to the manoeuvres with normal visual feedback. Means and standard deviations of δ_{sa} are presented together in Fig. 6.6 on the abcis and ordinate respectively. This figure also shows the amplitude variability data for the pull-out steering action in the lane change Experiment IV. A comparison between both data sets clearly shows that inaccuracies in the preview task to be about twice as large as those in the precognitive task (hypothesis 1). A further discussion of this result will be given in Section 6.4.

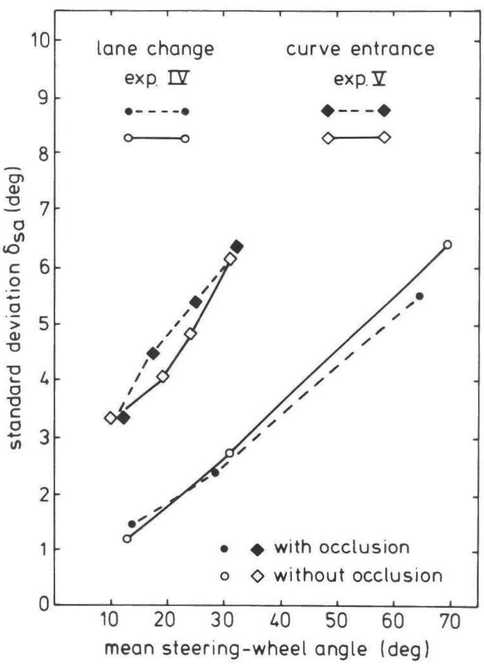


Fig. 6.6 Means (abcis) and standard deviations (ordinate) of the anticipatory steering actions δ_{sa} (exp. V) and of the pull-out steering action δ_{sl} (exp. IV).

The question remains how these curvature and occlusion effects are reflected in compensatory control during the 2-second period after the anticipatory steering action. Fig. 6.7 presents the mean steering-wheel velocity and the fixation time T_f for this period and the curvature effect ($p < 0.01$) comfirms hypothesis 2, saying that larger steering inaccuracies during the anticipatory phase result in more pronounced corrections during the compensatory phase. It is evident also that, despite a significant occlusion effect ($p < 0.01$), the curvature effect also holds for the manoeuvres with normal visual feedback. Therefore, it can be concluded that the accuracy of the anticipatory steering action, as dependent on road curvature (Fig. 6.6), largely effects the nature of the compensatory actions both in manoeuvres with and without visual feedback. A further discussion of this result will also be given in Section 6.4.

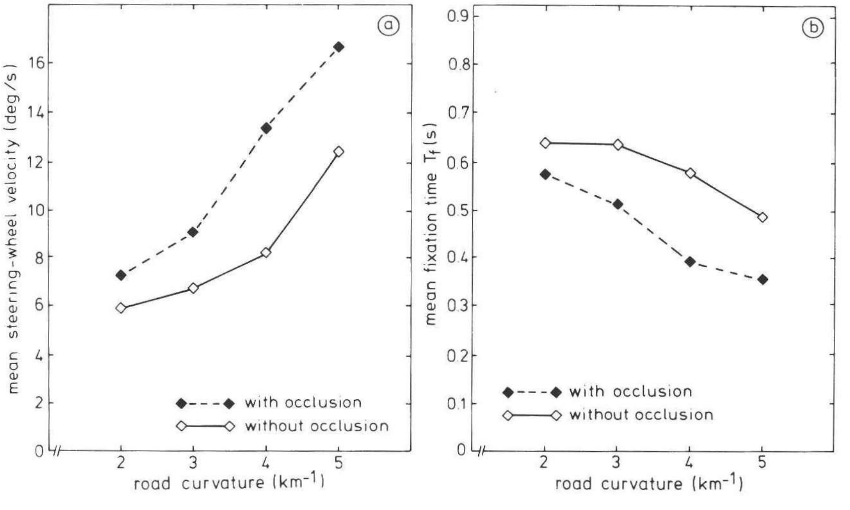


Fig. 6.7 Mean absolute steering-wheel velocity $\dot{\delta}_{sm}$ and fixation time T_f as a function of road curvature and occlusion.

6.2.4 Conclusions

The following conclusions can be drawn as the basis of the results of Experiment V.

1. Drivers are quite well able to generate the correct (average) anticipatory steering action for a particular curvature.
2. Inaccuracy of the anticipatory steering action δ_{sa} increases about linearly with road curvature, the latter parameter being proportional to the extent of δ_{sa}.
3. Steering inaccuracies for preview, curve entrance tasks are larger as those found in the precognitive, lane change task, described in Experiment IV.
4. Steering activity during the compensatory phase largely depends on the accuracy of the preceding anticipatory action δ_{sa}, thus resulting in stronger corrections for the sharper curves; this effect being of importance for manoeuvres, both with and without visual feedback.
5. Steering force does not influence steering accuracy in the curve entrance task.

6.3 Experiment VI: Effects of driving speed and road curvature

6.3.1 Background

As argued in the introduction of this chapter steering through a curve can be regarded as a process in which the anticipatory and compensatory control mode act in serial order rather than in parallel. It was indicated also that, particularly after the initial, anticipatory steering action δ_{sa} at curve entrance, the necessity to switch over to compensatory control will strongly depend on the inaccuracies in δ_{sa}. Experiment V illustrated this inaccuracy to increase about linearly with the amplitude of δ_{sa} and thus with road curvature. A reference can now be made to the TLC calculations given in Chapter 3, which indicated that TLC levels will be about equal for different road curvatures, assuming a constant steering accuracy. The findings of Experiment V, i.e. larger steering inaccuracies for sharper curves, thus lead to the hypothesis that TLC just after the anticipatory steering-wheel action will be shorter the sharper the curves. Experiment VI was performed to verify this hypothesis by way of determining the TLC values at the end of the anticipatory steering action. This analysis could not be made for the data of Experiment V, because of the absence of the lateral position signal. Principally Experiment VI, which was conducted as a field experiment, did not differ from Experiment V. Driving speed was introduced as independent variable in order, a) to quantify driver's ability to take account of speed effects in the required anticipatory steering action (see Fig. 6.2), and b) to analyse the TLC-speed relationship.

6.3.2 Method

Instrumented car

This experiment was conducted with the instrumented car as described in Section 3.2.1 and Appendix A.

Roadway

The winding roadway consisted of a series of straight and curved road section with a total length of 1.30 km. Roadway geometry was that of a two-lane rural road without paved shoulder, lane width being 4.00 m and without other traffic. Fig. 6.8 gives the sequence, length and direction of the curves, each having a constant curvature. Curvatures were c_r = 3.85, 5 and 10 km^{-1}, representing curve radii of 260 m, 200 m and 100 m respective-

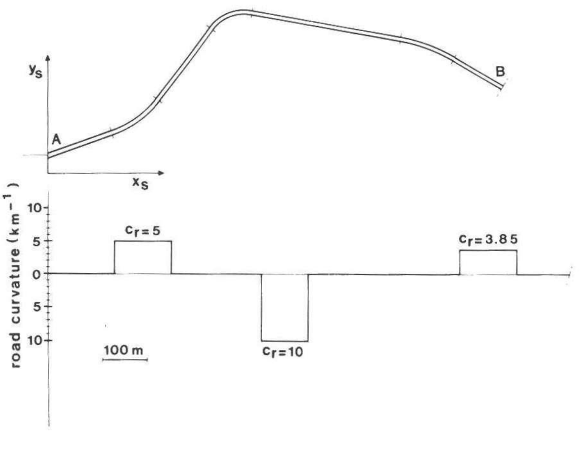


Fig. 6.8 Sequence, length and direction of the straight and curved road sections of the winding road in the field study.

ly. In the experimental design, the procedure and the ultimate data analysis, the straight road section ($c_r = 0$) between the curves $c_r = 10\ km^{-1}$ and $c_r = 3.85\ km^{-1}$ was also treated as a "curve", thus giving four curves in this experiment.

Subjects

Six male subjects, ranging in age from 25-34 participated in the experiment. All had at least three years and 30,000 km driving experience. They were paid for their participation.

Procedure

Each S participated on one day, during which he made 3 sets of runs, which will be noted as set I, II and III. Each set lasted about 60 min and consisted of 20 runs from A to B (see Fig. 6.8). After arrival at B, S turned the car and drove back to the starting position at A. Time between sets was at least 30 min. Speed levels (40 km/h and 60 km/h) and occlusion (with/without) were randomly distributed over a set giving 5 runs for each speed-occlusion combination in a set. In a run with occlusion the visual field of the driver was occluded at 0.5 s before the beginning of each of the curves during a period of 1.5 s (60 km/h) or 1.8 s (40 km/h). Each of these occlusion periods covered about the time needed for the anticipatory steering action, δ_{sa}, as this resulted from a pilot study. Instructions were the same as in Experiment V. Before the first set was started S made a series of four training runs, one at each of the speed-occlusion combinations. Speed was automatically kept constant with the device, described in Section 3.2.1.

Data analysis

Data storage started at about 40 m before the first curve and continued till about 40 m after the end of the last curve. Sampling rate was 10 Hz. The following signals were registrated:

δ_s steering-wheel angle

r yaw-rate

y lateral position

OCC occlusion

\- vehicle position on the track

The vehicle position on the track was identified by way of a pulse-signal from a photocell which triggered a white stripe as this was transversally placed on the roadway at 25 m before and after each curve. Actually this trigger signal was also used as a timing aid for the start of the occlusion period. Steering-wheel angle and velocity analysis was done similar as in Experiment V, giving the anticipatory steering-wheel angle δ_{sa}, the mean absolute steering-wheel velocity $\dot{\delta}_{sm}$ and the fixation time T_f. Furthermore, TLC's were calculated at t_{sa} (TLC_{sa}) and during the 2 second period after t_{sa}($TLC_{sa,\,sa+2}$). For a subject the median TLC_{sa} level was determined for each curve and for each speed-occlusion combination, whereas the median $TLC_{sa,\,sa+2}$ level was determined for each manoeuvre. Differences between conditions were tested by way of an ANOVA, which contained the following main factors: subjects (Ss), occlusion (OCC), road curvature (CU) and speed.

6.3.3 Results and discussion

Fig. 6.9a presents means of δ_{sa} for the different speed-occlusion combinations. The ANOVA revealed main effects of CU, OCC and speed (all $p < 0.01$). Both the CU and the speed effect correspond quite well with predictions as these can be made on the basis of the theoretical formula (4), for which the graphical representation is also given in Fig. 6.9a. A comparison between required and actual behavior shows - just as in Experiment V - a tendency for δ_{sa} to be slightly smaller than the theoretically required level, this tendency being strongest for the manoeuvres with occlusion. However, it is also evident from these data that Ss are very well able to take account of both curvature and speed effects. The first part of this conclusion is similar to the findings of Experiment V. Subjects' ability to take account of speed differences illustrates that drivers also have a rather good internal representation of the effect of speed on the relationship given in formula (4).

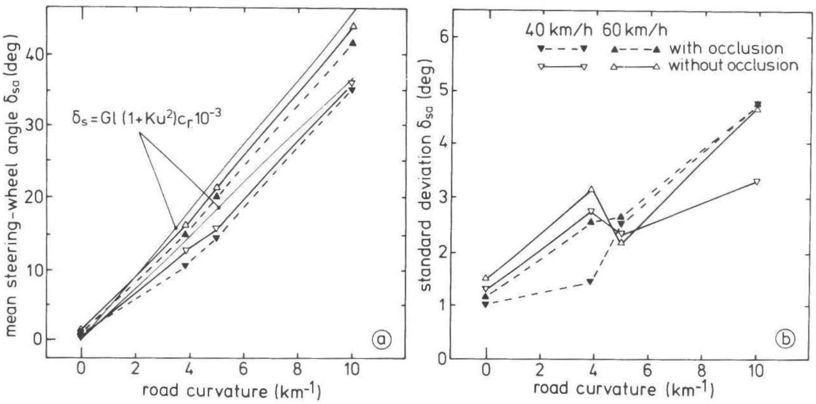


Fig. 6.9 Means and standard deviations of δ_{sa} as a function of road curvature and for each of the speed-occlusion combinations.

Fig. 6.9b gives the δ_{sa} standard deviations for the different speed-occlusion combinations. The ANOVA for these data indicated main effects of CU ($p < 0.01$) and speed ($p < 0.05$), whereas no effect of OCC was found. Fig. 6.10 shows the same data as a function of the steering-wheel movement amplitude together with the results of Experiment V and the pull-out steering data of Experiment IV. A comparison between the Experiment V and VI data shows that the δ_{sa} variability is lower in case of the field study as compared to the simulator study on curve entrance. This difference is in agreement with findings of Blaauw (1984), who indicated that variability in driving performance measures is larger in the fixed base driving simulator than in the instrumented car.

However, despite the differences in results between Experiment V and VI, the present data again fully confirm the hypothesis that steering-wheel angle variability in a preview, curve entrance task is larger as compared to this variability in a precognitive, lane change task (Experiment IV).

Experiment VI was designed particularly to be able to interpret driver's anticipatory steering performance in terms of its efficiency in time. The TLC_{sa} results given in Fig. 6.11a definitely confirm the hypothesis that sharper curves and thus larger δ_{sa} variability will lead to relatively short TLC's. The ANOVA on the TLC_{sa} results revealed main effects of CU, OCC and speed (all with $p < 0.01$). An OCC x speed interaction ($p < 0.05$) shows the OCC effect to be most pronounced at the lowest speed condition.

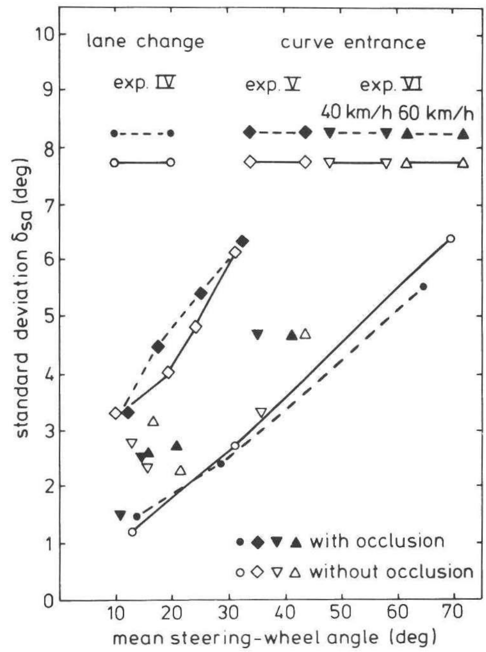


Fig. 6.10 Means (abcis) and standard deviations (ordinate) of the anticipatory steering action δ_{sa} (exp. V + VI) and of the pull-out steering action δ_{sl} (exp. IV).

The efficiency of δ_{sa} in terms of time can also be illustrated by TLC_t, i.e. the sum of t_{sa} and TLC_{sa}. As such TLC_t represents the time during which the driver may rely on the anticipatory control mode, starting from the begin of the curve and lasting till the moment in time the lane boundary would have been reached. Fig. 6.11b gives the TLC_t results and illustrates that these curves are about similar to those for TLC_{sa} with an about 1 second higher level for the TLC_t data.

Performance during the 2 second period after t_{sa} is illustrated in the Figs. 6.12 and 6.13, and these results are largely in line with our previous findings. Steering-wheel velocity $\dot{\delta}_{sm}$ increases with sharper curves, whereas the fixation time T_f decreases. In the same sense, the median TLC during the 2 second period after t_{sa} (Fig. 6.13) decreases with sharper curves, thus illustrating the consequences of larger δ_{sa} variability.

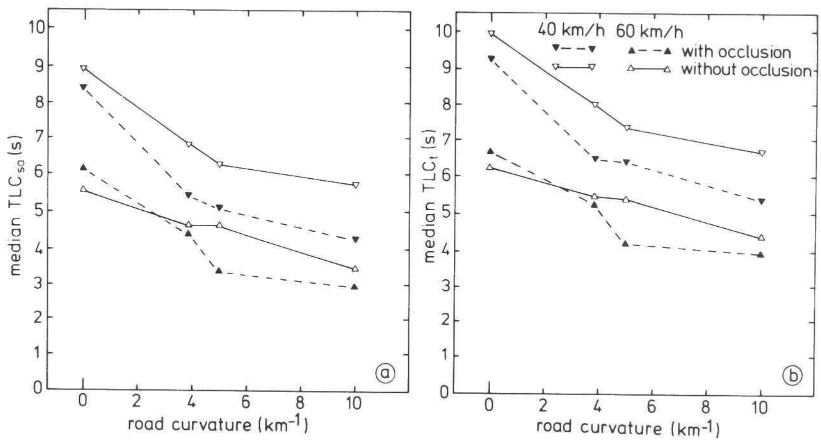


Fig. 6.11 TLC_{sa} and TLC_t levels for different curvatures.

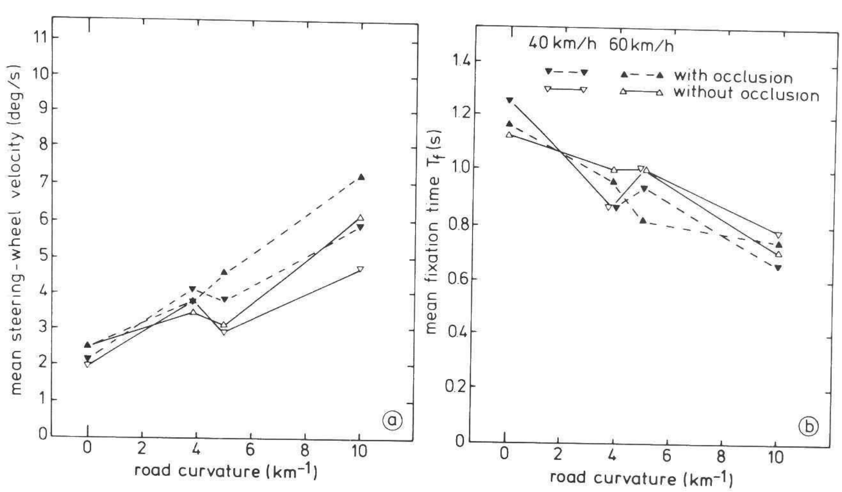


Fig. 6.12 Mean absolute steering-wheel velocity $\dot{\delta}_{sm}$ and fixation time T_f (for the 2 second period after t_{sa}) as a function of road curvature and for different speed-occlusion combination.

For each of these sets of data the ANOVA revealed a main effect of CU ($p < 0.01$), whereas main effects of speed and OCC were only found for the mean steering-wheel velocity and the median TLC (both $p < 0.01$). For the Fig. 6.12 data a CU x speed and a CU x OCC interaction ($p < 0.05$), furthermore, shows that the speed and occlusion effects may differ slightly between curvatures.

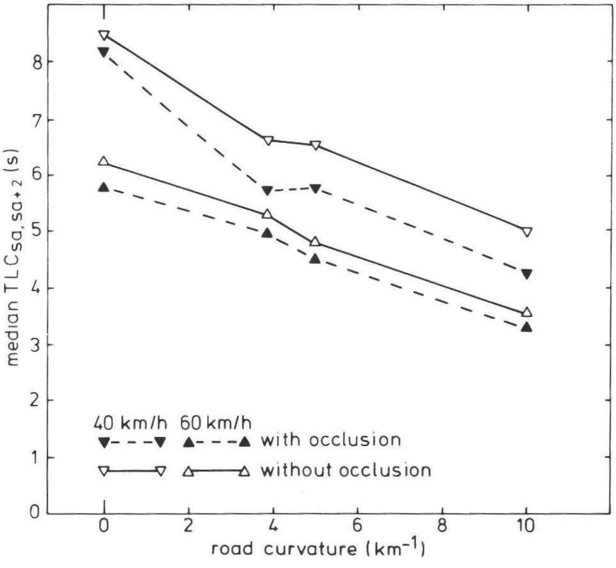


Fig. 6.13 Median TLC for the 2 second period after t_{sa} as a function of road curvature and for different speed-occlusion combinations.

6.3.4 Conclusions

The following conclusions can be drawn on the basis of the results of Experiment VI.

1. The finding (Experiment V) that drivers are able to generate the correct (average) anticipatory steering action δ_{sa} for a particular curvature is confirmed in the present experiment. With respect to this ability it can be concluded also that drivers are very well able to take account of the speed dependency of the required anticipatory steering action.

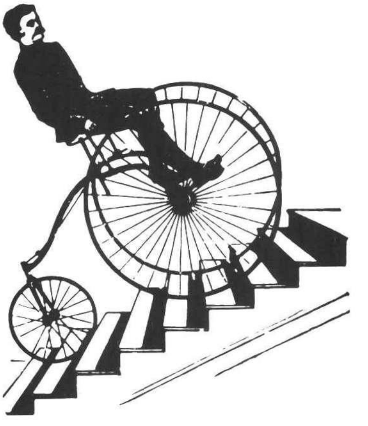
2. The finding (Experiment V) that variability of the anticipatory steering action δ_{sa} increases about linearly with the extent of δ_{sa} is largely confirmed in the present experiment.
3. Despite the fact that variability in the anticipatory steering action δ_{sa} as found in Experiment VI is smaller as compared to the Experiment V data, it can still be concluded that steering inaccuracies for a preview, curve entrance task are larger as those found in a precognitive, lane change task (Experiment IV).
4. Just as in Experiment V it can be concluded that steering actitivity during the compensatory phase largely depends on the accuracy of the preceding anticipatory action δ_{sa}, thus leading to stronger corrections for the sharper curves, this effect being important for manoeuvres both with and without occlusion. In the same sense the median TLC for the 2 second period after the anticipatory action decreases with sharper curves.

6.4 General discussion

Drivers appear to be very well able to take account of curvature and speed effects when generating the anticipatory steering action at curve entrance. This important finding illustrates that experienced drivers have a rather good internal representation of the vehicle characteristics. By consequence, it can be expected that drivers may use this knowledge during curve negotiation to allow a temporary loss of visual feedback. The limitations of this process appear to be strongly related to the inaccuracies of the anticipatory steering action. For both the conditions with and without occlusion these inaccuracies increase with the extent of the anticipatory steering-wheel angle and thus with road curvature. Principally this result is in correspondance with the findings on preprogrammed lane change steering as found in Experiment IV, although the absolute level of the inaccuracies is higher in case of the present preview task as compared to the precognitive task. This latter result is in correspondence with hypothesis 1. In the present analysis on curve driving this finding helps us to explain the relation between road curvature and the necessity for compensatory control. The larger inaccuracies of the anticipatory steering action at sharper curves are clearly reflected in the stronger corrections during the compensatory phase, as this was predicted by hypothesis 2. Furthermore, the fact that this result is also found for the manoeuvres with normal visual feedback supports the assumption that the anticipatory steering mode plays a dominant role during the curve entrance phase.

The data for steering inaccuracies are also reflected in the TLC analysis. This analysis clearly shows that the larger anticipatory steering-wheel errors for the sharper curves result in shorter TLC's, thus indicating that in sharper curves drivers will have to switch over to the error-correction mode at an earlier moment in time. Actually this reasoning gives us an explanation for the fact that sharp curves require most attention.

A final conclusion may be drawn regarding the use of the TLC analysis. Conventional measures to quantify driving performance, such as lateral position, lateral speed and steering-wheel angle standard deviations, are most frequently used to characterize straight lane keeping. However, most of these measures are highly inefficient to describe curve negotiation. The preview-predictor approach, as presently used to calculate TLC's, seems particularly suited to solve this problem and may serve as a valuable method to quantify curve driving performance.



CHAPTER 7

7. COMPENSATORY CONTROL: OPEN AND CLOSED LOOP DRIVING IN STRAIGHT LANE KEEPING

7.1 Introduction

In the previous chapters it was shown that in precognitive and preview steering tasks, drivers are quite well able to control their vehicle without immediate visual feedback, during a certain period of time. However, it also became evident that the error-correction or compensatory control mode is ultimately needed to keep the vehicle path within the lane boundaries. Furthermore, it was argued that the time actually available for open loop control will largely depend on a) the open loop steering accuracy and b) the time available for error-neglection, as this may depend on factors like lane width and speed. With regard to open loop driving and error-neglection strategies, two fundamental questions remain: First, for how long is a driver actually willing to control his vehicle without immediate visual feedback and second, how long is a driver ultimately allowed to wait before switching over to the error-correction mode. These two questions will be answered in Chapters 7 and 8 respectively.

The question how long a driver is actually willing to control his vehicle in an open loop mode was investigated by measuring Ss' self chosen occlusion times in a straight lane keeping task (Godthelp et al, 1983; Godthelp et al, 1984a en b). Earlier studies (Senders et al., 1966; Zwahlen and Balasubramania, 1974; Milgram et al., 1982) tried to explain the (average) duration of a drivers' self-chosen occlusion periods from uncertainty models, in which it is assumed that the driver uses an estimate of the vehicle path during the open loop period to choose the length of the occlusion period. This estimate is thought to be the result of the integration of one or more vehicle output variables, with the amplitude and spectral characteristics of which the driver is presumed to be familiar.

In the present analysis all of these assumptions are transformed to one general hypothesis, which predicts that drivers will choose the length of the occlusion period somehow in relation with the time actually available, as it can be quantified in terms of the TLC analysis given in Section 3.4.Fig. 7.1 gives a representative example of the time histories of the steering-wheel angle, lateral position, and TLC signals as these may occur in a straight lane keeping task, during which drivers may request for 0.5 s looking periods. The time between looking requests represents the voluntary occlusion time T_{occ}. The steering-wheel time history illustrates that most

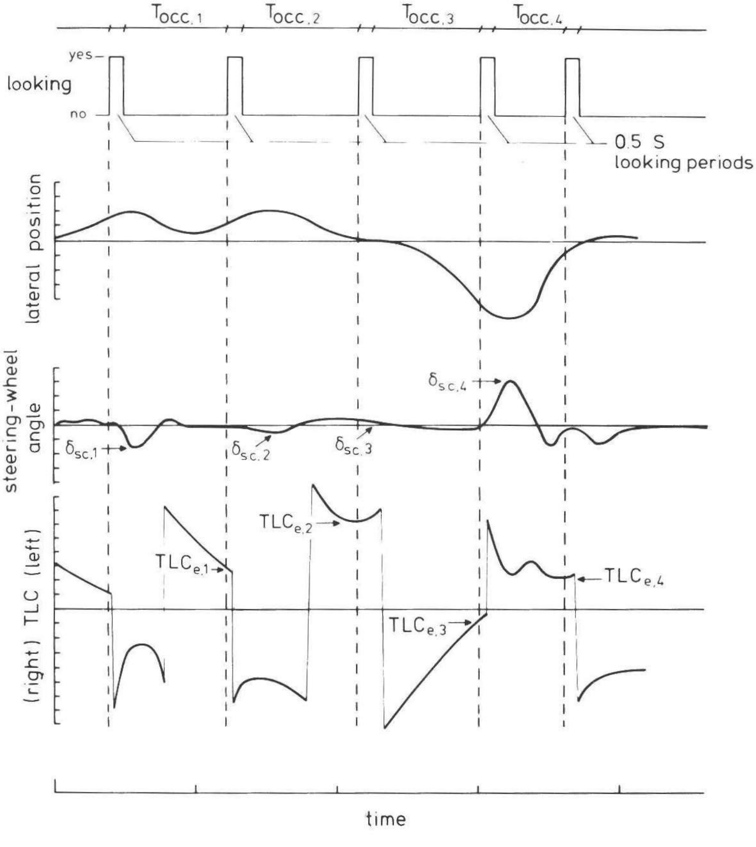


Fig. 7.1 Time histories of the steering-wheel, lateral position and TLC signal as measured in a straight lane keeping task, in which drivers can request for 0.5 s looking periods.

of the path error corrections are made in the period just after the 0.5 s look. After this correction, of which the initial amplitude is noted as δ_{sc}, the steering-wheel is kept more or less fixed until the moment in time the driver requests a new look. During the fixed steering-wheel period TLC is decreasing about proportionally with time. Hence, the TLC_e value at the end of the occlusion period gives an estimate of the time which was actually left at the moment of a new request. From this reasoning it can be understood that for each occlusion interval the sum (TLC_{tot}) of T_{occ} and TLC_e represents the time which was actually available from the beginning of the occlusion period until the moment in time the lane boundary would have been reached.

It can be hypothesised now that the duration of driver's self chosen occlusion times will be related to TLC_{tot} (hypothesis 1). Further, it is important to notice that in case of short looking periods drivers are forced to generate the error correcting steering-wheel movements largely during the occlusion period. From the steering accuracy data as found in the former chapters it can be expected, therefore, that larger amplitudes δ_{sc} and thus larger inaccuracies, will result in a shorter TLC_{tot}. As a consequence, it can be predicted that relatively large steering-wheel corrections will result in shorter occlusion periods (hypothesis 2). Two experiments will be presented now in which the validity of the hypotheses described in this paragraph was investigated for different speed levels.

7.2 Experiment VII: Effects of driving speed

7.2.1 Background

The purpose of the experiment reported in this section is twofold:

1. to evaluate TLC as a driving performance measure which characterises lane keeping not only by lateral position data but also in terms of time;
2. to verify whether TLC might serve as a predictor of a drivers' self chosen occlusion times.

Speed was chosen as the major independent variable in this experiment, because this variable seems of particular interest when developing a time-related driving performance measure. Furthermore, Ss made runs with normal vision ("without occlusion") and with a voluntary occlusion task ("with occlusion"). In this latter task the duration of the looking periods was 0.5 s. The 0.5 s duration was chosen after a pilot study which indicated this period to be long enough to give S an impression of the path error, but also short enough to force drivers to generate the correcting steering-wheel action largely during the occlusion period. The suggestion that larger amplitudes δ_{sc} will result in shorter occlusion periods in such a task will also be tested in the present analysis. Effects of looking period duration will be analysed in detail in Experiment VIII.

7.2.2 Method

Instrumented car

The experiment was conducted with the instrumented car as described in Section 3.2.1 and Appendix A.

Roadway

The experiment took place on an approximately 2 km long straight section of an unused four-lane, divided motorway. Subjects drove in only one direction along the 3.5 m wide right lane, with a broken centre stripe on their left and a solid stripe on their right, shoulder width being 2.5 m.

Subjects

Six male subjects, ranging in age from 24 to 29 participated in the experiment. All had at least three years and 30,000 km driving experience. They were paid for participating in the experiment.

Procedure

Each S participated in the experiment on one day, during which he made five sets of runs, which will be noted as set I to V. A set consisted of six runs, each at one of the following speeds: 20, 40, 60, 80, 100 and 120 km/h. Sets I and V were performed with normal vision ("without occlusion"), whereas the visor was closed in the runs of sets II, III and IV ("with occlusion"). In the latter runs S was instructed to request (0.5 s) looks by pressing the horn lever whenever he felt it was necessary. Speeds were randomly ordered within each set. Sets lasted about 45 minutes with rest periods of 15 minutes in between.

Before the beginning of set I, S was given six practice runs with normal vision (one at each of the speeds mentioned) in order to become familiar with the vehicle. After set I, i.e. before the beginning of the runs with occlusion, S made three practice runs (60, 80 and 100 km/h) with the visor closed in order to become familiar with the occlusion task.

The general instruction was to drive safely at a prescribed speed, which could be held fixed with the speed control unit (see Section 3.2.1). No explicit lane-keeping instructions were given; however, during the practice sessions it was implied that excessive wandering beyond the lane markings was unacceptable. It was also made implicitly understood to S that this was not an experiment in risk taking. During the experiments the experimenter was present in the front passenger's seat. In no case there was a need for the experimenter to take over the control of the car.

Data analysis

Sampled measurements were made on:

δ_s	steering-wheel angle
r	yaw rate
y	lateral position
OCC	occlusion

Sample times were 140, 130, 85, 80, 65 and 50 seconds for runs with a speed of 20, 40, 60, 80, 100 and 120 km/h, respectively. This specific relation between sample time and speed was chosen in order to get an about equal number of looking requests for runs at different speeds. The sample rate was 10 Hz, this rate being high enough to analyse straight driving steering-wheel signals of which signal frequency is below 1 Hz.

Heading angle was derived from the lateral speed signal which on its turn was calculated by way of differentiating the lateral position signal. Furthermore, TLC values were calculated for each sampled point in time.

For each run, means and standard deviations were determined of steering-wheel angle, lateral position, lateral speed and occlusion times. In addition, the medians and 15% TLC level were derived from the histogram of the absolute TLC values in a run (15% of the TLC values was below the "15% TLC level").

In a further analysis TLC_e, TLC_{tot} and δ_{sc} were determined for each occlusion interval, see Fig. 7.1. The maximum steering-wheel angle in the 1.5 second period after a looking request was taken as δ_{sc} for a particular occlusion interval. Medians for TLC_e and TLC_{tot} were derived for each run, while the δ_{sc} data were used to illustrate their relation with the duration of the subsequent occlusion periods.

Differences between conditions (speed, occlusion) were tested on their statistical significance by ANOVA. A preliminary ANOVA indicated no learning effects in the sets I and V (without occlusion) and sets II, III and IV (with occlusion). Hence, it was decided for the ANOVA's containing the factor OCC to compare the sets I and V with the sets III and IV, thus giving two equal data blocks (6 subjects, 6 speeds, with/without occlusion, 2 replica). For the ANOVA on the runs "with occlusion" the sets II, III and IV were taken together as one datablock (6 subjects, 6 speeds, 3 replica).

7.2.3 Results and discussion

The mean lateral position data (Fig. 7.2a) show that Ss choose the centre of the lane (1.8 m) as their preferred position both for the runs with and without occlusion. A slight but significant ($p < 0.01$) effect of speed indicates a shift to the left for the higher speed levels. Fig. 7.2b illustrates that deviations in lateral position were quite large in runs with occlusion as compared to runs with normal vision ($p < 0.01$). It is remarkable here that speed hardly affects these deviations, which indicates that the path width used for the different speed conditions was about constant. The effect of driving speed is more pronounced in the lateral speed data (Fig. 7.2c). Finally, a significant interaction ($p < 0.01$) between speed and occlusion for the steering-wheel angle deviations (Fig. 7.2d) indicates that, particularly at low speeds, the large path deviations in the runs with occlusion resulted in relatively large steering-wheel angles.

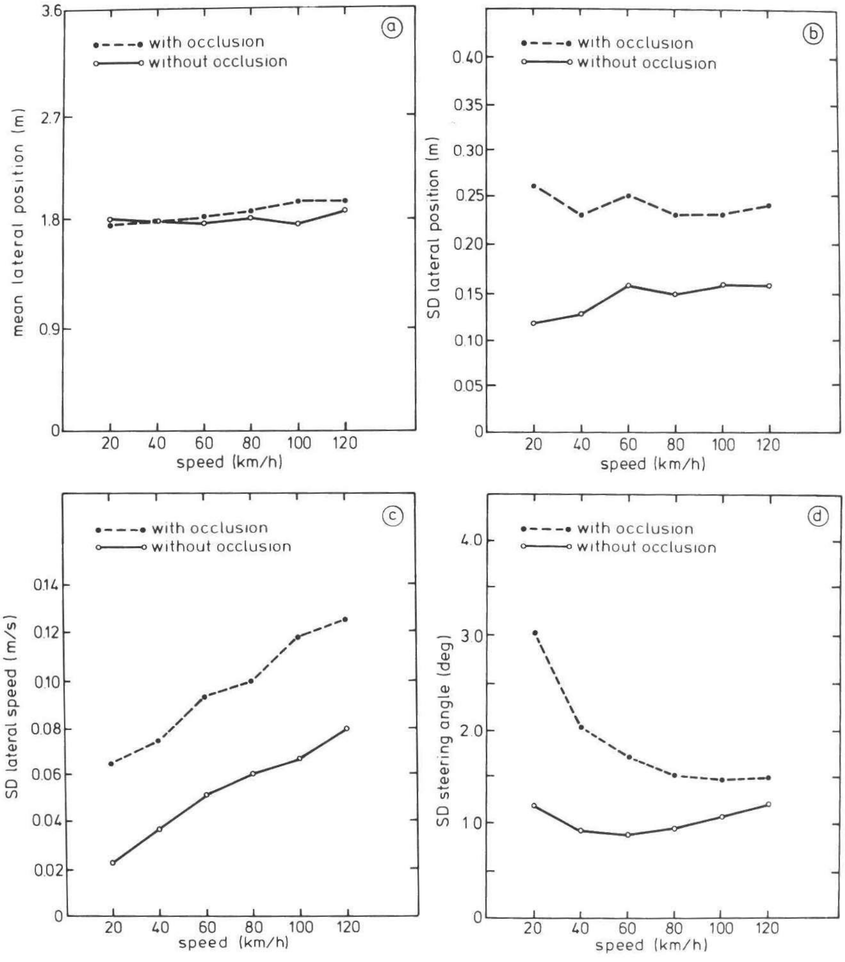


Fig. 7.2 Speed dependency of the conventional driving performance measures for runs with and without occlusion. a) Mean lateral position; b) standard deviation of lateral position; c) standard deviation of lateral speed; d) standard deviation of steering-wheel angle.

An important question in the present analysis concerns the relationship between the data in Fig. 7.2 and the TLC measure which has been proposed in order to clarify the lateral position and steering data in an integrated and quantitative way. Fig. 7.3 presents the median and 15% TLC values. These data illustrate that TLC is relatively long at low speeds, and that the speed dependency is becoming smaller at the higher speeds. The larger path deviations in the runs with occlusion (Fig. 7.2b) are reflected here in the smaller TLC values.

The major reason for developing a time-related measure like TLC was our 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% TLC level and the mean of the occlusion times, T_{occ}, is shown in Fig. 7.4. The correspondence between T_{occ} and TLC clearly shows that the TLC descriptor has predictive power with respect to the driver's occlusion strategy.

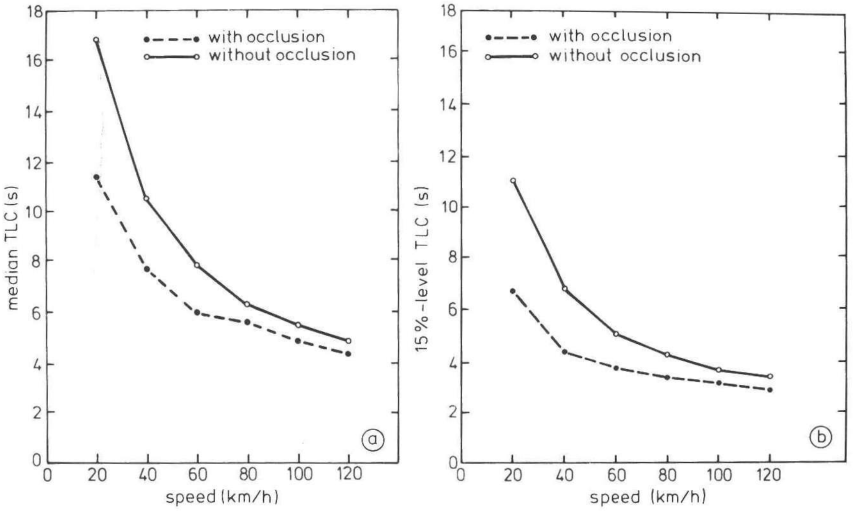


Fig. 7.3 Speed dependency of the median and 15% TLC level for the runs with and without occlusion.

In a further analysis TLC_e values were determined, representing the spare time at the end of the occlusion interval (see Fig. 7.1). For each occlusion interval, therefore, the sum of T_{occ} and TLC_e represents the total time TLC_{tot} which was available from the beginning of the occlusion period until the moment the lane boundary would have been reached. In Fig. 7.5 median values of T_{occ}, TLC_e, and TLC_{tot} are presented. The fact that TLC_e is larger than T_{occ} implies that the median time which was still available at the moments of requesting new looks was long compared to the occlusion time.

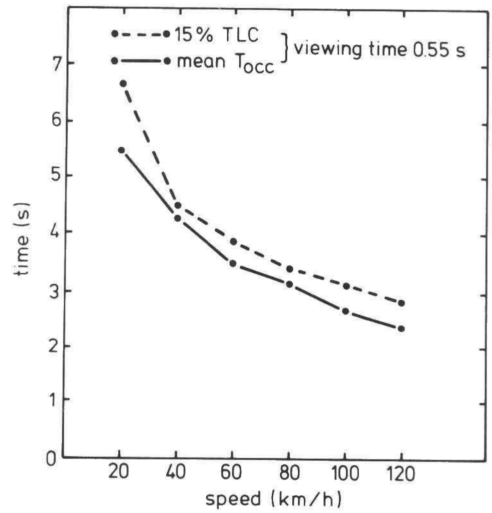


Fig. 7.4 Mean occlusion time and mean 15% TLC value for the occlusion runs.

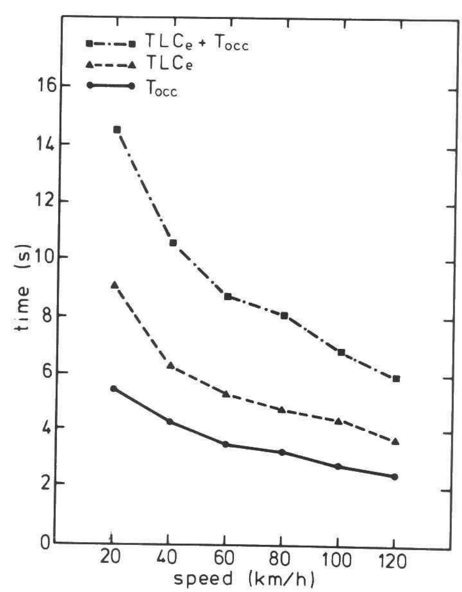


Fig. 7.5 Speed dependency of the median values of T_{occ}, TLC_e and of their sum.

Table 7.I gives additional information about the relation between T_{occ}, TLC_e and TLC_{tot}. For each occlusion interval the ratio between T_{occ} and TLC_{tot} was calculated. The median of this ratio was determined for each run and the fourth column in Table 7.I gives the mean of these medians. The result is quite clear: The ratio is constant over speed levels ($p > 0.20$).

Table 7.I Median of 1) the occlusion time, T_{occ}; 2) the TLC level at the end of the occlusion period, TLC_e; 3) the ratio between T_{occ} and TLC_{tot}.

speed (km/h)	T_{occ}	TLC_e	$\frac{T_{occ}}{TLC_{tot}}$
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

A final analysis was performed to illustrate the relation between the amplitude of driver's steering-wheel correction δ_{sc} and the duration of the subsequent occlusion period. For the sake of this analysis the set of (absolute) δ_{sc} values for each speed/subject combination was subdivided in four quartiles, Q1 to Q4, with the 25% largest values of δ_{sc} in Q4. Fig. 7.6 gives the median T_{occ} values as a function of speed for the occlusion intervals belonging to each of the four δ_{sc} quartiles. A three-level ANOVA (6 subjects, 6 speeds and 4 quartiles) revealed a main effect of quartile ($p < 0.05$), thus indicating the shortest occlusion times after the relatively large steering-wheel corrections. Furthermore, a speed x quartile interaction ($p < 0.05$) shows this effect to be strongest for the low speed conditions.

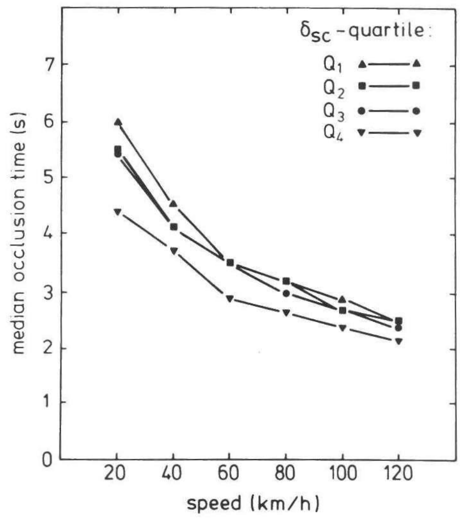


Fig. 7.6 Median occlusion times as a function of speed for the four δ_{sc} quartiles Q1 to Q4.

7.2.4 Conclusions

The following conclusions can be drawn on the basis of the results of Experiment VII.

1. The hypothesis that drivers will choose the length of occlusion periods somehow in relation with the actually available time was fully confirmed in the present analysis.
2. The correspondence between the TLC measures and the self chosen occlusion times implies that TLC should be of use not only as a quantitative measure of driving performance but also as a more behavioral descriptor, and thus predictor, of drivers' occlusion strategy and its dependency on speed.
3. The constancy over speed of the ratio between occlusion times and totally available time, shows that drivers use a constant portion, i.e. about 40%, of the available time, rather than leave a constant amount of time at the end of the occlusion interval.

4. The hypothesis that drivers will choose shorter occlusion times after a relatively large steering-wheel correction was also confirmed in the present analysis. This result is in line with the conclusions of the earlier experiments, which indicate that open loop steering inaccurancies increase with steering-wheel movement amplitude.

7.3 Experiment VIII: Effect of looking time duration and driving speed

7.3.1 Background

When performing an occlusion task as in Experiment VII, the driver is given only a small amount of time to observe the vehicle position error and, consequently, a large part of the subsequent error-correcting steering-wheel action has to be carried out during occlusion. With respect to this point it can be argued, however, that at high speeds the 0.5 s looking period can be more efficiently used as compared to low speed runs. Fig. 7.7 may serve as an illustration of this point, showing (representative) examples of steering-wheel corrections during and just after a looking request for runs at 20 km/h and 120 km/h. The differences in movement amplitude and timing are quite obvious: In case of the low speed condition the duration of the steering-wheel movement may last up to 5 seconds, whereas this duration is far less in high speed driving. It can also be seen that in case of the high speed runs the initial steering-wheel action δ_{sc} can largely be made during the 0.5 s looking period, whereas this is certainly not possible with low speeds. As a consequence, it can be expected that a looking time limitation to 0.5 s will most strongly affect the low speed runs. Experiment VIII was designed to verify this effect: The possibility to carry out the error-correcting steering-wheel movement during the looking period was manipulated by varying the looking time duration for which five values were considered: 0.25, 0.50, 1.00, 2.00 and 4.00 seconds. The consequence of the aforementioned speed effects should be that, particularly, the low speed condition may take advantage of the increased looking time. Furthermore it can be expected that for longer looking times, the vehicle position error at the end of the preceeding occlusion period as also reflected in the steering-wheel angle amplitude δ_{sc}, will only slightly effect the duration of the subsequent occlusion period. In other words: the relation between δ_{sc} and T_{occ} as shown in Fig. 7.6 should be less pronounced with longer looking times.

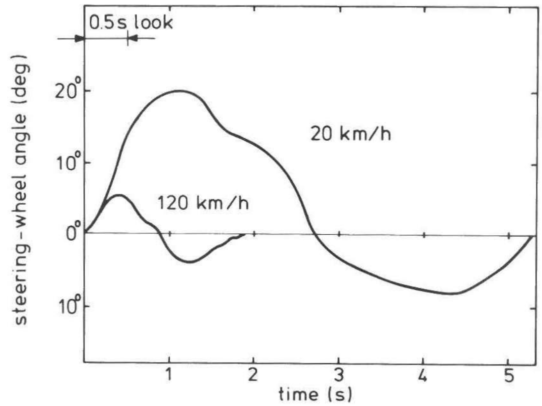


Fig. 7.7 Representative examples of the steering-wheel angle time histories as occuring after an occlusion period and illustrating the effect of speed on movement timing and amplitude.

7.3.2 Method

Instrumented car, roadway and subjects were the same as in Experiment VII. The procedure differed slightly. Again, each S participated on one day. On this day S made four consecutive sets of runs which will be noted as set I to IV. Both sets I and IV consisted of three runs with normal vision each at one of the following speeds: 20, 60 and 100 km/h. Sets II and III contained 15 runs with five looking times (0.25, 0.50, 1.00, 2.00 and 4.00 seconds) and three speeds (20, 60, 100 km/h) randomly distributed in a set. Before set I and set II, S made three practice runs at each of the speeds mentioned and respectively without and with occlusion (looking time 0.5 s).

Data analysis was also largely the same as in Experiment VII. The ANOVA contained three main factors i.e. (6) Subjects, (3) Speeds and (5) Looking Times (LT) and two replica. In a part of this analysis the data of the runs with normal vision were added as a sixth level to the factor LT (LT = ∞).

7.3.3 Results and discussion

Table 7.II presents means and standard deviations of the vehicle motion and steering-wheel angle data. Regarding the influences of speed, these data are fully in correspondance with the results of Experiment VII, i.e. a tendency to drive (slightly) more to the left with higher speeds ($p < 0.01$) and no effects of speed on the lateral position standard deviations. Furthermore, the standard deviations of the lateral speed again increase quite strongly with speed ($p < 0.01$), whereas the steering-wheel angle standard deviations become smaller ($p < 0.01$). Looking time does not

Table 7.II Mean lateral position, standard deviation lateral position, standard deviation lateral speed and standard deviations steering-wheel angle as a function of looking time and speed.

	speed (km/h)	looking time (s)					
		0.25	0.50	1.00	2.00	4.00	∞
mean lateral position (m)	20	1.74	1.81	1.81	1.74	1.77	1.78
	60	1.79	1.84	1.83	1.77	1.83	1.78
	100	1.91	1.82	1.90	1.90	1.85	1.81
SD lateral position (m)	20	0.26	0.25	0.21	0.19	0.18	0.17
	60	0.32	0.21	0.24	0.22	0.20	0.15
	100	0.21	0.23	0.22	0.19	0.19	0.16
SD lateral speed (m/s)	20	0.057	0.054	0.047	0.038	0.041	0.021
	60	0.088	0.078	0.083	0.078	0.074	0.047
	100	0.104	0.106	0.096	0.085	0.084	0.063
SD steering-wheel angle (deg)	20	3.0	2.9	2.5	2.2	2.7	1.2
	60	1.8	1.5	1.7	1.6	1.5	0.9
	100	1.5	1.6	1.4	1.3	1.3	1.1

influence the mean lateral position, but improves the lateral position standard deviations significantly ($p < 0.01$). Similar effects of LT are found for the standard deviation of lateral speed ($p < 0.01$) and steering-wheel angle ($p < 0.05$). For the set of data given in Table 7.II the ANOVA revealed not any Speed x LT interaction, which suggests that the benefits of a longer looking time are about equal for each of the speeds. This suggestion is contrary to the expectations as formulated in Section 7.3.1, where it was argued that particularly at low speed the driver may take advantage of the longer LT. However, these expectations are confirmed in the TLC analysis. Fig. 7.8 shows the median TLC for which the ANOVA indicated main effects of LT ($p < 0.01$) and Speed ($p < 0.01$) as well as a Speed x LT interaction ($p < 0.01$). The latter result illustrates clearly that the LT effect is most pronounced for the low speed conditions.

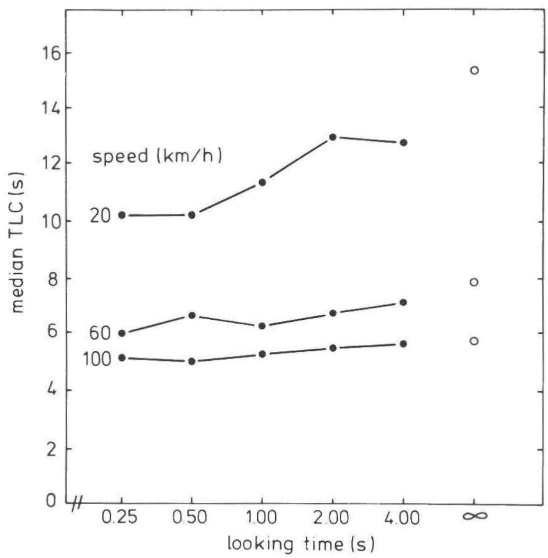


Fig. 7.8 Median TLC for the different looking times and speeds.

An important question to answer is how these TLC results are related to the driver's looking strategy, i.e. the occlusion times. On the one hand this strategy may have been to use about equal occlusion times for each of the LT conditions. Such a strategy effectively may have resulted into longer TLC's with long looking times just because of the increased looking time. Another strategy may be to "use" the longer TLC's as these occur with long

LT and thus take longer occlusion times when more time is available. The T_{occ} and 15% TLC data shown in Fig. 7.9 suggest this latter strategy to be most likely: The longer TLC's with long looking times are resulting in longer occlusion times. Here also the correspondance with the Experiment VII results is quite good, showing that drivers choose occlusion times which are slightly below the 15% TLC level. This reasoning is also confirmed in the ANOVA on the ratio's of T_{occ} and TLC_{tot} (see also Section 7.2.3) which indicated this ratio to be independent on LT. The mean ratio was 0.37, 0.41 and 0.42 for the speeds of 20, 60 and 100 km/h, respectively. Although these values are almost the same as those found in Experiment VII (see Table 7.I), the present ANOVA revealed a main effect of speed ($p < 0.05$) for which an additional Newman-Keuls test showed that the 20 km/h runs differed from the two other speeds. However, despite this effect it seems justified to consider these findings as largely in line with the Experiment VII results, which indicated that drivers choose (average) occlusion times of about 40% of the available time.

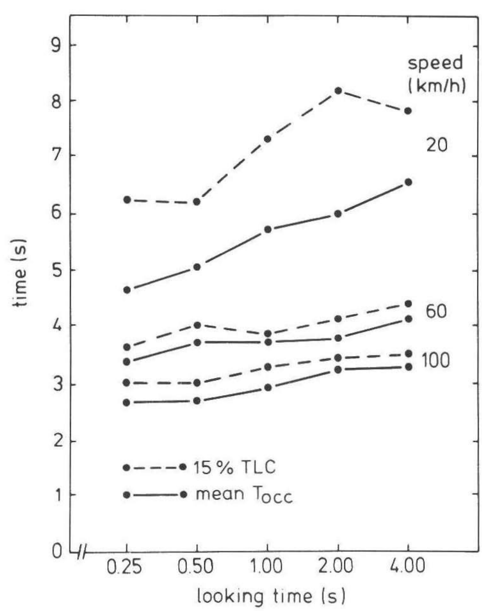


Fig. 7.9 Mean occlusion time and 15% TLC for the different looking times and speeds.

The final analysis of the present data was concerned with the relation between the amplitude δ_{sc} of drivers error-correcting steering-wheel action and the duration of the subsequent occlusion period. For the sake of this analysis the set of (absolute) δ_{sc} values for each speed/looking time/ subject combination was also subdivided into four quartiles Q1 to Q4, with the 25% largest values of δ_{sc} in Q4. Fig. 7.10 gives the median T_{occ} values as a function of looking time for the different speeds and with the quartile as parameter. A four-level ANOVA (6 Subjects, 3 Speeds, 5 Looking Times and 4 Quartiles) indicated effects of speed ($p < 0.01$), looking time ($p < 0.01$) and quartile ($p < 0.01$) as well as a Speed x LT interaction ($p < 0.01$). The quartile effect confirms the idea that large steering-wheel amplitudes are succeeded by relatively short occlusion times. Visual inspection of Fig. 7.10, furthermore, confirms our suggestion that particularly at low speeds the quartile-effect will diminish with the longer looking times. The absence of a Quartile x LT interaction, however, indicates that for now such a conclusion is not justified. The relatively small number of occlusion intervals for the longer looking times may have played a role here.

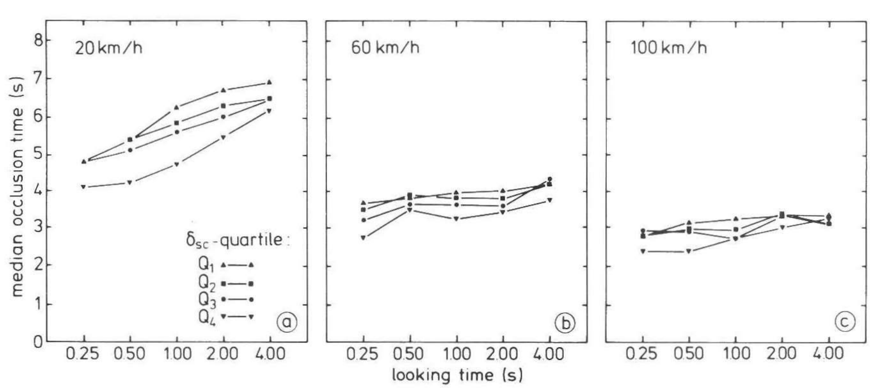


Fig. 7.10 Median occlusion times as a function of looking time for the four δ_{sc} quartiles Q1 to Q4 and for three speeds.

7.3.4 Conclusions

The following conclusions can now be added to those of Experiment VII:

1. The effects of limiting the duration of drivers' visual samples - as in the present occlusion experiments - are dependent on speed. Particularly at low speeds drivers take advantage of longer looking times.
2. The speed dependency of the looking time effect as described in the first conclusion was shown by the TLC analysis and did not appear from the isolated lateral position and steering-wheel angle data, thus illustrating the usefulness of TLC as an integral quantification of driving performance.
3. The similarity between the TLC data and driver's self-chosen occlusion times, as also found in Experiment VII, shows again that TLC may serve as a valuable predictor of drivers looking strategy and its dependency on looking time and speed.

7.4 General discussion

The major question to answer in the present experiments was for how long a driver is actually willing to control his vehicle without immediate visual feedback. Regarding this point it was hypothesised that drivers will choose the duration of occlusion periods in relation with 1) the time available for error-neglection and 2) the amplitude of the correcting steering-wheel actions made during occlusion. In order to deal with these questions a time-domain analysis of driving was developed as a method to characterize lane keeping not only by lateral position data but also in terms of time. Two occlusion experiments were conducted which allowed us to compare drivers self-chosen occlusion periods with the results of this time-domain analysis, as these are described by way of the Time-to-Line-Crossing concept. The results of these experiments fully confirm the hypotheses: Occlusion times correspond closely with TLC and are shorter with larger steering-wheel corrections.

Speed was chosen as the major independent variable in these experiments, because this factor seems of particular interest when developing a driving performance measure in terms of time. The results in Fig. 7.2 and Table 7.II illustrate how conventional measures such as standard deviations in lateral position and lateral speed are affected by speed. Actually, the lateral position standard deviation appears to be independent of speed, whereas lateral speed standard deviation increases approximately linearly with speed. Fig. 7.3 and 7.8 describe the same data in terms of TLC and it could be illustrated clearly that TLC offers an opportunity to integrate lateral position and steering-wheel data. Furthermore, the correspondence between the 15% TLC and the occlusion times as shown in Fig. 7.4 and 7.9 implies that the TLC measure should be of use not only as a unified quantitative measure of driving performance but also as a more behavioral descriptor, and thus predictor, of drivers' occlusion strategy and its dependency on factors like speed and looking time. In this way, TLC may also provide insight into the probability of lane exceedance during a particular run. Allen and O'Hanlon (1979) proposed an index for this probability. They started from the assumption of a Gaussian distributed lateral position and used the standard deviation to calculate the a posteriori probability of lane exceedance. One of the limitations of this index is illustrated in the present data: The absence of a speed effect in Fig. 7.2b would result in a constant probability of lane exceedance over the range of speeds shown here. This conclusion is contrary not only to intuition but also to the actual TLC results given in Fig. 7.3, which are a summary of the actual times to lane exceedance.

The median and 15% TLC level in Figs. 7.3 and 7.8 are representative values which characterize the total TLC distribution of a particular run or condition. However, in our further analyses we used the TLC_e values, which describe the driving situation at those particular moments at which the driver decided to request a new look. A major advantage of the present experimental approach thus becomes clear: The opportunity to compare and combine drivers' self chosen occlusion times with the TLC_e values, thereby allowing us to determine the open loop times which were actually available. In this way it becomes possible, 1) to quantify the efficiency of drivers' steering behavior during the occlusion interval, and 2) to describe the relationship between occlusion time and actual available time. The constancy over speed of the latter relationship (Table 7.I) is a remarkable result, which shows that drivers tend to use a constant portion, i.e. about 40%, of the available time, rather than leave a constant absolute amount of time at the end of the occlusion interval.

This result is also consistent with Milgram et al.'s (1982) open loop analysis of the same data which showed that drivers base their decisions to sample their visual surroundings on a strategy of maintaining a constant level of redundancy in their estimate of the vehicle's state information.

CHAPTER 8

8. THE LIMITS OF ERROR-NEGLECTION IN STRAIGHT LANE KEEPING

8.1 Introduction

As indicated in Section 2.2.2 the actual literature does not present any error-neglection description of driving. It was argued that such a description should fulfill two major requirements: 1) it should give insight into the time available for error-neglection at each moment of a run and 2) it should provide a description of the actual limitations of error-neglection. The first of these requirements has been dealt with through the development of the TLC concept as it is based on a preview-predictor approach. Regarding the second requirement it is important to note that, up to now, the TLC concept has been used as a measure, representing the time until the lane boundary will be reached. An error-neglection driver model, however, should contain decision rules describing how drivers switch from an error-neglection to an error-correction strategy.

The experiment to be presented in this chapter was designed to provide these rules for a straight lane keeping task. Drivers were instructed to neglect the vehicle path error and to switch over to error-correction only at that moment in time, the vehicle motion still could comfortably be corrected to prevent a crossing of the lane boundary.

Fig. 8.1 gives an illustration of such an event. At $t = t_0$ the driver was instructed to neglect further path errors and thus to behave in a fixed steering mode. The time history shows how TLC decreases to TLC_s, i.e. until the moment t_s, at which the driver decides to generate a compensatory steering action for which the initial amplitude is noted as δ_{sc}. At t_s the lateral distance from the lane boundary is y_s, while the lateral speed with which the vehicle is approaching the lane boundary is $\dot{y}_s$.

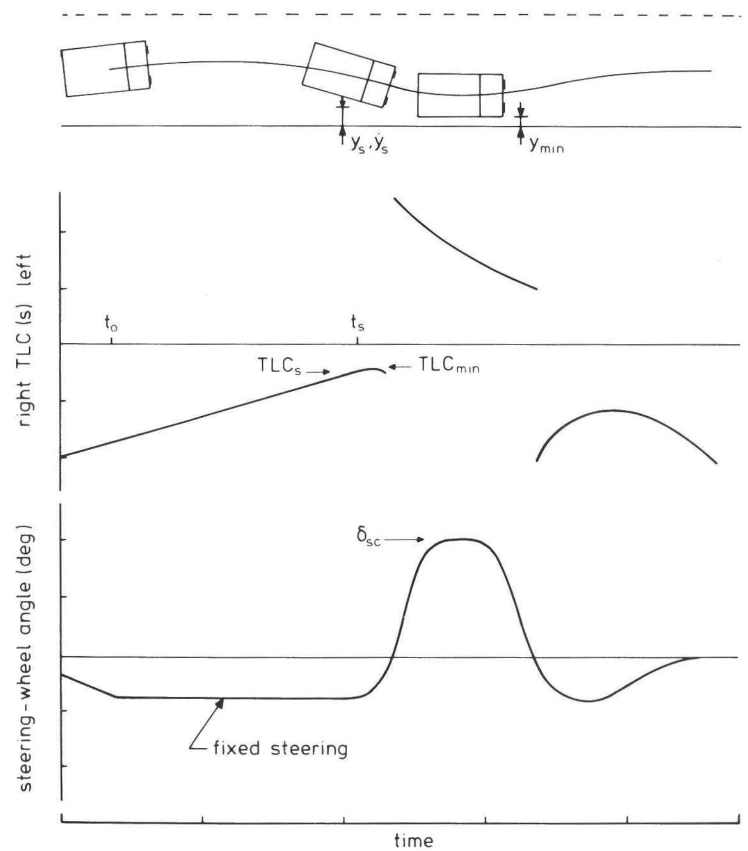


Fig. 8.1 Time-histories of lateral position, TLC and steering-wheel angle, illustrating a period of error-neglection ($t_o \rightarrow t_s$) and the subsequent steering-wheel correction.

The strategy adopted by drivers in this decision making process can now be characterised in terms of the vehicle motion and position data at t_s. Fig. 8.2 gives an illustration of two hypothetical strategies. In case of strategy A drivers use a constant lateral distance y_s for their decision to switch over to error-correction. A consequence of such a strategy would be that TLC_s's are shorter with higher lateral speeds $\dot{y}_s$. Example B represents a strategy where drivers compensate for a higher lateral approach speed by taking a longer distance y_s. A consequence of the latter strategy might be that TLC_s's are about constant for different $\dot{y}_s$ levels. Both strategies assume a more or less linear relation between the various variables. It is evident that, in practice, non-linearities may affect these control strategies. Another important question is how vehicle speed will influence this strategy. Therefore the experiment to be presented now was performed at various speed levels.

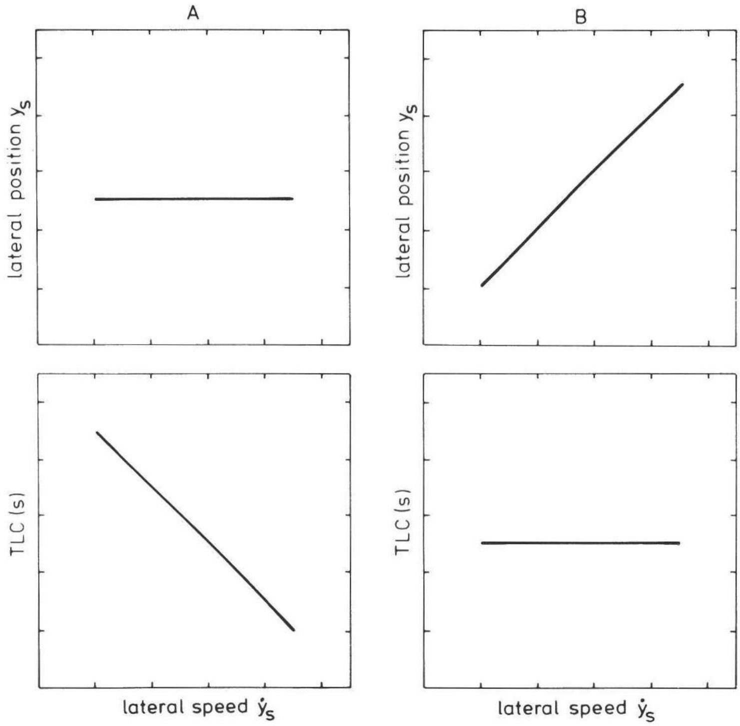


Fig. 8.2 Schematic representation of different strategies as may be adopted by drivers when switching from error-neglection to error-correction at t_s.

8.2 Experiment IX: The limits of error-neglection in straight lane keeping

8.2.1 Method

Instrumented car

The experiment was carried out with the instrumented car as described in Section 3.2.1 and Appendix A.

Roadway

The roadway used for this experiment, was the same as in the Experiments VII and VIII, i.e. a 2 km long, straight, divided highway, with two lanes in each direction, no other traffic and lane width 3.5 m. Ss drove in only one direction with a broken centreline on their left and a solid edgeline on their right, shoulder width being 2.5 m. Centreline configuration was 3-9-3, i.e. 3 m striping, 9 m no-striping, 3 m striping, etc.

Subjects

Six male subjects, ranging in age from 22 to 31 participated in the experiment. All had at least three years and 30.000 km driving experience. They were paid for participating in the experiment.

Procedure

Each S participated in the experiment on half a day, during which he made 18 runs i.e. 4 runs at 20 km/h, 6 runs at 60 km/h and 8 runs at 100 km/h. The number of runs for a speed was chosen to get an about equal number of decision events for each speed. The sequence of the speeds was randomised. Before the first actual run S made three practice runs, one at each of the speeds mentioned. The total time of driving for a subject was about 2 hours, with a 15 min pause after run 9.

S was instructed to neglect path errors immediately after the presentation of a tone and to switch over to error-correction only then when the vehicle motion could still comfortably be corrected to prevent a crossing of the lane boundary. It was made understood to S that in the case of this experiment error-neglection should be interpreted as a fixation of the steering-wheel immediately after the tone. The experimenter, who was seated in the front-passenger seat, initiated the tone by pressing a button at that moment t_0, which he considered as useful for the next event. In this way the experimenter was able to accomplish a certain variation in lateral approach speeds and to guarantee an about equal number of approaches to the left (centreline) and the right (edgeline). Speed was automatically held constant with the device described in Section 3.2.1.

Data analysis

Sampled measurements (4 Hz) were made on:

δ_s steering-wheel angle

r yaw rate

y lateral position

The position of the push button, as it was used by the experimenter to initiate a period of error-neglection, was recorded as a fourth channel, which allowed us to mark the moment t_o after which the driver fixated the steering-wheel. Sample times were 300 s, 105 s and 65 s for runs with a speed of 20, 60 and 100 km/h, respectively.

Heading angle was derived from the lateral speed signal, which on its turn was calculated by way of differentiating the lateral position signal. Furthermore TLC values were calculated for each sampled point in time.

Drivers' decision points t_s were determined by way of localising the first sample after t_o, at which the steering-wheel angle differed more than 0.1 δ_{sc} from its original value (0.1 δ_{sc} = 10% of the amplitude of the subsequent steering-wheel action).

For each decision point y_s, y_{min}, $\dot{y}_s$, TLC_s and TLC_{min} values were derived (see Fig. 8.1). The total number of decisions as analysed in this way was 486, 306 and 263 for speeds of 20, 60 and 100 km/h, respectively, with an about equal number of approaches to the left and the right. The difference in the number of decisions analysed for the three speeds illustrates that the strategy to equalize this number by taking different number of runs and sample times for the various speeds was not completely successful.

For the total set of data an ANOVA was performed to test the significance of differences between the conditions speed and left-/rightward approach (LR). The number of replica for this analysis was taken as 50, resulting into an incomplete datablock, for which the unavailable cells were coded as missing data.

In a further analysis the $\dot{y}_s$ data for each speed/subject combination were divided into four $\dot{y}_s$ quartiles i.e. Q_1 to Q_4 with the 25% highest lateral speed values in Q_4. Mean TLC_s, y_s and $\dot{y}_s$ values were derived for each $\dot{y}_s$ quartile, thus allowing an analysis of driver's strategy in choosing y_s and TLC_s for different $\dot{y}_s$ levels.

8.2.2 Results

Fig. 8.3 presents mean values for y_s, y_{min} and $\dot{y}_s$ as a function of speed. The ANOVA indicated no effect of LR and therefore the data were averaged over left- and rightward approaches. These results illustrate that drivers take larger values of y_s and $\dot{y}_s$ for the higher speeds, whereas the minimum distance to the lane boundary is about constant, i.e. 15 cm.

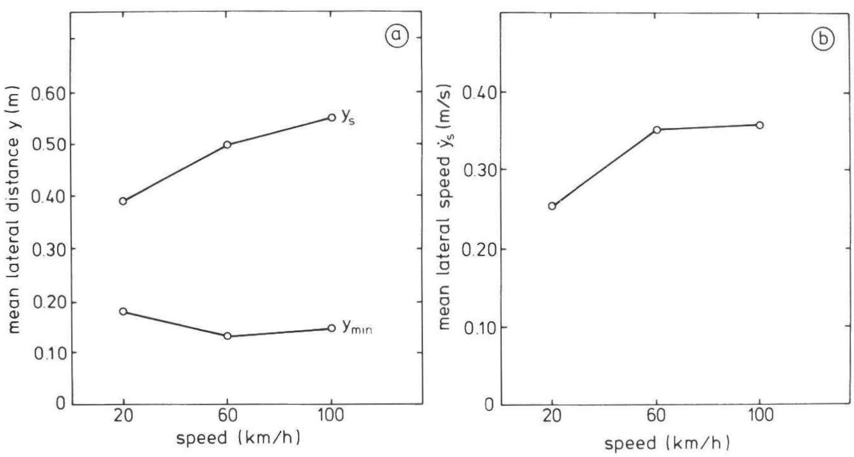


Fig. 8.3 Mean values of y_s, y_{min} and $\dot{y}_s$ as a function of driving speed.

The question now is how these lateral position and lateral speed results are reflected in the TLC data. Fig. 8.4 gives mean values of TLC_s and TLC_{min} for which the ANOVA indicated no effects of speed and LR, thus illustrating that drivers take about constant TLC_s (1.3 s) and TLC_{min} (1.1 s) levels for a broad range of speeds.

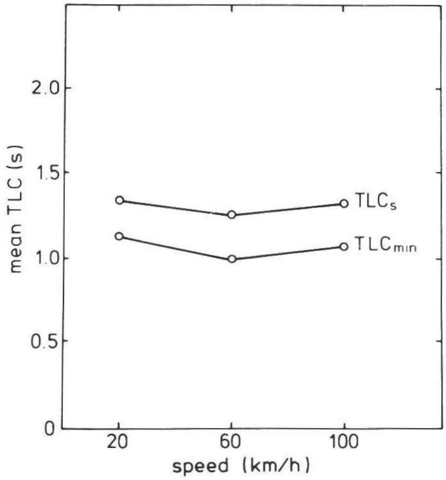


Fig. 8.4 Means of TLC_s and TLC_{min} as a function of driving speed.

The consistency of drivers decision rules can be tested further by way of analysing the SD's of the different variables. The SD of TLC_s appears to be independent of speed and LR with a mean value of 0.43 s. Fig. 8.5 gives the

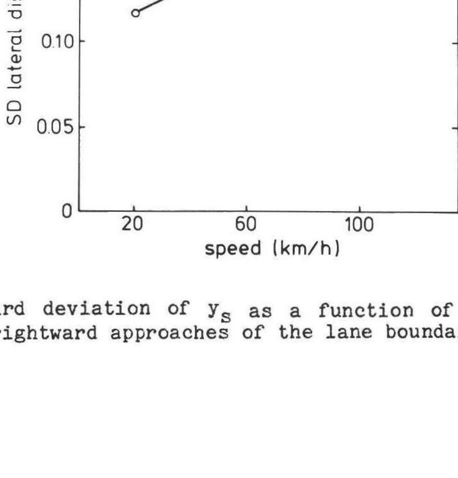


Fig. 8.5 Standard deviation of y_s as a function of speed and for leftward/rightward approaches of the lane boundary.

SD of y_s for which the ANOVA revealed a main effect of speed ($p < 0.01$) and a tendency ($p < 0.06$) towards smaller variability for leftward approaches. This latter tendency is most probably caused by the fact that driver's position in the car allows for a better observation of the distance to the left centreline as to the right edgeline.

The strategy adopted by drivers in deciding to switch from error-neglection to error-correction can be characterized in more detail by considering the relation between y_s, TLC_s and $\dot{y}_s$, in the way as suggested in Fig. 8.2. This type of presentation is given in Fig. 8.6, which presents the means of y_s and TLC_s as a function of the mean lateral speed for the quartiles Q_1 to Q_4 (see Section 8.2.1). Fig. 8.6a shows an about linear relationship between y_s and $\dot{y}_s$, thus illustrating how drivers choose larger distances y_s with higher approach speeds $\dot{y}_s$. Actually, this mechanism corresponds closely with strategy B (Fig. 8.2), the only difference being that, in case of the actual data, the linearity between y_s and $\dot{y}_s$ does not pass the origin. As a consequence, the TLC_s data in Fig. 8.6b show a slight decrease with higher approach speeds $\dot{y}_s$. Nevertheless, it seems justified to conclude on the

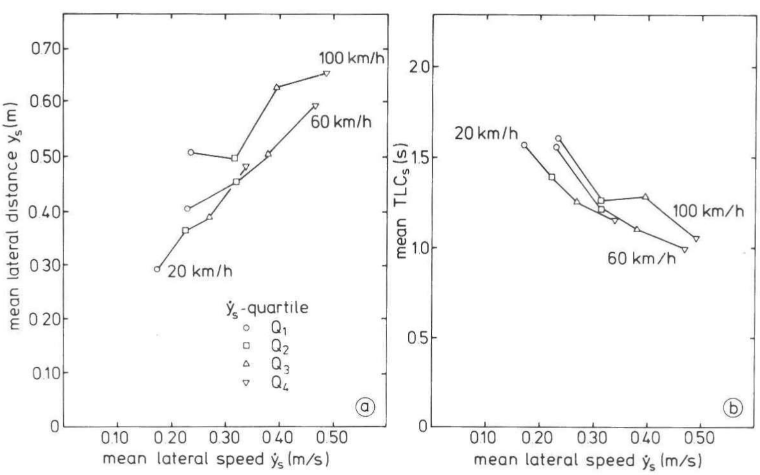


Fig. 8.6 Lateral distance y_s and TLC_s as a function of mean lateral speed for the quartiles Q_1 to Q_4, (with the 25% highest lateral speed values in Q_4).

basis of the complete set of data that drivers' strategy to switch from error-neglection to error-correction can be characterized by the y_s-$\dot{y}_s$ relationship given in Fig. 8.6a and that TLC_s levels change only minorly as a function of lateral and forward speed.

8.3 Discussion and conclusions

In the introduction of this chapter a distinction was made between two hypothetical strategies, A and B, as these may be adopted by drivers when deciding to switch from error-neglection to error-correction. In case of strategy A drivers were assumed to use a constant lateral distance to the lane boundary for their decision to switch over to error-correction. A consequence of this strategy would be that TLC_s's, i.e. TLC at the moment of switching to error-correction, are shorter with higher lateral speed. With strategy B drivers are assumed to compensate for higher lateral approach speeds by way of switching to error-correction at a larger lateral distance from the lane boundary. A consequence of the latter strategy might be that TLC's are about constant for different lateral speed levels. The actual results indicate that drivers choose a strategy which corresponds closely with strategy B: Lateral distance from the lane boundary at which drivers switch from error-neglection to error-correction increases about linearly with lateral speed, whereas the TLC_s values decrease only slightly with higher lateral approach speeds.

Regarding the effects of driving speed it is found that the lateral distance from the lane boundary at which drivers switch from error-neglection to error-correction increases with driving speed. This mechanism results in an about constant TLC_s level for the range of speeds considered (20-100 km/h). The relation of this remarkable finding with the results of Experiments VII will be discussed in Chapter 9.

In summary the following conclusions can be drawn on the basis of Experiment IX:

1. The lateral distance from the lane boundary at which drivers switch from an error-neglection to an error-correction strategy increases with driving speed.
2. Conclusion (1) can largely be explained by the fact that the lateral distance from the lane boundary, at which drivers switch from error-neglection to error-correction, increases about linearly with lateral speed.

3. The mechanism described in conclusions (1) and (2) results in an about constant TLC_s level at the moments drivers switch from error-neglection to error-correction for a broad range of driving speeds.
4. The lateral distance from the lane boundary at which drivers switch from error-neglection to error-correction shows a smaller variability for leftward approaches. This tendency is most probably the result of the fact that driver's position in the car allows for a better observation of the distance to the (left) centreline as to the (right) edgeline.

CHAPTER 9

9. GENERAL DISCUSSION AND APPLICATIONS

9.1 Discussion

The purpose of this study was to increase our insight into the potential role of error-neglection and visually open loop strategies in vehicle control. Apart from a more fundamental understanding of this driving subtask this insight also may lead to applications in vehicle design and traffic engineering.

The basic assumption of the study was that the time available for a driver to control his vehicle in an open loop mode, i.e. without immediate visual feedback, largely depends on two factors:

(1) The accuracy of the open loop generated steering-wheel actions,

(2) the time available for error-neglection.

(1) With regard to the accuracy of manual control actions, it was argued that anticipation based on preprogramming and/or preview may give the driver an almost perfect knowledge of the steering actions needed for a specific manoeuvre, even during periods without immediate visual feedback. The ultimate accuracy of open loop steering actions, however, will be limited because of inaccuracies in the motor system, i.e. a driver's limitations to transform desired into actual steering-wheel movements. So, the first question raised was whether the linear speed/accuracy trade-off as known for closed loop, step movements (Fitts, 1954; Schmidt et al., 1978) would also be valid for open loop, continuous control actions. The results of a reproduction experiment, in which subjects tracked movement patterns of a single sine-wave under open as well as closed loop conditions, indicated that this was not the case. For closed loop tracking, amplitude accuracy indeed appeared to be linearly dependent on movement velocity, thus illustrating the validity of Fitts' law for continuous

closed loop movements. However, for open loop conditions this relation was not found: In that case the results indicated the amplitude accuracy to be only dependent on movement amplitude. This result suggests that movement velocity mainly influences the relative importance of the visual feedback processes. Otherwise stated: With visually guided movements, higher velocities lead to a suppression of the visual feedback process, resulting in less accurate movements. Hence, it is clear that velocity effects will not be found in case of open loop movements in which visual feedback processes are absent anyway.

The finding that open loop steering accuracy primarily depends on the amplitude or extent of the steering-wheel action was verified and tested for its implications for actual driving in two vehicle control tasks, i.e. a lane change and a curve entrance task. In actual driving the open loop steering action can be considered as the outcome of an information processing chain which contains three major stages:

a. Perception of the desired path,
b. translation from the estimated path into a desired steering-wheel action,
c. motor control process that transforms the desired steering-wheel action into a manual action.

The results of the reproduction experiment can be considered as a quantification of stage c. The degree to which the inaccuracies of the stages a and b will be "added" to those of stage c is assumed to depend on the level of predictability of a particular driving task.

In view of this, it was hypothesised that steering inaccuracy in a precognitive task will still mainly originate from stage c, and that inaccuracies will be larger in case of a preview task. The experimental results confirm this hypothesis rather well: A precognitive, lane change task requiring a single sine-wave shaped steering-wheel movement (similar to the reproduction experiment), resulted in steering-wheel amplitude inaccuracies of the same absolute level as those found in the reproduction experiment. In comparison, a preview curve entrance task resulted in larger amplitude inaccuracies. These data also confirm the hypothesis that inaccuracies increase about linearly with movement amplitude.

(2) Before discussing the results of (1) in terms of their implications for driving performance we also will have to consider the second factor influencing the possibility for open loop control, i.e. the time available for error-neglection. The literature review indicated an absence of de-

scriptive models that include a quantification of the potential role of error-neglection, i.e. no-steering periods. In this study a description like this was developed by application of the path prediction techniques as commonly used in preview-predictor models. For each moment the future vehicle path is predicted with the assumption that the steering-wheel will remain in its momentary position during the time span of the prediction process. From such predictions the Time-to-Line-Crossing (TLC) can be calculated, representing the time the driver has available to neglect path errors, until the moment at which any part of the vehicle reaches one of the lane boundaries. TLC's can be calculated on the basis of sampled data: For each sample the momentary lateral position, heading angle and steering-wheel position is used to predict TLC. Vehicle and roadway characteristics are implemented in the TLC software package and can be changed optionally. Hence, the TLC concept answers directly to one of the main purposes of this study, i.e. the quantification of the potential role of path error-neglection in driving. A first illustration can be found in the TLC data from Experiment VII on straight road driving with constant speeds varying between 20 and 120 km/h: A classical description of driving performance in terms of lateral position standard deviations gave no speed effects, whereas TLC clearly showed how the time available for path error-neglection decreases with higher speeds. For curve driving and straight lane keeping the TLC concept allows the development of new views on the role of error-neglection and open loop control in driving.

Now, we will return to the results of the steering accuracy experiments, which indicated steering inaccuracies to increase about linearly with the amplitude or extent of the steering-wheel movement. In case of curve driving this relation implies that inaccuracy of the initial, anticipatory steering-wheel action made at curve entrance, increases about linearly with road curvature. Based on this finding it was hypothesised that, for sharper curves, 1) steering corrections made after the anticipatory steering action will be stronger, and 2) TLC just after the anticipatory steering action will be shorter. Both predictions were confirmed by the empirical findings. The TLC data, in particular, illustrated the possibility for error-neglection to be smallest for sharp curves. For these curves drivers will have to switch over to error-correction at a relatively early moment in time, which clarifies why sharper curves require more attention.

The results discussed thus far illustrate that in precognitive and preview steering tasks, drivers are quite well able to control their vehicle without immediate visual feedback during a certain time period. However, it also became evident that the error-correction or compensatory control mode ultimately is needed to keep the vehicle path within the lane boundaries. With respect to open loop control and error-neglection, therefore, two fundamental questions remained: First, for how long is a driver actually willing to control his vehicle without immediate visual feedback and second, how long is a driver ultimately allowed to wait before switching over to the error-correction mode.

The first of these questions was investigated by measuring drivers' self-chosen occlusion times in a straight lane keeping task with constant speeds varying between 20 and 120 km/h. The following hypotheses were formulated: 1) Occlusion times will be related to the actual time available as it can be described in terms of the TLC, and 2) Relatively large steering-wheel corrections made during occlusion, and thus large inaccuracies, will result in relatively short occlusion times. Both hypotheses were confirmed. Occlusion times corresponded closely with TLC and are shorter with larger steering-wheel corrections. The usefulness of the TLC concept could be further illustrated by combining the occlusion time and the TLC at the end of the occlusion interval, the sum of which can be considered as the total time available. In this way drivers' occlusion strategy can be clarified in more detail by calculating the ratio between occlusion time and total time available. The constancy over speed of this ratio is a remarkable result, which shows that drivers tend to use a constant fraction, i.e. about 40%, of the time available, rather than leave a constant amount of time at the end of the occlusion period. This result can be compared with the findings of the last experiment of this thesis, in which drivers were instructed to neglect path errors and to switch over to error-correction only at that moment in time, the vehicle motion still could comfortably be corrected to prevent a crossing of the lane boundary. The strategy adopted by drivers in this task, was to switch over to error-neglection at an about constant TLC distance from the lane boundary. This result also appeared to be consistent for a large range of speeds (20 to 100 km/h).

Together, the findings on open loop control and error-neglection indicate that the timing processes involved may differ fundamentally. During open loop control drivers have to rely on their estimate of the vehicle trajectory and this uncertainty results in the strategy to leave a fraction of the time available at the end of the occlusion interval. In an error-neglection task with deliberate neglection of path errors, drivers will be quite certain about the vehicle motion in relation to the lane boundary and this certainty results in the strategy to leave a constant amount of time before the lane boundary would have been reached. These findings indicate that drivers' way of timing, i.e. leaving a fraction of time or a constant amount of time, is strongly related to the degree of uncertainty about the vehicle trajectory.

In summary the following conclusions can be drawn from the entire set of 9 experiments:

1. The inaccuracy of open loop steering-wheel movements, in terms of amplitude standard deviations, increases about linearly with movement amplitude. The relation between movement inaccuracy and movement velocity, as known for closed loop movements, does not hold for open loop movements.
2. With precognitive steering tasks steering force helps to improve steering-wheel movement accuracy.
3. The amplitude inaccuracies of open loop steering-wheel movements in a preview, curve entrance task are larger compared to those in a precognitive, lane change task.
4. Drivers are able to take into account both speed and curvature effects when generating anticipatory steering-wheel actions at curve entrances.
5. Inaccuracies of the anticipatory steering action at curve entrance increase with road curvature, thus leading to more frequent steering corrections and shorter TLC's during the period immediately following the anticipatory action.
6. The occlusion times chosen by drivers in a straight lane keeping task, closely correspond with TLC.
7. When choosing the duration of occlusion periods in a straight lane keeping task, drivers tend to use a fraction, i.e. 40%, of the available time, rather than leave a constant amount of time at the end of the occlusion period. This effect is consistent over a large range of speeds.
8. After deliberately neglecting path errors in a straight lane keeping task, drivers switch over to error-correction at a rather constant TLC distance (1.3 s) before the lane boundary is reached. Also this effect is consistent over a large range of speeds.
9. Combining conclusions 7 and 8 leads to the conclusion that drivers timing strategy in open loop control and/or error-neglection, i.e. leaving a constant fraction of time or a constant absolute amount of time, strongly depends on the degree of uncertainty about the vehicle trajectory.
10. TLC provides a quantitative measure of driving performance, which characterizes driving not only by integrating vehicle motion and steering behavior but also by implementing roadway and vehicle charac-

teristics. As such, TLC may be fruitfully applied to describe driving on straight roads and in curves, and to optimize roadway and vehicle characteristics.

9.2 Applications and future research

The results of the research discussed in this thesis may find their way in various areas of application, some of which are discussed here.

Driving performance analysis

It was illustrated in this thesis that TLC can be used as a descriptor of driving performance, that characterizes lane keeping on the basis of an integration of speed, lateral position, heading angle and steering-wheel angle data. As such, TLC has proven to be not only a unified quantitative measure of driving performance, but also a more behavioral descriptor, and thus predictor, of drivers' occlusion and error-neglection strategy. In this way, TLC may also provide insight into the probability of lane exceedance during a particular run. Furthermore, TLC may be particularly useful in curve driving analysis. Conventional measures such as lateral position, lateral speed and steering-wheel angle standard deviations are highly inefficient for the description of curve negotation. The preview-predictor approach, as presently used to calculate TLC's, seems suited to solve this problem and may serve as a valuable method for the quantification of curve driving.

Vehicle handling

The techniques which are presently used to qualify the handling characteristics of vehicles are mostly based on the assumption that drivers behave in an error-correction mode with permanent attention allocated to vehicle control. An important finding in this type of studies is that drivers very easily adapt to differences in vehicle characteristics. This ability can be used to perform about equally well with vehicles of bad and good handling properties. Despite its attractiveness, this mechanism makes it rather difficult to evaluate vehicle properties in terms of the attention needed for vehicle control and to develop objective criteria for this.

The methods developed in this study can be used to describe vehicle characteristics in terms of TLC. In a recent study for the Dutch Army, Godthelp and Käppler (in prep.) repeated Experiment VII of this thesis with vehicles of bad, moderate and good handling characteristics. During straight lane keeping, measurements were made of driving performance and occlusion times. The results confirmed the adaptation effect described previously: Ultimate performance in terms of lateral position standard deviations was equal for each vehicle. However, TLC's and occlusion times differed significantly between vehicles, thus qualifying the actual differences between the vehicles. This finding suggests that the TLC analysis may be fruitfully applied to develop objective vehicle handling criteria.

Lane width and advisory speeds

Lane widths of roads may differ considerably between road categories. Furthermore, temporary narrowing of lanes is needed in construction zones. In many of these situations speed limits are related to road width, i.e. the narrower the road the lower the tolerated speed. However, until now,

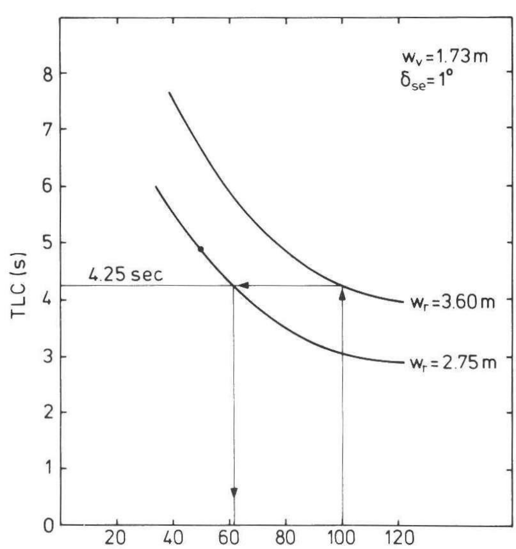


Fig. 9.1 TLC as a function of speed for two levels of lane width as calculated with formula (3) with w_v = 1.73 m and δ_{se} = 1°.

the rules describing the relationship between lane width and acceptable speed could not be based on an integrated quantification of vehicle lateral and longitudinal (speed) control. The TLC analysis enables such a quantification as illustrated in Fig. 9.1. The two curves in this figure are based on the TLC formula (3) given in Section 3.3. They show how TLC's for a specific lane width varies with speed: A lane width of 3.60 m leads to a TLC of 4.25 s at 100 km/h, assuming a car width of 1.73 m. After narrowing the lane to 2.75 m, TLC can be held constant with a speed of 62 km/h. Field experiments are needed to validate this technique by which speed limits are related to available lane width. As such, this method can be used to increase our understanding of speed-space relationships and to evaluate present guidelines on speed limits.

Relation with TTC

A description of conflicts between two crossing vehicles can be given in terms of the Time-To-Collision (TTC) concept (Van der Horst and Riemersma, 1981). This approach is similar to the TLC analysis in that it uses path predictions of vehicles which, in case of TTC, are used to calculate the time to a potential collision. However, a principle difference between both methods is that the path predictions made in the TTC analysis are based on the assumption that the future vehicle trajectory remains straight. Regarding the results of both analysis an interesting correspondence can be noticed: The constancy over speed of the minimum TLC as found in the error-neglection Experiment IX is analogous to the constancy of the minimum TTC as usually found for interacting vehicles. A further mutual tuning of both methods, therefore, can be considered as promising and may enlarge our insight into the processes underlying lateral and longitudinal vehicle control. As such, the results of this thesis may be helpful to relate results of studies on traffic conflicts and on vehicle control.

Risk handling analysis

The findings that drivers leave a constant fraction of the available time in case of open loop control and a constant absolute amount of time in case of deliberate error-neglection both can be considered as a quantification of ris-taking behavior. Godthelp et al. (in prep.) repeated Experiment VIII of this thesis with inexperienced drivers and found that the occlusion durations chosen by these unskilled subjects can also be described as a constant fraction of the time available. However, this fraction was considerably smaller compared to experienced drivers, i.e. 30% instead of 40%. In the same terms, the influence of roadway properties (e.g. type of shoulder), visibility (e.g. preview) and vehicle characteristics (e.g. car versus trucks) can be analysed. In this way TLC and its related measures may serve as a useful quantification of risk taking behavior.

Driver modeling

On the basis of the TLC analysis presented in this thesis, a serial strategy model of driving can be developed containing a "preview-predictor" part for the simulation of error-neglection periods, and a conventional, "compensatory" part for the error-correction intervals. The rules defining a driver's strategy to use open loop and/or error-neglection periods should form basic elements for such a model. On the one hand, these rules should describe the driver's criteria to request new looks after an open loop period, whereas on the other hand, they should represent driver's decision making process in switching from error-neglection to error-correction. Quantitative data for each of these aspects have been presented in this thesis. The ultimate aim of the type of model proposed here is to predict the effects of the various task elements which determine the sequential distribution of the driver's combined use of open and closed loop and/or error-neglection and error-correction strategies in both straight lane keeping and curve driving.

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A P P E N D I X A

Mathematical vehicle model used to describe instrumented car and driving simulator characteristics

A.1 INTRODUCTION

Ever since the development of the automobile, research has been done to describe vehicle motion characteristics in terms of a mathematical model. Especially, Segel (1956) made a major contribution. Mathematical vehicle models as they are available nowadays can be roughly divided into two groups i.e. 1) models with only two or three degrees of freedom, which describe the most elementary motion characteristics of the car in a lateral acceleration area below 0.3 g m/s^2 and 2) very comprehensive models, mostly with six degrees of freedom and also describing motions of vehicle components such as suspension elements. The latter type of model is particularly suited for vehicle design purposes, whereas the type 1 model has proven to be most useful in vehicle handling and human factors research. Fig. A.1 presents an illustration of the latter model, in which the vehicle dimensions are reduced to one horizontal plane at road level: rotations about the longitudinal and lateral axis, as well as vertical translations are neglected. Three degrees of freedom remain, i.e. two translations (longitudinal and lateral) and the rotation around the vertical axis (yaw). Vehicle position is related to a non-moving set of axes OX'Y'. Forces acting upon the vehicle and the resulting translational and rotational motions will be considered in relation to a set of axes XY coupled to the vehicle. The origin of this set of axes is situated at the centre of gravity (c.g.) of the vehicle. Axes and rotations are presented in Fig. A.1 in a positive direction.

Because all driving experiments in the present study were performed with a constant speed, the presentation of the vehicle dynamics will be given now only for the lateral and steering system dynamics. Godthelp, Blaauw and Van der Horst (1982) gave a more complete overview of the instrumented car vehicle dynamics, not only in terms of a mathematical model but also on the basis of a series of field- and laboratory tests. Some of these tests will be shortly referred to in the following paragraphs.

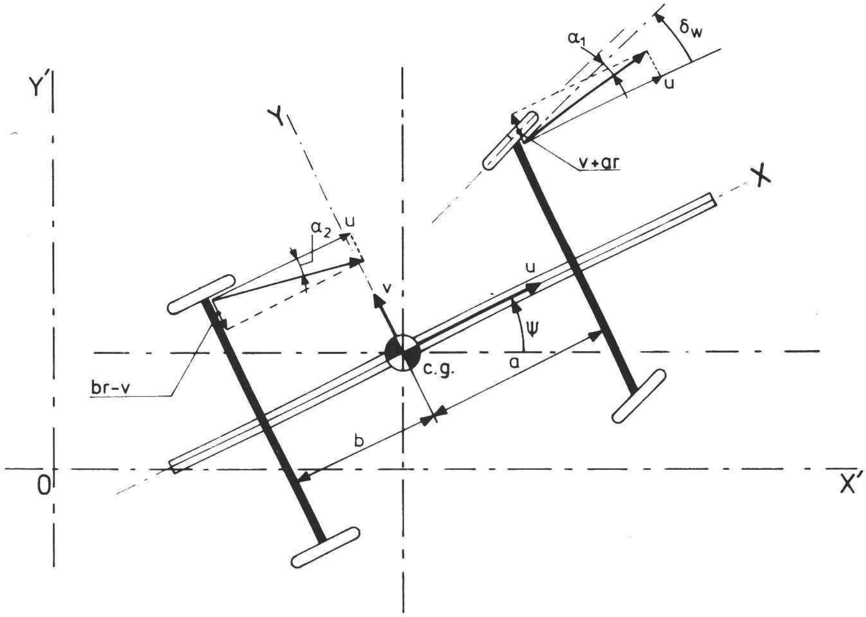

Fig. A.1 Illustration of the vehicle model.

A.2 LATERAL DYNAMICS

Vehicle behavior in lateral direction can be described by the following equations of motion[1]:

$$m(\dot{v} + ur) = Y_1 + Y_2 \tag{8}$$

$$I\dot{r} = Y_1 a - Y_2 b \,. \tag{9}$$

[1]The nomenclature is presented separately at page 146.

The lateral forces Y_1 and Y_2 in the contact area between tyre and road surface are affected by wheel load, tyre pressure and momentary side slip angles. Fig. A.1 illustrates these slip angles as they are dependent on the direction of the front and rear wheel speed vectors. After linearizing, these angles can be written as:

$$\alpha_1 = \delta_w - \frac{v + ar}{u} \tag{10}$$

$$\alpha_2 = \frac{br - v}{u} + \varepsilon \quad . \tag{11}$$

At a lateral acceleration level below 0.3 g m/s^2 the lateral tyre force can be calculated from:

$$Y_1 = C_1 \alpha_1 \tag{12}$$

$$Y_2 = C_2 \alpha_2 \quad . \tag{13}$$

The cornering stiffnesses C_1 and C_2 are influenced by tyre type, wheel load and tyre pressure. Measurements on the mass, moment of inertia and tyre properties of the instrumented car were made by the Vehicle Research Laboratory at Delft University of Technology (Timan, 1980). Table A.I gives the results of the tyre measurements.

Table A.I Wheel load and cornering stiffness of the instrumented car (Timan, 1980; Godthelp et al., 1982).

	pressure (bar)	wheel load (N)	C' (rad^{-1})	cornering stiffness (N/rad)
front tyre	1.9	3602	13.2	$1/2\ C_1 = 47553$
rear tyre	2.9	5835	9.6	$1/2\ C_2 = 56028$

The other results were:

$$a = 1.62 \quad m$$

$$b = 1.00 \quad m$$

$$m = 1924 \quad kg$$

$$I = 3315 \quad kgm^2 .$$

Because the model shown in Fig. A.1 did not account for the steering system elasticity and the roll degree of freedom, these aspects should be involved in the model by replacing the cornering stiffness C_1 and C_2 by the so-called effective cornering stiffness C_{1e} and C_{2e}.

Hence, steering system elasticity can be taken into account as an element of the front wheel effective cornering stiffness C_{1e}:

$$Y_1 = C_1 \alpha_1 = C_1 \left(\frac{\delta_s}{G} - \frac{tC_1\alpha_1}{G^2 k_s} - \frac{v + ar}{u}\right) \tag{14}$$

$$= C_{1e} \left(\frac{\delta_s}{G} - \frac{v + ar}{u}\right)$$

with:

$$C_{1e} = \frac{C_1}{1 + \frac{t}{G^2 k_s} C_1} . \tag{15}$$

In the same way roll steer effects can be involved in the effective rear wheel cornering stiffness C_{2e}:

$$Y_2 = C_2 \alpha_2 = C_2 \left(\varepsilon + \frac{br - v}{u}\right) \tag{16}$$

$$= C_{2e} \left(\frac{br - v}{u}\right)$$

with:

$$C_{2e} = \frac{C_2}{1 - \frac{\varepsilon\, lh}{a\, C_\phi} C_2} \, . \qquad (17)$$

The following data were suplied by the manufacturer:

$C_\phi = 45700$ Nm/rad

$G = 19.8$

$h = 0.40$ m

$k_s = 13$ Nm/rad

$t = 0.034$ m

$\varepsilon = 0.18.$

The equations of motion in Y- and ψ-direction (8) and (9) can now be rewritten as:

$$m(\dot{v} + ur) = \frac{C_{1e}}{G}\delta_s - \frac{C_{1e}}{u} v - \frac{C_{1e}a}{u} r - \frac{C_{2e}}{u} v + \frac{C_{2e}b}{u} r \qquad (18)$$

$$I\dot{r} = \frac{C_{1e}a}{G}\delta_s - \frac{C_{1e}a}{u} v - \frac{C_{1e}a^2}{u} r + \frac{C_{2e}b}{u} v - \frac{C_{2e}b^2}{u} r \, . \qquad (19)$$

These equations of motion can be transformed into the following transfer functions:

$$\frac{v}{\delta_s} = \frac{G_v(T_v s + 1)}{\frac{1}{\omega_r^2} s^2 + \frac{2\beta_r}{\omega_r} s + 1} \qquad (20)$$

$$\frac{r}{\delta_s} = \frac{G_r(T_r s + 1)}{\frac{1}{\omega_r^2} s^2 + \frac{2\beta_r}{\omega_r} s + 1} . \tag{1}$$

Steady state cornering tests were performed with the instrumented car to determine the yaw rate gain G_r. The vehicle stability factor K is an important element of this gain:

$$G_r = (\frac{r}{\delta_s})_{ss} = \frac{\frac{u}{G\,l}}{1 + Ku^2} . \tag{21}$$

The steering-wheel angle for steady state cornering can be derived from this relation:

$$\delta_s = \frac{r\,G\,l}{u}(1 + Ku^2) = \frac{G\,l}{R}(1 + Ku^2) . \tag{22}$$

The solid dots in Fig. A.2 present the results of the steering-wheel angle measurements in the steady state cornering test for different speeds and for a curve with radius R = 200 m. From these data the stability factor K was determined by calculating a linear regression line:

$$K = 19.46 \,.\, 10^{-4}\ s^2/m^2 .$$

In addition to the steady state cornering tests, a series of random steering tests was conducted, which resulted in a transfer function description in the frequency domain for different speeds. On the basis of a total set of data i.e. those supplied by the car manufacturer (Jaksch, 1973a) and those resulting from the field and laboratory measurements, the following effective cornering stiffnesses were derived (see Blaauw, 1984):

$$C_{1e} = 58103 \text{ N/rad}$$

$$C_{2e} = 157774 \text{ N/rad} .$$

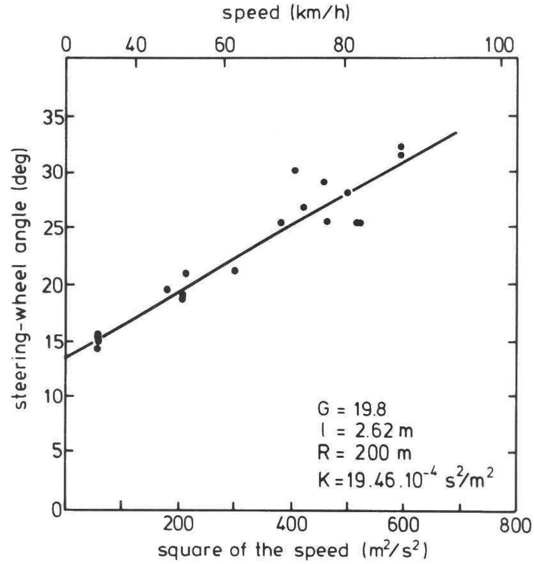

Fig. A.2 Relation between steering-wheel angle and vehicle speed for steady state cornering, curve radius R = 200 m.

The combined set of data allowed us to calculate the transfer function parameters, which are presented in Table A.II.

Table A.II Yaw rate to steering-wheel angle transfer function parameters for different speeds.

speed (km/h)	G_r (1/s)	T_r (s)	ω_r (rad/s)	β_r (-)
20	0.100	0.042	18.39	1.01
40	0.172	0.084	9.96	0.93
60	0.207	0.126	7.40	0.84
80	0.216	0.167	6.26	0.74
100	0.212	0.209	5.66	0.66
120	0.201	0.251	5.30	0.58

A.3 STEERING SYSTEM DYNAMICS

The steering system dynamics were not implemented as a separate part of the mathematical model as it was described in the previous paragraph. Therefore a compensation in the front wheel cornering stiffness was necessary in order to match the model with field data about the instrumented car dynamics. However, in the driving simulator, this compensation is superfluous, because the steering system dynamics were also modelled. In this submodel the relation between front wheel angle and steering-wheel angle as well as the steering torque to be generated by the torque motor were computed by means of equations of motion which describe the dynamics of the steering system. A mass-spring representation as it is used for this purpose is shown in Fig. A.3.

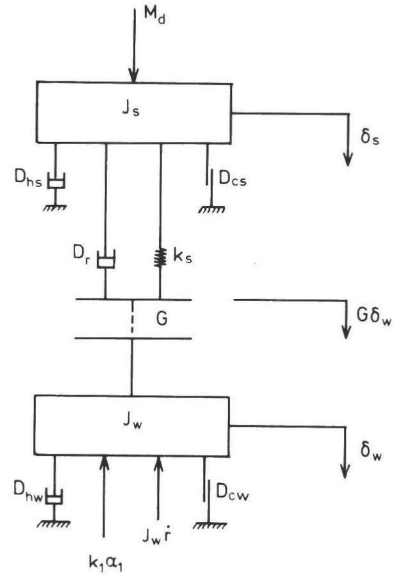

Fig. A.3 The mass-spring representation of the steering system.

The equations of motion of this system are:

$$J_w \ddot{\delta}_w = k_s G(\delta_s - G\,\delta_w) + D_r G(\dot{\delta}_s - G\,\dot{\delta}_w) + \tag{23}$$

$$- D_{hw} \dot{\delta}_w - k_1(\delta_w - \frac{v}{u} - \frac{ar}{u}) - J_w \dot{r} - D_{cw} \tag{24}$$

$$J_s \ddot{\delta}_s = M_d - M_t \tag{25}$$

$$M_t = G_t\{k_s(\delta_s - G\,\delta_w) + D_{hs}\,\dot{\delta}_s + D_r(\dot{\delta}_s - G\,\dot{\delta}_w)\} + D_{cs} \,. \tag{26}$$

The steering torque to steering-wheel angle transfer function can mainly be characterised by its steady state value i.e. the steering torque gradient:

$$(\frac{M_t}{\delta_s})_{ss} = G_t \frac{m\,b\,t\,u^2}{G^2\,l^2(1 + Ku^2)} \,. \tag{2}$$

Steering ratio G and steering system spring constant k_s are known from data supplied by the manufacturer (Jaksch, 1973a). Estimates of the steering system damping coefficients were made on the basis of Jaksch (1973b). Front wheel trail and self-aligning torque were chosen in correspondence with the results of Par. A.2, i.e. about the relation between the front tyre effective cornering stiffness C_{1e} and the tyre stiffness C_1. The steering torque coefficient G_t was used in the Experiments III and V to vary the steering torque gradient without effecting the other steering system dynamics. The total set of data resulted in the following values for the steering system parameters:

G	=	19.8	
k_s	=	13.0	Nm/rad
J_w	=	1.0	kg m^2
k_1	=	3246.0	Nm/rad
t	=	0.034	m

D_{cw} = 0 Nm

D_{cs} = 0 Nm

D_{hs} = 0.35 Nm s/rad

D_{r} = 1.0 Nm s/rad

D_{hw} = 100.0 Nm s/rad

The lateral and steering system dynamics, i.e. the mathematical models as presented in the Par. A.2 and A.3 have been integrated and transformed into an analog computer model. The coefficients of this model were calculated from the instrumented car and steering system parameters as presented in these paragraphs.

N O M E N C L A T U R E

a	Distance between vehicle centre of gravity (c.g.) and front axis	m
a_{la}	Vehicle lateral acceleration	m/s^2
b	Distance between vehicle c.g. and rear axis	m
c_r	Road curvature	km^{-1}
c_v	Vehicle path curvature	km^{-1}
C_1	Cornering stiffness front wheel tires	N/rad
C_{1e}	Effective cornering stiffness front wheel tires	N/rad
C_2	Cornering stiffness rear wheel tires	N/rad
C_{2e}	Effective cornering stiffness rear wheel tires	N/rad
C'	Cornering coefficient per unit wheel load	rad^{-1}
C	Vehicle roll stiffness	Nm/rad
d	Distance between vehicle c.q. and aimpoint	m
D	Manoeuvre distance in lane change	m
D_{cs}	Steering wheel coulomb friction	Nm
D_{cw}	Front wheel coulomb friction	Nm
D_{hs}	Steering-wheel damping related to $\dot{\delta}_s$	Nm s
D_{hw}	Front wheel damping related to $\dot{\delta}_w$	Nm s
D_r	Steering-wheel damping related to $(\dot{\delta}_s - G\dot{\delta}_w)$	Nm s
g	Gravitational acceleration	9.81 m/s^2
G	Steering system gear ratio	-
G_{la}	Lateral acceleration gain	m/s^2
G_r	Yaw rate gain	1/s

G_t	Steering torque coefficient	
G_v	Lateral velocity gain	m/s
h	Roll axis height	m
I	Vehicle moment of inertia around Z-axis	$kg\ m^2$
J_s	Steering wheel moment of inertia	$kg\ m^2$
J_w	Front wheel moment of inertia around king pin	$kg\ m^2$
k_s	Steering system stiffness	Nm/rad
k_1	Self aligning torque	Nm/rad
K	Stability factor	s^2/m^2
l	Wheel base	m
l_f	Distance between c.g. and vehicle front	m
m	Vehicle mass	kg
M_d	Driver steering-wheel torque	Nm
M_t	Steering-wheel torque to be generated with the torque motor in the simulator	Nm
N_{y_1}	Moment around Z-axis due to Y_1	Nm
N_{y_2}	Moment around Z-axis due to Y_2	Nm
r	Yaw rate (in -direction)	rad/s
r_w	Tire effective radius	m
R	Radius of the vehicle path	m
s	La Place operator	1/s
t	Front wheel trail (mechanical + pneumatic)	m
t_b	Moment of curve begin	s
t_e	Moment of curve end	s

t_s	Moment of switching from error-neglection to error correction	s
t_{sa}	Moment of δ_{sa}	s
t_{sc}	Moment of δ_{sc}	s
t_{se}	Lane change moment of manoeuvre ending	s
t_{sl}	Moment of δ_{sl}	s
t_{sr}	Moment of δ_{sr}	s
t	Lane change moment of maximum heading angle	s
TLC	Time-to Line-Crossing	s
TLC_e	TLC at end of occlusion period	s
TLC_s	TLC at t_s	s
TLC_t	Sum of TLC_{sa} and t_{sa}	s
TLC_{sa}	TLC at t_{sa}	s
TLC_{min}	Minimum TLC	s
TLC_{tot}	Sum of T_{occ} and TLC_e	s
T_m	Movement time in reproduction experiment II	s
T_{occ}	Occlusion time	s
T_r	Yaw rate time constant	s
T_f	Steering-wheel fixation time	s
T_v	Lateral speed time constant	s
u	Vehicle forward speed (in X-direction)	m/s
v	Vehicle lateral speed (in Y-direction)	m/s
w_r	Road width	m
w_v	Vehicle width	m

w_{ve}	Effective vehicle width	m
y	Lateral position	m
y_{min}	Minimum lateral distance	m
y_s	Lateral position at t_s	m
Y_1	Lateral tire force, front wheels	N
Y_2	Lateral tire force, rear wheels	N
α_1	Slip angle front wheels	rad
α_2	Slip angle rear wheels	rad
β_{la}	Lateral acceleration numerator damping coefficient	-
β_r	Yaw rate damping coefficient	-
δ_s	Steering-wheel angle	rad
δ_{sa}	Curve entrance anticipatory steering-wheel angle	rad
δ_{sc}	Amplitude of the initial steering-wheel action at the begin of an error-correction period	rad
δ_{se}	Steering-wheel angle error	rad
δ_{sl}	Lane change maximum steering-wheel angle to the left	rad
δ_{sr}	Lane change maximum steering-wheel angle to the right	rad
δ_w	Front wheel steering angle	rad
ε	Roll steer coefficient rear axis	-
ϕ	Roll angle	rad
ψ	Heading angle	rad
ψ_m	Lane change maximum heading angle	rad
ω_{la}	Lateral acceleration numerator frequency	rad/s
ω_r	Yaw rate natural frequency	rad/s

LIST OF ABBREVIATIONS

ANOVA	analysis of variance
CU	road curvature
DI	curvature direction
F	frequency
LT	looking time
OCC	occlusion
Q	quartile
R	reproduction
S (Chapter 4)	stimulus
S (others)	subject
Ss	subjects
ss	steady state
SA	steering-wheel angle amplitude
SD	standard deviation
SF	steering force
SR	stimulus/reproduction

S A M E N V A T T I N G

De meeste beschrijvingen van voertuigbesturing zijn gebaseerd op de veronderstelling dat de bestuurder continu koersfouten minimaliseert en daarbij steeds gebruik maakt van visuele, teruggekoppelde informatie. M.a.w. de bestuurder wordt verondersteld steeds alle aandacht aan de stuurtaak te besteden. Dergelijke beschrijvingen van stuurgedrag zijn daarom in principe ongeschikt iets te verklaren van de mate waarin de bestuurder tijd kan besteden aan andere aspecten van de rijtaak, zoals bijv. de snelheidsregeltaak, de waarneming van ander verkeer, borden e.d. Toch is het een bekend gegeven dat dergelijke, niet rechtstreeks aan de voertuigbesturing gerelateerde subtaken een essentieel bestanddeel vormen van de totale rijtaak, zelfs zodanig dat ze op bepaalde momenten sterk kunnen interfereren met de stuurtaak. Een consequentie kan bijv. zijn dat de bestuurder gedwongen is optredende koersfouten tijdelijk te verwaarlozen en/of de ogen van de weg af te wenden waardoor de directe visuele terugkoppeling over de voertuigbeweging wordt onderbroken. Dit proefschrift gaat in op deze laatste vormen van stuurgedrag. Het beoogt daarbij inzicht te verschaffen in de mate waarin de besturingstaak toestaat dat koersfouten tijdelijk worden verwaarloosd en/of de visuele informatie wordt onderbroken.

Gesteld wordt dat de periode waarin een voertuig zonder directe visuele informatie bestuurd kan worden in principe afhangt van:

1. de nauwkeurigheid van de tijdens deze periode gegenereerde stuurhandelingen;
2. de tijd gedurende welke koersfouten eventueel verwaarloosd kunnen worden, waarin dus tijdelijk niet wordt gestuurd.

Deze beide aspecten werden experimenteel onderzocht, waarbij gebruik werd gemaakt van een speciaal daartoe ontwikkelde tijdsdomein-analyse van het rijgedrag.

De nauwkeurigheid van zonder visuele terugkoppeling gegenereerde stuurhandelingen hangt sterk af van de mate van voorspelbaarheid van de taak. Indien de bestuurder beschikt over aanzienlijke ervaring met een bepaald voertuig en een uit te voeren manoeuvre kan de taak een sterk gepreprogrammeerd karakter hebben. De voorspelbaarheid van de taak kan ook minder zijn bijv. indien alleen op basis van momentane preview geanticipeerd kan worden. In beide gevallen kan de bestuurder echter een vrij goede schatting maken van de in de komende tijdsperiode te genereren stuurhoeken en deze schatting kan gebruikt worden tijdens een onderbreking van de visuele

informatie. De uiteindelijke nauwkeurigheid van zo'n handeling zal echter altijd begrensd zijn vanwege de onnauwkeurigheid van het motorisch systeem. In eerste instantie werd daarom ingegaan op de vraag of de lineaire relatie tussen handelingssnelheid en handelingsnauwkeurigheid voor stapvormige handbewegingen met visuele terugkoppeling, bekend als Fitts' law, eveneens geldt voor continue bewegingen zonder visuele terugkoppeling. Hiertoe werd de nauwkeurigheid van het genereren van enkelvoudige sinusvormige bewegingen onderzocht in een z.g. reproductie-experiment, waarin beurtelings mét en zonder visuele terugkoppeling een handelingspatroon werd uitgevoerd. Door variatie van bewegingsamplitude en -frequentie kon worden aangetoond dat mét visuele terugkoppeling de amplitude-onnauwkeurigheid inderdaad lineair toeneemt met de handelingssnelheid. Bij afwezigheid van visuele terugkoppeling blijkt de onnauwkeurigheid echter alleen afhankelijk te zijn van de bewegingsamplitude en niet van de snelheid. De bewegingssnelheid lijkt dus vooral van invloed op het gebruik van visuele terugkoppeling. M.a.w. bij hogere bewegingssnelheden wordt het gebruik van visuele informatie a.h.w. onderdrukt, waardoor de nauwkeurigheid afneemt. Het wordt hiermee begrijpelijk dat snelheidseffecten geen overwegende invloed zullen hebben op bewegingen waarin de visuele terugkoppeling volledig afwezig is.

De resultaten van het reproductie-experiment werden op hun betekenis voor stuurgedrag in voertuigen onderzocht in twee voertuigbesturingstaken, t.w. het wisselen van rijstrook en het inrijden van bogen. In een groot aantal ritten werd hierbij de visuele informatie aan het begin van de manoeuvre onderbroken d.m.v. occlusie-technieken. De tijdens zo'n onderbreking gegenereerde stuuractie kan worden beschouwd als het uitvloeisel van een informatieverwerkingsproces, waarin met name de drie volgende fasen onderscheiden kunnen worden:

a. de waarneming van de gewenste koers;
b. de transformatie van geschatte koers naar gewenste stuuractie;
c. de transformatie van gewenste stuuractie naar feitelijke handeling.

In het reproductie-experiment werd met name fase c beschreven. Verwacht werd dat in feitelijke besturingstaken, afhankelijk van de voorspelbaarheid, de onnauwkeurigheid van de fasen a en b zullen worden toegevoegd aan die van fase c. In dit verband werd aangenomen dat in een rijtaak met een sterk gepreprogrammeerd karakter de stuurfouten nog vnl. een gevolg zullen zijn van fase c, terwijl in een preview taak de onnauwkeurigheden zullen toenemen. De experimentele resultaten bevestigen deze redenering volledig. Bij het uitvoeren van de rijstrookwisseling, waarvoor een enkelvoudige, sinusvormige stuurbeweging nodig is (zoals in het reproductie-experiment) en welke door herhaling een sterk gepreprogrammeerd karakter had, traden amplitude onnauwkeurigheden op welke volledig overeenstemden met die uit het reproductie-experiment. In de preview-taak, d.i. het inrijden van een boog, waren de onnauwkeurigheden inderdaad groter. In beide taken werd overigens bevestigd dat de amplitude onnauwkeurigheid lineair toeneemt met de benodigde stuurhoek.

Alvorens de betekenis van deze resultaten voor het stuurgedrag in voertuigen te bespreken, wordt ingegaan op een tijdsdomein-beschrijving van rijgedrag waarmee de mogelijkheid om koersfouten te verwaarlozen kan worden gekwantificeerd. Deze beschrijving werd ontwikkeld door gebruik te maken van de voorspellingstechnieken welke worden toegepast in z.g. preview-predictor modellen. Hierbij wordt op ieder moment de toekomstige voertuigbaan voorspeld op grond van de veronderstelling dat de stuurwielpositie niet verandert tijdens de voorspelperiode. Op grond van zo'n voorspelling kan de Time-to-Line-Crossing (TLC) worden berekend, d.i. de tijd die (fictief) verloopt totdat de rand van de rijstrook wordt bereikt. De TLC berekening kan worden uitgevoerd op grond van gegevens welke worden gemeten in een rijexperiment. Voor ieder meetmoment wordt op basis van de momentane laterale positie, koershoek, snelheid en stuurwielpositie de TLC berekend. De voertuig- en wegeigenschappen kunnen in de TLC programmatuur worden ingevoerd. De ontwikkeling van het TLC-concept sluit direct aan bij de doelstelling van dit proefschrift, nl. een kwantitatieve beschrijving te geven van de mogelijkheid koersfouten te verwaarlozen. De mogelijkheden van het TLC-concept bleken o.a. in een experiment waarin het koershouden op een rechte weg werd onderzocht in ritten met constante snelheden variërend tussen 20 en 120 km/h. Een klassieke beschrijving van de resultaten in standaard-deviatie van de laterale positie toonde geen snelheidseffecten, terwijl de tijdsdomein analyse duidelijk illustreerde hoe TLC afneemt bij hogere snelheid. Zoals ook uit het navolgende zal blijken is het TLC-concept uitermate geschikt om inzicht te verschaffen in de mate waarin koersfouten kunnen worden verwaarloosd en/of de visuele informatie kan worden onderbroken.

Ook de resultaten van het experiment, waarin de stuurnauwkeurigheid bij het inrijden van bogen werd gemeten, kunnen beter worden geïnterpreteerd met behulp van TLC. Als algemeen resultaat kwam uit dit experiment naar voren dat de stuurnauwkeurigheid afneemt bij grotere stuurhoeken. Bij het ingaan van een boog impliceert dit dat de stuurfouten groter zijn naarmate de boog scherper is. Op grond van deze redenering werden de volgende hypothesen geformuleerd: 1) de noodzaak tot het uitvoeren van stuurcorrecties na het insturen van de boog zal het sterkst zijn naarmate de boog scherper is, en 2) TLC op het moment juist na het insturen van de boog is korter naarmate de boog scherper is. Beide hypothesen werden bevestigd, waarbij met name de TLC analyse illustreerde dat de mogelijkheid om koersfouten tijdelijk te verwaarlozen het minste is in scherpe bogen. Hiermee geeft deze analyse dus een verklaring voor het feit dat scherpere bogen meer aandacht vergen.

Zowel bij de rijstrookwisseling als bij het inrijden van bogen bleek dat bestuurders vrij goed in staat zijn hun voertuig tijdelijk zonder directe visuele terugkoppeling te besturen. Het werd echter eveneens duidelijk dat uiteindelijk steeds visuele informatie en correctie van koersfouten nodig zijn om het voertuig binnen de beschikbare ruimte op de weg te houden. In dit verband resteren nog twee vragen: 1) hoe lang is een bestuurder feitelijk bereid het voertuig zonder visuele informatie te besturen, en 2) hoe lang is de bestuurder bereid koersfouten te negeren, zodanig dat de rand van de rijstrook net niet wordt overschreden.

De eerste vraag werd beantwoord door het meten van de door bestuurders gekozen occlusietijden bij het koershouden op een rechte weg, waarbij gereden werd met constante snelheden variërend tussen 20 en 120 km/h. M.b.t. de duur van de occlusieperioden werden een tweetal hypothesen geformuleerd: 1) de occlusietijden zullen langer zijn naarmate de TLC toeneemt, en 2) naarmate de amplitude van de tijdens de occlusieperioden gemaakte stuurcorrecties groter is - en daarmee dus de onnauwkeurigheid - neemt de occlusietijd af. Ook deze hypothesen werden beide bevestigd. De occlusietijden correspondeerden sterk met TLC en waren bovendien korter naarmate de tijdens de betreffende occlusieperiode uitgevoerde stuurcorrecties groter waren. De occlusie-strategie kon verder worden beschreven door combinatie van de occlusietijd en de TLC aan het eind van het betreffende occlusie-interval. De som van deze twee tijden kan worden beschouwd als de feitelijk beschikbare tijd totdat de rand van de rijstrook zou zijn bereikt. Een analyse van de ratio van occlusietijd en beschikbare tijd geeft aan dat bestuurders voor alle snelheden ongeveer 40% van de beschikbare tijd aan occlusie "besteden" en dus niet steeds een vaste absolute hoeveelheid tijd overhouden aan het einde van het occlusie-interval. Dit gegeven kan worden vergeleken met de resultaten van het laatste experiment van dit proefschrift, waarbij bestuurders geïnstrueerd werden opzettelijk koersfouten te negeren en wel zodanig dat de rand van de rijstrook net niet wordt overschreden. Hierbij bleek dat de TLC op het moment van ingrijpen constant was over een groot snelheidsgebied (20-100 km/h). Een vergelijking met de eerdere resultaten leert hier dus dat er een fundamenteel verschil bestaat tussen de strategie, welke wordt gehanteerd bij het rijden zonder visuele informatie en die bij het negeren van koersfouten. In het eerste geval heeft de bestuurder slechts beschikking over een schatting van de voertuigpositie en de TLC met als gevolg dat gekozen wordt voor de strategie om de informatie te vernieuwen nadat een bepaalde fractie van de beschikbare tijd is verstreken. In het tweede geval, d.i. bij het negeren van koersfouten, beschikt de bestuurder continu over informatie m.b.t. de voertuigpositie ten opzichte van de rand van de rijstrook, hetgeen leidt tot een strategie, waarbij eerst wordt ingegrepen wanneer TLC een vaste waarde heeft bereikt.

De conclusies van de in dit proefschrift beschreven experimenten kunnen thans als volgt worden samengevat:

1. De amplitude-onnauwkeurigheid van stuurbewegingen, welke worden gemaakt zonder directe visuele terugkoppeling, neemt ongeveer lineair toe met de bewegingsamplitude. De lineaire relatie tussen bewegingssnelheid en bewegingsonnauwkeurigheid, zoals bekend voor stuurbewegingen mét visuele terugkoppeling, geldt niet voor bewegingen zonder visuele terugkoppeling.
2. In geval van voertuigbesturingstaken met een sterk gepreprogrammeerd karakter, draagt stuurkracht er toe bij dat de nauwkeurigheid van de stuurbeweging verbetert.
3. De nauwkeurigheid van de stuurbewegingen in een preview taak (het inrijden van een boog) is minder dan die in een gepreprogrammeerde taak (rijstrookwisseling).
4. Bestuurders zijn goed in staat de voor een bepaalde boog benodigde stuurhoek te schatten en daarbij rekening te houden met effecten van boogkromming en rijsnelheid.
5. De nauwkeurigheid van de bij het ingaan van een boog gegenereerde stuurbeweging neemt af naarmate de boog scherper is. Als gevolg hiervan is de noodzaak van stuurcorrecties tijdens het rijden in de boog het sterkst bij scherpe bogen, terwijl daarbij ook de laagste TLC waarden optreden.
6. De bij het rijden op een rechte weg door bestuurders gekozen occlusietijden zijn sterk gerelateerd aan TLC.
7. De bij het rijden op een rechte weg door bestuurders gekozen occlusietijden kunnen m.b.v. TLC beschreven worden als een constant percentage (40%) van de beschikbare tijd. Dit resultaat is geldig bij verschillende snelheden (20-120 km/h).
8. De strategie die bestuurders hanteren bij het bewust verwaarlozen van koersfouten kan goed beschreven worden m.b.v. TLC. Bij een TLC van ongeveer 1.3 s voor het bereiken van de rand van de rijstrook wordt overgegaan op koerscorrecties; ook dit resultaat is geldig over een groot snelheidsgebied (20-100 km/h).

9. Combinatie van 7 en 8 leidt tot de conclusie dat de strategie om een vast percentage van de beschikbare tijd over te houden, dan wel een vaste absolute hoeveelheid tijd, sterk bepaald wordt door de mate van onzekerheid over de voertuigbeweging.
10. TLC vormt een maat voor rijgedrag waarin de voertuigbeweging en het stuurgedrag geïntegreerd worden beschreven en waarbij bovendien rekening wordt gehouden met voertuig- en wegkenmerken. Als zodanig is TLC geschikt om rijgedrag op rechte wegen en in bogen te beschrijven en daarbij de voertuig- en/of wegeigenschappen te optimaliseren.

Aan het eind van dit proefschrift wordt tenslotte aangegeven hoe de resultaten kunnen worden toegepast. Met name wordt gewezen op de mogelijkheden van TLC als beschrijvingsmaat van rijgedrag. Het feit dat TLC de voertuigbeweging en het stuurgedrag in combinatie met voertuig- en wegkenmerken geïntegreerd beschrijft, lijkt een groot voordeel. Enerzijds biedt dit de gelegenheid om deze methode toe te passen bij het optimaliseren van voertuigeigenschappen. Daarnaast en in combinatie daarmee kunnen de effecten van wegkenmerken en snelheidsgedrag worden geëvalueerd op een wijze die voorheen niet mogelijk was, nl. in onderlinge samenhang. TLC is daarnaast tevens geschikt om rijgedrag in termen van risicogedrag te beschrijven. Tenslotte geldt dat de TLC methode en de gepresenteerde onderzoekresultaten gezamenlijk de voornaamste bouwstenen vormen voor een strategiemodel van stuurgedrag waarin de stuurtaak wordt opgevat als een serieel proces en waarmee het rijgedrag op rechte wegen en in bogen op zinvolle wijze kan worden nagebootst.

S U M M A R Y

Most of the available vehicle control models are based on the fundamental assumption that drivers steer their vehicle in a continuous error-correction mode with permanent visual feedback, i.e. closed loop. However, as it is commonly accepted, driving cannot be considered as such a continuous closed loop task. On the one hand, it can be argued that under many circumstances driving does not require permanent path error control, whereas on the other hand, the driver may be forced, temporarily, to pay (visual) attention to other driving task aspects which, by definition, makes it impossible to steer the vehicle under permanent visual feedback. Therefore, the purpose of this thesis is to enlarge our understanding about the potential role of visually open loop strategies and error-neglection in vehicle control.

The study started from the assumption that the time available for a driver to control his vehicle in an open loop mode, i.e. without immediate visual feedback, largely depends on two factors:

- The accuracy of the open loop generated steering-wheel action,
- the time available for error-neglection.

Regarding the accuracy of manual control actions it was argued that anticipation strategies based on preprogramming and/or preview may give the driver an almost perfect knowledge of the steering actions to be made in a particular manoeuvre, even during periods without immediate visual feedback. Ultimate accuracy of open loop steering actions, however, will be limited because of inaccuracies in the motor system. With respect to this point the first question raised was, whether the linear speed/accuracy trade-off as known for closed loop, step movements would also be valid for open loop, continuous control actions. The results of a reproduction experiment, in which subjects tracked movement patterns consisting of a single sine-wave under both open and closed loop conditions, indicated this not to be true. For closed loop conditions, amplitude accuracy indeed appeared to be linearly dependent on movement velocity, thus illustrating the validity of the empirical relationship, known as Fitts' law, for continuous, closed loop movements. However, for open loop conditions this relation was not found: In that case the results indicated the amplitude accuracy to be only dependent on movement amplitude and not on velocity. This finding was confirmed in two vehicle control studies: A precognitive, lane change task requiring a steering-wheel movement similar to that in the reproduction experiment, resulted in steering-wheel amplitude inaccuracies

of the same absolute level as those found in the reproduction experiment. Furthermore, a preview curve entrance task resulted in larger amplitude inaccuracies as compared to the lane change task. Both data sets also confirmed the suggestion that inaccuracies increase about linearly with movement amplitude.

The time available for error-neglection was analysed by application of the path prediction techniques as commonly used in preview-predictor models. Based on this technique the Time-to-Line-Crossing (TLC) can be calculated, representing the time available for the driver to neglect path errors, until the moment in time at which any part reaches one of the lane boundaries. The TLC concept answers directly to one of the main purposes of this study, i.e. to quantify the potential role of path error-neglection in driving. As such, TLC could very well be used to answer two important questions: First, how long is a driver actually willing to control his vehicle without immediate visual feedback and second, how long is a driver ultimately allowed to wait before switching over to the error-correction mode.

The first of these questions was investigated by measuring drivers' self-chosen occlusion times in a straight lane keeping task with constant speeds varying between 20 and 120 km/h. Occlusion times appeared to correspond closely with TLC. In the same analysis it was shown that drivers choose occlusion times, which can be described as a constant fraction, i.e. 40%, of the available time. This result was compared with the findings of the last experiment of this thesis, in which drivers were instructed to neglect path errors and to switch over to path error-correction only at that moment in time, the vehicle motion could still comfortably be corrected to prevent a crossing of the lane boundary. The strategy adopted by drivers in this task, is to switch over to error-correction at an about constant TLC distance from the lane boundary. Together the results on open loop control and error-neglection indicate that the driver's timing strategy, i.e. leaving a fraction of time or a constant amount of time, is strongly related to the degree of uncertainty about the vehicle trajectory.

Finally it is shown that the results of this thesis may find their way in various areas of application. The TLC-concept seems particularly suited to describe driving strategy in straight lane keeping as well as curve negotiation. As such this time-domain analysis of driving may be helpful to analyse drivers' risk taking behavior and to optimize vehicle as well as roadway characteristics. Furthermore, it is argued that the TLC analysis can be applied to develop a serial strategy model of driving, which describes the sequential distribution of a driver's combined use of open and closed loop and/or error-neglection and error-correction strategies.

C U R R I C U L U M   V I T A E

De auteur werd geboren op 8 augustus 1947 te Rotterdam. Na het behalen van het HBS-B diploma aan het Johannes Calvijn Lyceum te Rotterdam werd in 1965 een begin gemaakt met de studie in de werktuigbouwkunde aan de Technische Hogeschool Delft. In aansluting op het kandidaatsexamen volgde een specialisatie in de voertuigtechniek. In het kader van een assistentschap bij het Instituut voor Wegtransportmiddelen TNO verrichtte hij in die tijd onderzoek naar de stabiliteit van personenauto-aanhangwagen combinaties. In 1971 werd het doctoraal-examen afgelegd en werd aansluitend begonnen met de vervulling van de militaire dienstplicht als gedetacheerde bij het Instituut voor Zintuigfysiologie TNO, waar hij in 1973 in dienst trad. Na aanvankelijk betrokken te zijn geweest bij de ontwikkeling van de rijsimulator, specialiseerde hij zich op het gebied van de verkeersergonomie met als interesse o.a. visuele geleiding en besturing van voertuigen.