CAR DRIVING AS A SUPERVISORY CONTROL TASK

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SUMMARY

In the literature automobile driving has almost exclusively been modeled on the basis of the lateral position of the car inside the traffic lane, i.e. lateral vehicle control, and, to a lesser extent, on the basis of the velocity of the car, i.e. longitudinal vehicle control. Thereto, it is assumed that the drivers are continuously fully attentive in order to minimize all path deviations. However, this assumption is in contradiction with actual driving, in which drivers normally do not attempt to compensate for all path deviations because, for instance, drivers are confronted with more tasks to perform simultaneously. The models developed for vehicle control are valuable for driving situations in which lateral control requires all the driver's attention, for example during the compensation of heavy sidewind disturbances or during driving a strongly curved road. Normally, however, these situations are not frequently met. Therefore, a description of driving should take its starting point differently.

In this thesis new approaches are discussed by considering driving within the context of supervisory control. This means that the driver is assumed to supervise the singular tasks like lateral and longitudinal vehicle control, each of which is assumed to be autonomously controlled to a certain extent. The driver only intervenes when the conditions of a singular task are forcing him to do so. In this approach an integral description of multitask performance in driving becomes possible.

In the so-called Supervisory Driver Model a distinction is made between an observation/prediction block, a control block and a decision-making block. As criteria for the evaluation of driving are taken 1) driving performance in terms of the variations in the lateral position and yaw rate of the vehicle on the road, 2) driver's observation strategy in terms of a "free time" when it is not necessary to observe lateral vehicle control, and 3) driver's control strategy in terms of the amplitudes and frequencies of the steering-wheel movements.

In this thesis a description is given of supervisory driving for lateral vehicle control in a relatively simple driving situation, i.e. driving on a straight motorway, without sidewind disturbances and without other traffic. Preceding these experiments, a description is given of the vehicle dynamics and the perceptual cues available for the driver.

The first experiment shows that by analyzing eye movements, drivers fixate specific road objects, like markings and pavement, only quite

infrequently, and also that they are often looking above the horizon. These results already suggest that lateral control does not ask for continuous foveal visual information. In a second experiment, visual information on lateral vehicle control is experimentally reduced by instructing drivers "to scan the off-road environment and to report on what is seen". Driving of skilled and unskilled drivers was studied because it was assumed that both groups would considerably differ in the use of the perceptual cues. Moreover, task demands were varied by introducing in addition the longitudinal instruction to drive with a constant velocity of 100 km/h. It is shown that in conditions creating a minimum level of attention for lateral vehicle control, both skilled and unskilled drivers show an acceptable lateral control performance, i.e. drivers stay within their lane, although variations in lateral control were larger than in other conditions. Differences in the amplitudes and frequencies of the steering-wheel movements indeed indicate that the inexperienced drivers are less skilled than the experienced drivers in combining the demands of the various tasks.

The Supervisory Driver Model approach has in addition been used in a series of experiments to investigate the relation between lateral vehicle control and the available perceptual cues, as a function of task demands and driving skill. The results show that experienced drivers have learned to perform better when observing and predicting the lateral speed cue. Moreover, it is indicated that the yaw rate cue and/or both lateral acceleration and yaw acceleration cues are already used in an early stage of driving practice. When the driver has to perform more tasks simultaneously ("multitask driving"), for instance when he has to drive with a particular speed or when he drives under deteriorated conditions (fog, night-driving), the results show improved lateral control for experienced drivers, being a result of self-paced higher task demands. In general, the inexperienced drivers then have a similar or worse lateral control performance. Larger steering-wheel movements, in combination with a shift in the steering-wheel frequencies, again reflect less skills to combine the various tasks of driving.

In another series of experiments the timing aspects of driver's observations are investigated with respect to lateral vehicle control, in order to establish when and how long, drivers allow themselves to observe aspects beyond lateral control. To do so, the Supervisory Driver Model is used first, to predict this free time in relation to the use of the perceptual cues, and second, to measure this free time, or occlusion time, when drivers drove with the visual occlusion technique. Thereto, drivers can obtain visual information on lateral vehicle control only on request.

In general, it is found that driving performance during occlusion is not very much affected in relation to multitask or deteriorated driving conditions. However, drivers' observation strategy shows that the skilled drivers choose longer occlusion times than the unskilled drivers for comparable levels of driving performance. It is also found that the skilled drivers adapt with their observation strategy better than the unskilled drivers, by having more observation transfers during multitask driving and deteriorated driving conditions.

In a final chapter, the value of the criteria for the description of supervisory car driving, is studied during the evaluation of various delineation systems in practice. This study is presented as a general example for the study of road and car designs. The recommendations for the application of the delineation systems clearly show that drivers' observation strategy in terms of the free times, and drivers' control strategy in terms of the amplitudes and frequencies of the steering-wheel movements, form essential criteria in addition to the description of lateral control performance during everyday, multitask driving.

HET AUTORIJDEN ALS SUPERVISIETAAK

SAMENVATTING

Bij het kwantitatief beschrijven en voorspellen van het rijgedrag van automobilisten wordt in de literatuur de nadruk gelegd op een analyse van de positieregeling op de weg (laterale regeltaak) en, in veel mindere mate, op de snelheidsregeling (longitudinale regeltaak). Hierbij wordt er vrijwel uitsluitend van uitgegaan dat de bestuurder zo'n deeltaak met maximale aandacht uitvoert om alle optredende afwijkingen te minimaliseren. Dit uitgangspunt is echter duidelijk strijdig met de feitelijke rijtaakuitvoering waarbij er niet naar wordt gestreefd om alle fouten weg te regelen en waarbij bovendien vaak meer dan één deeltaak uitgevoerd moet worden. De in het verleden ontwikkelde beschrijvingen voor het koershouden hebben hun waarde bewezen voor situaties waarbij de laterale regeltaak inderdaad vrijwel alle aandacht van de bestuurder opeist, bijvoorbeeld als gevolg van forse zijwindverstoringen en/of een snelle opeenvolging van bogen in de te volgen weg. Bij de rijpraktijk van alledag komen dergelijke situaties echter niet steeds voor en dient het bestuurdersgedrag op een andere wijze beschreven te worden.

In het proefschrift worden nieuwe mogelijkheden aangegeven door het bestuurdersgedrag op te vatten als supervisorgedrag. Hierbij treedt de bestuurder op als supervisor van min of meer autonoom verlopende deeltaken, zoals de laterale en longitudinale regeltaak, en grijpt hij slechts in indien de omstandigheden vanuit een deeltaak daartoe aanleiding geven. Binnen een dergelijk kader kunnen meer deeltaken integraal worden beschreven.

Bij de beschrijving van het bestuurdersgedrag wordt uitgegaan van het zgn. Supervisory Driver Model, waarin een onderscheid wordt gemaakt tussen een waarnemend/voorspellend, een regelend en een beslissend gedeelte. De criteria voor het beschrijven van het superviserend bestuurdersgedrag richten zich op 1) de rijprestatie in termen van spreidingen van de laterale voertuigpositie op de weg en van de gierhoeksnelheid, 2) de waarneemstrategie in termen van een 'vrije tijd' wanneer het niet nodig is om de laterale regeltaak te observeren, en 3) de regelstrategie in termen van amplituden en frequenties van de corrigerende stuurbewegingen.

In het onderzoek is volgens verschillende invalshoeken nader ingegaan op het supervisiegedrag bij het uitvoeren van de laterale regeltaak in een relatief simpele taakomgeving: rijden op een rechte autosnelweg, zonder

invloed van zijwindverstoringen of van het overige verkeer. Voorafgaand aan de serie experimenten is echter eerst een beschrijving gegeven van de voertuigdynamica en van de perceptieve cues die voor de bestuurder beschikbaar zijn.

In het eerste experiment leert een analyse van de oogbewegingspatronen dat bestuurders slechts in geringe mate hun ogen fixeren op specifieke wegkenmerken, zoals belijning, wegdek, e.d., en zelfs dat zij vrij vaak boven de horizon kijken. Deze resultaten suggereren reeds dat het voor de uitvoering van de laterale regeltaak niet nodig is om voortdurend foveale visuele informatie te verzamelen. Vervolgens is in een tweede experiment getracht om de visuele informatie over de laterale regeltaak zoveel mogelijk te beperken door de bestuurders via instructie op te dragen "zoveel mogelijk in de omgeving rond te kijken en te zeggen wat zij zien". Ervaren zowel als onervaren bestuurders zijn onderzocht vanwege de aanname dat beide groepen aanzienlijk zouden variëren in het gebruik van de perceptieve cues. Bovendien is in dit experiment de inhoud van de supervisietaak gevarieerd door bestuurders met een toegevoegde longitudinale regeltaak op te dragen met een zeer constante snelheid van 100 km/h te rijden. Aangetoond kan worden dat in die condities, waarbij met een vrijwel minimale aandacht voor de laterale regeltaak moet worden gereden, ervaren en onervaren bestuurders nog uitstekend in staat zijn om binnen de rijstrookmarkeringen te blijven en zodoende veilig te rijden, alhoewel zij grotere slingeringen in de voertuigposities vertonen dan in de andere condities. Kenmerkende verschillen in de amplituden en frequenties van de stuurbewegingen wijzen erop dat de onervaren bestuurders minder goed dan de ervaren bestuurders in staat zijn om de verschillende deeltaken te combineren.

Binnen de context van het Supervisory Driver Model is vervolgens in een serie experimenten onderzocht hoe het uitvoeren van de laterale regeltaak afhangt van de aanwezige perceptieve cues; e.e.a. afhankelijk van de rijervaring en de taakeisen. Het blijkt daarbij dat de ervaren bestuurders hebben geleerd om via het waarnemen/voorspellen van de laterale voertuigsnelheid een betere prestatie te behalen. Eveneens zijn aanwijzingen gevonden dat de gierhoeksnelheid en/of de laterale- en gierhoekversnelling reeds in een vroeg stadium van de rijpraktijk gebruikt worden. Een meervoudige rijtaak (toegevoegde longitudinale taak) of een verslechterde rijsituatie (nacht) blijkt bij de ervaren bestuurders te leiden tot een betere prestatie bij het koershouden als gevolg van zelfopgelegde, hogere taakeisen. Bij onervaren bestuurders blijkt dan over het algemeen een gelijkwaardige of slechtere prestatie op te treden. Grotere stuurbewegingen, in combinatie met een verschuiving in de stuurfrequenties, wijzen wederom op minder vaardigheden om de verschillende deeltaken te combineren.

Vervolgens is binnen de context van het Supervisory Driver Model nagegaan op welke tijdstippen bestuurders het koershouden opnieuw observeren, of anders gesteld, hoe lang bestuurders visuele aandacht aan andere aspecten kunnen besteden. Daartoe is eerst met het Supervisory Driver Model berekend hoe deze vrije tijd afhangt van het gebruik van de perceptieve cues. Vervolgens is in een aantal veldexperimenten de vrije tijd, of occlusie tijd, bepaald door de bestuurders te laten rijden met de zgn. visuele occlusietechniek. Hierbij zijn de bestuurders slechts op aanvraag in staat om naar de weg te kijken. Over het algemeen blijkt de rijprestatie tijdens occlusie niet sterk te veranderen bij een meervoudige rijtaak of bij verslechterde rijsituaties. De waarneemstrategie daarentegen, geeft aan dat ervaren bestuurders langere occlusietijden hanteren dan de onervaren bestuurders bij vergelijkbare rijprestaties. Bovendien passen de ervaren bestuurders de waarneemstrategie beter aan dan de onervaren bestuurders door tijdens meervoudige taken en verslechterde rijsituaties vaker te observeren.

In een afsluitend hoofdstuk is de waarde van de criteria voor het beschrijven van het superviserend bestuurdersgedrag nader aangegeven bij het in de praktijk beoordelen van verschillende wegmarkeringssystemen. Dit onderzoek geldt als voorbeeld voor het beoordelen van weg- of voertuigontwerpen in het algemeen. De afgeleide aanbevelingen voor het toepassen van de wegmarkeringssystemen geven aan dat de waarneemstrategie in termen van de vrije tijd, en de regelstrategie in termen van de amplituden en frequenties van de corrigerende stuurbewegingen, waardevolle criteria vormen in aanvulling op de beschrijving van de rijprestatie bij het koershouden.

1. INTRODUCTION

1.1 Purpose of the study

In everyday driving it can be frequently observed that car drivers do not continuously pay attention to the road ahead, even when they are driving with high speeds. For instance, during short periods drivers look in the rearview mirror, switch on the radio, or scan the off-road environment. However, there are also conditions, in which drivers indeed look continuously at the road ahead. These situations may occur while driving on narrow traffic lanes, under the condition of heavy sidewind disturbances when the car has relatively bad handling characteristics, or when the driver is unskilled.

Most driving studies in relation to car and road design, e.g. vehicle dynamics, sidewind effects or curve lay-out, are restricted to situations in which drivers are fully attentive to the control of one singular task, like lateral position control or velocity control during car-following. However, the more common situations of multitask driving have been less subject to experimentation.

The present study deals with an analysis of multitask driving in terms of supervisory control, in which each singular task is performed more or less automatically under supervision of the driver. To do so, the observation strategy and the control strategy, i.e. the output of the driver, and the performance, i.e. the output of the overall driver-vehicle system, are studied in relation to driving skill, task demands and perceptual cues.

In addition, it is studied when and for how long, observations have to be made for each singular task. Stated otherwise, it is described and predicted whether and when drivers allow themselves to neglect a specific task so that they are able to pay attention to other tasks or even to activities other than driving, like switching the radio or scanning the off-road environment. "Free times" are quantified with regard to the observation strategy. These free times are of vital importance for the evaluation of car and road design with respect to driver's strategy and performance. Relatively large free times suggest ample possibilities for a driver to monitor aspects beyond the task demands which may lead to the early detection and compensation of unexpected traffic events and thus serve traffic safety.

1.2 Outline

Chapter 2 presents some theoretical considerations for the study of driver's strategy and performance. A general Supervisory Driver Model is proposed which allows a description of multitask driving. This model is used as a hypothetical framework for the study of driver's strategy and performance during straight-road driving as affected by driving skill, task demands and perceptual cues. Chapter 3 gives an analysis of the dynamics of the system to be controlled in combination with a description of the perceptual cues of the driver. For lateral vehicle control these cues are associated with lateral position, lateral speed, yaw rate, lateral acceleration and yaw acceleration. A general description of the experiments is given in Chapter 4. The experimental techniques used, are, firstly, calculations with the Supervisory Driver Model simulating the driver in a simulated vehicle, and secondly, the collection of empirical data with drivers in a fixed-base simulator in the laboratory, and in an instrumented car on the road.

Chapter 5 deals with two experiments on the road illustrating the relatively undemanding task of normal straight-road driving of inexperienced and experienced drivers. Driver's observation strategy and control strategy are studied to investigate whether drivers can pay attention to other tasks, and whether in the mean time they can keep an acceptable level of lateral control performance (Experiments 1 and 2).

Chapter 6 presents driver's control strategy and performance for different task demands and driving skills, in relation to perceptual cues. Driving performance is predicted with the Supervisory Driver Model for different combinations of the cues. As a basic condition the observation and control of the lateral position cue is selected, whereas in addition the effects of several other cues are considered (Experiment 3). Empirical data are gathered on the effects of acceleration cues by comparing driving in a car on the road and in a fixed-base simulator (Experiment 4). Also, field data are obtained for driving in day and night conditions reflecting situations of deteriorated visibility (Experiment 5).

Chapter 7 deals with driver's observation strategy and performance and, more in particular, the timing aspects of driver's observations in relation to task demands, driving skills and perceptual cues. Again, the Supervisory Driver Model is used to calculate driver's free times for the observation strategy for different sets of perceptual cues (Experiment 6). Empirical data are gathered with the car on the road using a visual occlusion technique to measure when and for how long drivers allow themselves to neglect visual information (Experiments 6 and 7). Finally, in Chapter 8 a design application with respect to road delineation at night is considered (Experiment 8), whereas in Chapter 9 the main conclusions of this thesis are summarized and possibilities for further applications are suggested.

2. THEORETICAL FRAMEWORK

2.1 Psychological considerations

In a task analysis of driving, McKnight and Adams (1970) defined about 65 main and 1700 elementary tasks. There is some consensus to categorize driving tasks on three hierarchically ordered levels (Allen et al., 1971). First, a strategical level is defined for tasks related to route selection and route following. Second, a situational level describes tasks of manoeuvring in relation to road geometry, traffic signs and other traffic. The third level, the control level, implies tasks of vehicle control in relation to both previous levels and in relation to disturbances from sidewind gusts or roadway irregularities. These control tasks are usually subdivided in lateral vehicle control, i.e. control of the lateral position inside the traffic lane, and longitudinal vehicle control, i.e. velocity control.

Driving may then be seen as a process during which performance is optimized to meet the demands of the singular tasks in combination, i.e. the process of multitask driving. To do so, it is assumed that the driver has the disposal of an internal criterion (e.g. Kelley, 1969; Chenchanna, 1971, 1974), or monitoring function (Rockwell, 1972), that governs the rules for optimization, prescribed by task demands for travel time, safety, comfort, costs, etc. This internal criterion is not fixed, but submissive to changes over time as a result of driving skill development. Also, when improvement of the driving skill can no longer be observed, the internal criterion may show large variations between individuals, resulting in what usually is referred to as differences in driving style. One of the aims of the study of driving is to define basic information processes, and to investigate in what way driving performance, i.e. the output of the overall driver-vehicle system, and the observation strategy and control strategy, i.e. the output of the driver, are affected by the task demands, and how these measures change during driving skill development.

According to Schlesinger (1972), driver's basic information processes can be divided into search, identification, prediction, decision-making and execution. It is of interest to notice the similarity with the literature on supervisory control (par. 2.2). The processes of search, identification and prediction are categorized by Schlesinger under guidance, "the cybernetic task of obtaining and processing information from the environment", while decision-making and execution are categorized under control, "the task of translating guidance data into decisions and psychomotor control of the vehicle".

Driver's basic information processes can also be categorized in accordance with the theory of "Successive Organisation of Perception" (Krendel and McRuer, 1960, 1968). In this theory three levels have been distinguished which differ in potential for prediction:

- Compensatory level: On the lowest level, the driver has no information about the future values of the variables and has a maximum uncertainty. The strategies on this level are closed-loop and prediction is not possible, e.g., compensatory tracking of random sidewind gusts, following an unfamiliar road in a heavy fog.
- Pursuit level: Driver's uncertainty can be decreased by information about future values of the variables (perceptual anticipation). The strategies on this level are closed-loop in combination with prediction control, e.g., preview of the road to be followed.
- Precognitive level: On the highest level, driver's actions are based on learned input/output relations (cognitive anticipation). The strategies on this level are open-loop, mainly with respect to visual feedback, e.g., passing manoeuvres and curve negotiation by very skilled drivers.

With increasing driving skill it can be expected that driver's strategies shift from the compensatory level towards the higher levels due to an increased use of preview information and an increased knowledge of input-/output relations, making anticipation more or less possible. A singular task is then executed by open-loop control on the higher levels, and an additional, intermittent closed-loop control on the lowest level. In other terms, it can be stated that the task is performed more automatically, and less cognitively controlled (e.g., Schneider and Shiffrin, 1977; Schneider, 1982). Consequently, skilled drivers have to pay less attention to a singular task and may neglect that task temporarily, in order to pay attention to other tasks. Therefore, skilled drivers cope better with multitask driving situations, and/or deteriorated driving conditions within a singular task.

2.2 Cybernetic considerations

Since the early fourties it is tried to apply system and control theory for the description and prediction of the performance and strategy of human operators in dynamic situations. In terms of cybernetics (Wiener, 1948), the human and his immediate environment, like car, ship, airplane or industrial process, are described by dynamic models in which the overall performance is evaluated in control terms. The cybernetic models can be divided in models with respect to manual control and supervisory control. With manual control the human operator acts in the control loop as the direct controller of the relatively fast system. With supervisory control the human operator controls the system indirectly by monitoring the automated (sub)systems. Beaverstock et al. (1977) characterized the supervisor's functions during process control by:

- Learning, understanding, and interpreting the externally imposed task performance criteria;
- Monitoring the system outputs so that from the control actions the dynamics of the system, and the disturbances acting on the system can be identified;
- Planning and determining which control actions should be performed;
- Giving the appropriate input data to the automated control system for both initialization and on-line adjustments, so teaching the control system or the process computer, and
- Intervening in order to switch from supervisory to manual control in those cases where the system is not controlled correctly.

In car driving the distinction between manual control and supervisory control can also be introduced to illustrate open-loop versus closed-loop control, and automatic versus controlled task performance (par. 2.1). Novice drivers are assumed to behave primarily in a manual mode (closed-loop, controlled), and continuously they need full attention in performing and combining the primary driving tasks, like lateral and longitudinal vehicle control. With increasing driving skill, tasks can be combined to a larger extent, and driving can be said then to have shifted towards a more supervisory mode (open-loop, automatically). Supervisory control during car driving allows a more easy detection and handling of unsafe traffic situations apart from the primary tasks, to be compared with fault detection and fault management in general supervisory control.

The models developed for car driving (Blaauw, 1979; Reid, 1983) can also be divided into manual control models and supervisory control models. In the literature attention has almost exclusively been paid to manual control models describing driving in one singular task, e.g. lateral control and sometimes longitudinal control during car-following, in which drivers are enforced to continuously pay full attention to the task. These models mostly refer to conditions in which drivers have to compensate for heavy wind gusts or where they have to follow a strongly winding road.

Models for lateral vehicle control are mostly based on the cross-over model (McRuer et al., 1959, 1967, 1974, 1977), which assumes that driver's strategy corresponds with the most possibly ideal physical servo system with respect to stability requirements, taking into account human inherent limitations. Weir and McRuer (1968, 1970) used the cross-over model during compensatory control to evaluate the use of different perceptual cues, e.g. lateral position, heading angle, yaw rate. They found that lateral vehicle control cannot be executed sufficiently by controlling the actual lateral position, but that it needs predicted values of the lateral position in order to compensate for time lags in the driver and the system to be controlled. The predicted values are determined from the heading angle and the actual lateral position and they seem to be related to the use of an aimpoint during driving. However, Weir and McRuer showed that other cues like the heading angle or yaw rate can also be used for lateral vehicle control when, in addition, the actual lateral position is intermittently used. They defined a multiloop structure where the innerloop refers to the control of heading angle or yaw rate, and where the outerloop refers to the control of the actual lateral position. Allen and McRuer (1977) extended the cross-over model for driving on curved roads by adding a third cue reflecting the local roadway curvature. Consequently, the original compensatory driver model has been transformed to a pursuit driver model. Donges (1978) made this distinction more explicit in his "two-level model" where the first level reflects driver's anticipation with respect to road curvature, and the second level describes closed-loop, compensatory control of lateral position, heading angle and curvature. Crossman and Szostak (1968) developed a "three-level, information-processing model" where the levels are processed sequentially. On the first level the curvature of the vehicle's trajectory is set via an open-loop in accordance with the road curvature. The second level implies a closed-loop control of heading angle or lateral speed, while the third level controls lateral position. Carson and Wierwille (1978) introduced a non-linear element in the feedback loops of the original cross-over model. By defining indifference thresholds in the error feedback loops of lateral position and heading angle, they modelled a combination of driver's perceptual thresholds and a lack of concern about minor deviations in these cues. Baxter and Harrison (1979) introduced a hysteresis element in the error feedback loop in order to explain disturbances induced by the driver for situations without any externally applied disturbance. However, these non-linear models can only be applied to situations for which the model is developed, and they lack generality.

Although the latter models in particular have been developed to describe driving also in relatively undemanding situations without the need for the driver to control continuously with full attention, it is still very difficult to incorporate multitask driving. The second category of driver models, based on supervisory control, seems to be more appropriate to describe multitask driving. However, in the literature no references were found with respect to supervisory models for car driving. Therefore, a Supervisory Driver Model will be proposed in par. 2.3, based on models developed in the area of aircraft control and process control. Godthelp (1984) made a similar approach in terms of supervisory driving, by distinguishing the various levels of open and closed-loop driving.

2.3 A Supervisory Driver Model

Multitask driving can be described by a driver model integrating the psychological and cybernetic considerations of both previous paragraphs. The model is based on the concepts of, first, the Optimal Control Model (OCM, Baron and Kleinman, 1969; Kleinman, Baron and Levison, 1971), reflecting manual control aspects, and second, the Optimal Control Decision Model (OCDM, Kok and Van Wijk, 1978; Kok and Stassen, 1980; White, 1983), reflecting supervisory control aspects of driving. The OCDM was originally derived from the OCM to describe supervisory control of slowly responding systems. In the application presented in this thesis, the structure of the OCM and OCDM is adapted to a Supervisory Driver Model in order to describe the automobile driver as a system supervisor of a relatively fast responding system.

The Supervisory Driver Model, SDM, describes the driver as a combined observer/predictor, controller and decision-maker (Fig. 2.3.1). The driver receives information about the system to be controlled via the perceptual cues in the display vector $\underline{y}$ and generates control actions, like steering-wheel movements and accelerator positions, represented by the control vector $\underline{z}$.

The "observation/prediction" block forms the first essential part of the SDM, transforming the perceptual cues into estimates of the system states with the associated variances of the estimation errors (uncertainties). This transformation is based on knowledge about the system and display dynamics, lead variables, e.g. road to be followed, and disturbances. The observation noise $V_{\underline{y}}$ (Fig. 2.3.1) is added to each perceptual cue and describes the "quality" (noise-to-signal ratio) of each cue in various driving situations, e.g. day time, night time, fog. This noise-to-

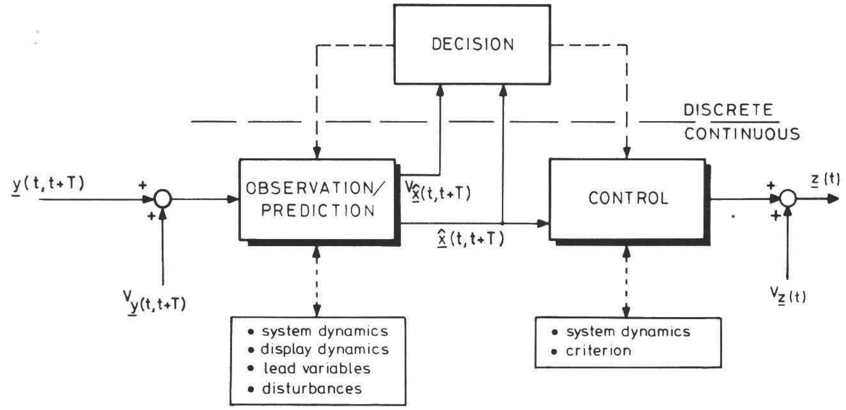

Fig. 2.3.1 The Supervisory Driver Model.

signal ratio is defined to be infinite when the driver pays no attention to the cues, e.g. during a temporary occlusion of information, or diversion of attention. Hence, driver's uncertainties will then increase as a function of the occlusion time.

It is important to notice that the display vector $\underline{y}$ should include both status and preview information covering a certain distance ahead of the vehicle (Fig. 2.3.1: a time interval (t, t + T) is indicated), and that driver's estimates contain present as well as future values of driving performance, in order to allow prediction control and increased anticipation as a result of driving skill development. In the original Optimal Control Model a prediction element was implemented for the compensation of time delays of the human operator and the system to be controlled. However, it should be noticed that "prediction" in the Supervisory Driver Model should cover a much wider range in time. The objective TLC-concept (Time to Line Crossing) introduced by Godthelp and Konings (1981), and its subjective interpretation as an element of driver's estimates, offer a quantitative approach in describing present and future values of driving performance. However, the TLC structure, with reference to either the left or right lane marker, does not allow for easy implementation within the "observation/prediction" block of the Supervisory Driver Model. Therefore, the preview interval is practically restricted to the singular time t and anticipation will be implemented by the additional observation of higher derivatives of driving performance at time t (Johannsen and Govindaraj, 1980).

The "control" block forms the second essential part of the SDM, transforming the estimates via an optimization criterion into commanded control actions such as steering-wheel movements. According to an optimization criterion drivers evaluate task demands like tolerated variations in lateral position due to the lane widths, and then they try to minimize deviations of specific variables. In addition, these control actions are based on knowledge of the control and system dynamics, as well as a good understanding of the task to be performed.

In addition to the observation/prediction block and the control block derived from the OCM, a "decision" block as implemented in the OCDM, is incorporated as a discrete representation for supervisory activities. Decisions for new observation and control actions are based on driver's estimates in combination with the variances (uncertainties) associated with these estimates (output variables of the observation/prediction block). On the one hand, drivers decide to make new observations of perceptual cues whenever the corresponding uncertainty increases to too high a level, and/or whenever the estimate approaches some critical limitation. As a consequence, the estimate then is updated and no observations are necessary for a short period of time. Then, a "free time" is obtained in which the task demands of the separate task may be neglected. At this point a parallel is available with the uncertainty models for driver's observation strategy, developed by Senders et al. (1967) during lateral vehicle control, and by Ceder (1977) during longitudinal vehicle control. On the other hand, decisions with respect to new control actions are initiated whenever it is perceived and/or predicted that driving performance, e.g. the lateral position in the traffic lane, will deviate too much. These decisions stipulate the timing of the control actions; the corresponding amplitudes are assumed to be set by the optimization criterion in the control block.

2.4 Evaluation of driving

Driving can now be evaluated in terms of the aforementioned considerations. Drivers perform better, or safer, when they cope with multitask driving situations and behave more as a supervisory controller. In a similar way, car and road designs are considered to be better when they allow drivers also to behave more as a supervisory controller. Then, each singular task is performed more automatically under supervision of the driver, giving ample possibilities for the detection and compensation of unsafe traffic events. With respect to the Supervisory Driver Model, task execution will be identified by larger free times before new observations and control actions become necessary. Hence, complex task demands and/or deteriorated perceptual cues can be better processed.

In this thesis, driver's observation strategy and control strategy as well as the overall driving performance are evaluated to serve as criteria for driver's capabilities to cope with multitask driving and to behave as a supervisory controller. To do so, the availability of perceptual cues, task demands and driving skill, are taken as independent variables.

The availability of perceptual cues refers to experimental conditions with a reduced set of cues, e.g. due to deteriorated visual cues in darkness, or due to an absence of the acceleration cues. This latter condition refers also to the design of simulator systems where it is of importance to compare fixed-base and moving-base configurations. In terms of the Supervisory Driver Model, the availability of the perceptual cues is assumed to affect primarily the observation/prediction block (par. 2.3 and Table 2.4.1).

Table 2.4.1 Primary relationships between the independent variables and two blocks of the Supervisory Driver Model.

	observation/prediction block	control block
availability of perceptual cues	x	-
task demands	-	x
driving skill	x	x

Task demands are experimentally varied by the number of tasks to be performed in combination, each with its required accuracy. Although some artificial tasks may be added, in this thesis the task demands of longitudinal vehicle control, as a substantial element of driving, are selected in addition to the primary task demands of lateral vehicle control. Drivers are then instructed to perform lateral vehicle control in combination with a very constant forward velocity. A similar accuracy requirement is also asked for lateral vehicle control by instructing drivers to drive as straight as possible. In terms of the Supervisory Driver Model, task demands are assumed to affect primarily the optimalisation criterion in the control block (par. 2.3 and Table 2.4.1).

Driving skill is experimentally varied by the participation of inexperienced and experienced drivers. When skill develops, drivers may change in the use of the perceptual cues. This may result in improved anticipation, allowing increased free times for a singular task, and better task combinations at the same time. During straight-road driving, improved anticipation then may be the result of a shift towards the use of first and higher derivatives of the lateral position, like the lateral speed and lateral acceleration. In terms of the Supervisory Driver Model, driving skill is assumed to affect the use of perceptual cues in both the observation/prediction block and the control block (par. 2.3 and Table 2.4.1).

Table 2.4.2 Criteria, variables and methods for the Experiments 1-8.

EXPERIMENT	CRITERIA			VARIABLES			METHOD	
	observation strategy	control strategy	driving performance	perceptual cues	task demands	driving skill	SDM	field
1	x	x	x					x
2	x	x	x		x	x		x
3		x	x	x	x	x	x	
4		x	x	x	x	x		x
5		x	x	x	x	x		x
6	x		x	x	x	x	x	
7	x		x	x	x	x		x
8	x	x	x	x				x

Table 2.4.2 summarizes the main features of the Experiments 1-8. Next to the aforementioned criteria and independent variables, also both experimental methods are indicated. First, a quantification of the Supervisory Driver Model (SDM), derived from the Optimal Control Model (Baron and Berliner, 1974) is used to predict the effects of changes in the availability and use of the perceptual cues on multitask driving. Differences in the level of driving skill are defined by the use of different perceptual cues for the observation and control strategy of the skilled and unskilled drivers. Pew and Baron (1978, p. 76) already suggested the interesting applications of the Optimal Control Model for the study of shifts in attention allocation to various cues as a function of practice. Differences in the task demands are studied by both the presence and non-presence of

the perceptual cues in the control block. Second, empirical data on multitask driving are collected in a fixed-base simulator in the laboratory and in an instrumented car on the road.

From Table 2.4.2 it can be seen that the Experiments 1 and 2 (Chapter 5) deal with multitask driving in a general way by studying all three types of criteria empirically. In the Experiments 3-5 (Chapter 6) driver's control strategy and the overall driving performance are studied more explicitly, both with the Supervisory Driver Model and with field experiments. The Experiments 6 and 7 (Chapter 7) are in an identical way explicitly related to driver's observation strategy and the overall driving performance. Finally, Experiment 8 (Chapter 8) again integrates all three types of criteria in an empirical application study with respect to road delineation.

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3. SYSTEM TO BE CONTROLLED

It is only worthwhile to present experimental results after a description is given of the system to be controlled. Par. 3.1 presents the equations for the vehicle dynamics, and par. 3.2 gives the equations for the perceptual cues for the driver. The description of the vehicle dynamics is related to the measured dynamics of the instrumented car on the road, whereas the results are used in simulating vehicle dynamics, as well as in the experiments with the fixed-base vehicle simulator, and in the computer simulations with the Supervisory Driver Model.

3.1 Vehicle dynamics

A basic theoretical description of vehicle performance is presented by e.g. Segel (1956). Mathematical models for vehicle dynamics can be roughly divided into two categories. First, relatively simple models which describe most of the elementary characteristics below a 3 m/s^2 lateral acceleration level. Second, a much more comprehensive category due to the addition of the dynamics of vehicle components such as suspension elements. These more comprehensive models are used in vehicle development research. The "simple" models have proven to be very useful in vehicle handling and human factors

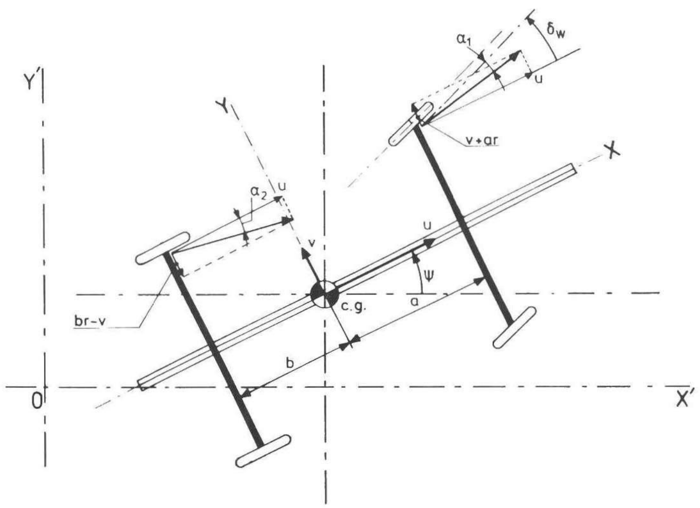

Fig. 3.1.1 The vehicle model.

research (e.g., McRuer et al., 1977); they are also used in this thesis.

Fig. 3.1.1 illustrates the simple model, with the vehicle dimensions reduced to one horizontal plane at road level. Rotations along the longitudinal and lateral axis, as well as vertical translations are neglected, leading to three degrees of freedom, two translations (longitudinal and lateral), and one rotation along 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 are considered in relation to a set of moving axes XY coupled to the centre of gravity (c.g.) of the vehicle.

The <u>longitudinal vehicle dynamics</u> can be described by the following equation of motion:

$$m\ [\ \dot{u}(t)-v(t)r(t)\ ] = \Sigma \text{ forces in X-direction} = X_D(t)-X_B(t)-X_R-X_A(t) \qquad [3.1]$$

with m = vehicle mass

$\dot{u}(t)$ = longitudinal acceleration

$v(t)$ = lateral velocity (in the cross plane of the vehicle)

$r(t)$ = yaw rate

$$X_D(t) = \text{drive force} = \frac{s_g\, s_a(t)}{r_w}\, M_e(t) \qquad [3.2]$$

with s_g = gearbox ratio
$s_a(t)$ = accelerator position
r_w = tire effective radius
$M_e(t)$ = engine torque

$X_B(t)$ = braking force (will be neglected)

X_R = rolling resistance force = $C_R\, m\, g$ [3.3]

with C_R = coefficient of rolling resistance
g = gravitational acceleration

$X_A(t)$ = aerodynamic force = $C_A\, u^2(t)$ [3.4]

with C_A = aerodynamic coefficient
$u(t)$ = longitudinal velocity.

The <u>lateral vehicle dynamics</u> can be described by the following equations of motion (see also Fig. 3.1.1):

$$m\ [\ \dot{v}(t)+u(t)r(t)\ ] = \Sigma \text{ forces in Y-direction} = Y_1(t)+Y_2(t) \qquad [3.5]$$

$$I_R\,\dot{r}(t) = \Sigma \text{ moments in } \psi\text{-direction} = aY_1(t)-bY_2(t) \qquad [3.6]$$

with $\dot{v}(t)$ = lateral acceleration
$\dot{r}(t)$ = yaw acceleration
I_R = moment of inertia around Z-axis
$Y_1(t)$ = lateral tire forces at front wheels
$Y_2(t)$ = lateral tire forces at rear wheels
a = distance between c.g. and front axis
b = distance between c.g. and rear axis.

The lateral tire forces are given by:

$$Y_1(t) = C_{1e}\ \alpha_1(t) \qquad [3.7]$$

$$Y_2(t) = C_{2e}\ \alpha_2(t) \qquad [3.8]$$

with C_{1e} = effective cornering stiffness coefficient front wheel tires
$\alpha_1(t)$ = slip angle front wheels
C_{2e} = effective cornering stiffness coefficient rear wheel tires
$\alpha_2(t)$ = slip angle rear wheels.

The slip angles are defined by (Fig. 3.1.1):

$$\alpha_1(t) = \delta_w(t) - \frac{v(t) + a\ r(t)}{u(t)} \qquad [3.9]$$

$$\alpha_2(t) = \frac{b\ r(t) - v(t)}{u(t)} \qquad [3.10]$$

with δ_w = front wheel steering angle.

For the purpose of this thesis, this paragraph is further restricted to the equations for lateral vehicle dynamics, used in the calculations with the Supervisory Driver Model. A more general description of the system to be controlled, including curve negotiation and car following, is given by Blaauw (1980a). It can be shown that the equations [3.1] - [3.10] can be re-arranged to the state-space equation of lateral vehicle dynamics:

$$\begin{bmatrix} \dot{w}_g \\ \dot{v} \\ \dot{r} \\ \dot{y} \\ \dot{\psi} \\ \dot{\delta}_s \end{bmatrix} = \begin{bmatrix} -\frac{1}{\tau_1} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{-C_{1e}-C_{2e}}{m\bar{U}} & \frac{-aC_{1e}+bC_{2e}-m\bar{U}^2}{m\bar{U}} & 0 & 0 & \frac{C_{1e}}{mN} \\ 0 & \frac{-aC_{1e}+bC_{2e}}{I_R\bar{U}} & \frac{-a^2C_{1e}-b^2C_{2e}}{I_R\bar{U}} & 0 & 0 & \frac{aC_{1e}}{I_R N} \\ 0 & 1 & 0 & 0 & \bar{U} & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ \frac{1}{\tau_2} & 0 & 0 & 0 & 0 & -\frac{1}{\tau_2} \end{bmatrix} \cdot \begin{bmatrix} w_g \\ v \\ r \\ y \\ \psi \\ \delta_s \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{\tau_2} \end{bmatrix} \delta_{sc} + \begin{bmatrix} \frac{1}{\tau_1} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} w$$

$$\text{or: } \underline{\dot{x}}(t) = A\,\underline{x}(t) + B\delta_{sc}(t) + E\,w(t) \qquad [3.11]$$

with: $\underline{x}(t)$ = state vector (dimension 6), with the state variables:

$w_g(t)$ = filtered white noise, added to the driver's actual steering-wheel angle
$v(t)$ = lateral velocity (in the crossplane of the vehicle)
$r(t)$ = yaw rate
$y(t)$ = lateral position (in the crossplane of the road)
$\psi(t)$ = heading angle
$\delta_s(t)$ = actual steering-wheel angle

$\underline{\dot{x}}(t)$ = first derivative of the state vector (dx/dt)
$\delta_{sc}(t)$ = steering-wheel angle commanded by the driver
$w(t)$ = white noise
A = system matrix (dimension 6 x 6)
B = input matrix (dimension 6 x 1)
E = disturbance matrix (dimension 6 x 1)

It should be noticed that equation [3.11] includes a first-order filter for generating from a white noise source $w(t)$ the disturbances $w_g(t)$, which are added to driver's steering-wheel movements. The time constant τ_1 of the filter is set to adjust the bandwidth of these disturbances via the ratio of the standard deviations of the yaw rate and the steering-wheel movements during the model calculations in accordance with the same ratio as measured with the real vehicle. Equation [3.11] also includes a second first-order filter equation with respect to the steering-wheel angle which restricts the steering-wheel rate with a time constant $\tau_2 = 0.01$ s. This latter filter equation is added in order to present the lateral acceleration cue and the yaw acceleration cue as perceptual cues in the display equation (par. 3.2). Both these filter equations are added for the calculations with the Supervisory Driver Model, and may be neglected in considering the pure lateral dynamics of the instrumented car on the road and the fixed-base simulator.

Most parameters of equation [3.11] were available from the car manufacturer, others had to be determined in a series of laboratory and field tests with the instrumented car (Godthelp et al., 1982). A steady-state cornering test and a random steering input test were included to estimate both effective cornering stiffness coefficients C_{1e} and C_{2e} via the yaw rate to steering-wheel angle transfer function:

$$\frac{r}{\delta_s} = \frac{G_r\,(T_1 s + 1)}{\frac{1}{\omega_r^2} s^2 + \frac{2\beta_r}{\omega_r} s + 1} \qquad [3.12]$$

with: r = yaw rate

δ_s = steering-wheel angle

G_r = yaw rate gain, or yaw rate sensitivity:

$$G_r = \left[\frac{r}{\delta_s}\right]_{ss} = \frac{\bar{U}/Nl}{1 + K\,\bar{U}^2} \qquad [3.13]$$

with: ss = steady state
$\bar{U}$ = mean longitudinal velocity
N = steering system gear ratio
l = wheel base
K = vehicle stability factor, describing the understeer/oversteer characteristics of the car according to:

$$K = \frac{m}{l^2}\left[\frac{b\,C_{2e} - a\,C_{1e}}{C_{1e}\,C_{2e}}\right] \qquad [3.14]$$

T_l = lead time constant:

$$T_l = \frac{a\,m\,\bar{U}}{C_{2e}\,l} \qquad [3.15]$$

ω_r = yaw rate natural frequency:

$$\omega_r = \sqrt{\frac{m\,\bar{U}^2\,(b\,C_{2e} - a\,C_{1e}) + C_{1e}\,C_{2e}\,l^2}{m\,I_R\,\bar{U}^2}} \qquad [3.16]$$

β_r = yaw rate damping coefficient:

$$\beta_r = \frac{(C_{1e} + C_{2e}) / m \bar{U} + (a^2 C_{1e} + b^2 C_{2e}) / I_R \bar{U}}{2 \omega_r} \qquad [3.17]$$

The steady-state cornering test was conducted to determine the yaw rate gain G_r. The steering-wheel angle in a curve with radius R is derived from equation [3.13]:

$$\delta_s = \frac{r}{\bar{U}} Nl \, (1 + K \bar{U}^2) = \frac{Nl}{R} (1 + K\bar{U}^2) \qquad [3.18]$$

Fig. 3.1.2 presents the results of the steady-state cornering test for different speeds in a curve with 200 m radius. Via a linear regression line

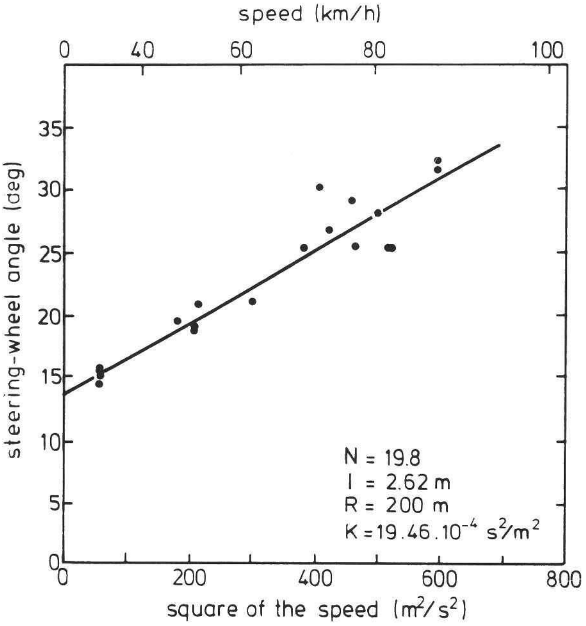

Fig. 3.1.2 Steady-state cornering test for different speeds in a curve with 200 m radius.

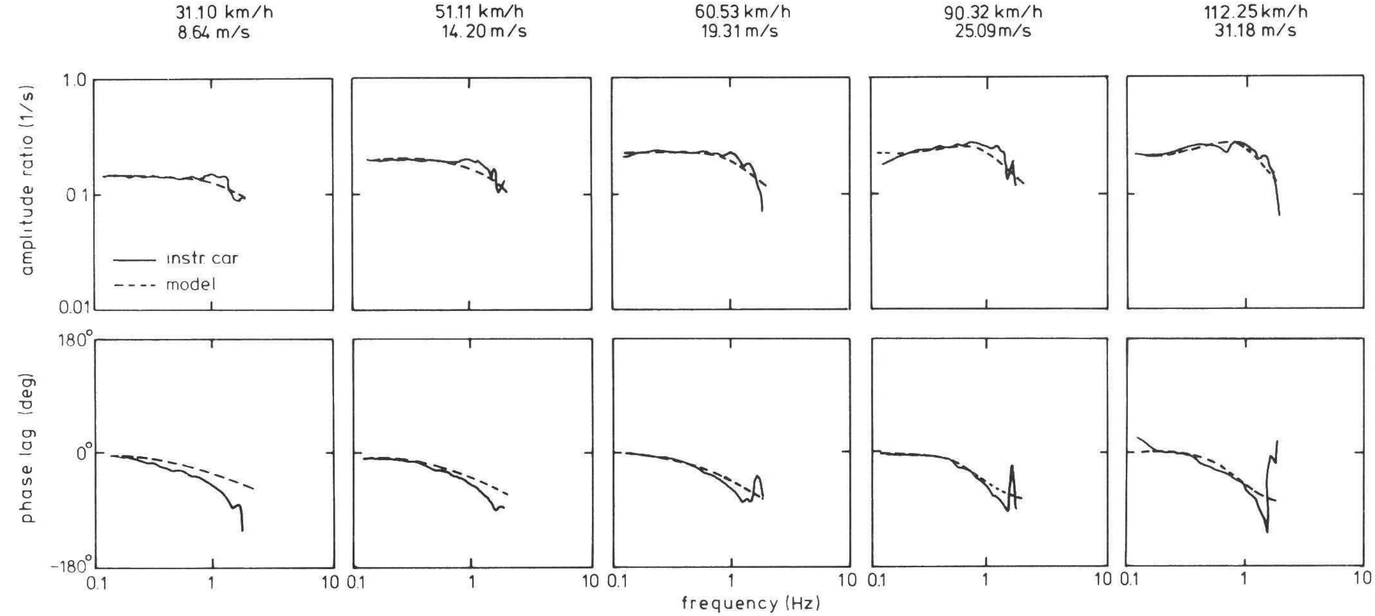

Fig. 3.1.3 Yaw rate to steering-wheel angle transfer function at five different speed levels, based on measurements with the instrumented car on the road (solid lines), and on predictions with the mathematical vehicle model (dashed lines).

the stability factor K was determined and, hence, the yaw rate gain G_r is known as a function of speed according to equation [3.13]. Moreover, the relationship between C_{1e} and C_{2e} is known according to equation [3.14].

The random steering input test was conducted to determine the values of C_{1e} and C_{2e} via an estimation of the parameters of the transfer function [3.12]. To do so, random steering-wheel movements were generated by a driver during runs with different speeds on a wide, straight road. Resulting car movements were neglected in order to guarantee an open-loop procedure. Fig. 3.1.3 presents the amplitude and phase plots of the transfer functions at five speed levels (solid lines), as well as similar plots based on the estimated parameters of the mathematical model according to equation [3.12] (dashed lines).

During the estimation procedure the parameters G_r, T_1, ω_r and β_r were transformed into vehicle-related parameters according to the equations [3.13] - [3.17], leaving only one free parameter (C_{2e}) to be estimated. Table 3.1.1 summarizes the values of the vehicle-related parameters.

Table 3.1.1 Vehicle parameters for the lateral car dynamics.

m	1924	kg
I_R	3315	kgm^2
a	1.62	m
b	1.00	m
l	2.62	m
N	19.8	-
K	$19.46.10^{-4}$	s^2/m^2
C_{1e}	58103	N/rad
C_{2e}	157774	N/rad

Table 3.1.2 gives the coefficients according to equation [3.11] and [3.12] for six different constant velocities in the range of 20 - 120 km/h.

Table 3.1.2 Coefficients of the equations [3.11] and [3.12] for the lateral dynamics of the instrumented car for six different velocities as used in the predictions with the Supervisory Driver Model.

Element	20 km/h	40 km/h	60 km/h	80 km/h	100 km/h	120 km/h	
A (1,1)	- 2.1	- 2.1	- 2.1	- 2.1	- 2.1	- 2.1	
A (2,2)	- 20.18	- 10.11	- 6.73	- 5.05	- 4.04	- 3.37	
A (2,3)	0.39	- 8.13	- 14.69	- 20.73	- 26.59	- 32.34	
A (2,6)	1.53	1.53	1.53	1.53	1.53	1.53	
A (3,2)	3.45	1.73	1.15	0.86	0.69	0.58	
A (3,3)	- 16.83	- 8.42	- 5.61	- 4.21	- 3.37	- 2.81	
A (3,6)	1.43	1.43	1.43	1.43	1.43	1.43	
A (4,2)	1.0	1.0	1.0	1.0	1.0	1.0	
A (4,5)	5.56	11.11	16.67	22.22	27.78	33.33	
A (5,3)	1.0	1.0	1.0	1.0	1.0	1.0	
A (6,1)	100	100	100	100	100	100	
A (6,6)	-100	-100	-100	-100	-100	-100	
B (6)	100	100	100	100	100	100	
E (1)	2.1	2.1	2.1	2.1	2.1	2.1	
G_r	0.10	0.17	0.21	0.22	0.21	0.20	(1/s)
T_1	0.04	0.08	0.13	0.17	0.21	0.25	(s)
ω_r	18.39	9.96	7.40	6.26	5.66	5.30	(rad/s)
β_r	1.01	0.93	0.84	0.74	0.66	0.58	(-)

3.2 Perceptual cues

Equation [3.11] presents the dynamics of the system to be controlled. A set of transformation equations is now necessary in order to describe the perceptual cues which may be used by the driver during lateral vehicle control. These cues are formed by linear combinations of the variables in the state-space equation [3.11]; they are of primary importance for the calculations with the Supervisory Driver Model. In this paragraph the equations will be given for the perceptual cues associated with lateral position, lateral speed, yaw rate, lateral acceleration and yaw acceleration.

The lateral position of the car in the lane is the ultimate variable during lateral vehicle control and is considered to be available via a transformation due to a perspective visual perception of the road ahead. Riemersma (1981) argued that driver's perception of lateral position variations is based on the perception of variations in the inclination angles of the road markers projected onto a vertical plane. Wewerinke

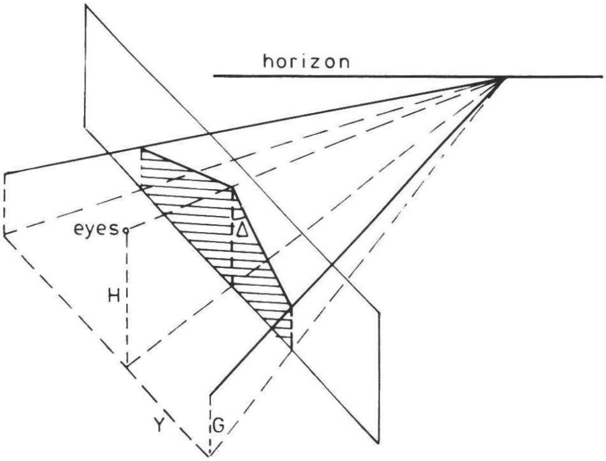

Fig. 3.2.1 Perspective perception of lateral position during straight road driving.

(1978) made a similar analysis for the perceptual properties of pilots during a final runway approach.

Fig. 3.2.1 shows the position of the driver's eyes at height H above a straight road; the lateral distance between the eyes and a given marker is defined as Y. It is assumed that the marker is at a height G above the road surface. Common lane markers are described by G = 0, while for guardrails, postmounted delineators, bulbs, public lighting etc., G > 0. All elements are assumed to be perceivable by the driver as continuous lines. By defining an inclination angle Δ between the projection of the marker and the vertical, it yields the following equation:

$$\mathrm{tg}\ \Delta = \frac{Y}{H - G} \qquad [3.19]$$

The effect of variations in the lateral position now can be studied by introducing small deviations around a predetermined working point for the variables Y and Δ (H and G are assumed to be constant). By defining

$$\Delta(t) = \bar{\Delta} + \alpha(t) \qquad [3.20]$$

$$Y(t) = \bar{Y} + y(t) \qquad [3.21]$$

it can be shown that:

$$\alpha(t) = \frac{H - G}{(H - G)^2 + \bar{Y}^2} \, y(t) \qquad [3.22]$$

and for the special case of lane markers on the road (G = 0):

$$\alpha(t) = \frac{H}{H^2 + \bar{Y}^2} \, y(t) \qquad [3.23]$$

Blaauw (1980b) discussed some practical implications of formula [3.22] by calculating the perspective sensitivity for drivers of passenger cars and trucks in using different types of delineation on and above the road. For night driving without public lighting, for instance, a considerable deterioration in theoretical sensitivity is noticed on a wet road when the lane markers become invisible and only the postmounted delineators give any guidance information. (See also Chapter 8.) It is also shown that a maximum sensitivity for position variations is achieved when the guidance elements are placed at inclinations of ± 45 degrees from the driver's eyes.

The lateral speed of the car relative to the road enables the driver to anticipate by prediction of future situations. Lateral speed is considered to be available for the driver in a comparable way as the lateral position, via the inclination of the road markers projected onto the vertical plane. By differentiating equation [3.23], it yields:

$$\dot{\alpha}(t) = \frac{H}{H^2 + \bar{Y}^2} \, \dot{y}(t) \qquad [3.24]$$

In combination with the equation (see [3.11]):

$$\dot{y}(t) = v(t) + \bar{U} \, \psi(t) \qquad [3.25]$$

equation [3.24] becomes:

$$\dot{\alpha}(t) = \frac{H}{H^2 + \bar{Y}^2} \, v(t) + \frac{H \, \bar{U}}{H^2 + \bar{Y}^2} \, \psi(t) \qquad [3.26]$$

Here, it should be noticed that equation [3.25] indicates a direct relationship between the lateral speed and heading angle for small values of the vehicle-related velocity v(t). In general, heading angle variations appear to vary below the perceptual threshold value during straight road driving (Riemersma, 1981) and, therefore, the heading angle is not incorporated in the set of perceptual cues.

The yaw rate represents the variable to be controlled for the rotational movements of the car. It can be perceived by a horizontal velocity of all points in the visual field (Riemersma, 1981); this variable is assumed to be observed by the driver as such, without any transformation.

Both lateral acceleration a_1 and yaw acceleration $\dot{r}$ form higher derivatives of the variables representing the transversal and rotational movements of the car. Both the acceleration cues can be derived from equation [3.5]:

$$a_1(t) = \dot{v}(t) + u(t)r(t) \qquad [3.27]$$

and the following two equations of the system description [3.11]:

$$\dot{v}(t) = A(2,2)\ v(t) + A(2,3)\ r(t) + A(2,6)\ \delta_s(t) \qquad [3.28]$$

$$\dot{r}(t) = A(3,2)\ v(t) + A(3,3)\ r(t) + A(3,6)\ \delta_s(t) \qquad [3.29]$$

By rearranging the equations [3.23], [3.26], [3.27], [3,28] and [3.29], finally, it results in the display equation of the system to be controlled:

$$\begin{bmatrix} a_1 \\ \dot{r} \\ \dot{\alpha} \\ r \\ \alpha \end{bmatrix} = \begin{bmatrix} 0 & A(2,2) & A(2,3)+\bar{U} & 0 & 0 & A(2,6) \\ 0 & A(3,2) & A(3,3) & 0 & 0 & A(3,6) \\ 0 & \frac{H}{H^2+\bar{Y}^2} & 0 & 0 & \frac{H\bar{U}}{H^2+\bar{Y}^2} & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{H}{H^2+\bar{Y}^2} & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} w_g \\ v \\ r \\ y \\ \psi \\ \delta_s \end{bmatrix}$$

or $\underline{y}(t) = C \qquad \underline{x}(t)$ [3.30]

with: $\underline{y}(t)$ = display vector (dimension 5), with the perceptual cues:

$a_1(t)$ = lateral acceleration (in the crossplane of the vehicle)

$\dot{r}(t)$ = yaw acceleration

$\dot{\alpha}(t)$ = lateral speed, measured as rate of change of the inclination angle due to the perspective observation of the road ahead

$r(t)$ = yaw rate

$\alpha(t)$ = lateral position, measured as inclination angle due to the perspective observation of the road ahead

$\underline{x}(t)$ = state vector (dimension 6)

C = display matrix (dimension 5 x 6).

It should be clear that sensory dynamics are ignored in these equations.

Table 3.2.1 gives the numerical values for the coefficients of equation [3.30] for the same speed levels as given in Table 3.1.2. In these coefficients driver's eye height is assumed to be H = 1.15 m and mean lateral position Y = 1.80 m as the distance between the driver's eyes and relevant lane marker. Blaauw (1980b) gives an extension of the display equation for other driving scenarios involving car following, and approaching and entering curves. A combination of equation [3.11] and [3.30], together with the values of Table 3.1.2 and 3.2.1, gives the linearised description of the system dynamics for the experiments in this thesis. However, depending on the perceptual cues considered, a reduced set of the display equation [3.30] may be taken into account.

Table 3.2.1 Coefficients of the display equation [3.30] for six different constant velocities as used in the predictions with the Supervisory Driver Model.

Element	20 km/h	40 km/h	60 km/h	80 km/h	100 km/h	120 km/h
C (1,2)	- 20.18	- 10.10	- 6.73	- 5.05	- 4.04	- 3.37
C (1,3)	5.95	2.98	1.98	1.49	1.19	1.00
C (1,6)	1.53	1.53	1.53	1.53	1.53	1.53
C (2,2)	3.45	1.73	1.15	0.86	0.69	0.58
C (2,3)	- 16.83	- 8.42	- 5.61	- 4.21	- 3.37	- 2.81
C (2,6)	1.43	1.43	1.43	1.43	1.43	1.43
C (3,2)	0.25	0.25	0.25	0.25	0.25	0.25
C (3,5)	1.40	2.80	4.20	5.60	7.00	8.40
C (4,3)	1.0	1.0	1.0	1.0	1.0	1.0
C (5,4)	0.25	0.25	0.25	0.25	0.25	0.25

3.3 References

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4. GENERAL METHODOLOGICAL CHARACTERISTICS

This chapter gives the general characteristics of the experiments. Information on specific procedures, instrumentation and data analysis will be discussed in the context of the experiments.

4.1 Driving scenario

The study primarily investigates lateral vehicle control during straight road driving, without external disturbances. External disturbances, such as sidewind gusts or roadway irregularities have been omitted for two reasons. First, most driving situations are relatively undemanding and do not involve these types of disturbances. Second, these types of disturbances require manual control on a compensatory level and driver's corresponding control strategies have already extensively been studied (McRuer et al., 1977). Instead of external disturbances, all variations are assumed to be initiated by the drivers themselves.

The experiments have been performed on several 1-4 km straight sections of a four-lane divided motorway, having a constant road geometry and an emergency lane at the right. Subjects drove in the 3.60 m wide right lane, with a 0.15 m solid shoulderline at the right and a 0.10 m centre line in a 3 / 9 / 3 / 9 m dashed pattern at the left. There was no interaction with other traffic during the measurements. All experiments were conducted during daytime, with the exception of Experiment 8 and one night condition in the Experiments 5 and 7.

4.2 Subjects

Both experienced and inexperienced male drivers between the ages of 18 and 36 years participated. The experienced drivers had their licences for at least three years and a total distance driven of at least 30,000 km. The inexperienced drivers either had followed a driver-training course or had just passed their driving tests. None of the subjects ever participated in similar experiments. All participants were paid.

4.3 Procedure

Task demands were varied by adding tasks to the primary task of lateral vehicle control. These additional tasks were not artificial, but related to longitudinal vehicle control as a substantial element of driving. Task demands for lateral and longitudinal vehicle control were manipulated by instruction and varied between subjects, with the exception of Experiment 2, where task demands were varied in accordance with a within-subject design.

Subjects were instructed on the type of task but did not receive any training either with the instrumented car or simulator. The initial position of the car was in the emergency lane, where subjects were instructed how to handle the car or simulator. They then accelerated to the desired speed and changed to the right lane, from which point driver's vehicle control was measured regularly. For the conditions without specific longitudinal instruction, subjects were advised to drive with a normal motorway speed.

4.4 Instrumentation

4.4.1 Instrumented car

Experiments 1, 2, 4, 5, 6, 7 and 8 were conducted on the road with an instrumented car, a Volvo 145 Express (Blaauw and Burrij, 1980); see Fig. 4.4.1. Recordings were made of the steering-wheel angle, lateral position (except in Experiment 8), yaw rate (except in Experiments 1 and 2), accelerator position, and velocity. The variables in Experiments 1 and 2 were recorded on an analog recorder, while Experiments 4, 5, 6, 7 and 8 were conducted with an on-board instrumentation system allowing for digital storing on floppy-discs. In general, variables were sampled over six periods of 32 s (Experiment 2 over three periods of 128 s), with a 4 Hz sampling frequency.

The steering-wheel angle and the accelerator position were recorded with potentiometers. The lateral position of the car was measured by a transducer, scanning the road luminance by a fast rotating prism in front of a photo-amplifier. The constrasting light level due to the right shoulderline acted as critical signal in measuring the lateral distance between this line and the driver. Yaw rate was measured with a small gyro, while forward velocity was measured with a pulse-counter mounted on the cardan-

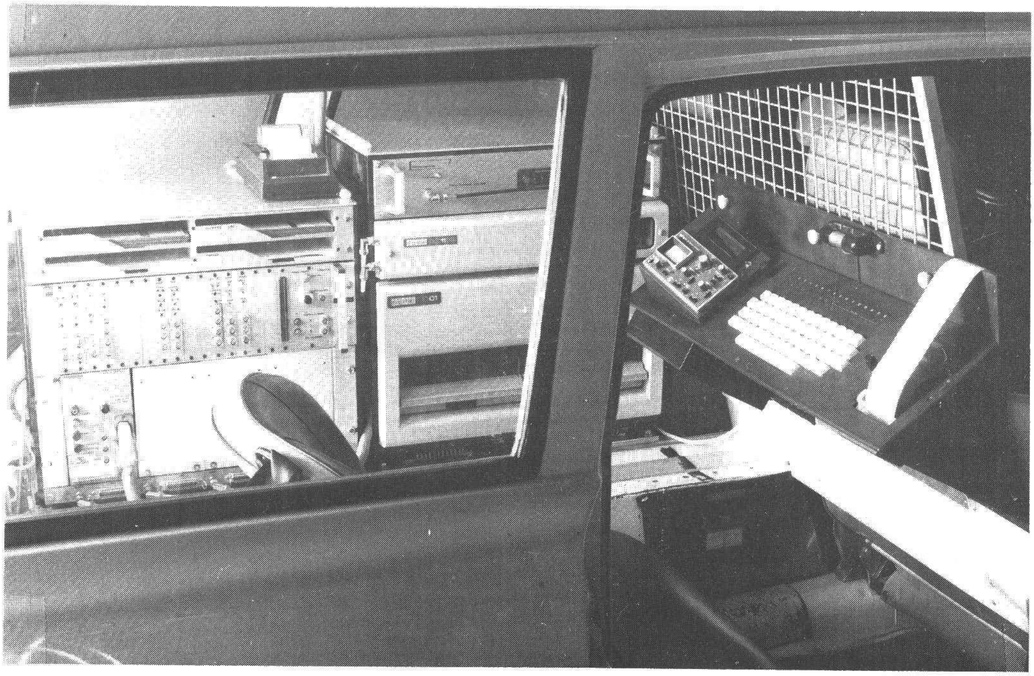

Fig. 4.4.1 The instrumented car with the on-board computer system. A minicomputer, floppy-disc unit and interface are placed directly behind the driver. A technician supervises the system with a keyboard, displays and a small printer. An experimenter uses a push-button unit to label special events during driving.

axis immediately after the gearbox. Lateral speed was derived by differentiating the lateral position signal.

During all runs, two experimenters were present in the vehicle, one taking care of the instrumentation and one for the supervision of the subjects and procedures. The latter experimenter was a driver-training instructor whose presence also served to legalize the runs with the inexperienced subjects having no driving licence.

4.4.2 **Fixed-base simulator**

Experiment 4 was conducted with a fixed-base vehicle simulator (Institute for Perception TNO, 1978); see Figs. 4.4.2 and 4.4.3. This simulator is characterized by the following aspects:

(1) The visual scene is created with three TV projection systems (black and white) on screens surrounding the mock-up of a vehicle. Horizontal and vertical field of view are 120° and 30°, respectively.

(2) The TV recordings are made in-line from a 1 : 87.5 scale model by a mirror block with three endoscopes and three cameras. The movements of this recording system are computer controlled and imply three translations and one rotation (yaw around the vertical axis). By means of a moving-belt system, there is no time limit to driving.

(3) The movements of the mirror block are controlled by the actions of the driver via a mathematical representation of the vehicle dynamics (par. 3.1). This mathematical model allows velocities between 0 and 120 km/h, including clutching and changing gears. Lateral accelerations are restricted up to 3 m/s^2.

(4) The mathematical model of the vehicle includes the dynamic calculation of steering-wheel forces that are presented to the driver by an electric torque motor.

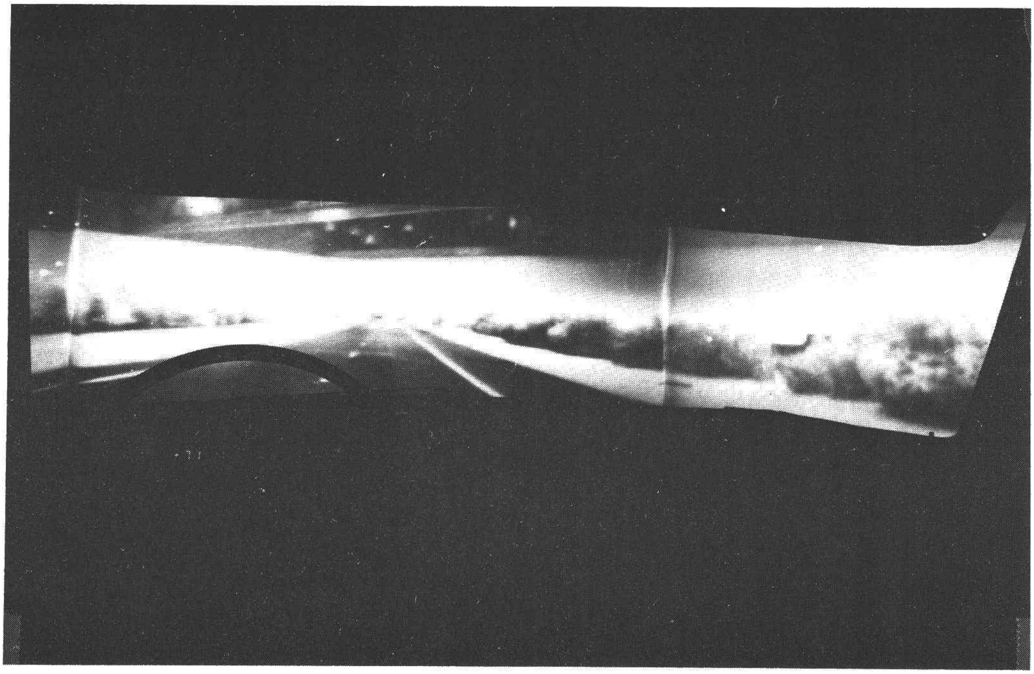

Fig. 4.4.2 The 120° TV image, as presented to the driver in the simulator.

(5) The simulator is fixed-base, i.e., the mock-up simulates no vehicle movements.

(6) Engine and wind sound are simulated by a four-channel system that relates sound to velocity, engine torque, and rotational speed of the engine.

(7) The vehicle (mock-up as well as mathematical representation) is a copy of the instrumented car.

Recordings were made of the steering-wheel angle, lateral position, yaw rate, accelerator position, and velocity. All variables were sampled over six periods of 32 s each, with a 4 Hz sampling frequency. The steering-wheel angle and the accelerator position were recorded with potentiometers, while the lateral position, yaw rate and velocity were directly derived from the signals controlling the movements of the mirror block. Lateral speed was derived by differentiating the lateral position signal.

During all runs, one experimenter was present in the mock-up of the simulator to supervise the subjects.

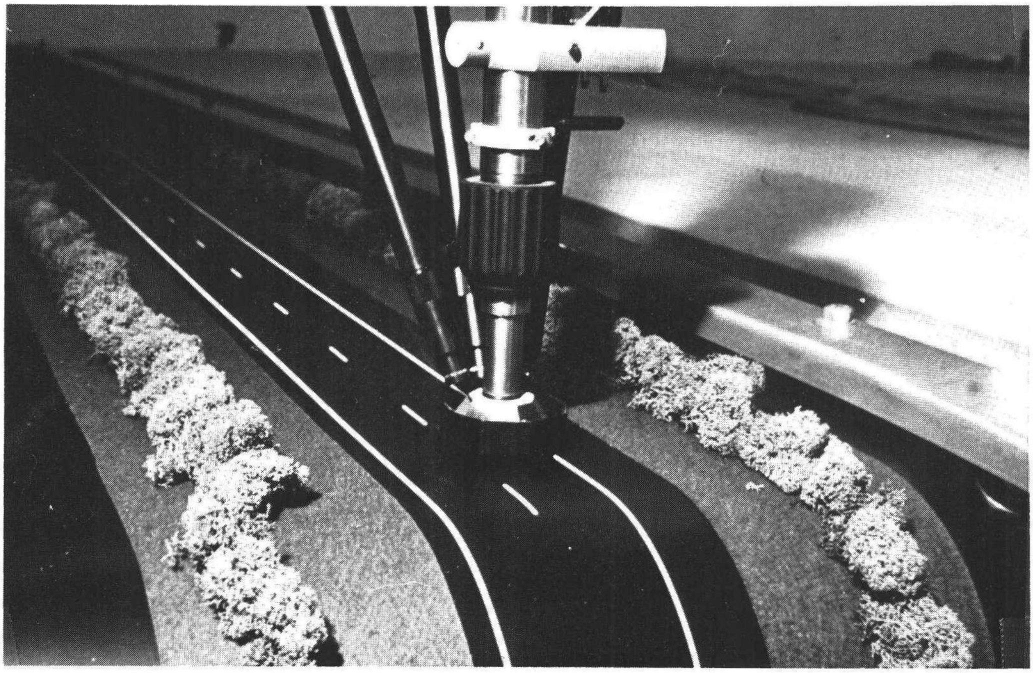

Fig. 4.4.3 The mirror block that simulates the eye of the driver during straight road driving on the moving-belt system.

4.4.3 Supervisory Driver Model

Experiments 3 and 6 were related to computer predictions with respect to the Supervisory Driver Model described in par. 2.3. The calculations were performed with the Optimal Control Model programme MANMOD (Baron and Berliner, 1974) provided by the National Aerospace Laboratory NLR and implemented on a Cyber 74.

During the model calculations the following fixed conditions were imposed:

- **System dynamics:** The system dynamics were chosen in accordance with the lateral dynamics of the instrumented car, for six different speed levels (Table 3.1.2). The display equations were formed as subsets of Table 3.2.1, in order to define the set of perceptual cues for each model condition.
- **No time delay, no thresholds:** Due to the relatively undemanding and supervisory nature of driving, drivers' time delays and perceptual thresholds were assumed to be of minor importance in the model calculations and therefore they were set equal to zero.
- **No external disturbances:** System variations were assumed to be initiated by internally generated variations added to the commanded steering-wheel movements (motor noise). Therefore, the state space equation (par. 3.1) included a first-order filter for deriving these disturbances originating from a white noise source. The bandwidth of the filter was set by adjusting the ratio of the standard deviations of the steering-wheel movements and the yaw rate in order to correspond with the same ratio measured with the real vehicle. The variance of the white noise source was based on results obtained by Godthelp et al. (1983), who instructed subjects in a simulator experiment to reproduce discrete and continuous steering-wheel movements, and where standard deviations of about 10% of the desired amplitudes were measured.
- **Internal model:** The dynamics of the system to be controlled were assumed to be perfectly known in the observation/prediction block and control block.
- **Weighting of variables:** It was assumed that the optimization criterion in the control block involves only weighting coefficients for the perceptual cues, as defined for each model condition, and for the steering-wheel rate. The remaining weighting coefficients for the state variables and the steering-wheel angle were set to zero. The non-zero weighting coefficients for the perceptual cues were chosen to be inversely proportional to the square of the corresponding tolerated variations, based on either

the lane boundaries for lateral position or on the measured maximum deviations for the other variables. These weighting coefficients were 46, 18, 1736, 2.5 and 44, for the inclination rate and angle of the left lane marker, the yaw rate, the lateral acceleration and the yaw acceleration, respectively (par. 3.2). The weighting value for the steering-wheel rate coefficient was adjusted iteratively in order to ensure that the time constant of the driver's neuromuscular system is equal to 0.1 s.

- **The observation noise level:** Associated with the perceptual cues, this noise level was assumed to be equal for each cue. This parameter can be considered to be the only free parameter for the model predictions in each condition.

The SDM results have been obtained as time histories for the mean values and standard deviations of vehicle-related variables like lateral position, yaw rate and velocity as well as driver-related variables with respect to the estimates and associated uncertainties of the mentioned variables.

4.5 Data analysis

Mean values and standard deviations were computed for lateral position, lateral speed, yaw rate, steering-wheel angle, accelerator position, and velocity, for each run with the instrumented car and simulator. Spectral density functions were estimated and plotted for the steering-wheel angle by using a direct Fast-Fourier Transform (FFT; Cooley and Tukey, 1965). Spectral resolution was 0.03 Hz. A special set of subroutines was written to perform the signal analyses (Konings and Blaauw, 1981). The spectra were studied in detail by analysing the proportion of energy in specific frequency bands. The limits of these bands were chosen in accordance with par. 5.2, and are given in Table 4.5.1. The proportion was defined as: (energy in band II) * 100%/(energy in band I + energy in band II).

Table 4.5.1 The limits of the two freqency bands for the analysis of driver's steering-wheel movements.

Band	Frequency in Hz
I	0 - 0.3
II	0.3 - 0.6

Additional calculations were done to derive the Time to Line Crossing (TLC; Godthelp et al., 1984) for each sample. For each run histograms were made for the TLC values with respect to the left and right lane boundary separately, and a median left TLC and right TLC were calculated.

The dependent variables were subjected to analyses of variance (ANOVAs) and Newman-Keuls tests, in order to test whether any main effects of the experimental conditions or their interactions may have occurred by chance or not (Winer, 1962; Riemersma and Burrij, 1973). Only significant effects ($p \leq 0.05$) are mentioned, whereas the subject effects, both main and interactive, are omitted.

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5. DRIVER'S OBSERVATION STRATEGY, CONTROL STRATEGY AND PERFORMANCE ON A STRAIGHT ROAD

5.1 Introduction

This chapter presents two experiments to study whether drivers do exclusively attend to lateral vehicle control, and whether they temporarily allocate their attention to other tasks or activities not necessarily related to driving.

In Experiment 1 driver's visual scanning and control strategy is studied during lateral vehicle control without any additional task. It is investigated to what extent and with what consequences for lateral control performance, drivers allow themselves to observe objects which are not directly related to lateral control.

In Experiment 2 additional tasks are defined so that drivers are not able to continuously attend to lateral control. Consequences for the lateral control strategy and performance are discussed.

5.2 Experiment 1: Driver's visual scanning and control strategy[1]

5.2.1 **Introduction**

During straight road driving, the visual scanning strategy of drivers, as part of the observation strategy, is characterized by the positions of the eye fixations with regard to the vanishing point of the lane markers at the horizon. The scanning strategy sometimes is also described by the angular distance between two successive fixations and by the fixation duration. It should be emphasized that the registration of eye positions only gives information about the location of the 2° central part of the eye (fovea), and that less is known about what is processed via the peripheral field. Moreover, there may be a discrepancy between the measured eye fixations and driver's object of attention (par. 5.2.4).

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[1] The present study was part of a more comprehensive experiment in which the visual scanning and control strategy was studied both on straight and curved roads (Blaauw and Riemersma, 1975).

According to Rockwell (1972), in normal straight road driving about 90 percent of the fixations falls within ± 4° from the vanishing point. He also found that most eye movements are of less than 6 degrees travel and that most fixations have a duration of 100 to 350 ms.

A research group at the Ohio State University (1969) reported that the central horizontal point of view is 4° to the right and the central vertical point is 1 degree above the vanishing point. The drivers fixate at the road and edge markers only a small percentage of the time, whereas the centre of the scanning patterns is covered most of the time. According to Babkov (1970), 44 percent of the eye fixations is situated in the direction of the car at the horizon, 29 per cent just in front of the car and 7 percent at each side of the car on the roadway markers.

Babkov and Lobanov (1973) studied the visual concentration field (defined as the area which covers 85% of driver's eye fixations) and found an inverse relation with driving speed. Whereas the horizontal and vertical dimensions of this field are 30° x 10° at 40 km/h, the dimensions are reduced to 10° x 6° at a speed of 100 km/h. The fixation duration also decreased with speed: The authors observed 0.4 s at a speed of 100 km/h and 1.5 - 2 s at 20 km/h.

Rockwell (1972) and Mourant and Rockwell (1971) noticed significant changes in the scanning patterns due to <u>driving skill</u>. Novice drivers switch from large travel distances and fixations on non-relevant cues to alternate sampling near and far. The far fixations are assumed to be primarily direction cues, while the near fixations seem to be foveal determinations of lane positioning. With increased driving skill a decrease in visual scanning activity is found. Experienced drivers concentrate their eye fixations near the vanishing point at the horizon and it is assumed that they use peripheral viewing for lane positioning. In general, experienced drivers maintain a 2.5 - 3.5 s minimum preview time, while novice drivers use foveal determination for lane positioning in very near samples with a preview time less than 1 s. Mourant and Rockwell (1971) suggested that the patterns of novice drivers might be due to their high degree of concentration in controlling the vehicle laterally and longitudinally. Novice drivers sample their mirrors quite infrequently, but they show a relatively large number of speedometer fixations.

Driver's <u>control strategy</u> during straight road driving may be studied by an analysis of the spectral density function of the steering-wheel movements, or by the steering-wheel reversal rate. McLean and Hoffmann (1971, 1972, 1973 and 1975) found dominant frequency ranges at 0.1 - 0.3 Hz and sometimes at 0.35 - 0.6 Hz (or in the area above 0.4 Hz). The authors suggested that during lateral vehicle control both peaks may correspond to different perceptual cues controlled by the driver (par. 3.2). Small, high-frequent steering-wheel movements are associated with yaw rate control, while the low-frequent movements are associated with heading angle control. Due to the direct relationship between heading angle and lateral speed (via the forward velocity; equation [3.25] in par. 3.2) these low-frequent steering-wheel movements can also be seen to be linked to lateral speed control. The lateral position of the car seems not to be controlled continuously, but intermittently. Results obtained by McLean and Hoffmann suggest a shift to higher frequencies of the steering-wheel movements (more energy in the area above 0.4 Hz) as a result of higher task demands in lateral control (narrow lane width, high speed, restricted preview). Hence, in these situations drivers attend more to yaw rate control.

Greenshields (1963), Greenshields and Platt (1967) and Kimball et al. (1971) found that more skilled drivers produced lower steering-wheel reversal rates. Smiley et al. (1980) noticed a similar tendency. Wierwille et al. (1967) compared an experienced subject with an inexperienced subject and found more abrupt steering-wheel movements (more high-frequent components) for the inexperienced subject. However, in contrast with these results, Riemersma (1972) reported a greater number of reversals with a smaller variance for more experienced drivers. These contradictory findings will be discussed in par. 5.3.4.

In the present experiment visual scanning and control strategy is studied during lateral vehicle control without any additional task. Visual scanning strategy is analysed in terms of the objects fixated by the eyes, and in terms of the horizontal and vertical probability density functions of the eye fixations in relation to the vanishing point of the road at the horizon. Driver's control strategy is studied via the spectral density functions of the steering-wheel movements in order to verify the literature with respect to the dominant frequency ranges.

5.2.2 **Method**

Nine experienced male subjects drove in the instrumented car three times on a straight motorway with the instruction to drive normally in the right traffic lane.

In addition to the equipment mentioned in par. 4.4.1, the instrumented car was also equipped to record driver's visual scanning strategy, by measuring head and eye movements. Head movements were recorded automatically by a small video camera (52° x 39° field of view) attached to the driver's head. Eye movements were added to the video picture from electrodes around the eye in order to record the horizontal and vertical components of eye movements. This technique is known as electro-oculography (EOG). Both, horizontal and vertical voltages of the electrodes were transformed to the corresponding movements of a white spot in the video picture and indicated the direction of the driver's line of sight. The composed video picture was recorded on a video recorder for a quantitative analysis afterwards. The eye movements were, first, plotted with respect to the positions relative to the Vanishing Point of the Straight road, the VPS, and second, categorized with respect to the objects on which the eyes were fixated. The positions were measured with a resolution of about 2° and with a sampling frequency of 50 Hz. Due to the time-consuming plotting procedures the eye positions of only five subjects were analysed.

5.2.3 **Results**

Figs. 5.2.1 and 5.2.2 give the horizontal and vertical probability density functions of the eye positions relative to VPS, the Vanishing Point of the Straight road.

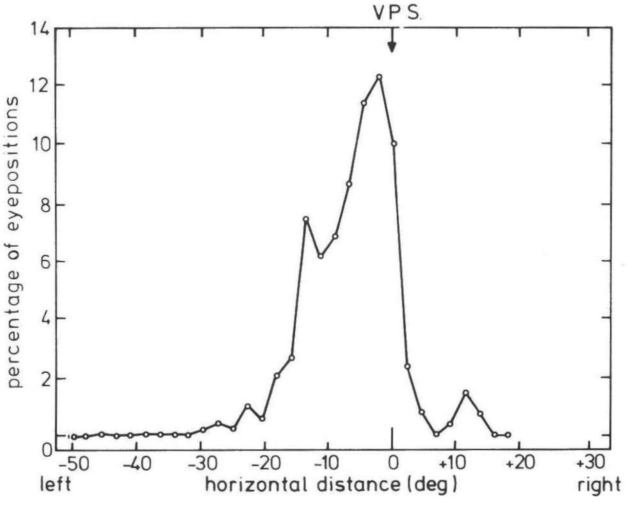

Fig. 5.2.1 Probability density function of the horizontal eye positions.

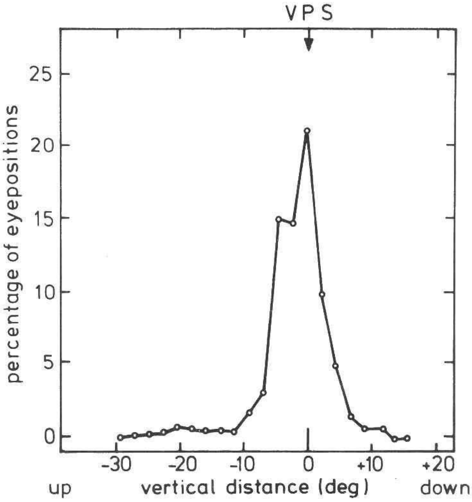

Fig. 5.2.2 Probability density function of the vertical eye positions.

Mean horizontal and vertical positions are 8°30' leftwards and 2° upwards, with a 3°30' variance, both in horizontal and vertical direction. The asymmetry of the horizontal eye positions to the left may be caused by looking at oncoming vehicles in the opposite lanes, which is also visible from the local peak at -13°. The objects on which the eyes are fixated during at least 100 ms are given in Table 5.2.1 as percentages of the total number of fixations. "Out of view" refers to eye positions outside the field of view of the video camera, due to large eye movements which were not accompanied by equal head movements. "Sky" and "out of view" result in significantly greater percentages than for any other object ($p \leq 0.01$). All other objects are observed about equally. Relevant road objects are fixated only for about 30%. With respect to the travel distance it is found that about 50% of all eye transfers does not exceed a travel distance of 10°; 70% falls within a 20 degrees distance. About 30% of the fixated objects is identical to the preceding fixations.

Driver's control strategy was analysed by the spectral density function of the steering wheel movements. Fig. 5.2.3 presents for nine subjects the mean spectra, as averaged over three trials. No significant differences were found between these trials.

It is found that subjects 3 and 6 both drove with significantly less energy than subjects 4 and 9 ($p \leq 0.01$). Furthermore, mainly two dominant

Table 5.2.1 Percentages of eye fixations on different objects during straight road driving.

object	percentage of fixations
left edge	6.6
left marker	2.4
left lane	11.6
centre marker	4.8
right lane	10.1
right marker	2.0
right edge	5.5
sky	31.0
out of view	21.0
others	5.0

peaks can be noticed which differ in energy and, hence, show that drivers spread their individual steering-wheel movements differently over the frequency range. The different control strategies are indicated particularly by changes in the energy of the second peak. Fig. 5.2.4 presents a spectral density function of the steering-wheel movements averaged over all subjects and trials. It then appears that drivers activated the steering-wheel with two dominant frequencies: a first peak at about 0.1 Hz and a second peak at about 0.45 Hz.

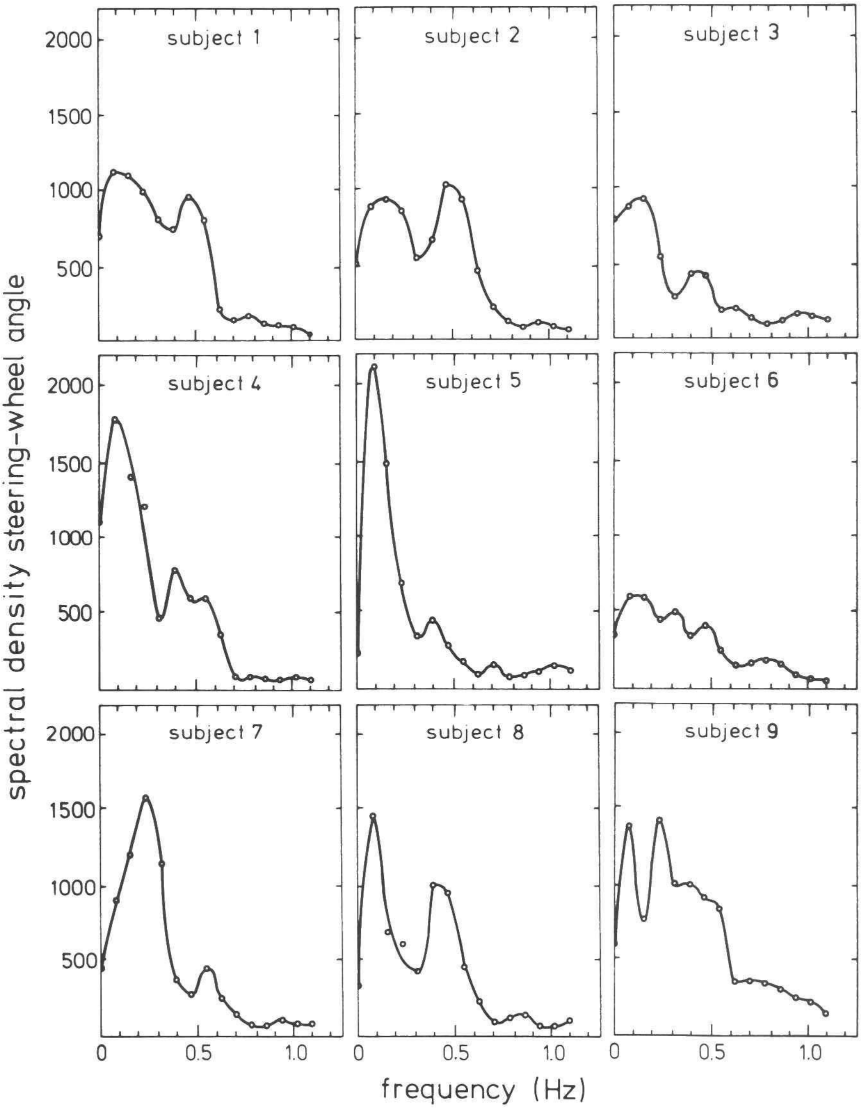

Fig. 5.2.3 Spectral density functions of the steering-wheel angle for nine subjects, averaged over three trials.

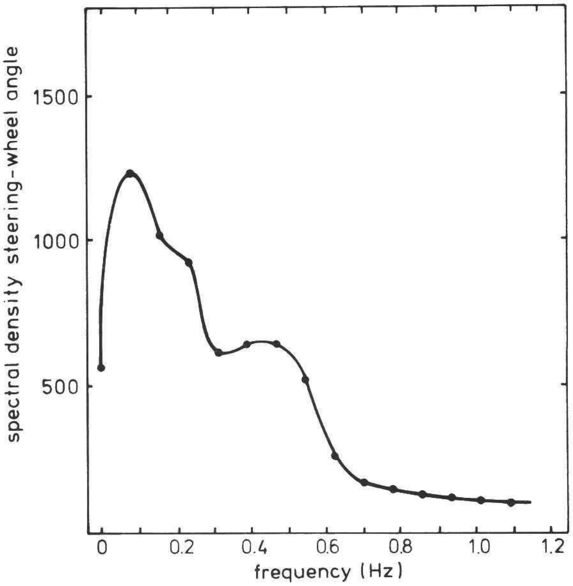

Fig. 5.2.4 Spectral density function of the steering-wheel angle, averaged over subjects and trials.

5.2.4 **Discussion**

Visual scanning strategy seems to confirm the results in the literature that lateral vehicle control on straight roads requires only a small amount of foveal attention for experienced drivers. The number of eye fixations shows that no specific road object attracted driver's attention in particular, and that "sky" and "out of view" covered 52% of all fixations. It seems that, in driving on a straight road, experienced drivers visually scan the total environment, with a centre position near the vanishing point of the road at the horizon, and a standard deviation of 3°30' around that point. The centre position may be seen as an optimal position for peripheral observations of driving performance.

However, the techniques for recording eye movements do not allow measurements of peripheral vision, while for foveal vision the line of sight (as measured) does not necessarily correlate with the driver's object of attention. In order to overcome these problems and to measure the foveal and peripheral needs specifically, it is necessary to study driver's observation and control strategy during temporary occlusion: Whereas normally the driver's visual field is completely occluded, it is only possible to obtain visual information about driving performance during short time intervals (Senders et al., 1966; Farber and Gallagher, 1972; Triggs and Caple, 1978). The Experiments 6, 7 and 8 are based on this technique.

Driver's control strategy in the present experiment was studied by the spectral density functions of the steering-wheel movements. In accordance with the literature, one dominant peak is found in the frequency band 0-0.3 Hz, and sometimes a second peak in the frequency band 0.3-0.6 Hz. Individual differences with respect to the amount of energy in the second peak seem to indicate different control strategies for yaw rate control. Now it is of further importance to study driver's conrol strategy, and more specifically shifts in the steering-wheel spectra, in relation to task demands and driving skill within a multitask driving context.

5.3 Experiment 2: Driver's control strategy affected by driving skill and task demands[2]

5.3.1 Introduction

Experiment 2 has been designed in order to manipulate driver's visual information in a multitask situation. Due to the results of Experiment 1, which indicated that only a small amount of foveal information is gathered by experienced drivers during lateral control, and that peripheral vision seems to be important, it was decided to minimize driver's possibilities to obtain visual information about lateral control. Therefore, drivers were instructed to scan actively the off-road environment and to mention details of what was seen. In this way foveal and peripheral information about lateral control was assumed to be minimal and drivers could visually verify driving performance only intermittently. This "minimum condition" was complemented by a "maximum condition" in which drivers were urged to do their utmost in lateral control and in which drivers could obtain visual information continuously. Effects of task demands and driving skill were analysed by the lateral control performance in terms of the mean and

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[2] The data of this experiment were previously published (Blaauw et al., 1977), while the TLC (Time to Line Crossing) values were introduced by Godthelp and Konings (1981).

standard deviations of the lateral position on the road, and the lateral control strategy in terms of the amplitudes and frequencies of the steering-wheel movements.

5.3.2 **Method**

Three inexperienced and three experienced subjects drove in the instrumented car. Task demands were manipulated by instructions. There were two conditions for lateral vehicle control:

(1) MIN(inimum) - "to keep lane" with the instruction to observe the off-road environment and to report on what was seen. This instruction was chosen in order to provoke a relaxed criterion for lateral control and to provide only minimum visual needs to do so. Subjects were told that their comments would be recorded on tape which, in fact, was not done.

(2) MAX(imum) - "to drive as straight as possible", informing the drivers that in particular their variations in straight driving were recorded, so that they should intensively concentrate on this task. This instruction attempted to provoke a strict internal criterion for lateral control and aimed at providing maximum visual needs to do so.

Both instructions for lateral vehicle control were combined with one of the following instructions for longitudinal control:

(3) FREE - no specific longitudinal instruction was given.

(4) + 100 KM/H - subjects' instructions were similar to those in condition 2, but now with respect to the variations in velocity: Therefore, they should concentrate on a constant velocity of 100 km/h. This instruction attempted to provoke a strict criterion for longitudinal control.

(5) + 80 KM/H - as condition 4, but now for 80 km/h.

Lateral and longitudinal instructions combined resulted in six conditions. Each subject drove each condition three times in a randomized sequence during daytime. Each trial on the straight section had a duration of 128 s. Because it took some time to reach and leave the experimental section, the total procedure for one subject was completed in two two-hour sessions on different days. For more detailed methodological information see Chapter 4.

5.3.3 **Results**

Lateral vehicle control

Table 5.3.1 presents lateral control performance as affected by task demands and driving experience; each result represents the average value over 9 runs (3 subjects x 3 trials). Table 5.3.2 gives similar data for driver's control strategy reflected by the amplitudes and frequencies of the steering-wheel movements (par. 4.5).

Longitudinal instructions and trials did not show a main effect on lateral control, whereas lateral instructions did. Compared with the MAX condition, the MIN condition resulted for all drivers in:

- larger distance to the right shoulderline ($p \leq 0.01$)
- larger S.D. (standard deviation) of lateral position ($p \leq 0.01$)
- larger S.D. of lateral speed ($p \leq 0.01$)
- smaller median left TLC ($p \leq 0.05$)
- no differences in the median right TLC

Table 5.3.1 Lateral control performance for the inexperienced (INEXP) and experienced (EXP) drivers with two lateral control task demands (MIN and MAX visual needs) and three additional velocity task demands (FREE, + 80 KM/H and + 100 KM/H).

	MAX			MIN			
	FREE	+100 KM/H	+ 80 KM/H	FREE	+100 KM/H	+ 80 KM/H	
lateral position (m)	1.87	1.95	1.84	2.01	2.06	2.08	INEXP
	1.89	1.72	1.68	1.95	1.96	1.98	EXP
S.D. lateral position (m)	0.19	0.21	0.21	0.24	0.29	0.29	INEXP
	0.20	0.16	0.14	0.26	0.28	0.29	EXP
S.D. lateral speed (m/s)	0.07	0.07	0.07	0.11	0.12	0.12	INEXP
	0.07	0.07	0.06	0.10	0.11	0.11	EXP
median left TLC (s)	8.8	8.5	9.4	6.3	5.9	6.2	INEXP
	8.2	9.1	9.9	7.0	6.7	6.7	EXP
median right TLC (s)	6.4	6.4	5.9	5.2	5.3	5.5	INEXP
	6.0	5.2	5.2	5.4	5.0	5.2	EXP

Table 5.3.2 Driver's control strategy for the inexperienced (INEXP) and experienced (EXP) drivers with two lateral control task demands (MIN and MAX visual needs) and three additional velocity task demands (FREE, + 80 KM/H and + 100 KM/H).

		MAX			MIN			
steering-wheel angle		FREE	+100 KM/H	+ 80 KM/H	FREE	+100 KM/H	+ 80 KM/H	
S.D.	(°)	1.8	2.1	1.9	3.2	3.1	3.0	INEXP
		1.8	1.6	1.8	2.3	2.5	2.7	EXP
energy $\frac{0.3\text{-}0.6\ \text{Hz}}{0 - 0.6\ \text{Hz}}$	(%)	25.1	19.9	19.0	29.3	28.9	29.6	INEXP
		16.0	23.8	22.3	30.6	27.7	25.7	EXP

- larger S.D. of steering-wheel movements ($p \leq 0.01$)
- higher steering-wheel frequencies ($p \leq 0.05$).

Interactions between lateral and longitudinal instructions were absent but, in combination with driving experience a significant effect ($p \leq 0.05$) was present for driver's control strategy: Results for the frequencies of the steering-wheel movements indicated that each group of drivers reacted differently on an additional speed instruction in the MAX condition (Table 5.3.2), whereas no differences were present in the MIN condition. Within the MAX condition the steering-wheel movements of the experienced drivers showed a significant shift to higher frequencies for the additional speed instruction, while the inexperienced drivers showed an inverse relation with the same instruction indicating more energy in the lower frequencies. With respect to the S.D. of the steering-wheel movements, there were no differences within the MAX condition, but the MIN condition resulted in significantly larger S.D. for the inexperienced drivers than for the experienced drivers ($p \leq 0.05$).

Longitudinal vehicle control

There were no main effects of driving experience, lateral instruction and trial on the mean and standard deviation of the velocity. However, longitudinal instructions resulted in some significant differences (Table 5.3.3). Mean velocity did not differ significantly between the FREE and +

100 KM/H conditions. With respect to the required velocity it is noticed that drivers had a rather low velocity at the + 100 KM/H condition, while the + 80 KM/H instruction was followed rather precise. The standard deviation of the velocity for both speed instructions was not different, but was smaller in these conditions as compared to the FREE velocity condition ($p \leq 0.001$).

Table 5.3.3 Longitudinal control performance for the inexperienced (INEXP) and experienced (EXP) drivers with the three additional velocity task demands (FREE, + 80 KM/H and + 100 KM/H).

	FREE	+ 100 KM/H	+ 80 KM/H	
velocity (km/h)	92.8	97.1	82.2	INEXP
	94.2	95.6	79.1	EXP
S.D. velocity (km/h)	4.5	3.1	2.8	INEXP
	3.0	2.6	2.4	EXP

5.3.4 **Discussion**

Although it is not surprising that the MIN condition for lateral vehicle control gave larger variations of lateral position than the MAX condition, the absolute S.D. values during the MIN condition indicate that both groups of drivers still were quite able to stay within their lane (S.D. values of 0.31 m correspond with only a 0.3% chance to exceed the lane boundaries when a normal distribution function is assumed for lateral positions). Evidence for acceptable lateral control performance is also found in both TLC medians, indicating that only the median left TLC is decreased in the MIN condition as compared to the MAX condition, but still appeared to be comparable with the median right TLC values, which were not different in both MIN and MAX conditions. Neither the number of short TLC values within a run changed significantly, because Godthelp and Konings (1981) noticed identical effects for the 15% TLC values (15% of the time with a shorter TLC) as compared with the presented median TLC values. In conclusion, during multitask driving when tasks are added to the primary lateral control task, e.g. to scan the off-road environment or to control the speed of the car explicitly, both inexperienced and experienced drivers still show a quite satisfactory driving performance.

With respect to driver's control strategy some remarks can be made about the spectral changes of the steering-wheel movements in relation to the task demands. As was shown before (par. 5.2.1), during lateral control without any additional task, the spectral density function can be related to high-frequent control of the yaw rate and low-frequent control of the lateral speed (heading angle). A spectral shift can be linked to the task demands: A high task demand for lateral control results in a shift to higher frequencies of the steering-wheel movements. However, with additional tasks it becomes of importance whether drivers can combine these tasks without a decrease in attention for lateral vehicle control. MacDonald and Hoffmann (1980) reviewed the relationships between task demands and steering-wheel reversal rate, and concluded that low levels of steering-wheel reversal rate, or less energy at high frequencies, might indicate either low task demands due to relatively undemanding lateral control, or a very high total task demand due to additional tasks resulting in a decrease in attention for lateral control.

Within the MAX condition of the present experiment, the additional speed instruction resulted for the inexperienced drivers in a shift towards lower frequencies, with unaffected S.D. of the steering-wheel movements, and it suggests such a decrease in attention for lateral vehicle control. Obviously, inexperienced drivers cannot combine lateral and longitudinal vehicle control sufficiently. A similar shift is absent for the experienced drivers (even a shift to higher frequencies is noticed) and suggests no decrease in attention for lateral control for this group of drivers. The shift to higher frequencies even indicates that the required higher task demands for longitudinal control are associated with self-chosen higher task demands for lateral control, although it is not confirmed by a significantly better lateral position performance (in Experiment 4 it will be shown that a better lateral position performance can indeed be achieved in a similar situation). These results are consistent with those of Safren et al. (1970), who observed a positive correlation between the steering-wheel reversal rate and speed change rate for experienced drivers, and a negative correlation for inexperienced drivers. They concluded that inexperienced drivers seem to switch between lateral and longitudinal control, and that the experienced drivers perform both tasks simultaneously. Kimball et al. (1971) also stated that the combination of lateral and longitudinal control requires a substantial amount of driving skill.

The interaction for the frequencies of the steering-wheel movements between driving experience and speed instruction within the MAX condition, probably also forms the answer to the contradictory findings in the literature for the relationship between steering-wheel reversal rate and level of driving skill (par. 5.2.1). Some authors found that experienced drivers drove with less steering-wheel reversals than inexperienced drivers, but Riemersma (1972) found an inverse relationship. However, in considering the experimental conditions of Riemersma's study it appeared that subjects were always instructed to drive with an additional forced velocity, while in the other studies no such instruction was given. Consequently, the mentioned interaction of the present experiment explains these contradictory findings.

The addition of the task to scan the off-road environment (MIN condition) also creates a situation with decreased attention for lateral vehicle control due to a very high total task demand. In accordance with the above-mentioned considerations a shift to lower steering-wheel frequencies, with unaffected S.D., might be expected. However, in this MIN condition the steering-wheel movements shifted to higher frequencies as compared to the MAX condition, and its S.D. increased significantly for the experienced drivers and even to a much larger extent for the inexperienced drivers. These changes in driver's control strategy might be explained by the extreme characteristics of the scanning task, forcing drivers to occlude the visual cues for vehicle control for as long as possible, resulting in relatively large drifts in lateral position. Consequently, when drivers again are observing their driving performance, rather large and abrupt (high frequent) steering-wheel movements are necessary to reset the lateral position of the car inside the lane. Thereby, inexperienced drivers have to correct with larger steering-wheel movements than experienced drivers. The additional + 100 KM/H condition, in combination with the scanning task, does not affect driving performance and driver's control strategy any further.

5.4 Discussion and conclusions

Experiments 1 and 2 showed that experienced as well as inexperienced drivers need few foveal and/or peripheral observations for lateral vehicle control, and that both groups of drivers may temporarily allocate their attention to other tasks or activities not related to driving. When tasks are added, their lateral control performance remains acceptable, i.e. drivers stay within their lane. However, in conditions where drivers are temporarily forced to neglect the visual cues for lateral control (as in Experiment 2 with the task to scan off-road) the control strategy of experienced drivers shows relatively large, abrupt steering-wheel movements, whereas inexperienced drivers even need larger steering-wheel movements to correct the vehicle position.

With only a speed control task in addition to lateral control, and when the visual cues are continuously present, driver's control strategy also shows changes in the steering-wheel frequencies, suggesting that inexperienced drivers cannot combine both tasks sufficiently, and that experienced drivers have learned to combine lateral and longitudinal control considerably.

Now it is of importance to analyse driver's strategy for different task demands and driving skills in view of the question which perceptual cues, and on which moments in time, are used for a satisfactory lateral control performance during multitask driving. Hence, driver's control strategy and overall driving performance are studied in relation to specific perceptual cues (Chapter 6). Driver's observation strategy is analysed with respect to the moments in time for new observations, and with respect to free times when drivers allow themselves to neglect lateral control (Chapter 7).

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6. DRIVER'S CONTROL STRATEGY AND PERFORMANCE AFFECTED BY PERCEPTUAL CUES

6.1 Introduction

In this chapter the contribution of various continuously present perceptual cues to the overall driving performance and driver's control strategy is discussed.

First, a study with the Supervisory Driver Model has been conducted to predict the effects on driving performance of different combinations of perceptual cues, either in the observation/prediction block or in the control block of the model (Experiment 3). Second, empirical data have been gathered in driving situations which differ in the availability of perceptual cues: With and without acceleration cues (Experiment 4), and with deteriorated visibility due to driving in darkness (Experiment 5).

6.2 Experiment 3: Model predictions for different combinations of perceptual cues[1]

6.2.1 **Introduction**

A study with the Supervisory Driver Model, the SDM, has been conducted to predict the effects on lateral control performance of different combinations of perceptual cues. Following par. 2.3 and 2.4, the conditions for the model analyses refer to the use of different combinations of perceptual cues in both the observation/prediction block and the control block of the SDM. As a basic condition, the observation and control of lateral position alone is considered, whereas in the other conditions various cues in the observation/prediction block and control block are added. Accordingly, the most complete condition consists of the simultaneous observation and

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[1] The data of the model predictions were partially presented at the Third European Annual Conference on Human Decision Making and Manual Control (Blaauw et al., 1983) and the XXth FISITA Conference (Godthelp et al., 1984). They were also accepted for publication in Vehicle System Dynamics (Blaauw et al., 1984).

control of the lateral position via the inclination angle, lateral speed via the inclination rate, yaw rate, lateral acceleration and yaw acceleration (par. 3.2). During the SDM calculations fixed conditions have been imposed as described in par. 4.4.3.

6.2.2 **Predictions based on the observation/prediction block**

Fig. 6.2.1 shows the relationship between the observation noise level and the standard deviation of the lateral position and yaw rate, for a driving speed of 100 km/h. The axis of the observation noise is defined according to decreasing noise levels in order to correspond with increasing levels of attention. The sensitivity of the S.D. of the heading angle and the steering-wheel angle for different combinations of cues appeared to correspond with the sensitivity of the S.D. of the yaw rate and, therefore, it is not presented separately. The relationships in Fig. 6.2.1 are given for six combinations of the perceptual cues $\dot{\alpha}$, α, r, a_l and $\dot{r}$ (par. 3.2) in the observation/prediction block, depending on the availability of the cues, or driving skill (par. 2.4). The optimization criterion in the control block (task demands) only considers control of the lateral position via the inclination angle α.

The results show smaller S.D. of lateral position and yaw rate for lower observation noise levels, when driving performance can be estimated more accurately. In comparison with the exclusive use of the lateral position cue in the observation/prediction block (via the inclination angle α; curve 1 in Fig. 6.2.1), it appears that the additional observation/prediction of yaw rate r (curve 2), and lateral acceleration a_l and yaw acceleration $\dot{r}$ (curve 3) only gives marginal improvements. However, the additional use of the lateral speed cue in the observation/prediction block (via the inclination rate $\dot{\alpha}$; curve 4) gives a relatively large decrease in the S.D. of the lateral position and yaw rate. But again, the additional observation/prediction of yaw rate (curve 5) and, lateral acceleration and yaw acceleration (curve 6), only gives marginal improvements.

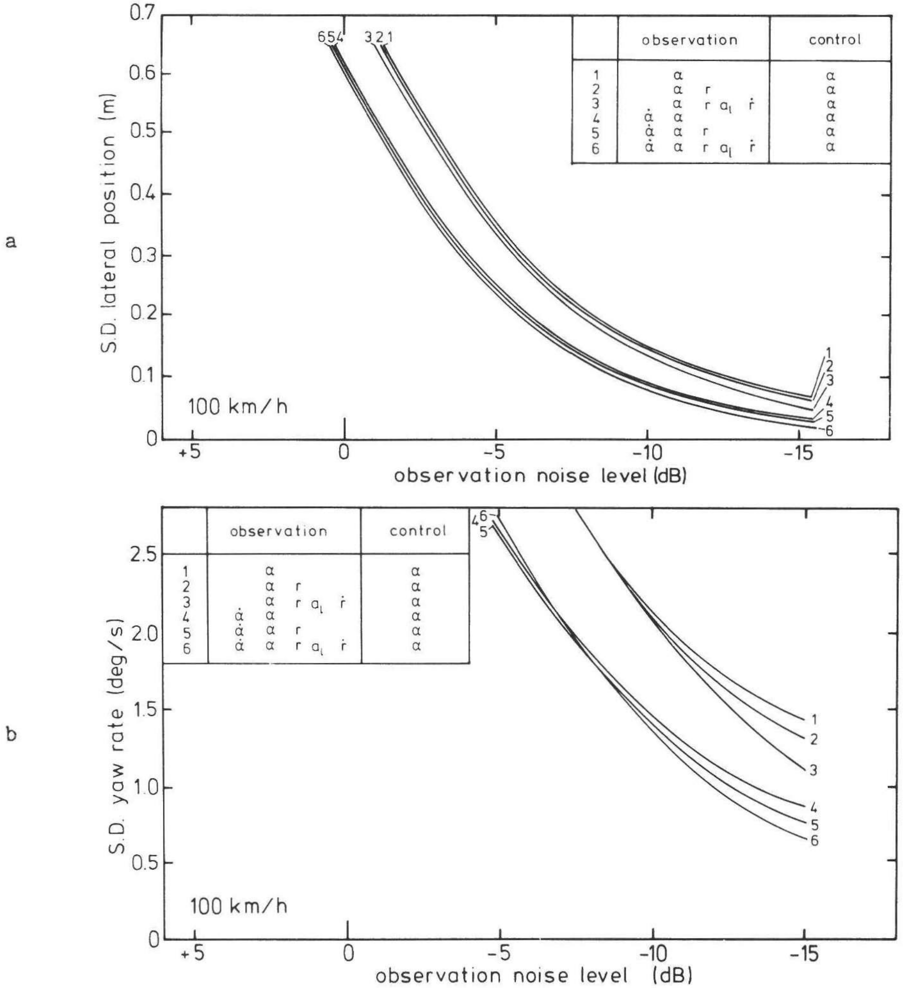

Fig. 6.2.1 Predicted relationships between the standard deviation (S.D.) of lateral position (Fig. 6.2.1a) and yaw rate (Fig. 6.2.1b), and the observation noise level for the observation/prediction of six combinations of perceptual cues (inclination rate $\dot{\alpha}$, inclination angle α, yaw rate r, lateral acceleration a_l, and yaw acceleration $\dot{r}$), for the exclusive control of the inclination angle α. The relationships are given for a driving speed of 100 km/h.

6.2.3 **Predictions based on the control block**

The results of par. 6.2.2 can be extended with predictions when more perceptual cues are controlled via the optimization criterion of the control block, as a result of changes in task demands or driving skill (par. 2.4). When all five cues are used in the observation/prediction block (Fig. 6.2.2), it is shown that an additional control of the lateral speed cue (curve 2) leads to a relatively large decrease in the S.D. of the yaw rate, whereas the S.D. of the lateral position decreases only over a few centimeters, especially at high levels of observation noise. An additional control of yaw rate (curve 3), both acceleration cues (curve 4) or their combination (curve 5) leads to an even larger improvement (decrease) in the S.D. of yaw rate. However, this improvement is obtained at the cost of an increase in the S.D. of the lateral position as compared to the curves 1-2. Similar results are obtained when all cues except the lateral speed cue are used in the observation/prediction block (Fig. 6.2.3), when the yaw rate (curve 2), both accelerations (curve 3), or their combination (curve 4) are controlled additionally.

6.2.4 **Predictions based on both blocks**

In addition to the separate effects of changes in the set of cues for the observation/prediction block and the control block, predictions have been made for the combined changes in both blocks. Fig. 6.2.4 shows that an additional control of lateral speed in the control block (via the inclination rate; curves 4-6) leads to only small decreases in the S.D. of the lateral position of the car. With respect to the S.D. of the yaw rate the similar improvement is shown as in Fig. 6.2.2 (curve 2), but now rather independently for the set of cues used in the observation/prediction block (curves 4-6).

Fig. 6.2.5 presents predictions with respect to the use of lateral speed and both accelerations in the two blocks. The observation and control of lateral speed results in an overall improvement of the S.D. of the lateral position. It is also found that the results of an addition of both acceleration cues depends on the use of the lateral speed cue. Without observation and control of the lateral speed cue (curves 1-2), larger improvements in lateral control performance are found due to both acceleration cues than with the use of lateral speed (curves 3-4). Similar results are found with respect to the S.D. of the yaw rate.

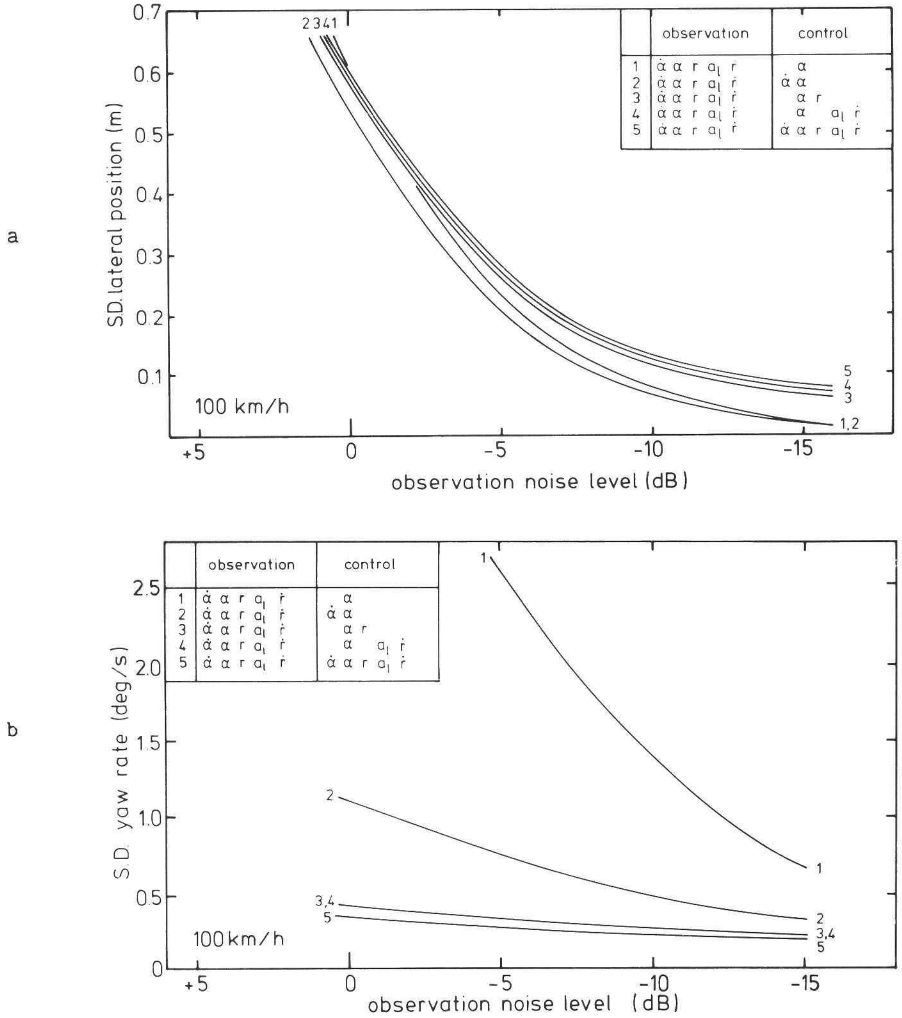

Fig. 6.2.2 Predicted relationships between the standard deviations (S.D.) of lateral position (Fig. 6.2.2a) and yaw rate (Fig. 6.2.2b) and the observation noise level for an additional control in the control block of lateral speed (via the inclination rate $\dot{\alpha}$), yaw rate r, and both lateral acceleration a_1 and yaw acceleration $\dot{r}$, during the combined use of all five perceptual cues in the observation/prediction block.

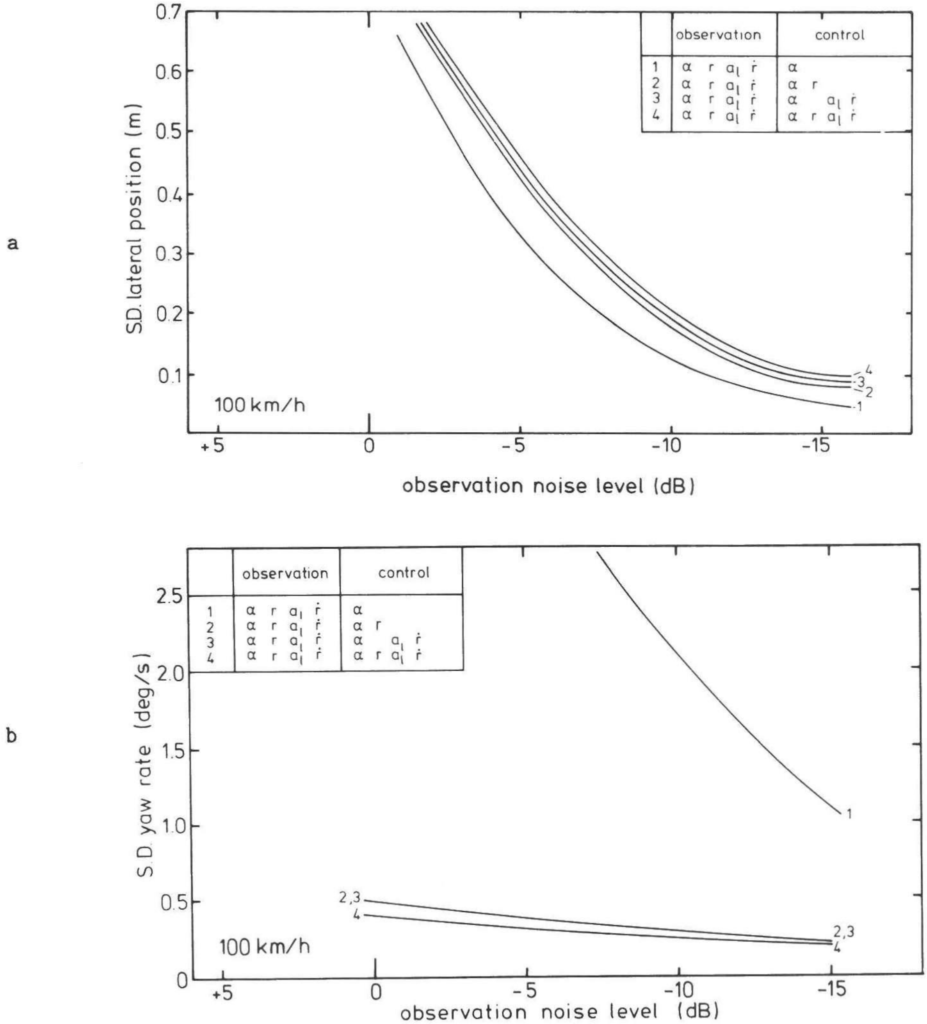

Fig. 6.2.3 As Fig. 6.2.2, but now for the combined use of only four perceptual cues (no inclination rate) in the observation/-prediction block.

6.2.5 **Discussion**

The Supervisory Driver Model shows that lateral control performance (S.D. of lateral position and yaw rate) improves considerably when additional perceptual cues are used in the observation/prediction block or in the control block, as compared to the exclusive use of the lateral position cue. The additional use of cues in the observation/prediction block may be the result of changes in driving skill, or more cues available to the driver (Table 2.4.1). The additional use of cues in the control block may also be the result of driving skill development, or changes in task demands.

With respect to the observation/prediction block it is shown that the S.D. of lateral position and yaw rate decreases when also the lateral speed cue is used (Fig. 6.2.1); the additional observation/prediction of yaw rate and both accelerations hardly improves lateral control performance, unless these cues are also controlled explicitly (Fig. 6.2.5). When a rather complete set of cues is present in the observation/prediction block, it appears than an additional control of lateral speed, and, especially, of yaw rate and of both the accelerations, via the criterion in the control block, leads to relatively large improvements (decreases) in the S.D. of the yaw rate. The S.D. of lateral position then remains unaffected or deteriorates slightly (Figs. 6.2.2 and 6.2.3).

Hence, the lateral speed cue which was assumed to improve driver's anticipation, indeed seems to be most effective within the observation/prediction block, and it aids in achieving an improvement in the S.D. of lateral position and yaw rate. The Supervisory Driver Model indicates that a similar lateral control performance can be obtained with a larger observation noise level (less attention) when the lateral speed cue is taken into account. Hence, the model predicts that it is helpful to learn drivers to use that cue. There is some experimental evidence that the use of the lateral speed cue indeed is related to the level of driving skill. Riemersma (1982) restricted the visual field close to the car and noticed a deterioration in control performance for the experienced drivers, whereas the performance of the inexperienced drivers was not affected. Because the lateral speed cue can be perceived best close to the car, it can be concluded that the inexperienced drivers did not use the lateral speed cue.

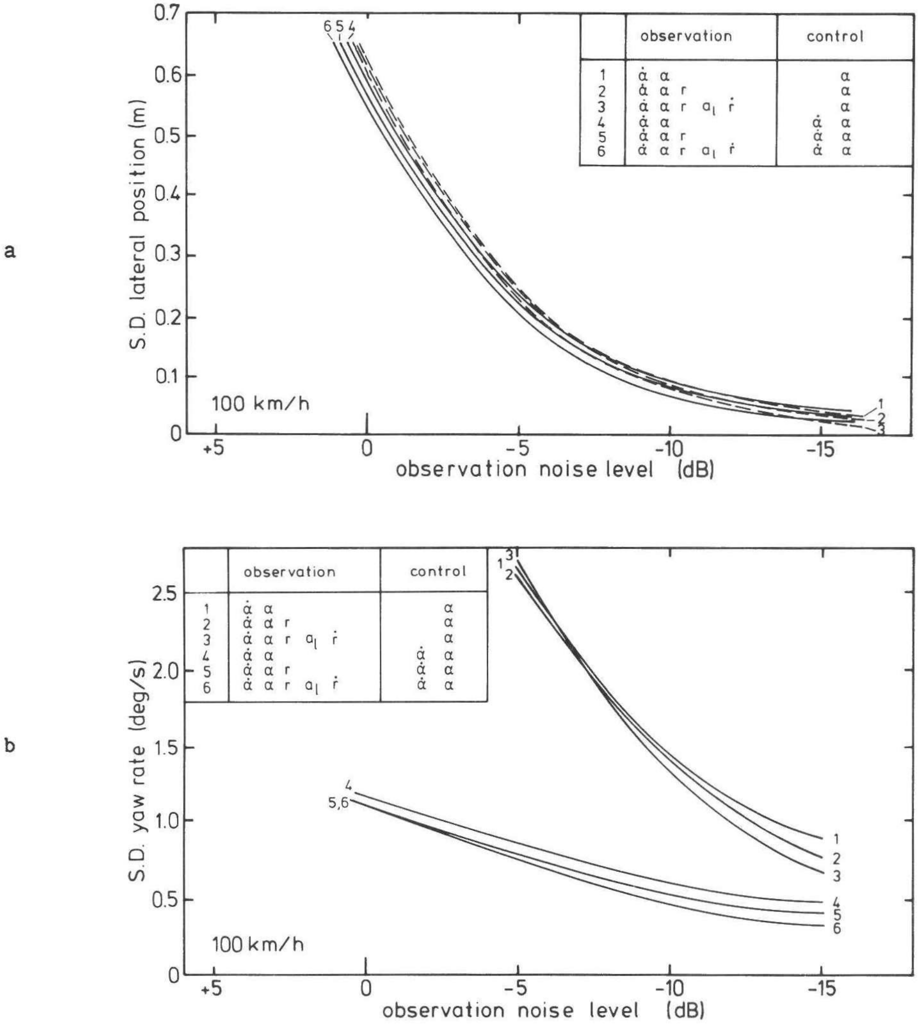

Fig. 6.2.4 Predicted relationships between the standard deviations (S.D.) of lateral position (Fig. 6.2.4a) and yaw rate (Fig. 6.2.4b) and the observation noise for an additional control of the inclination rate $\dot{\alpha}$ (curves 4-6) compared to an exclusive control of the inclination angle α (curves 1-3) via the optimization criterion of the control block. The relationships are given for three combinations of perceptual cues for the observation/prediction block, as presented in Fig. 6.2.1.

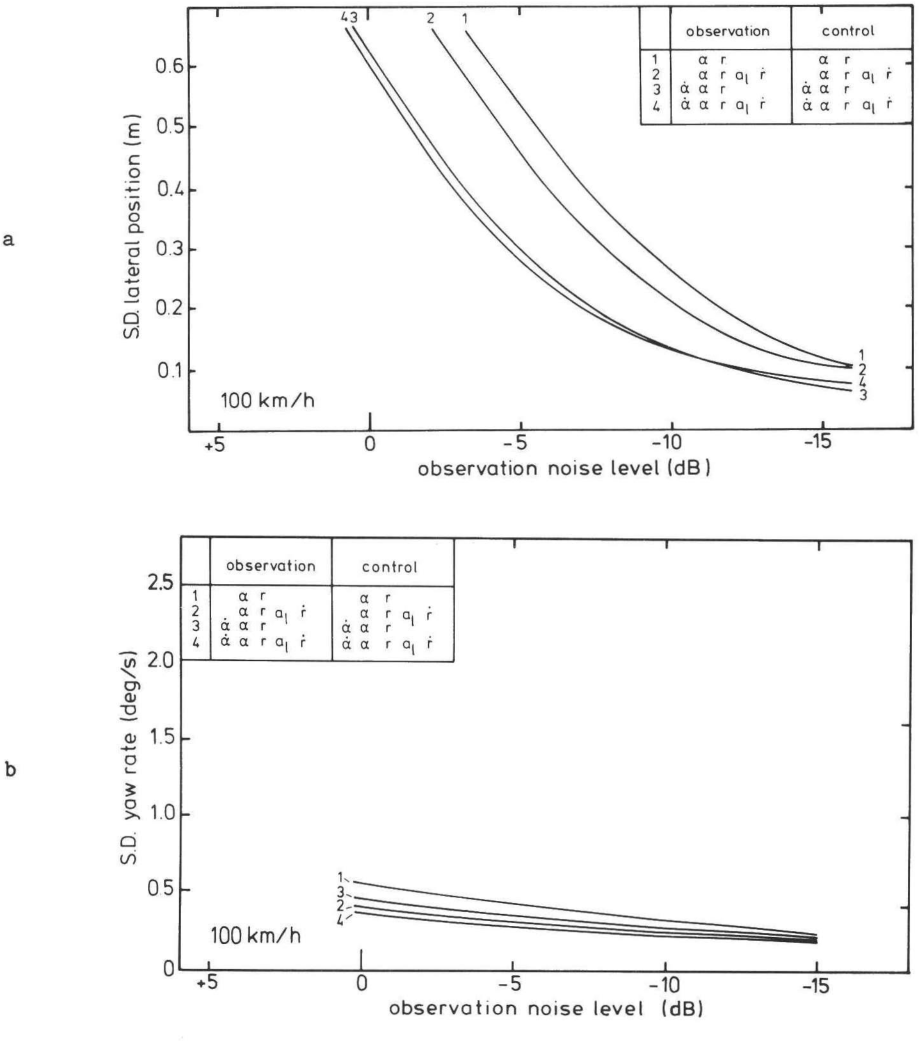

Fig. 6.2.5 Predicted relationships between the standard deviations (S.D.) of lateral position (Fig. 6.2.5a) and yaw rate (Fig. 6.2.5b) and the observation noise for an additional observation/prediction and control of lateral speed (via the inclination rate $\dot{\alpha}$) and both lateral acceleration a_l and yaw acceleration $\dot{r}$ on lateral control performance.

6.3 Experiment 4: Driving skill, task demands and acceleration cues[2]

6.3.1 Introduction

The contribution of acceleration cues to the observation and control strategy of drivers during lateral vehicle control has mainly been studied for compensatory driving tasks, e.g. with respect to sidewind gusts. In general, it is found that in these types of tasks the absence of acceleration cues results in poorer driving performance in terms of larger standard deviations of lateral position and yaw rate (McRuer and Krendel, 1974; McLane and Wierwille, 1975; McRuer and Klein, 1976). Weir and McRuer (1967) concluded in their model studies on sidewind compensation, that the addition of the lateral acceleration cue to visual cues makes little difference in the heading and path deviations of the vehicle for moderate gains (comparable with the weighting factors in the optimization criterion of the control block). However, it can make the driver/vehicle system unstable if the gain is sufficiently high. The authors conclude "... the driver is probably better off not trying to use the lateral acceleration cue unless he has no other choice". The latter case will happen, e.g., during complete visual occlusion when the use of the lateral acceleration cue will keep the steady-state errors and drifts from increasing too rapidly, but cannot prevent off-lane drifting. Weir and McRuer illustrate these conclusions by stating that during visual occlusion a car will leave a 20-feet wide lane within 5 s when the acceleration cues are not used, while that period may increase to 40 s for a skilled, attentive driver with the use of the acceleration cues.

Some data can also be obtained from experiments with respect to the design of flight simulators. Baron et al. (1982) compared a complex helicopter control task in fixed-base and moving-base conditions and found that predictions by the Optimal Control Model (OCM) resulted in almost 50% worse fixed-base performance measures than corresponding moving-base measures. Curry et al. (1976), however, noticed only a small difference between fixed-base and moving-base conditions in a VTOL (Vertical Take Off and Landing) task for both OCM predictions and empirical data. The authors argue that only small differences are found because the simulator seemed

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[2] The results of this experiment were previously used to evaluate the validity of the fixed-base vehicle simulator of the Institute for Perception TNO during straight road driving (Blaauw, 1982).

mostly to operate near the vestibular thresholds of the pilots. In a review on piloted aircraft simulation, Stapleford (1978) states that pilots use motion cues primarily as high-frequent adjuncts to the visual cues, and the more difficult the compensatory task, the larger the benefit of motion appears to be.

For driving conditions studied in this thesis (with small, low-frequent disturbances which are assumed to be generated by the drivers), the calculations with the Supervisory Driver Model (par. 6.2) indicated that the additional observation/prediction of both the lateral acceleration cue and the yaw acceleration cue has only marginal effects on the S.D. of the lateral position and yaw rate (Fig. 6.2.1). An additional control of both cues leads to an improvement of the S.D. of lateral position and yaw rate, only when the lateral speed cue is not taken into account (Fig. 6.2.5, curves 1-2). With the lateral speed cue, the differences are smaller (Fig. 6.2.5, curves 3-4). When the use of this cue indeed is characteristic for the more experienced drivers (par. 6.2.5), it may be expected that an absence of both acceleration cues should deteriorate driving performance for the inexperienced drivers to a larger extent than for the experienced drivers. In order to obtain additional empirical data on driving performance and driver's control strategy with and without acceleration cues, an experiment has been conducted in the instrumented car and in the fixed-base simulator, for different driving skills and task demands.

6.3.2 **Method**

Twenty-four experienced drivers and twenty-four inexperienced drivers drove in the instrumented car and in the simulator. Task demands were varied between subjects, and were manipulated by instruction. There were two conditions for lateral vehicle control:

(1) FREE - no specific lateral instruction was given.

(2) MAX(imum) - "to drive as straight as possible", informing the drivers that their variations in straight driving were recorded, so that they should intensively concentrate on this task. This instruction attempted to provoke a strict internal criterion for lateral control, and aimed at maximum visual needs to do so.

Both instructions for lateral vehicle control were combined with one of the following instructions for longitudinal control:

(3) FREE - no specific longitudinal instruction was given.

(4) + 100 KM/H - subject's instructions were similar to those in condition 2, but now with respect to the variations in velocity: Therefore, they should concentrate on a constant velocity of 100 km/h. This instruction attempted to provoke a strict criterion for longitudinal control. Due to the absence of differences between the conditions + 80 KM/H and + 100 KM/H in Experiment 2, the + 80 KM/H condition was omitted.

Lateral and longitudinal instructions combined resulted in four conditions. Each subject drove an experimental condition in two one-hour sessions during one day, one hour in the simulator and one hour in the instrumented vehicle. From the six subjects each day, three started in the simulator in the morning and transferred to the instrumented vehicle in the afternoon, whereas the remaining three did the reverse. For more detailed methodological information see Chapter 4.

6.3.3 **Results**

Lateral vehicle control

Table 6.3.1 presents lateral control performance in both the car and simulator for two task demands, and for both levels of driving experience; each result represents the average value over 36 runs (6 subjects x 6 trials). Table 6.3.2 gives similar data for driver's control strategy reflected by the amplitudes and frequencies of the steering-wheel movements (par. 4.5). The MAX and FREE task demands for lateral vehicle control did not differ and, therefore, Tables 6.3.1 and 6.3.2 are restricted to the FREE condition. The first trial for the inexperienced drivers in both the simulator and the instrumented car resulted in significantly ($p \leq 0.05$) larger S.D. of the yaw rate and steering-wheel angle, as compared to the other five trials.

Compared with driving in the instrumented car on the road, the runs in the simulator resulted in:

- larger distance to the right shoulderline ($p \leq 0.001$)
- larger S.D. of the lateral position ($p \leq 0.001$)
- larger S.D. of lateral speed ($p \leq 0.001$)
- smaller S.D. of yaw rate for the experienced drivers ($p \leq 0.01$)
- no differences in the median left TLC, which value is larger ($p \leq 0.001$) than the median right TLC
- larger median right TLC for the experienced drivers ($p \leq 0.05$)
- lower steering-wheel frequencies ($p \leq 0.05$).

Table 6.3.1 Lateral control performance in the instrumented car and in the simulator for the inexperienced (INEXP) and experienced (EXP) drivers with the FREE and + 100 KM/H task demands.

		instrumented car		simulator		
		FREE	+ 100 KM/H	FREE	+ 100 KM/H	
lateral position	(m)	1.79	1.82	2.00	1.93	INEXP
		1.73	1.65	1.90	1.98	EXP
S.D. lateral position	(m)	0.16	0.22	0.36	0.42	INEXP
		0.21	0.11	0.30	0.20	EXP
S.D. lateral speed	(m/s)	0.06	0.10	0.16	0.20	INEXP
		0.13	0.07	0.14	0.11	EXP
S.D. yaw rate	(°/s)	0.30	0.34	0.27	0.31	INEXP
		0.36	0.29	0.25	0.24	EXP
median left TLC	(s)	5.4	5.0	5.0	4.9	INEXP
		4.9	6.4	6.0	5.9	EXP
median right TLC	(s)	3.5	3.5	4.6	3.7	INEXP
		3.0	3.3	4.2	4.6	EXP

Table 6.3.2 Driver's control strategy in the instrumented car and in the simulator for the inexperienced (INEXP) and experienced (EXP) drivers with the FREE and + 100 KM/H task demands.

		instrumented car		simulator		
steering-wheel angle		FREE	+ 100 KM/H	FREE	+ 100 KM/H	
S.D.	(°)	1.5	1.8	1.4	2.3	INEXP
		1.6	1.3	1.2	1.2	EXP
energy $\frac{0.3\text{-}0.6 \text{ Hz}}{0 - 0.6 \text{ Hz}}$	(%)	24.9	29.9	17.4	23.0	INEXP
		24.5	33.0	20.1	25.3	EXP

Greater driving experience had no overall effect on the measures in the instrumented car (and appeared to be dependent on the task demands; see below), but in using the simulator, it resulted in:

- smaller S.D. of the lateral position ($p \leq 0.001$)

- smaller S.D. of the lateral speed ($p \leq 0.001$)
- larger median left TLC ($p \leq 0.05$)
- smaller S.D. of the steering-wheel angle ($p \leq 0.05$).

Together with the driving experience, the + 100 KM/H condition showed interaction effects for the standard deviations of the lateral position ($p \leq 0.01$), lateral speed ($p \leq 0.001$), and steering-wheel angle ($p \leq 0.05$). For both the simulator and the instrumented car, inexperienced drivers had a significant increase in these measures when driving + 100 KM/H, whereas the experienced drivers then showed a decrease. Hence, differences between inexperienced and experienced drivers appear when the + 100 KM/H condition is added. The additional + 100 KM/H condition in the instrumented car and simulator resulted for both the inexperienced and experienced drivers in a shift to higher steering-wheel frequencies during the FREE lateral condition ($p \leq 0.06$). However, during the MAX lateral condition the experienced drivers still show a shift to higher steering-wheel frequencies when the + 100 KM/H condition is added, while the inexperienced drivers then show a shift to lower frequencies in the simulator, which did not occur in driving the car.

Longitudinal vehicle control

Table 6.3.3 presents the mean and standard deviation of velocity for the inexperienced and experienced drivers during the FREE condition and + 100 KM/H condition in both the instrumented car and simulator.

Table 6.3.3 Longitudinal control performance in the instrumented car and in the simulator for the inexperienced (INEXP) and experienced (EXP) drivers with the FREE and + 100 KM/H task demands.

	instrumented car		simulator		
	FREE	+ 100 KM/H	FREE	+ 100 KM/H	
velocity (km/h)	109.9	102.4	111.8	100.8	INEXP
	110.0	107.6	108.6	100.3	EXP
S.D. velocity (km/h)	1.1	0.8	2.3	1.8	INEXP
	1.4	0.7	2.6	0.8	EXP

Task demands during the FREE condition resulted for both groups of drivers in a higher ($p \leq 0.01$) velocity of about 110 km/h in both the instrumented car and simulator compared to the + 100 KM/H condition. With respect to the standard deviation of the velocity it was shown that the + 100 KM/H condition resulted in smaller variations compared to the FREE condition, for all drivers in simulator and car ($p \leq 0.05$). In general, velocity variations were greater in the simulator than in the car ($p \leq 0.05$).

6.3.4 **Discussion**

Without acceleration cues driver's control strategy showed in the FREE condition a shift to lower frequencies of the steering-wheel movements, resulting into an increase in the S.D. of the lateral position for the experienced drivers. This effect turned out to be even larger for the inexperienced drivers. This is consistent with the SDM predictions (Fig. 6.2.5) when it is assumed that the inexperienced drivers do not use the lateral speed cue in contrast to the experienced drivers. Together with the increase in the S.D. of the lateral position, drivers in the simulator show an increase in the S.D. of the forward speed and a mean shift of 0.18 m to the left in the traffic lane as compared to the runs with the car on the road. In TLC terms it is found that the inexperienced drivers do not show any difference for the median left TLC or median right TLC, neither between car and simulator, nor between the FREE and + 100 KM/H condition. However, the experienced drivers increase their median right TLC in the simulator as compared with the car, independently of both longitudinal conditions. Their median left TLC is higher in the car during the additional + 100 KM/H condition, and also higher during the runs in the simulator.

The + 100 KM/H condition, representative for multitask driving, results for the inexperienced drivers in an increased S.D. of the lateral position in both the simulator and car, whereas the experienced drivers show a decrease. Just as was found in Experiment 2, it again is noticed that for the experienced drivers the required higher task demands for longitudinal control are associated with self-chosen higher task demands for lateral control. This result is shown by the significant shift to higher steering-wheel frequencies in both the simulator and the car, without a corresponding increase in the S.D. of the steering-wheel movements. In contrast with the results of Experiment 2 where the changes in lateral control performance failed to be significant, the higher task demands in the present experiment are associated with significantly smaller S.D. of lateral position, and lateral speed. Even the inexperienced drivers show in this experiment a shift to higher steering-wheel frequencies due to the + 100 KM/H condition. However, due to the increased S.D. of the steering-wheel movements a completely different situation is present and a deterioration in lateral control performance is noticed. In parallel with the discussion of Experiment 2, this increased S.D. reflects less skill for the inexperienced drivers in combining lateral and longitudinal control, for both the car on the road and the simulator.

6.4 Experiment 5: Driving skill, task demands and visual cues during day- and nighttime[3]

6.4.1 Introduction

The contribution of the visual cues to the observation and control strategy of drivers has been studied by comparing day- and nighttime driving. Although in general, visibility is deteriorated during darkness, it is more difficult to define the specific effects of darkness on the availability of the visual cues. The lateral position and lateral speed can be perceived from the rotations of the road markers around the vanishing point of the road at the horizon, whereas the yaw rate can be perceived by a horizontal velocity of all points in the visual field (par. 3.2). During nighttime, the dipped headlamps cover about 40 m in front of the car and they illuminate the most relevant part of the road ahead allowing the perception of these three visual cues. However, at night the perception of the speed cue (longitudinal control) will be considerably deteriorated, because the absence of peripheral visual stimulation results in less accurate velocity estimates (Salvatore, 1968).

In order to test driver's strategy and performance during nighttime an experiment has been conducted with the instrumented car; results are compared with the daytime results of Experiment 4.

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[3] The data of this experiment were partially presented during the First European Annual Conference on Human Decision Making and Manual Control (Blaauw, 1981).

6.4.2 **Method**

Twelve experienced and twelve inexperienced drivers drove in the instrumented car during nighttime, whereas the data of the daytime conditions were taken from Experiment 4. Drivers task demands were varied between subjects and were manipulated by instruction. There were two conditions:

(1) FREE - no specific instruction was given.

(2) + 100 KM/H - subjects were instructed to concentrate on driving with a constant velocity of 100 km/h. This instruction was intended to provoke a strict criterion for longitudinal control.

Due to the absence of effects in lateral control instructions in Experiment 4 (FREE versus MAX), the MAX condition was omitted.

Each subject drove one of the experimental conditions in a one-hour session between 8.00 p.m. and midnight. There was no public lighting and the car had dipped headlamps. For more detailed methodological information see Chapter 4.

6.4.3 **Results**

Lateral vehicle control

Table 6.4.1 presents lateral control performance during day- and nighttime as affected by task demands and driving experience; each result represents the average value over 36 runs (6 subjects x 6 trials). Table 6.4.2 gives similar data for driver's control strategy reflected by the amplitudes and frequencies of the steering-wheel movements (par. 4.5). With respect to the six trials, only the first trial resulted in significantly ($p \leq 0.05$) larger S.D. of the yaw rate and steering-wheel angle compared with the other five trials, during day- and nighttime.

In general, the runs during nighttime resulted in a significantly larger distance to the right lane marker than during daytime ($p \leq 0.001$). During nighttime both median left and right TLC values are comparable, whereas during daytime the median left TLC is larger than the right TLC ($p \leq 0.001$). More driving experience had no overall effect during daytime (and appeared to be dependent on the task demands; see below), but it resulted during nighttime in:

- smaller S.D. of the lateral position ($p \leq 0.05$)
- smaller S.D. of lateral speed ($p \leq 0.01$)

Table 6.4.1 Lateral control performance for the inexperienced (INEXP) and experienced (EXP) drivers with the FREE and + 100 KM/H task demands, during day- and nighttime.

		day		night		
		FREE	+ 100 KM/H	FREE	+ 100 KM/H	
lateral position	(m)	1.80	1.83	2.17	2.25	INEXP
		1.73	1.65	2.16	2.12	EXP
S.D. lateral position	(m)	0.17	0.22	0.21	0.28	INEXP
		0.21	0.11	0.13	0.16	EXP
S.D. lateral speed	(m/s)	0.07	0.10	0.10	0.12	INEXP
		0.12	0.07	0.06	0.08	EXP
S.D. yaw rate	(°/s)	0.28	0.33	0.35	0.38	INEXP
		0.35	0.28	0.31	0.33	EXP
median left TLC	(s)	5.4	5.0	4.5	4.2	INEXP
		4.9	6.4	5.4	4.9	EXP
median right TLC	(s)	3.5	3.5	4.6	4.4	INEXP
		3.0	3.3	5.4	4.7	EXP

Table 6.4.2 Driver's control strategy for the inexperienced (INEXP) and experienced (EXP) drivers with the FREE and + 100 KM/H task demands, during day- and nighttime.

		day		night		
steering-wheel angle		FREE	+ 100 KM/H	FREE	+ 100 KM/H	
S.D.	(°)	1.5	1.7	1.5	1.8	INEXP
		1.6	1.3	1.1	1.3	EXP
energy $\frac{0.3\text{-}0.6 \text{ Hz}}{0 - 0.6 \text{ Hz}}$	(%)	24.9	28.5	27.7	26.3	INEXP
		24.5	33.0	40.8	32.4	EXP

- smaller S.D. of the yaw rate ($p \leq 0.05$)
- larger median left and right TLC ($p \leq 0.06$)
- smaller S.D. of the steering-wheel angle ($p \leq 0.05$)
- higher steering-wheel frequencies ($p \leq 0.05$).

The + 100 KM/H condition resulted during daytime in a shift to higher steering-wheel frequencies for both the inexperienced and experienced drivers ($p \leq 0.05$). During nighttime the inexperienced drivers showed no spectral shift, whereas the experienced drivers turned to a shift to lower frequencies. Together with driving experience the + 100 KM/H condition showed also interaction effects for the standard deviations of lateral position ($p \leq 0.05$), lateral speed ($p \leq 0.05$), and steering-wheel angle ($p \leq 0.05$). During daytime inexperienced drivers showed a significant increase in these measures when the + 100 KM/H instruction was imposed, whereas the experienced drivers then showed a decrease. Hence, differences between both levels of driving experience become more obvious when the + 100 KM/H instruction is added. The same interaction is shown for the median left TLC during daytime resulting in a larger TLC value for the experienced drivers than for the inexperienced drivers ($p \leq 0.05$).

Longitudinal vehicle control

Table 6.4.3 presents the mean and standard deviation of velocity for the inexperienced and experienced drivers during the FREE and + 100 KM/H condition during night and day. No differences were present in the S.D. of velocity, but the mean velocity was significantly lower during nighttime for both levels of driving experience and task demands compared to the day condition ($p \leq 0.05$). In the FREE condition all subjects drove faster than during the + 100 KM/H condition ($p \leq 0.05$), during day- and nighttime.

Table 6.4.3 Longitudinal control performance for the inexperiened (INEXP) and experienced (EXP) drivers with the FREE and + 100 KM/H task demands, during day- and nighttime.

	day		night		
	FREE	+ 100 KM/H	FREE	+ 100 KM/H	
velocity (km/h)	109.9	102.4	104.3	99.7	INEXP
	111.0	107.6	106.3	102.0	EXP
S.D. velocity (km/h)	1.1	0.8	0.9	0.8	INEXP
	1.4	0.7	0.8	0.8	EXP

6.4.4 **Discussion**

In general, darkness did not affect the S.D. of lateral position or yaw rate, but resulted in a 0.42 m mean shift to the left in the traffic lane, and in a decreased velocity as compared to daytime. These results are consistent with the data of Matanzo and Rockwell (1967) who noticed similar changes in driving performance during darkness. With respect to the TLC values it is found that the median left TLC and median right TLC are comparable during nighttime, whereas the median right TLC is smaller than the left one during daylight.

The deteriorated visibility during darkness did not considerably affect the control strategy of the inexperienced drivers within the FREE condition, but led to higher frequencies and smaller S.D. for the steering-wheel movements of the experienced drivers. Hence, it may be concluded that the experienced drivers use the deteriorated night conditions to select higher task demands for lateral control, as was previously also found to be caused by the additional + 100 KM/H condition during daytime (Experiments 2 and 4). Due to these effects, lateral control performance of the experienced drivers at night is much better than the performance of the inexperienced drivers, for both the FREE and + 100 KM/H condition.

The effects of the + 100 KM/H condition during daytime, representative for multitask driving, appeared to be dependent on the level of driving skill (see also the Discussion of Experiment 4). From Table 6.4.1 it will be clear that, for the inexperienced drivers the + 100 KM/H condition during darkness leads to a further deterioration of lateral control performance (S.D. of lateral position) as compared to the day conditions, whereas the experienced drivers then do not have a further deterioration.

From driver's control strategy (amplitudes and frequencies of the steering-wheel movements) during daytime it was already concluded that the + 100 KM/H condition is associated for the experienced drivers with self-chosen higher task demands for lateral vehicle control, and resulted for the inexperienced drivers in less skills to combine both lateral and longitudinal control in accordance with the required task demands. The + 100 KM/H condition during the nighttime condition of the present experiment resulted for both levels of driving experience in larger steering-wheel movements with comparable (for the inexperienced drivers) or even lower (experienced drivers) frequencies. In line with the conclusion of the previous experiments, these changes suggest that during darkness the combination of lateral and longitudinal control is more difficult. Although this conclusion was drawn earlier for driving situations with inexperienced drivers, it is surprising that also for the experienced drivers this seems valid, be it for a rather high lateral performance level. However, when it is recalled that during darkness the peripheral visual field, with its possibilities for speed estimation (Salvatore, 1968) is deteriorated, speed estimates have to be based primarily on direct observations of the speedometer. Because during these periods no visual information can be gathered about lateral vehicle control, it becomes clear that then even the experienced drivers might have difficulties in combining tasks, when they perform at a high performance level.

6.5 Discussion and conclusions

Both the Supervisory Driver Model study and the empirical data show that driver's lateral control performance (S.D. of lateral position and yaw rate) is dependent on the availability of the perceptual cues. As a main conclusion from the SDM study it has been found that an improvement in lateral control performance is already obtained by the addition of the lateral speed cue in the observation/prediction block. The addition of yaw rate, and/or both acceleration cues gives improvements, when they are explicitly taken into account in the control block. A comparison of the predicted and experimental S.D. values of the lateral position indicates variations between 0.10 and 0.60 m, associated with observation noise levels ranging from -15 to 0 dB for the use of the various cues. A similar comparison for the S.D. of the yaw rate with experimental values below 0.6 deg/s suggests for the identical range of observation noise levels that SDM predictions are only valid for conditions with an additional control of yaw rate and/or both acceleration cues (Figs. 6.2.2 and 6.2.3). Stated otherwise, predicted relationships for an exclusive control of the lateral position lead to too large a S.D. of yaw rate. Hence, yaw rate, or lateral and yaw acceleration seem to be already explicitly controlled in an early stage of driving practice. Control of these cues seems to shift to the control of lateral speed with increasing driving experience (Riemersma, 1982).

Results with respect to the absence of the acceleration cues (Experiment 4) in general showed a control strategy with lower steering-wheel frequencies, resulting into larger S.D. of lateral position for the experienced drivers, and to a larger extent for the inexperienced drivers. From these results it can be concluded that both the experienced and the inexperienced drivers indeed seem to use the acceleration cues for lateral vehicle control. However, the inexperienced drivers have not yet developed the skills to compensate for the absence of these cues by using the lateral speed cue as the experienced drivers do and, hence, the inexperienced drivers obtained a worse driving performance than the experienced drivers. The deteriorated visibility during darkness (Experiment 5) resulted for the inexperienced drivers in a comparable lateral control performance as during daytime, whereas the experienced drivers showed a shift to higher steering-wheel frequencies leading to an improvement in performance which is comparable to their daytime level when the + 100 KM/H condition is added. Obviously, the deteriorated visibility at night result for these drivers in self-paced higher task demands for lateral vehicle control similar to the addition of the + 100 KM/H condition during daytime. In general, as discussed in par. 5.4 the shifts in the steering-wheel spectral density function during lateral vehicle control alone points to a relative increase in the use of lateral speed (or heading angle) when a shift to lower frequencies is noticed, or vice versa to a relative increase in the use of yaw rate when the steering-wheel movements shift to the higher frequencies. In comparing the frequency and amplitude shifts during the FREE conditions of the several experiments, it is suggested for Experiment 4 that the absence of the acceleration cues resulted in less yaw rate control in favor of more lateral speed control. During darkness the steering-wheel movements of the experienced drivers shifted to higher frequencies (Table 6.4.2) and suggest a more tight control of yaw rate at the cost of less control of lateral speed.

In general, during both experiments it appeared that lateral control during the deteriorated conditions (no acceleration cues, at night) was performed while the lateral position of the car inside the traffic lane was shifted significantly towards the centre line; see also the Discussion in par. 7.4.

The addition of the + 100 KM/H condition describes multitask driving representative for a supervisory control scenario and may indicate driver's skill to combine lateral and longitudinal vehicle control. Larger steering-wheel movements, especially in combination with a shift in the steering-wheel frequencies, suggest in general problems with the combination of lateral and longitudinal vehicle control when the + 100 KM/H condition is added. Mostly, these changes occur only for the inexperienced drivers and then to a larger extent during deteriorated circumstances (absence of the acceleration cues, at darkness). These results indicate that the inexperienced drivers have not yet developed skills to combine the task demands of lateral and longitudinal control to a level as the experienced drivers do.

However, in the series of experiments, there was one condition where the experienced drivers also show a lack of combination of both the lateral and longitudinal control: at night when they had to drive with the added + 100 KM/H condition. As it was discussed in par. 6.4.4 at night the speed cues in the visual field are deteriorated and speed estimations have to be based primarily on direct observations of the speedometer, leading to attention allocation between lateral and longitudinal vehicle control with the consequences mentioned for the lateral control strategy of even the experienced drivers. During these circumstances it becomes necessary to analyze driver's observation strategy for both tasks in order to measure on which moments in time drivers have to observe cues with respect to lateral control and longitudinal control. These timing aspects of driver's observation strategy are subject of Chapter 7.

6.6 References

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7. DRIVER'S OBSERVATION STRATEGY AND PERFORMANCE AFFECTED BY PERCEPTUAL CUES

7.1 Introduction

Chapter 7 deals with the question about driver's observation strategy and, more specifically, about the timing aspects of the driver's need to update his estimates with respect to driving performance. Permanent restrictions in the set of perceptual cues were studied in the previous chapter. In the present chapter driver's observation strategy is analysed for self-paced, temporary restrictions in the set of cues, being representative of lateral vehicle control during multitask situations. In this approach, driver's visual cues are occluded for a certain period during which his uncertainty increases. However, the driver may request a new observation whenever his uncertainty increases to too high a level, and/or whenever his estimate approaches a critical value. This visual occlusion technique has been used by several authors for the study of lateral vehicle control. Senders et al. (1967) and Zwahlen and Balasubramanian (1974) have attempted this method to develop mathematical models of their subjects' lateral control strategy for driving with different speeds. Milgram et al. (1982) adapted the occlusion technique for the modelling of driver's uncertainties by multivariate autoregressive time series analysis. Ceder (1977) developed uncertainty models with respect to longitudinal vehicle control.

The occlusion technique allows to measure when and for how long, observations have to be made for lateral and/or longitudinal vehicle control. Otherwise stated, in this way it becomes possible to analyse whether and when drivers allow themselves to neglect the separate task demands in order to observe other tasks or even activities other than driving, and to quantify free times with regard to their observation strategy for the separate task demands.

In the present chapter, first, predictions with the Supervisory Driver Model are made for drivers' free time with regard to their observation strategy during lateral vehicle control (Experiment 6). Second, free times, or occlusion times, are measured empirically in the car on the road by using the visual occlusion technique (Experiment 6 and 7).

7.2 Experiment 6: Model predictions for different combinations of perceptual cues in relation to driving skill and driving speed[1]

7.2.1 **Introduction**

The Supervisory Driver Model is used to predict driver's free times for the observation strategy during lateral vehicle control; these predictions are based on the model calculations during stationary conditions described in par. 6.2. In the model analysis the growing uncertainty is predicted during free time periods in which a set of perceptual cues is efficiently removed and used to compare with voluntary chosen occlusion times, found experimentally. In terms of the SDM, the occlusion times can be predicted by means of:

(1) the level of an observation noise that corresponds via the relationships of par. 6.2 with an experimentally observed standard deviation of lateral position during non-occluded vision, and,

(2) the infinite observation noise-to-signal level for the cues which have to be occluded temporarily. Then, during this simulated occlusion the driver's estimate of driving performance has to be based on previous knowledge of the occluded perceptual cues, in combination with momentary knowledge of the non-occluded perceptual cues like remaining acceleration cues. Uncertainty in driver's estimation (estimation error) will increase as a function of the occlusion time.

In accordance with the predictions of par. 6.2, conditions for the SDM analysis refer to the use of different combinations of perceptual cues in both the observation/prediction block and the control block. As a basic condition, again the observation and control of lateral position alone are considered, while the other conditions are defined by additional cues present in both blocks. During the model calculations, fixed conditions have been imposed as described in par. 4.4.3. The occlusion period starts with the introduction of the infinite observation noise-to-signal level for the temporary occluded cues, whereas the non-occluded cues (lateral acceleration and yaw acceleration) remain associated with the observation noise level of the pre-occlusion period. The weighting factors of the optimiza-

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[1] The data of this paragraph were partially presented at the Third European Annual Conference on Human Decision Making and Manual Control (Blaauw et al., 1983) and the XXth FISITA Conference (Godthelp et al., 1984). They were also accepted for publication in Vehicle System Dynamics (Blaauw et al., 1984).

tion criterion in the control block are assumed to be identical for the pre-occlusion and occlusion period. Although it is distinguished that non-identical weighting factors might be worthwhile for further analysis, priority has been given for the SDM calculations in relation to changes in the observation noise-to-signal level.

7.2.2 Model predictions for different combinations of perceptual cues

Fig. 7.2.1 presents the Supervisory Driver Model predictions as a function of the occlusion time, for the increase in the standard deviation of the lateral position during occlusion of lateral position, lateral speed and yaw rate. The predictions are made for a driving speed of 100 km/h and an initial 0.15 m standard deviation of lateral position, experimentally found to be representative for a normal, stationary run without occlusion. Visual occlusion of lateral position (via the inclination angle α), lateral speed (via the inclination rate $\dot{\alpha}$) and yaw rate r results in differences in the rate with which performance deteriorates (increase in standard deviation), depending on the observation and control of the cues. In general, the fastest deterioration is noticed when only the lateral position is observed and controlled (Fig. 7.2.1, curve 1). A small shift towards larger occlusion times is to be seen for conditions representing the additional observation (curve 2) and control (curve 3) of the lateral speed cue. The differences between curves 1-3 are caused in the pre-occlusion period resulting in different derivatives at the beginning of the occluded period (t = 0 s). In general, the rate of deterioration is hardly dependent on the observation of the cues (curves 1-4), but to a large extent on the control of specific cues (curves 5-6). A slower deterioration is already obtained for the additional control of lateral speed (curve 5), but a much slower deterioration in performance is present when all perceptual cues are controlled (curve 6).

Additional calculations show that the S.D. of yaw rate and steering-wheel angle remain rather constant during the periods of visual occlusion. However, the S.D. of the heading angle, and thus also of lateral speed, increases with increasing occlusion time. The rate of change in the latter S.D. for different sets of perceptual cues appears to correspond with the rate of change in the S.D. of the lateral position.

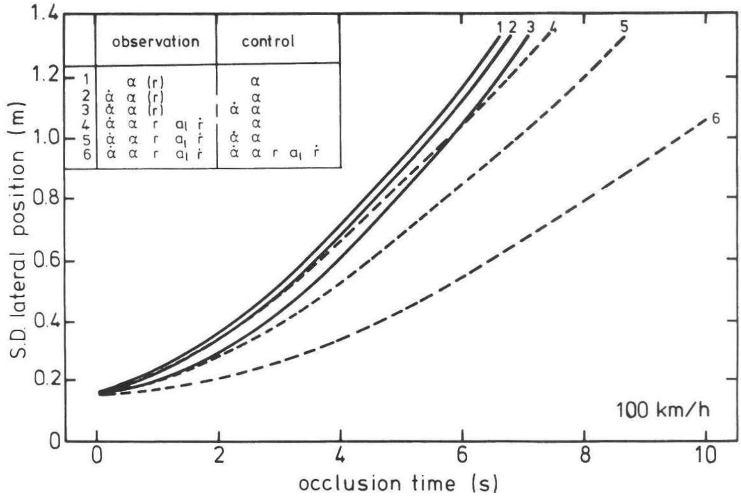


Fig. 7.2.1 Predicted standard deviation (S.D.) of lateral position during a period of occlusion for six conditions with respect to the observation and control of the inclination rate $\dot{\alpha}$, inclination angle α, yaw rate r, lateral acceleration a_1, and yaw acceleration $\dot{r}$. The relationships are given for a 100 km/h driving speed and a 0.15 m initial standard deviation of the lateral position.

7.2.3 **Model predictions in relation to driving skill and driving speed**

Two extreme conditions are now selected for a second series of SDM predictions. The first condition deals with the exclusive observation and control of the lateral position (via the inclination angle α; curve 1 in Fig. 7.2.1), and can be thought to be representative of unskilled drivers who are assumed to focus only on the lateral position cue. The second condition is thought to be representative of skilled drivers who are assumed to use all available information for their observation and control strategy during lateral position control. This condition deals with the combined use of inclination angle α and rate $\dot{\alpha}$, yaw rate r, lateral acceleration a_1 and yaw acceleration $\dot{r}$ (curve 6 in Fig. 7.2.1). Both extreme conditions are taken to predict standard deviations of the lateral position as a function of the observation noise level (similar to the presentations of par. 6.2), and as a function of occlusion time (in parallel with Fig. 7.2.1), but now for speed levels of 20, 40, 60, 80, 100 and 120 km/h.

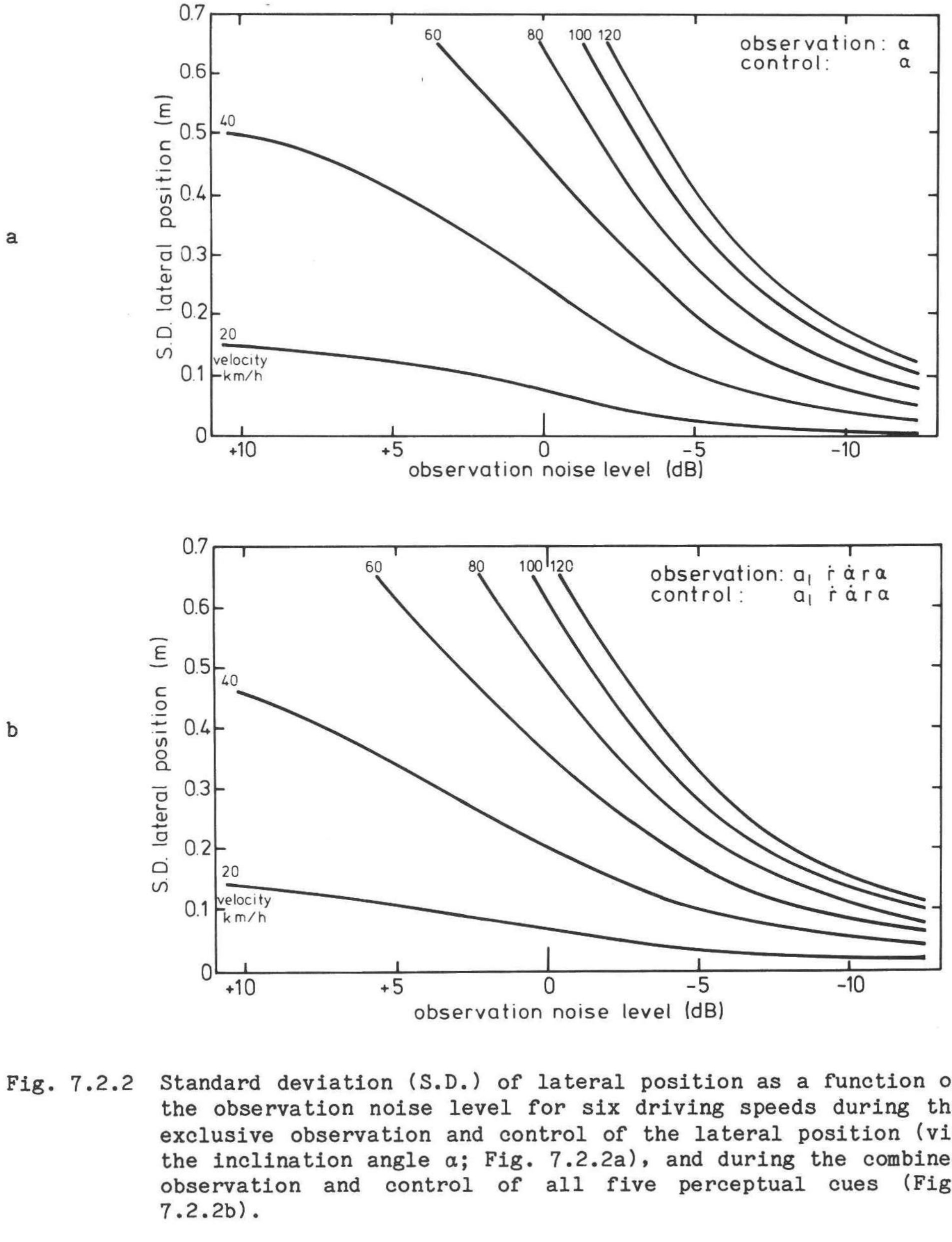


Fig. 7.2.2 Standard deviation (S.D.) of lateral position as a function of the observation noise level for six driving speeds during the exclusive observation and control of the lateral position (via the inclination angle α; Fig. 7.2.2a), and during the combined observation and control of all five perceptual cues (Fig. 7.2.2b).

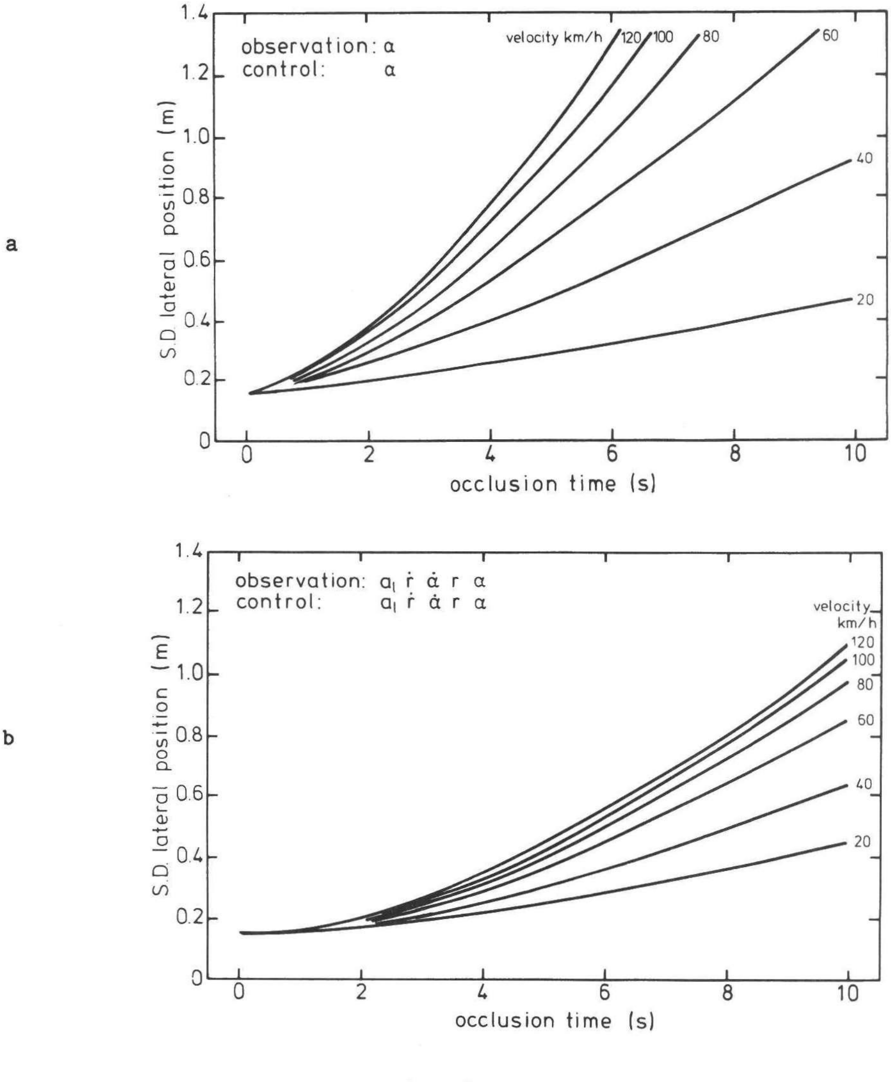


Fig. 7.2.3 Standard deviation (S.D.) of lateral position as a function of occlusion time for six driving speeds during the exclusive observation and control of the lateral position (via the inclination angle α; Fig. 7.2.3a) and during the combined observation and control of all five perceptual cues (Fig. 7.2.3b).

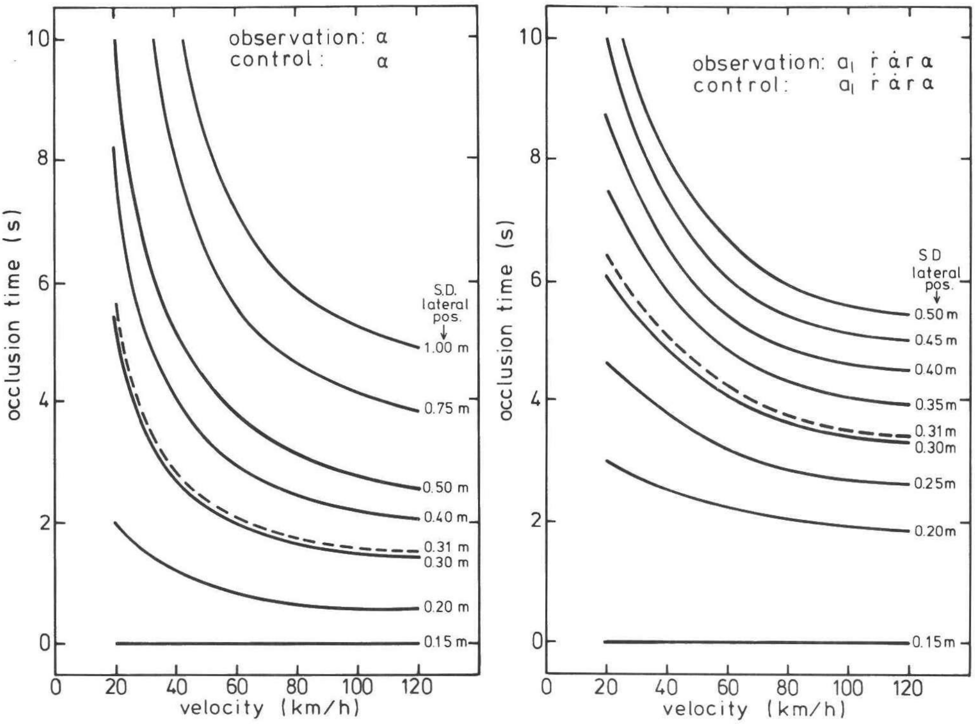
Fig. 7.2.2 shows the relationships between observation noise level and standard deviation of lateral position. The variations in the lateral position are limited at speeds of 20 and 40 km/h due to a relatively small variance of the internally generated random steering-wheel movements (motor noise). A comparison of Fig. 7.2.2a and 7.2.2b shows better driving performance, and smaller S.D. of lateral position, when all five perceptual cues are observed and controlled instead of lateral position exclusively (via the inclination angle α). An increase in driving speed, for a constant observation noise level, leads to a regressive increase in lateral position variations.

Fig. 7.2.3 shows the relationships between lateral control performance and occlusion time for the same conditions as Fig. 7.2.2. The curves in Fig. 7.2.3 are created for a 0.15 m initial standard deviation of the lateral position. This value was introduced for both sets of calculations because experimental data on this S.D. failed to show a significant difference between inexperienced and experienced drivers during non-occluded vision (Milgram et al., 1982; Godthelp et al., 1983).

From Fig. 7.2.3a it is clear that the lateral position variations increase very quickly when only the lateral position (via the inclination angle α) is observed and controlled, especially at high driving speeds. Much slower deteriorations are observed, and longer occlusion periods can be obtained for comparable variations in lateral position when observation and control are also related to the other cues, and where some of these cues (lateral acceleration and yaw acceleration) remain available during occlusion (Fig. 7.2.3b). An increase in driving speed, at a constant occlusion-time level, again leads to a regressive increase in lateral position variations for both conditions of Fig. 7.2.3a and 7.2.3b.

These results can be presented in a somewhat different way in order to illustrate more clearly the interchangeability between occlusion time and variation of the lateral position for the different speed levels.

Fig. 7.2.4 shows the functional relationships between occlusion time and speed for several levels of constant deviations in lateral position. Dependent on the variation accepted by the driver, Fig. 7.2.4 predicts the corresponding observation strategy in terms of a mean occlusion time. The initial condition with 0.15 m standard deviation in the lateral position corresponds to non-occluded observation and, consequently, a mean occlusion time of 0 s for all speeds (straight lines in Fig. 7.2.4). A comparison of Fig. 7.2.4a and 7.2.4b shows that observation and control of the five cues instead of the exclusive use of lateral position (via the inclination angle α) results in about twice as large occlusion times for a specific speed and



a

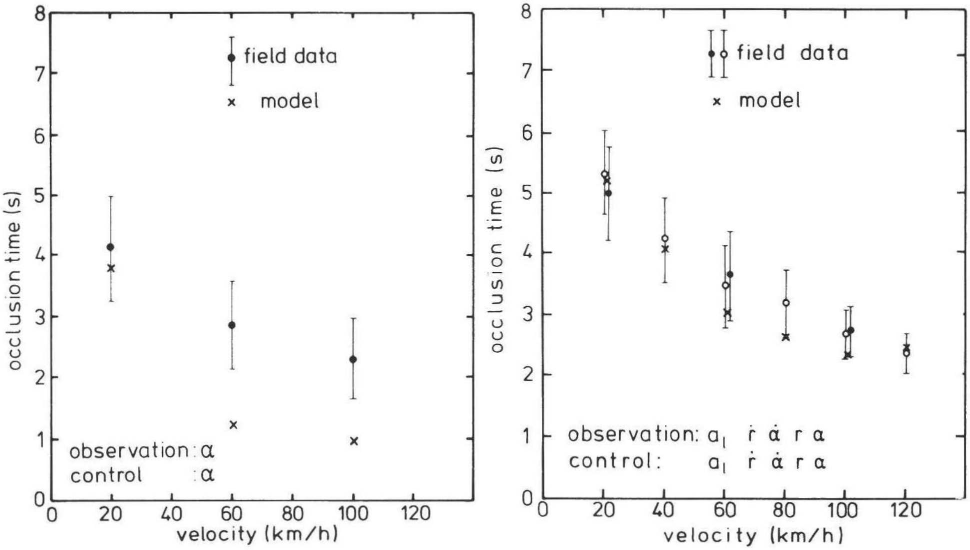
b

Fig. 7.2.4 As Fig. 7.2.3, but now for levels of constant standard deviation (S.D.) of the lateral position. The dotted lines at 0.31 m indicate the limitations in lateral position variation due to the 3.60 m lane width.

accepted variation of lateral position. This result is illustrated with respect to the available lateral tolerance between the lane- and car boundaries (dotted lines in Fig. 7.2.4 for a lane width of 3.60 m and a car width of 1.74 m). If drivers observe and control only lateral position, the mean occlusion time is 1.6 s at a driving speed of 100 km/h (Fig. 7.2.4a). The additional observation and control of the other cues result in an increased occlusion time of 3.5 s at a 100 km/h speed (Fig. 7.2.4b).

7.2.4 Comparison between the model predictions and field data

The SDM predictions can now be compared with data from field experiments with the instrumented car. Data points are available for lateral position control of experienced and inexperienced drivers for constant speed, straight-road driving with and without visual occlusion (Milgram et al., 1982; Godthelp et al., 1983). In these runs, drivers wore an electro-mechanically driven visual-occlusion device mounted on a lightweight bicycle helmet. In its normal state the visual field of the driver was completely occluded. The driver could request new visual information by pressing the horn lever, in this way obtaining information for 0.55 s. Speed was automatically controlled within deviations of approx. 1 km/h, by maintaining a reasonably constant pressure on the accelerator, so that drivers could concentrate on lateral vehicle control. For more detailed



a

b

Fig. 7.2.5 SDM predictions (symbols: x) for the mean occlusion time as a function of speed during the exclusive observation and control of lateral position (via the inclination angle α; Fig. 7.2.5a) and during the observation and control of all five perceptual cues (Fig. 7.2.5b); the field data present the mean values and standard deviations of measured occlusion times, for inexperienced (Fig. 7.2.5a) and experienced drivers (Fig. 7.2.5b).

methodological information see Chapter 4.

Fig. 7.2.5 gives the results in terms of measured occlusion time (mean and standard deviation over trials and subjects) in relation to the SDM occlusion times. Fig. 7.2.5b shows results of six experienced drivers in two experiments. The first experiment covered three trials for each subject at six different speed levels, while the second experiment had two trials for each subject at speed levels of 20, 60 and 100 km/h. The results of six inexperienced drivers (Fig. 7.2.5a) are related to only one experiment with two trials for each subject at speeds of 20, 60 and 100 km/h. As a main result, the experienced drivers appeared to have significant ($p \leq 0.06$) larger occlusion times than the inexperienced drivers.

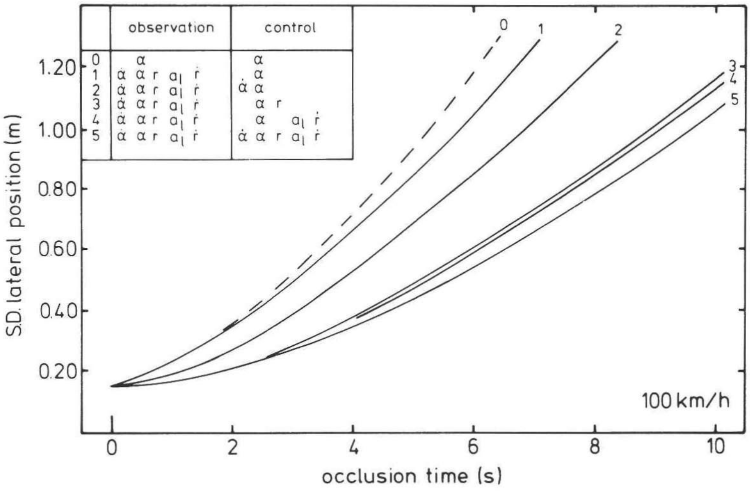
In general, the comparison between SDM and empirical occlusion times indicates a good correspondence (correlation coefficient $r = 0.977$) for the experienced drivers (Fig. 7.2.5b): The SDM predicts the experimental occlusion times within one standard deviation. However, the inexperienced drivers have larger occlusion times than predicted by the SDM, except at 20 km/h (Fig. 7.2.5a).

7.2.5 **Discussion**

During temporarily visual occlusion, drivers receive no further visual information of lateral position, lateral speed and yaw rate. Then, the SDM calculations show that the S.D. of lateral position and lateral speed increases with occlusion time, whereas the S.D. of yaw rate remains about constant. The constancy of the latter variable results from driver's non-occluded feedback of the variations of steering-wheel angle, which are linked directly to the variations of the yaw rate via the yaw-rate sensitivity of the car (par. 3.1; formula 3.13). Consequently, it can be concluded that visual occlusion does not affect yaw rate, but results in increasing uncertainty about heading angle (lateral speed), and to a larger extent, about lateral position inside the traffic lane, making new observations necessary.

The SDM predictions show that the occlusion times are dependent on the speed of the car, and on the cues used by the driver for observation and, to a larger extent, for control. In general, it is found that the occlusion time increases progressively with decreasing driving speeds. With respect to the perceptual cues a study was made for the observation and control of inexperienced and experienced drivers. The SDM and empirical occlusion times for the experienced drivers appeared to correspond rather closely, suggesting that these drivers use the five perceptual cues for their observation and control. However, the SDM predictions for the inexperienced drivers resulted in occlusion times less than what is found experimentally. Although the question can be raised whether the assumptions for the model calculations, e.g. no time delays, no thresholds, perfect knowledge of system dynamics, are valid for inexperienced drivers, this is very unlikely because the predicted occlusion times will then decrease instead of increase. However, it is again more likely that the inexperienced drivers are not driving by exclusively observing and controlling lateral position, but already use some more cues as indicated in Chapter 6. This is consistent with the conclusions of Smiley et al. (1980).

Supplementary SDM predictions, in accordance with the type of calculations for Fig. 7.2.1, indicate the separate contribution of the perceptual cues to the control block. Additional control of lateral speed leads to a small increase in occlusion time (Fig. 7.2.6, curve 2), but additional control of yaw rate (curve 3), both acceleration cues (curve 4), or their



	observation	control
0	α	α
1	$\dot{\alpha}$ α r a_l $\dot{r}$	α
2	$\dot{\alpha}$ α r a_l $\dot{r}$	$\dot{\alpha}$ α
3	$\dot{\alpha}$ α r a_l $\dot{r}$	α r
4	$\dot{\alpha}$ α r a_l $\dot{r}$	α a_l $\dot{r}$
5	$\dot{\alpha}$ α r a_l $\dot{r}$	$\dot{\alpha}$ α r a_l $\dot{r}$

Fig. 7.2.6 Predicted standard deviation (S.D.) of lateral position during a period of occlusion for conditions with the use of all five cues in the observation/prediction block and different combinations of the inclination rate $\dot{\alpha}$, inclination angle α, yaw rate r, lateral acceleration a_1 and yaw acceleration $\dot{r}$ in the control block. The relationships are given for a 100 km/h driving speed and a 0.15 m initial standard deviation of the lateral position.

combination (curve 5) increases occlusion time to a much larger extent and towards values comparable with the experimental occlusion times of the inexperienced drivers. Hence, these results confirm a conclusion of par. 6.5 suggesting that yaw rate, or lateral and yaw acceleration are already explicitly controlled in an early stage of driving practice.

7.3 Experiment 7: Driving skill, task demands and visual cues during day- and nighttime[2]

7.3.1 Introduction

Additional empirical data are gathered about the timing aspects of driver's observation strategy. Therefore, Experiment 5 (par. 6.4) is repeated, but as a new element the visual occluding technique is introduced. The observation strategy is studied for experienced and inexperienced drivers who drove during day- and nighttime in the instrumented car with various task demands for longitudinal vehicle control. The drivers were allowed only to look at the road or at the speedometer whenever they felt to be necessary. Although viewing time was free, drivers were instructed to observe the road, or speedometer, as shortly as possible.

Farber and Gallagher (1972) and Triggs and Caple (1978) already used the occlusion technique, with fixed viewing intervals of 0.5 s, to study driver's observation strategy during similar conditions. Farber and Gallagher concluded that visual degradation, e.g. driving in darkness, increases the difficulty of vehicular control, and that the more skilled drivers are then less affected than the novice drivers. Triggs and Caple found that night trials yielded shorter times between looks than did trials under daylight conditions, while greater emphasis on accuracy also led to higher visual sampling rates.

7.3.2 Method

Twelve experienced and twelve inexperienced drivers drove in the instrumented car during daytime, while the same number of subjects did

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[2] The data of this experiment were partially presented during the First European Annual Conference on Human Decision Making and Manual Control (Blaauw, 1981).

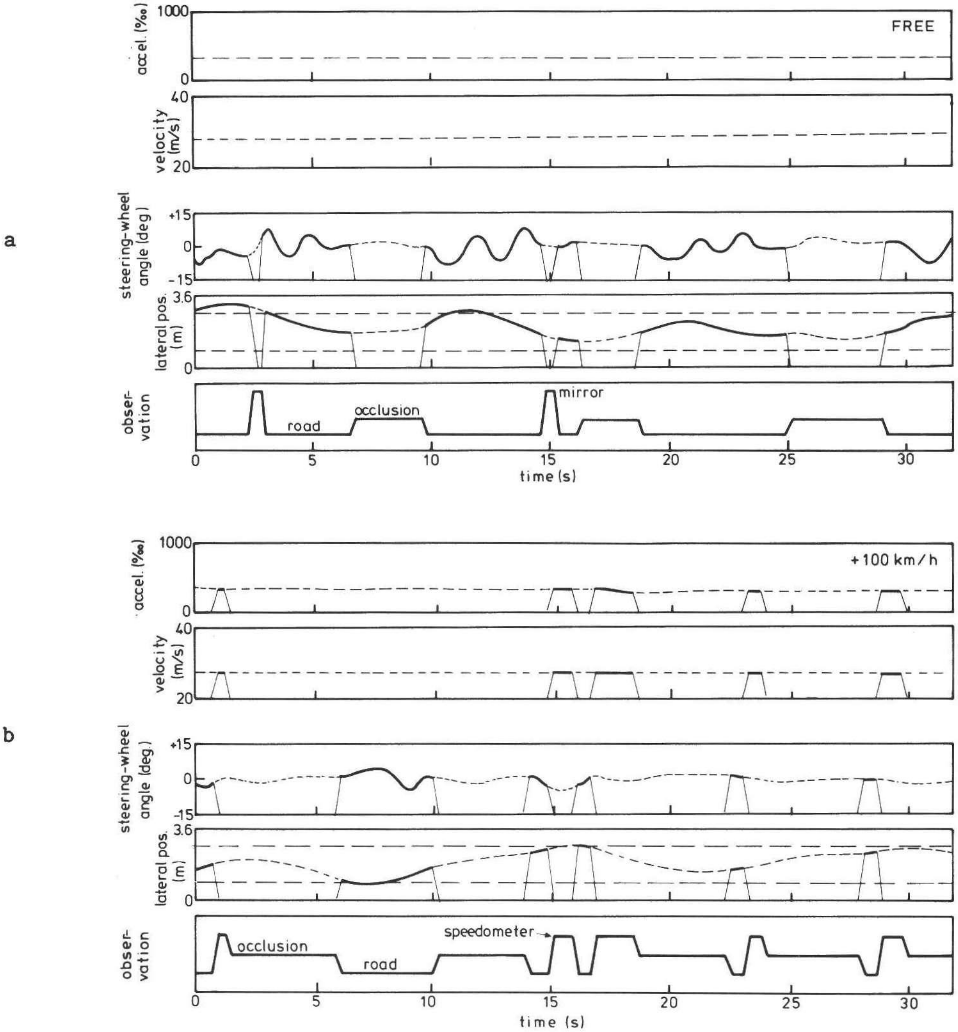

Fig. 7.3.1 An example of lateral and longitudinal vehicle control during the FREE condition (Fig. 7.3.1a) and the + 100 KM/H condition (Fig. 7.3.1b). Driver's observation strategy is indicated by a specific level for each category (road, occlusion, speedometer, etc.). The temporarily occluded variables are represented by dashed lines. The horizontal dashed lines besides the lateral position trajectory refer to both lane markers in relation to the vehicle width.

identical runs at night. Task demands were varied between subjects and were manipulated by instruction. There were two conditions:

(1) FREE - no specific instruction was given.

(2) + 100 KM/H - subjects were instructed to concentrate on driving with a constant velocity of 100 km/h. This instruction was intended to provoke a very strict criterion for longitudinal control.

Each subject drove his experimental condition in a one-hour session between 10.30 a.m. and 2.30 p.m., or between 8.00 p.m. and midnight. There was no public lighting during the latter runs and the car drove with dipped headlamps.

With respect to the occlusion technique drivers were instructed to occlude voluntarily their visual information during the measurement intervals by looking downwards within the car, instead of at the road or speedometer, for as long as possible. Peripheral vision was occluded as well in that situation. When driver's uncertainty became too high, they were allowed to look at the road or the speedometer, for as short as possible. One experimenter supervised driver's observation strategy and could interrupt because of traffic safety reasons. Drivers were urged, however, to observe in a manner such that any interference by the experimenter would be unnecessary.

Driver's observation strategy was recorded on videotape by means of a dashboard-mounted television camera looking at the head and eyes of the driver. During the night condition infrared illumination was applied to obtain a good video picture with the infrared-sensitive camera. The observation strategy was analysed off-line quantitatively by means of a special computer-controlled video plotting device (Van der Horst and Riemersma, 1981). The beginning and the end of each observation as well as the type of category, e.g. occlusion, road ahead, speedometer and mirror, were taken as dependent variables. The data of the observation strategy were combined with the variables from the floppy-discs in the instrumented car. Fig. 7.3.1 gives examples during the FREE and + 100 KM/H condition. For more detailed methodological information see Chapter 4.

7.3.3 Results on driving performance

Although the study is focused on driver's observation strategy, first emphasis will be given to the overall driving performance during visual occlusion and, more specifically, differences will be described in relation to driving without occlusion.

Lateral vehicle control

Table 7.3.1 presents lateral control performance without occlusion (already presented in par. 6.4.3) and with visual occlusion as derived from the present experiment. Data are given for both levels of driving experience, both task demands, during day and nighttime; each result represents the average value over 36 runs (6 subjects x 6 trials). With respect to the six trials, in both the occluded and non-occluded conditions only the first trial resulted in significantly ($p \leq 0.05$) larger S.D. of the yaw rate and steering-wheel angle compared to the other five trials.

Compared with the non-occluded runs, in general, visual occlusion resulted in:

- larger S.D. of yaw rate ($p \leq 0.001$)
- larger distance to the right shoulder line during daytime ($p \leq 0.001$)
- larger S.D. of lateral position ($p \leq 0.001$)
- larger S.D. of lateral speed ($p \leq 0.001$)
- smaller median left TLC-values during daytime ($p \leq 0.01$)
- smaller median right TLC-values at night ($p \leq 0.01$), and

Although without visual occlusion several significant effects in relation to the experimental conditions were found (Experiment 5; par. 6.4), the present condition with occlusion fails to show significant changes in the mean lateral position and the S.D. of the lateral position and lateral speed. Consequently, visual occlusion resulted for all drivers and conditions in a comparable lateral control performance. From the relatively large S.D. of lateral position (Table 7.3.1 and also the examples of Fig. 7.3.1) it can be seen that visual occlusion caused the vehicle to exceed the lane boundaries (for S.D. values exceeding 0.31 m). These excitations, as described by the most extreme left and right lateral position in each run, or by the percentages of time that the car drove outside the left or right lane marker, did not differ between the experimental conditions.

Longitudinal vehicle control

Table 7.3.2 presents the mean and standard deviation of velocity for the inexperienced and experienced drivers with and without visual occlusion, for both the FREE and + 100 KM/H condition at night and day.

Table 7.3.1 Lateral control performance with visual occlusion and without visual occlusion (from Table 6.4.1). Data are given for the inexperienced (INEXP) and experienced (EXP) drivers with the FREE and + 100 KM/H task demands, during day- and nighttime.

	day		night		
	FREE	+ 100 KM/H	FREE	+ 100 KM/H	
<u>With visual occlusion</u>					
lateral position (m)	2.19	2.28	2.20	2.32	INEXP
	2.10	2.14	2.48	2.30	EXP
S.D. lateral position (m)	0.53	0.42	0.51	0.50	INEXP
	0.48	0.45	0.41	0.46	EXP
S.D. lateral speed (m/s)	0.24	0.19	0.23	0.23	INEXP
	0.21	0.19	0.18	0.23	EXP
S.D. yaw rate (°/s)	0.66	0.68	0.68	0.65	INEXP
	0.67	0.45	0.54	0.73	EXP
median left TLC (s)	4.3	4.1	4.6	3.7	INEXP
	4.0	4.8	4.5	3.5	EXP
median right TLC (s)	2.5	3.9	3.3	3.4	INEXP
	3.1	4.1	3.6	3.4	EXP
<u>Without visual occlusion</u>					
lateral position (m)	1.80	1.83	2.17	2.25	INEXP
	1.73	1.65	2.16	2.12	EXP
S.D. lateral position (m)	0.17	0.22	0.21	0.28	INEXP
	0.21	0.11	0.13	0.16	EXP
S.D. lateral speed (m/s)	0.07	0.10	0.10	0.12	INEXP
	0.12	0.07	0.06	0.08	EXP
S.D. yaw rate (°/s)	0.28	0.33	0.35	0.38	INEXP
	0.35	0.28	0.31	0.33	EXP
median left TLC (s)	5.4	5.0	4.5	4.2	INEXP
	4.9	6.4	5.4	4.9	EXP
median right TLC (s)	3.5	3.5	4.6	4.4	INEXP
	3.0	3.3	5.4	4.7	EXP

In this Table the data for the condition without visual occlusion are taken from Table 6.4.3. Whereas without occlusion no differences were present in the S.D. of velocity, during the runs with occlusion the experienced drivers had smaller variations in velocity than the inexperienced drivers ($p \leq 0.05$). In general, drivers drove significantly slower during nighttime than during daytime ($p \leq 0.05$). Task demands had different effects on the mean velocity in the condition without and with visual occlusion. Without visual occlusion all drivers drove faster in the FREE condition than during the + 100 KM/H condition, whereas visual occlusion resulted in an opposite effect showing that all drivers drove slower during the FREE condition than during the + 100 KM/H condition, during day and night ($p < 0.05$).

Table 7.3.2 Longitudinal control performance with visual occlusion and without visual occlusion (from Table 6.4.3). Data are given for the inexperienced (INEXP) and experienced (EXP) drivers with the FREE and + 100 KM/H task demands, during day- and nighttime.

	day		night		
	FREE	+ 100 KM/H	FREE	+ 100 KM/H	
<u>With visual occlusion</u>					
velocity (km/h)	94.1	101.4	88.0	97.9	INEXP
	92.9	100.1	91.0	100.3	EXP
S.D. velocity (km/h)	1.1	1.1	1.0	0.9	INEXP
	0.9	0.8	0.7	0.8	EXP
<u>Without visual occlusion</u>					
velocity (km/h)	109.9	102.4	104.3	99.7	INEXP
	110.0	107.6	106.3	102.0	EXP
S.D. velocity (km/h)	1.1	0.8	0.9	0.8	INEXP
	1.4	0.7	0.8	0.8	EXP

7.3.4 Results on driver's observation strategy

Fig. 7.3.2 presents driver's observation strategy in terms of percentages of time spent on each category, while Table 7.3.3 gives the mean observation time for each category. Again, each result represents the average value over 36 runs (6 subjects x 6 trials) of 32 s each.

The percentage of time spent on the road ahead is higher at night than during daytime, for both groups of driving experience and both task demands ($p \leq 0.05$). Also, the mean observation time on the road ahead is longer during the night, compared to the day condition ($p \leq 0.01$). Both the

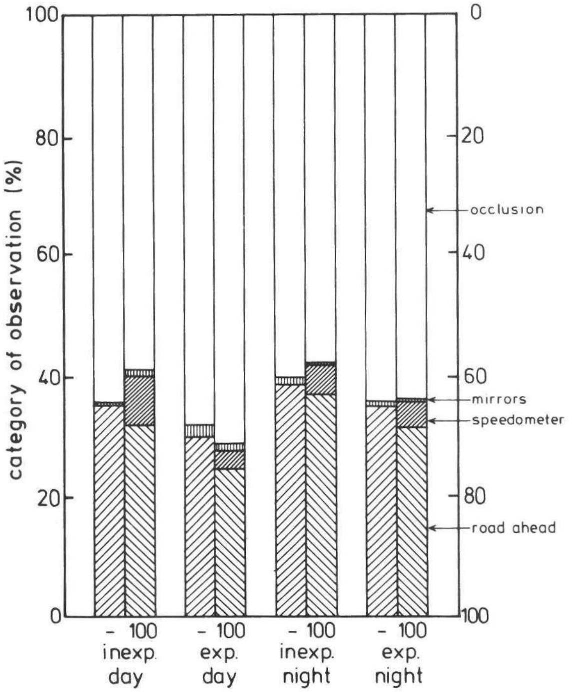

Fig. 7.3.2 Total time spent on the observation categories (road, speedometer, mirror, occlusion), in percentages of the driving time in each run, for the inexperienced (INEXP) and experienced (EXP) drivers with the FREE (-) and + 100 KM/H (100) task demands, during day- and nighttime.

percentage of time spent on the road ahead and the mean observation time are higher for the inexperienced drivers than for the experienced drivers (both $p \leq 0.01$). With the + 100 KM/H condition all drivers have a shorter mean observation time on the road ahead ($p \leq 0.05$), and a longer mean observation time on the speedometer than with the FREE condition ($p \leq 0.001$). In general, during the FREE condition drivers do not fixate at all the speedometer. With respect to the use of the mirrors no significant differences are to be observed.

The occlusion percentage is in all conditions higher for the experienced drivers than for the inexperienced drivers ($p \leq 0.01$). With respect to the mean occlusion time an interaction is found between the level of driving experience and day/night condition: The change to the night condition results in shorter occlusion times for the experienced drivers, whereas the inexperienced drivers allowed themselves then to occlude information for longer periods of time ($p \leq 0.01$). Together with the increased observation time on the road ahead for the inexperienced drivers at night, it can be concluded that these drivers have at night less changes in their observations of the different categories than the experienced drivers. This conclusion is confirmed by the data of Table 7.3.4, in which the total and individual number of transfers between the observation

Table 7.3.3 Mean observation time(s) to the observation categories for the inexperienced (INEXP) and experienced (EXP) drivers with the FREE and + 100 KM/H task demands, during day- and nighttime.

	day		night		
	FREE	+ 100 KM/H	FREE	+ 100 KM/H	
occlusion	4.5	4.3	5.8	4.5	INEXP
	4.9	5.0	3.9	3.7	EXP
mirrors	0.2	0.3	0.3	0.1	INEXP
	0.4	0.2	0.2	0.1	EXP
speedometer	0	0.8	0	0.5	INEXP
	0	0.5	0	0.5	EXP
road	2.5	1.6	3.1	2.7	INEXP
	2.0	1.4	2.1	1.9	EXP

categories (link values) are given for the various experimental conditions: The experienced drivers have more observation transfers at night than the inexperienced drivers ($p \leq 0.05$), while no differences between both levels of driving experience are present during daytime. In general, the number of transfers also increases by the addition of the + 100 KM/H condition in relation to the FREE condition ($p \leq 0.01$).

From this Table it can also be concluded that driver's observation strategy during the FREE condition switches between the road ahead and occlusion. The number of changes between occlusion and road, and vice versa, are about equal. However, during the + 100 KM/H condition the matrices of Table 7.3.4 are asymmetrically, showing more changes from occlusion towards road than in the reversed direction, and less changes from occlusion towards speedometer than from speedometer towards occlusion. There are also more changes from the road towards the speedometer than in the reversed direction. These findings strongly suggest that both groups of drivers, at day and night, give priority to the observation of the road above the speedometer and that they have an observation strategy with the following, general sequence: occlusion - road ahead - speedometer - occlusion, etc. However, the speedometer is not observed in each sequence, as can be concluded from the larger number of transfers for the road than for the speedometer. With respect to mirror use, it can be noticed that the mirrors are mostly scanned immediately before or after a road observation, and not in combination with the speedometer or occlusion.

Driver's observation strategy can also be related to the actual position of the vehicle on the road. Therefore, the lateral position, lateral speed and TLC are analysed on the moments in time that drivers decide to change their observations from the road towards a non-road category (mostly occlusion, see Table 7.3.4), and from occlusion towards the road ahead.

The first type of changes in observation indicates when drivers allow themselves to ignore driving performance. In general, results show that these decisions are taken by the inexperienced and experienced drivers over a comparable area of lateral positions, ranging extremely from left to right lane marker. However, at night decisions are taken on somewhat less extreme positions than during daytime (mean distance from the lane center 0.52 m and 0.45 m at day and night, respectively). The lateral speed on the decision moments differs between both groups of driving experience. Experienced drivers attempt to set a lower lateral speed on these moments than the inexperienced drivers; the values are 0.16 m/s and 0.21 m/s, respectively ($p \leq 0.05$). An identical effect is found in the TLC value, and more

Table 7.3.4 Number of transfers between the observation categories (occ = occlusion; road; spm = speedometer; mir = mirrors; Σ = total) for the inexperienced (INEXP) and experienced (EXP) drivers with the FREE and + 100 KM/H condition, during day- and nighttime. The data are given as mean values over 36 runs of 32 s each.

FREE						+ 100 KM/H					
DAY INEXP.	occ	road	spm	mir	Σ	DAY INEXP.	occ	road	spm	mir	Σ
occ	-	4.2	0.1	0.0		occ	-	4.1	0.5	0.0	
road	4.2	-	0.0	0.4		road	3.1	-	2.7	0.8	
spm	0.1	0.1	-	0.0		spm	1.2	1.9	-	0.0	
mir	0.0	0.4	0.0	-		mir	0.0	0.8	0.0	-	
Σ					9.5	Σ					15.1
DAY EXP.	occ	road	spm	mir	Σ	DAY EXP.	occ	road	spm	mir	Σ
occ	-	4.3	0.0	0.0		occ	-	4.8	0.3	0.0	
road	3.9	-	0.1	1.1		road	4.2	-	1.3	0.5	
spm	0.0	0.1	-	0.0		spm	0.7	0.8	-	0.0	
mir	0.1	1.1	0.0	-		mir	0.1	0.4	0.0	-	
Σ					10.7	Σ					13.1
NIGHT INEXP.	occ	road	spm	mir	Σ	NIGHT INEXP.	occ	road	spm	mir	Σ
occ	-	3.6	0.0	0.0		occ	-	3.7	0.6	0.0	
road	3.4	-	0.0	0.5		road	2.7	-	1.8	0.2	
spm	0.0	0.0	-	0.0		spm	1.4	0.9	-	0.0	
mir	0.0	0.4	0.0	-		mir	0.0	0.2	0.0	-	
Σ					7.9	Σ					11.5
NIGHT EXP.	occ	road	spm	mir	Σ	NIGHT EXP.	occ	road	spm	mir	Σ
occ	-	5.8	0.1	0.0		occ	-	5.1	0.8	0.0	
road	5.9	-	0.0	0.5		road	4.4	-	1.4	0.1	
spm	0.1	0.0	-	0.0		spm	1.5	0.7	-	0.0	
mir	0.0	0.4	0.0	-		mir	0.0	0.1	0.0	-	
Σ					12.8	Σ					14.1

specifically, in the minimum TLC value immediately after the decision time. Results show that the minimum TLC is not correlated with the level of experience within the group of inexperienced drivers (Pearson product-moment correlation coefficient $r = -0.10$), but the minimum TLC is correlated for the group of experienced drivers ($r = 0.61$; $p \leq 0.05$). Consequently, more experienced drivers try to adjust a more ideal initial position of the vehicle when they decide to ignore the cues of lateral vehicle control.

The second type of changes in observation is related to the moments in time when drivers want to make new observations about the actual vehicle position. Both the lateral deviation from the lane centre and lateral speed on the decision times to look again at the road ahead, are lower for the experienced drivers than for the inexperienced drivers (both $p \leq 0.05$). Hence, the corresponding minimum TLC values of the experienced drivers are higher than for the inexperienced drivers (2.5 s and 1.9 s, respectively; $p \leq 0.06$). However, with respect to these median values it should also be recalled that on a number of decision times the car had already approached, or even exceeded, the lane markers and obviously drivers tolerated larger variations in position than prescribed by the lane markers.

7.3.5 **Discussion**

In general, the visual occlusion condition resulted in a comparable performance and control strategy for the inexperienced and experienced drivers during the FREE and + 100 KM/H condition, and during day and night. However, during the FREE condition the forward velocity was set some 8 km/h lower than during the + 100 KM/H condition, while without visual occlusion the same condition resulted in a 8 km/h higher velocity. With respect to the mean lateral position, visual occlusion during daytime resulted in a 0.40 m shift to the left and is then comparable with the mean lateral position at night, when occlusion had no effect. The exact reason for the shift to the left is not known, but it is suggested that drivers adapt to the more difficult task demands in such a way, because smaller distances to a reference line result in a higher perspective sensitivity for lateral position variations (par. 3.2). Although this might also be true for the right lane marker, the literature shows some preference for the left one (Summala and Merisalo, 1978; Hotop and Burger, 1981). Due to the asymmetric position of the driver in the car, drivers are allowed to make better estimates of the distance between the left side of the car and the left lane marker than for distances between the right side of the car and the right lane marker. Unfortunately, no data on right-hand driving were found to confirm the opposite effects.

During the runs with temporarily, self-paced occlusion, drivers perform driving with road observations for maximally only 40% of the time. Hence, for some 60% of the driving time, drivers allow themselves to occlude the roadway and neglect driving performance visually.

Although no differences in driving performance and control strategy were shown between both groups of drivers, the observation strategy indicates that the inexperienced drivers need more observation time than the experienced drivers. The observation times are also longer at night than during daytime. These results are consistent with the results of Farber and Gallagher (1972) and Triggs and Caple (1970) (par. 7.3.1), although the present occlusion times are longer due to less strict criteria of the drivers with respect to the acceptable variations in lateral position. This interchangeability between occlusion times and S.D. of lateral position was already presented in Fig. 7.2.4. For these large occlusion times and S.D. of lateral position, again it is found that the measured and predicted values correspond for the experienced drivers, whereas the predicted occlusion times are less than measured empirically for the inexperienced drivers. Therefore, in line with the conclusions of par. 7.2.5 it is again concluded that the inexperienced drivers are also controlling explicitly yaw rate and/or both acceleration cues.

7.4 Discussion and conclusions

Both the Supervisory Driver Model study and the empirical data show that driver's observation strategy, in terms of occlusion times, is dependent on the speed of the car, and on the cues used by the driver for observation and, to a larger extent, for control. In general, it is found that occlusion time increases progressively with decreasing driving speed and, consequently, drivers have longer free times at lower speeds to be covered by aspects beyond lateral control. Thereby, inexperienced drivers have smaller occlusion times than experienced drivers for comparable S.D. of lateral position.

With respect to the perceptual cues, again it is indicated that experienced drivers indeed seem to use the five perceptual cues (lateral position, lateral speed, yaw rate, lateral acceleration and yaw acceleration) for their observation and control, while inexperienced drivers show an observation strategy which can be described by the SDM results when all perceptual cues except lateral speed, are used for observation and control. An exclusive use of the lateral position cue results in smaller SDM occlusion times than measured on the road and, hence, a conclusion of Chapter 6 is confirmed that the inexperienced drivers seem to use already the yaw rate cue and/or both acceleration cues.

In general, the empirical data of Experiment 7 show that visual occlusion results in comparable driving performance and control strategy for all drivers and task demands, although on a worse level than without occlusion where differences between the experimental conditions are present. However, within the occlusion condition, differences are also present with respect to the observation strategy. It is then once more shown that inexperienced drivers need longer observation times and allow themselves shorter occlusion times than the experienced drivers during daytime, leaving them less free time for multitask driving, or for coping with deteriorated driving conditions. Thereby, it should be recalled that the experienced drivers attempt to adjust a more ideal initial vehicle position inside the traffic lane when they decide to occlude the cues for vehicle control.

The deteriorated driving conditions during darkness and the multitask + 100 KM/H condition both result for the experienced drivers in an increased number of observation transfers, mainly by smaller occlusion times during darkness and smaller observation times with the + 100 KM/H condition. The inexperienced drivers have less observation transfers at night than the experienced drivers due to larger occlusion times and road observation times. No differences between both groups are present during daytime.

Finally, it can be concluded that visual occlusion, which in itself is representative for multitask driving, results only in differences with respect to driver's observation strategy, and equalizes driving performance for the various levels of driving experience and task demands.

7.5 References

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8. AN APPLICATION WITH RESPECT TO ROAD DELINEATION AT NIGHT[1]

8.1 Introduction

Results of the foregoing experiments are now used to demonstrate their relevance for the evaluation of road and car design in terms of supervisory driving. It is assumed that a better design will result in an increased free time, or occlusion time, giving better possibilities for the driver to cope with multitask driving. In this paragraph an example is presented with respect to road design and, more specifically, with respect to various configurations of road delineation at night. This experiment was carried out for the Working Committee E9 "Nighttime visibility of road markings on wet roads" of the Study Centre for Road Construction and the Study Centre for Traffic Engineering (Blaauw et al., 1984). The project has been sponsored also by the Transportation and Traffic Engineering Division of the Ministry of Transportation.

The various configurations consisted of different patterns of raised pavement markers and postmounted delineators, which were selected because of their proven capabilities to give minimally 3 s preview information at night on wet roads (Blaauw and Padmos, 1982). Because of the functioning of delineation in presenting perceptual cues on lateral vehicle control inside the traffic lane (short-range delineation), and on road curvature (long-range delineation), straight road sections as well as curves were considered. In general, the geometry of delineation configurations can be described by (Fig. 3.2.1):

- height between delineation and driver's eyes
- lateral distance between delineation and driver's eyes
- (longitudinal) spacing distance, and
- combinations of delineation.

The effect of the first two aspects on driver's perceptual cues has been presented in par. 3.2. The present experiment focusses on both other aspects. Thereby, two stages were defined. First, Experiment 8A with raised

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[1] The data of this experiment were previously presented at the Fourth European Annual Conference on Human Decision Making and Manual Control (Blaauw, 1984).

pavement markers on various longitudinal distances and, second, Experiment 8B with combinations of raised pavement markers and postmounted delineators. The evaluation of the various configurations is based on driver's observation strategy in terms of free times, on driver's control strategy in terms of the amplitudes and frequencies of the steering-wheel movements, and on the overall driving performance.

8.2 Method

Six experienced drivers drove the instrumented car during darkness. There was no public lighting and the car was driven with dipped headlamps. Each subject drove the road sections with the experimental configurations twice, in a two-hour session between 7.00 p.m. and midnight. Drivers made a training run on another road, prior to the experimental sessions. There was a two-month period between both experimental stages. Drivers had a FREE instruction for lateral vehicle control and had to drive with 80 km/h. Speed was automatically controlled within deviations of approx. 1 km/h, by maintaining a reasonably constant pressure on the accelerator, so that drivers could concentrate on lateral vehicle control. Speed reductions were possible by releasing the accelerator pedal.

Visual occlusion was realized by a pair of spectacles making use of the characteristics of liquid cristals (Milgram and van der Horst, 1984; Fig. 8.2.1). In its normal state the visual field of the driver was completely occluded. The drivers could request visual information as long as they pressed the horn lever; they were urged to do so only for short periods. Recordings were made of visual occlusion, steering-wheel angle, yaw rate, accelerator position and velocity. Lateral position could not be measured in most experimental road sections, because of the absence of the white lane markings. Variables were sampled over periods between 28 and 44 s (dependent on the length of a section), with a 10 Hz sampling frequency.

The experimental configurations were realized at straight sections and curves with radii of about 1000 m and 200 m, on a four-lane divided motorway not in use yet. The radii of 200 m were implemented in roadway diversions through the median. For each experimental stage 16 delineation configurations were studied within a 20 km run.

The experiments were performed under various weather conditions. Most subjects drove during dry weather with full moon (especially in Experiment 8B), while the others drove during rainy and/or clouded conditions. For more detailed methodological information see Chapter 4.

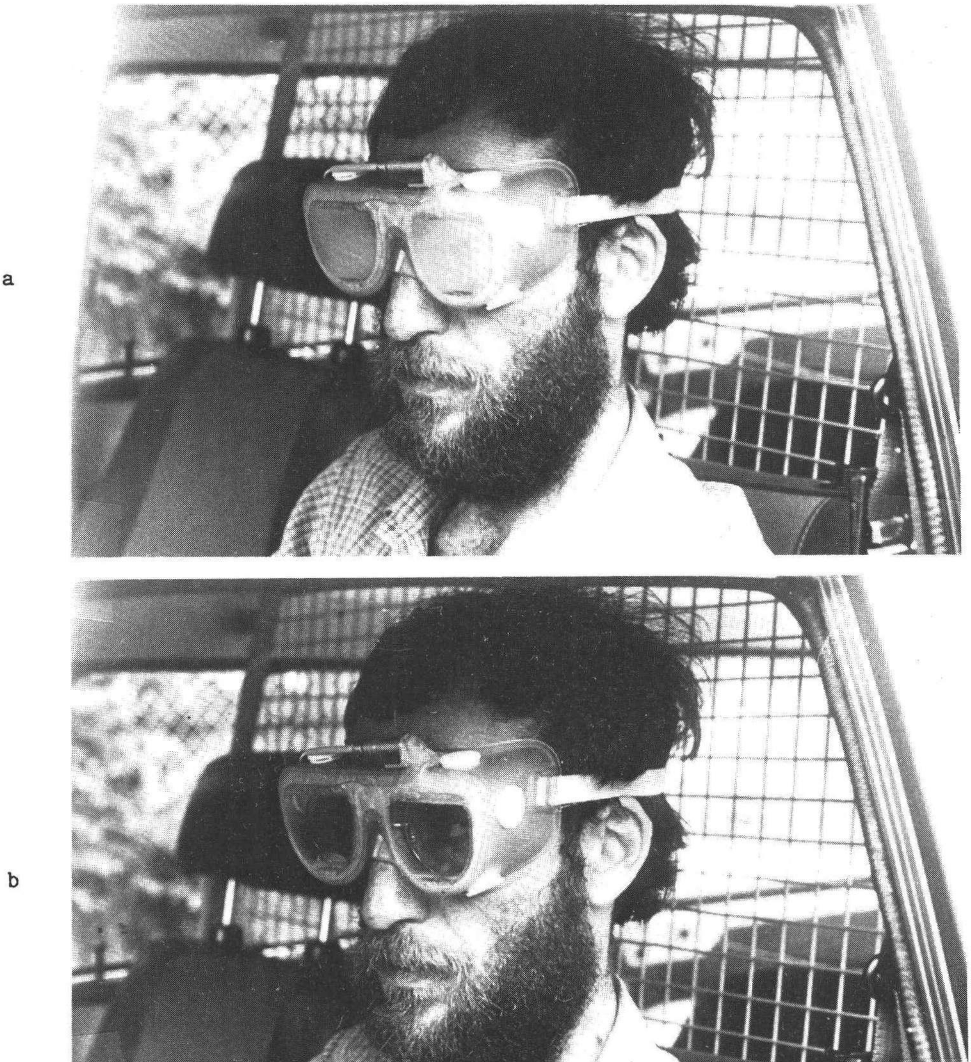

Fig. 8.2.1 Visual occlusion during driving. Liquid cristals in a pair of spectacles normally occlude driver's visual field completely (Fig. 8.2.1a), but by pressing the horn lever the liquid cristals allow perception of the road ahead (Fig. 8.2.1b).

8.3 Experiment 8A: Raised pavement markers on different longitudinal distances

8.3.1 **Configurations**

Table 8.3.1 presents the configurations with the white raised pavement markers on the straight and curved sections. The spacing distance between the markers was based on the present 3/9 m pattern of the standard motorway stripes. Spacing distances were defined as 12 m, 24 m, and 36 m for the raised pavement markers located at the left, centre and right. A fourth condition consisted of a 3/9 m spacing for the centre raised pavement

Table 8.3.1 Delineation configurations in Experiment 8A; conditions and spacing distances.

configuration	description	spacing distance (m)		
		left	centre	right
	straight sections			
3/9	white, raised pavement markers	12	3/9	12
12	white, raised pavement markers	12	12	12
24	white, raised pavement markers	24	24	24
36	white, raised pavement markers	36	36	36
stripes	white, retroreflective traffic paint	continuous	3/9	continuous
none	no delineation	-	-	-
	curves with 1000 m radius			
3/9	white, raised pavement markers	12	3/9	12
12	white, raised pavement markers	12	12	12
24	white, raised pavement markers	24	24	24
36	white, raised pavement markers	36	36	36
stripes	white, retroreflective traffic paint	continuous	3/9	continuous
none	no delineation	-	-	-
	curves with 200 m radius			
3/9	white, raised pavement markers	12	3/9	12
12	white, raised pavement markers	12	12	12
24	white, raised pavement markers	24	24	24
36	white, raised pavement markers	36	36	36

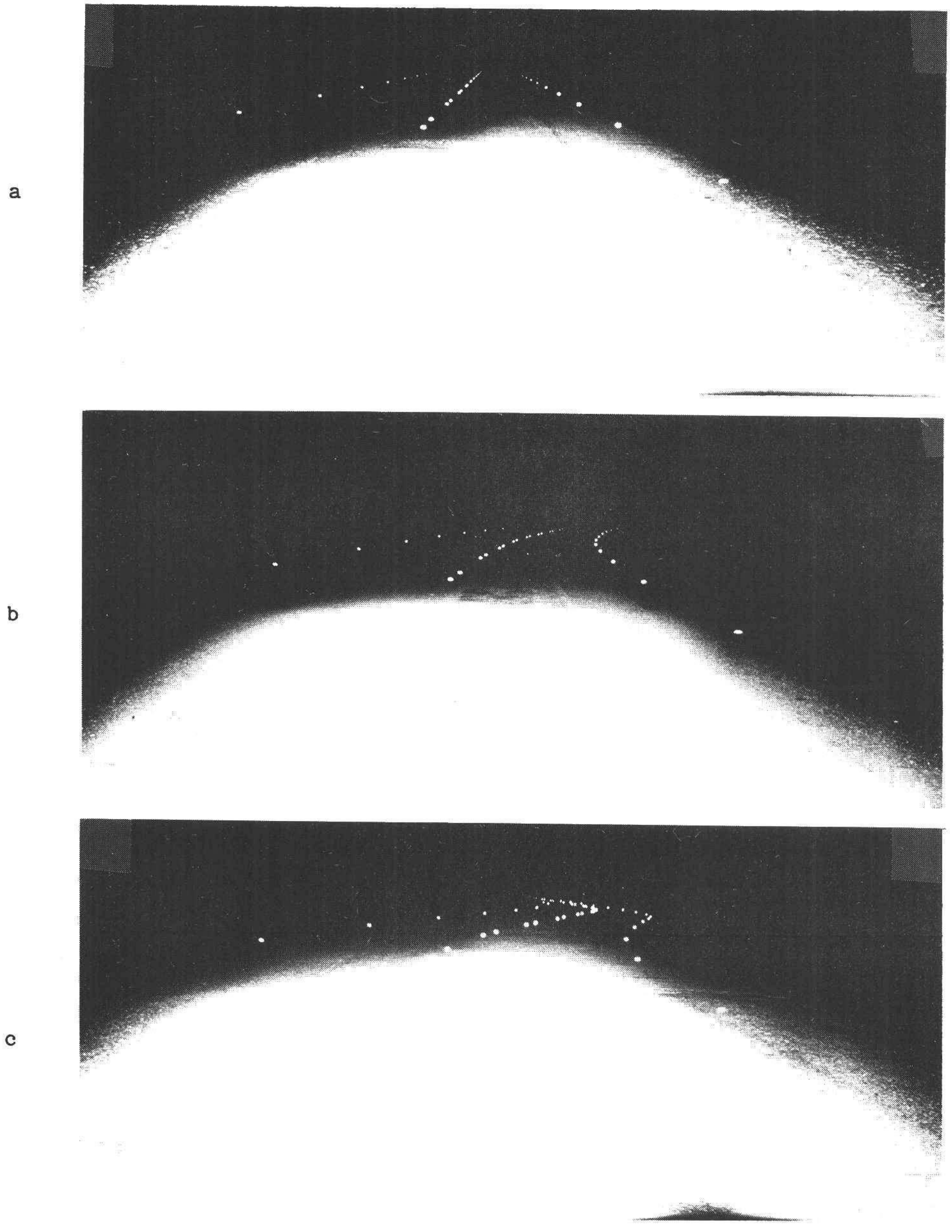

Fig. 8.3.1 The 3/9 m pattern on the straight section (Fig. 8.3.1a), the 1000 m curve (Fig. 8.3.1b) and the 200 m curve (Fig. 8.3.1c).

markers, in combination with 12 m spacing for the left and right raised pavement markers (Fig. 8.3.1).

On the straight sections and the 1000 m curves, two control configurations were added. The first configuration consisted of a standard motorway striping with white, retroreflective traffic paint. The second configuration had a bare pavement without any delineation. The 200 m curves did not offer any possibilities to apply similar control configurations.

8.3.2 **Results**

8.3.2.1 Observation strategy

Table 8.3.2 gives the total observation time (as a percentage of the run time), mean observation time and mean occlusion time for all configurations; each result represents the average value over 12 runs (6 subjects x 2 trials). There were significant differences between the individual drivers and also between the weather conditions. Drivers had a total observation time between 16 and 20% during dry, clear weather, and between 32 and 59% during the wet, clouded conditions. However, there were no interactions with the delineation configurations and, consequently, the configurations were not differently ranked for the individual drivers or weather conditions.

In general, it appears that the mean observation time was about equal for all configurations at the three sections. At the straight roads and both curves it is shown that the mean occlusion time decreased and the total observation time increased with smaller radii of the road sections. Hence, all configurations at the 200 m curves resulted in more frequent observations than the configurations at the 1000 m curves, and the configurations at these latter curves resulted again in more frequent observations than at the straight sections.

For the three road sections it is shown that the total observation time increased, and the mean occlusion time decreased when less delineation information is available per unit of road length; again the mean observation time was rather constant. Both control configurations were ranked at the extremes. The standard motorway striping in general necessitated a minimum observation time, while the bare pavement needed a maximum observation time for each road section. Furthermore, at the straight section the

Table 8.3.2 Configuration clustering (Experiment 8A) based on driver's observation strategy. The differences between the cluster numbers are related to the total observation time ($p \leq 0.05$).

cluster number	configuration	observation time		occlusion time
		total (%)	mean (s)	mean (s)
straight sections				
1	stripes	36.6	1.2	2.0
	3/9	33.7	1.0	2.2
	12	36.7	1.4	2.2
	24	35.3	1.2	2.1
2	36	42.9	1.4	1.8
	none	42.2	1.2	1.6
curves with 1000 m radius				
1	3/9	36.5	1.0	1.6
2	stripes	42.8	1.2	1.5
	12	43.3	1.2	1.5
	24	44.5	1.2	1.4
	36	45.2	1.1	1.4
3	none	53.6	1.6	1.2
curves with 200 m radius				
1	3/9	50.7	1.3	1.1
	12	46.3	1.2	1.1
2	24	55.7	1.6	1.0
3	36	65.3	1.4	0.8

3/9, 12 and 24 m configurations were similar to the standard striping, whereas the 36 m configuration resulted in an observation strategy similar to the bare pavement. At the 1000 m curves the 3/9 configuration caused less observations than all other configurations (on the straight road section this tendency was already noticed), and the bare pavement again was the worst configuration. At the 200 m curves both 3/9 and 12 m configurations resulted in a comparable observation strategy. The 24 m configuration follows, while the 36 m configuration needed most observations.

8.3.2.2 Control strategy and driving performance

Control strategy and driving performance were not different for the different weather conditions. Although differences were to be observed between the individual drivers, there was no interaction with the configurations.

The configurations at the straight sections and the 1000 m curves did not force the drivers to speed reductions or lateral positions outside the traffic lane. However, the 24 and 36 m configurations at the 200 m curves caused speed reductions and lane errors (Table 8.3.3). About 66% of all runs at the 36 m configuration was performed incorrectly.

Table 8.3.3 Percentage of runs at the 200 m curves causing speed reductions and/or lane errors.

configuration	speed reductions (%)	lane errors (%)
3/9	0	0
12	4	0
24	13	8
36	17	66

Table 8.3.4 presents driving performance in terms of the standard deviations of yaw rate, and driver's control strategy in terms of the standard deviations and frequencies of the steering-wheel movements. Data on the lateral position are also given for the standard motorway striping. The S.D. of yaw rate and steering-wheel angle increased with decreasing radii of the road sections. On each type of road some clusters of configurations can be defined. On the straight road it is found that the 3/9, 12 and 24 m configurations resulted in larger S.D. of yaw rate ($p \leq 0.05$) than the other configurations, which was not caused by larger S.D. of the steering-wheel angle (these appeared to be rather constant), but by a significant shift to higher steering frequencies. This is consistent with the lateral vehicle dynamics as presented in par. 3.1. In line with the control strategies during the previous experiments it can be said that such a shift, together with a constant or even smaller S.D., was caused by self-paced, higher task demands of the drivers for lateral vehicle control.

Table 8.3.4 Configuration clustering (Experiment 8A) based on driver's control strategy and driving performance. The differences between the cluster numbers are related to the standard deviation (S.D.) of yaw rate ($p \leq 0.05$).

cluster number	configuration	yaw rate	steering-wheel angle		lateral position	
		S.D. (°/s)	S.D. (°)	$\frac{0.3 - 0.6\ \text{Hz}}{0 - 0.6\ \text{Hz}}$ (%)	S.D. (m)	mean (m)
straight sections						
1	stripes	0.41	1.4	28.7	0.26	1.96
	36	0.41	1.2	29.4		
	none	0.42	1.5	22.7		
2	3/9	0.51	1.3	35.7		
	12	0.51	1.4	40.4		
	24	0.49	1.3	33.7		
curves with 1000 m radius						
1	stripes	0.61	1.9	22.1	0.30	2.01
	3/9	0.68	3.0	38.6		
	12	0.65	3.1	14.3		
	24	0.63	2.8	21.9		
	36	0.62	2.5	33.1		
2	none	0.78	3.6	19.7		
curves with 200 m radius						
1	3/9	1.36	7.2	3.3		
	12	1.42	7.1	3.4		
2	24	1.61	8.2	4.1		
3	36	1.85	9.1	8.6		

Unfortunately, it was not possible to verify driving performance in terms of lateral position variations. At the 1000 m curves it is found that the bare pavement resulted in a significantly increased S.D. of yaw rate. The significantly larger S.D. of the steering-wheel angle, in combination with the comparable steeringfrequencies, indicates another situation than at the afore-mentioned configurations at the straight sections. Increased S.D., with or without a shift to higher steering-wheel frequencies, indicates in general larger and more abrupt corrections due to less skill or increased task difficulty to perform lateral vehicle control during occlusion. Obviously, the 1000 m curve without any delineation presented drivers with increased difficulty. At the 200 m curves the decreased delineation information per unit of road length resulted also in an increased S.D. of yaw rate, caused by both an increased S.D. of steering-wheel angle and a shift to higher steering-wheel frequencies. Hence, drivers were faced with a significant increase in task difficulty in these curves when the longitudinal spacing of the raised pavement markers increases.

8.3.3 **Discussion**

In general, the mean occlusion time decreases (total observation time increases) and driving performance deteriorates when less delineation information is present per unit of road length. This is in particular to be observed for the 200 m curves where the 24 and 36 m spacing distances even lead to speed reductions and lane errors. Therefore, in these types of curves spacing distances of the raised pavement markers have to be restricted up to 12 m maximally. Driver's strategy at the 1000 m curves yields an unfavourable result for the bare pavement without any delineation, whereas the 3/9 configuration is more favourable in terms of less frequent observations, even compared with the standard motorway striping.

On the straight sections the observation and control strategy indicate two groups of configurations. The less favourable group is formed by the 36 m configuration together with the bare pavement. The more favourable group consists of the 3/9, 12 and 24 m configurations, leading to less observations and self-paced, higher task demands of the drivers. Hence, spacing distances of the raised pavement markers on straight roads have to be restricted up to 24 m maximally.

It should be recalled that the relatively bad weather conditions (rainy and clouded weather) were correlated with more frequent observations than dry and clean weather, but did not affect steering-wheel movements and yaw rate. Hence, driver's observation strategy changes with bad weather circumstances, while driver's control strategy remains unaffected. This conclusion is valid for all delineation configurations.

8.4 Experiment 8B: Combinations of delineation

8.4.1 **Configurations**

Table 8.4.1 presents the new configurations for the straight and curved sections. The delineation configurations were formed by raised pavement markers at the centre, and postmounted delineators left and right outside the roadway, and their combinations. The raised pavement markers

Table 8.4.1 Delineation configurations in Experiment 8B; conditions and distances.

config-uration	postmounted del. LEFT		raised pavement markers CENTRE	postmounted del. RIGHT	
	distance (m)		spacing (m)	distance (m)	
	outside lane	spacing		outside lane	spacing
	straight sections				
centre	-	-	12	-	-
1.5	1.5	36	-	1.5	36
3.5	1.5	36	-	3.5	36
centre + 1.5	1.5	36	12	1.5	36
centre + 3.5	1.5	36	12	3.5	36
stripes	white, retroreflective traffic paint in a pattern as during Experiment 8A				
	curves with 1000 m radius				
centre	-	-	12	-	-
1.5	1.5	36	-	1.5	36
3.5	1.5	36	-	3.5	36
centre + 1.5	1.5	36	12	1.5	36
centre + 3.5	1.5	36	12	3.5	36
	curves with 200 m radius				
centre	-	-	12	-	-
1.5	1.5	12	-	1.5	12
3.5	1.5	12	-	3.5	12
centre + 1.5	1.5	12	12	1.5	12
centre + 3.5	1.5	12	12	3.5	12

had a 12 m spacing distance. The postmounted delineators were situated 0.50 m above the pavement. White delineators were situated 1.5 m left from the location of the left marker, and red delineators were situated either 1.5 m or 3.5 m right from the location of the right marker. The different lateral distances were selected for roads without or with an emergency lane. The longitudinal spacing distances were chosen roughly in accordance with the directives of the Dutch Ministry of Transportation (1977).

One control configuration with a standard motorway striping with white, retroreflective traffic paint was added at the straight sections; a similar configuration could not be applied at the curves.

8.4.2 **Results**

8.4.2.1 Observation strategy

Table 8.4.2 gives the total observation time, mean observation time and mean occlusion time for the delineation configurations. Significant differences were observed between the individual drivers (ranging from 17 to 64% total observation time), but without interaction with the delineation configurations. Weather conditions did not result in different observation strategies (44.3 and 31.1% total observation time for the runs with and without rainy and clouded conditions, respectively). From the results for the standard motorway striping, as control condition in both Experiments 8A and 8B, it is found that the mean observation time decreased (1.2 s and 0.8 s for Experiments 8A and 8B, respectively), with a comparable mean occlusion time. Both values lead to total observation times of 36.6% and 28.7% in Experiments 8A and 8B, respectively. These different values went together with the weather conditions in Experiment 8B where more drivers could drive with dry and clear weather (full moon), than during Experiment 8A.

In general, mean observation time was again comparable for all configurations at the three types of sections. Mean occlusion time decreased and total observation time increased with decreasing radii of the sections. Just as was found in Experiment 8A it again is noticed that all drivers observed the configurations at the 200 m curves more frequently than at the 1000 m curves, and at the latter curves again more frequently than at the straight sections.

On the straight road, the standard motorway striping and the exclusive

Table 8.4.2 Configuation clustering (Experiment 8B) based on driver's observation strategy. The differences between the cluster numbers are related to the total observation time ($p \leq 0.05$).

cluster number	configuration	observation time		occlusion time
		total (%)	mean (s)	mean (s)
straight sections				
1	stripes	28.7	0.8	1.9
	centre	28.7	0.7	1.7
2	1.5	32.2	1.0	1.8
	3.5	33.3	1.0	1.7
	centre + 1.5	34.6	1.1	1.7
	centre + 3.5	32.7	1.0	1.7
curves with 1000 m radius				
1	centre	33.8	0.8	1.4
	1.5	35.5	0.8	1.3
	3.5	33.6	0.8	1.4
	centre + 1.5	32.2	0.8	1.4
	centre + 3.5	33.1	0.8	1.4
curves with 200 m radius				
1	1.5	38.3	0.9	1.1
	centre + 1.5	35.1	0.9	1.2
	centre + 3.5	40.7	1.0	1.1
2	centre	43.9	1.0	1.0
3	3.5	51.6	1.3	0.9

application of raised pavement markers at the centre both resulted in less observations than all other configurations. No significant differences were observed at the 1000 m curves. However, at the 200 m curves three clusters of configurations can be defined. A first group, with the fewest observations, consists of raised pavement markers at the centre in combination with postmounted delineators either on 1.5 m or 3.5 m outside the lane, and the exclusive use of postmounted delineators on 1.5 m distance. The second group is formed by the raised pavement markers at the centre, whereas the third group with the postmounted delineators on 3.5 m distance resulted in the most frequent observations.

8.4.2.2 Control strategy and driving performance

Control strategy and driving performance were not different for the weather conditions. Although again differences were to be observed between the individual drivers, there was no interaction with the configurations. The configurations at the straight sections and curves did not result in speed reductions or lateral positions beyond the traffic lane.

Table 8.4.3 presents driving performance in terms of the S.D. of yaw rate, and driver's control strategy in terms of the S.D. and frequencies of the steering-wheel movements. Data on the lateral position are also give.. for the standard motorway striping. Both S.D. increased with decreasing radii of the sections. On each section, the various configurations can also be distinguished. In contrast with some conditions of Experiment 8A, it is found that no configuration of Experiment 8B resulted in self-paced, higher task demands of the drivers. In that case, a configuration should be characterized by a larger S.D. of yaw rate resulting from more high-frequent steering-wheel movements, with comparable or even smaller amplitudes. The present larger S.D. of yaw rate, due to the larger S.D. of the steering-wheel movements, at some configuration in Experiment 8B can therefore be imputed to increased, external task demands. On the straight roads the configuration with postmounted delineators on 3.5 m distance, is ranked as relatively unfavourable, whereas the standard motorway striping has to be considered as relatively favourable. No differences were found between the configurations at the 1000 m curves. At the 200 m curves again three clusters of configurations can be defined. The first, relatively favourable, group is formed by the configurations with the postmounted delineators on 1.5 m distance, with or without the raised pavement markers at the centre. The second group consists of the same configurations, but now with respect to a 3.5 m distance. The relatively most unfavourable configuration is found for the exclusive application of raised pavement markers at the centre.

8.4.3 **Discussion**

In general, it is found that delineation configurations lead to more frequent observations and a worse driving performance when lateral distance between delineation and driver increases.

At the 200 m curves the postmounted delineators on 1.5 m distance, with or without raised pavement markers at the centre, lead to the fewest

Table 8.4.3 Configuration clustering (Experiment 8B) based on driver's control strategy and driving performance. The differences between the cluster numbers are related to the standard deviations (S.D.) of yaw rate ($p \leq 0.05$).

cluster number	configuration	yaw rate	steering-wheel angle		lateral position	
		S.D. (°/s)	S.D. (°)	$\frac{0.3 - 0.6\ \text{Hz}}{0 - 0.6\ \text{Hz}}$ (%)	S.D. (m)	mean (m)
straight sections						
1	stripes	0.44	1.9	33.3	0.28	2.03
2	centre	0.55	1.7	36.2		
	1.5	0.49	1.6	35.5		
	centre + 1.5	0.51	2.2	22.9		
	centre + 3.5	0.53	1.7	33.8		
3	3.5	0.59	2.5	29.4		
curves with 1000 m radius						
1	centre	0.66	3.2	26.4		
	1.5	0.69	3.6	23.3		
	3.5	0.69	3.7	25.3		
	centre + 1.5	0.64	3.6	27.3		
	centre + 3.5	0.72	3.8	28.7		
curves with 200 m radius						
1	1.5	1.35	7.0	5.2		
	centre + 1.5	1.34	6.9	3.5		
2	3.5	1.45	8.0	5.4		
	centre + 3.5	1.51	8.3	3.7		
3	centre	1.79	9.1	4.1		

observations and small amplitudes of the yaw rate and small, low-frequent steering-wheel movements. However, when the postmounted delineators are located on 3.5 m distance, both the observation and control strategy deteriorate, whereas these effects are also found for the exclusive use of raised pavement markers at the centre (relatively many observations in combination with relatively large, high-frequent steering-wheel movements). Obviously, the latter configurations fail to give a delineation to the drivers as an outer limitation of the road to be followed. Hence, at curves with these radii both sides of the lane or roadway have to be delineated. For instance, raised pavement markers at the centre can be used in combination either with raised pavement markers at the location of the right marker (12 m configuration of Experiment 8A), or with postmounted delineators close (1.5 m distance) to the location of the lane marker. These alternatives are roughly equivalent. Instead of the raised pavement markers at the centre it is also possible to apply postmounted delineators on a 1.5 m distance outside the left lane (for a two-lane motorway).

At the 1000 m curves no differences between the configurations are shown. At the 200 m curves the observation and control strategy of the drivers again indicate a clustering of configurations. The most favourable group (less observations) is formed by the standard motorway striping and raised pavement markers at the centre. The postmounted delineators on 3.5 m distance lead to an less favourable control strategy and driving performance, as compared to all other configurations. An additional application of postmounted delineators at a straight road or at curves with 1000 m radius, does not result in a more favourable observation and control strategy as compared to the exclusive use of raised pavement markers at the centre. It should be recalled that this conclusion is not valid for the 200 m curves.

8.5 Recommendations for road delineation at night

Driver's observation and control strategy, and driving performance were studied to evaluate various configurations at night for their functioning in presenting perceptual cues on lateral vehicle control inside the traffic lane (short-range delineation) and on road curvature (long-range curvature).

In general, no difference were observed at the 1000 m curves. The results for the 200 m curves with an accent on long-range delineation, and for the straight sections with an accent on the short-range delineation, can be integrated into a number of general recommendations:

- Road delineation, i.e. raised pavement markers, exclusively at the centre is favourable for lateral vehicle control inside the lane (short-range delineation), but is less sufficient for preview information on the lane to be followed (long-range delineation). Hence, it is necessary to delineate both lane boundaries.
- Delineation at the centre can be realized with raised pavement markers.
- Delineation at the outside of the traffic lane can be realized with raised pavement markers at the location of the lane boundary, or with

postmounted delineators on 1.5 m distance; both configurations are about equal. Postmounted delineators on 3.5 m distance are less efficient.
- Raised pavement markers at the location of the centre and/or lane boundaries, have to be applied with a spacing distance of 12 m maximally (200 m curves) or 24 m maximally (straight sections). It may be useful to relate spacing distances to road curvature in a corresponding way as already used in practice for spacing distances between stripes or postmounted delineators.
- Instead of raised pavement markers at the location of the centre and lane boundaries also wet-resistent stripes can be used.

8.6 Discussion and conclusions

Both experiments show that criteria related to the description of multitask driving in terms of supervisory control can be used for the evaluation of road design in practice. Thereby, it is shown that the occlusion time for lateral vehicle control is a sensitive criterion for the various delineation configurations, according to the relation that better delineations lead to better observations/predictions of driving performance (Supervisory Driver Model; par. 2.3). Hence, drivers occlude their visual cues for lateral control for longer periods, and have more possibilities to cope with other tasks beyond lateral control. Thereby, it is found that drivers need about equal observation times in each condition. Deteriorated circumstances due to bad weather conditions resulted in Experiment 8A in increased observations, while driver's control strategy was unaffected. These results are consistent with the Supervisory Driver Model structure when bad weather conditions are associated with increased levels of observation noise, which affect only the observation/prediction block, and not the control block.

With respect to driver's control strategy, the amplitudes and frequencies of the steering-wheel movements confirmed some results of the previous experiments. In general, two types of conclusions can be drawn. First, a shift to higher steering-wheel frequencies, in combination with similar or even smaller standard deviations, is related to self-paced, higher task demands in a given driving situation. Similar shifts in task demands were found previously for experienced drivers when the longitudinal control condition was added, or when they drove during darkness. Second, a shift to larger standard deviations of steering-wheel movements, with or without a shift to higher frequencies, is related to large, abrupt corrections of lateral position after periods of occlusion. These situations occur mostly when drivers are faced with high external task demands, or when they have less skills and cannot combine lateral control and other tasks (like visual occlusion) sufficiently. In some previous experiments, for instance during the instruction to scan the off-road environment, similar results were already shown for the experienced drivers, and to a larger extent for the inexperienced drivers.

8.7 References

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9. EPILOGUE

The purpose of the thesis was to describe and predict driver's capabilities to cope with the multitask situations of everyday driving. To do so, driving was studied in terms of supervisory control. Drivers were assumed to perform better, or safer, when they cope better with the multitask driving situations by behaving more as a supervisory controller. In a similar way, car and road designs were considered to be better when they allow drivers to spend attention to other tasks and, hence, to behave also more as a supervisory controller. Supervisory control was made operational during lateral vehicle control by the study of the following criteria: driver's observation strategy in terms of free times, driver's control strategy in terms of the amplitudes and frequencies of the steering-wheel movements, and the overall driving performance in terms of the variations in lateral position and yaw rate. The results of both the field studies and the calculations with the Supervisory Driver Model, the SDM, showed in general that these criteria were useful to describe multitask driving in relation to the availability of perceptual cues, task demands and driving skills.

In many multitask situations, driving performance of lateral vehicle control appeared to be quite satisfactory, i.e. both skilled and unskilled drivers stayed within the traffic lane. Thereby, the skilled drivers had longer free times for observations than the unskilled drivers for comparable levels of lateral control performance. The observation strategy of the skilled drivers showed an increased number of observation transfers during multitask driving or during deteriorated conditions. Their control strategy then showed self-paced, higher task demands for lateral vehicle control, i.e. higher steering-wheel frequencies, in combination with similar or smaller standard deviations of the steering-wheel movements. These higher task demands caused mostly also a better lateral control performance. In situations where the visual cues for lateral vehicle control were occluded temporarily, the skilled drivers also set a more ideal initial vehicle position immediately before occlusion. However, the unskilled drivers had a completely different control strategy during multitask driving and/or deteriorated conditions. They lacked not only the shift to self-paced, higher task demands, but even showed less skills in combining tasks like lateral and longitudinal control, resulting into a control strategy with large, and more abrupt steering-wheel movements.

These results clearly show that skilled drivers perform better, or safer, during multitask driving and/or deteriorated conditions than the unskilled drivers, due to the learned adaptations in their observation and control strategy. The SDM calculations showed, for instance, an increased use of the lateral speed cue by the more skilled drivers. With driving skill development, drivers then behave more as a supervisory controller and have more possibilities to monitor aspects beyond the task demands, which indeed may lead to the early detection and compensation of unexpected traffic events and, thus, may lead to increased traffic safety.

These findings strongly pronounce that an analysis of driver's observation and control strategy gives relevant data in addition to the "normal" measures of overall driving performance, and focusses on driver's capabilities for multitask driving. The free times describing driver's observation strategy during lateral vehicle control, and the steering-wheel amplitudes and frequencies describing driver's control strategy, can easily be used as criteria in new studies, also with respect to road and car design. The multitask aspects of driving can experimentally be obtained by the visual occlusion technique. The application study with respect to roadway delineation at night clearly demonstrated the relevance of these criteria in the field of road design. Similar studies can be conducted to study the effects of vehicle dynamics, i.e. stability, manoeuvrability and side-wind effects.

Some final remarks can be made about the Supervisory Driver Model. The SDM was introduced to provide a framework for multitask driving within a supervisory control context. The SDM calculations have proven to be valuable as a mathematical tool to predict the effects of changes in the use of the perceptual cues on the overall driving performance and driver's observation strategy. Similar sensitivity studies can, of course, be performed with respect to vehicle dynamics, (time-dependent) side-wind effects, etc. However, it was found experimentally that interactions between tasks may result into self-paced, higher task demands for lateral control. These interactions cannot be predicted by SDM and necessitate empirical studies.

NOMENCLATURE

a	distance between vehicle centre of gravity and front axis	m
a_l	lateral acceleration	m/s^2
A	system matrix	
b	distance between vehicle centre of gravity and rear axis	m
B	input matrix	
C	display matrix	
C_A	aerodynamic coefficient	Ns^2/m^2
C_R	coefficient of rolling resistance	
C_{1e}	effective cornering stiffness coefficient front wheel tires	N/rad
C_{2e}	effective cornering stiffness coefficient rear wheel tires	N/rad
E	disturbance matrix	
g	gravitational acceleration	$9.81\ m/s^2$
G	height of a marker above the road surface	m
G_R	yaw rate gain, or yaw rate sensitivity	1/s
H	height of driver's eyes above the road surface	m
I_R	moment of inertia around Z-axis	kgm^2
K	vehicle stability factor	s^2/m^2
l	wheel base	m
m	vehicle mass	kg
M_e	engine torque	Nm
N	steering system gear ratio	
r	yaw rate	rad/s
$\dot{r}$	yaw acceleration	rad/s^2
r_w	tire effective radius	m
R	curve radius	m
s	Laplace operator	
s_a	accelerator position (range 0-1)	
s_g	gearbox ratio	
t	time	s
T	preview time	s
T_l	lead time constant	s
u	longitudinal velocity	m/s
$\dot{u}$	longitudinal acceleration	m/s^2

$\bar{U}$	mean longitudinal velocity	m/s
v	lateral velocity	m/s
$\dot{v}$	lateral acceleration	m/s^2
V	covariance	
w	white noise	
w_g	filtered white noise, added to driver's actual steering-wheel angle	
$\dot{w}_g$	first derivative of filtered white noise w_g	
$\underline{x}$	state vector	
$\underline{\dot{x}}$	first derivative of the state vector	
$\underline{\hat{x}}$	estimation of the state vector $\underline{x}$	
X_A	aerodynamic force	N
X_B	braking force	N
X_D	drive force	N
X_R	rolling resistance force	N
y	lateral deviation	m
$\dot{y}$	lateral speed	m/s
$\underline{y}$	display vector	
Y	lateral distance between a marker and driver's eyes	m
$\bar{Y}$	mean lateral distance between a marker and driver's eyes	m
Y_1	lateral tire forces at front wheels	N
Y_2	lateral tire forces at rear wheels	N
$\underline{z}$	control vector	

α	inclination deviation	rad
$\dot{\alpha}$	inclination speed	rad/s
α_1	slip angle front wheels	rad
α_2	slip angle rear wheels	rad
β_r	yaw rate damping coefficient	
δ_s	actual steering-wheel angle	rad
$\dot{\delta}_s$	actual steering-wheel rate	rad/s
δ_{sc}	commanded steering-wheel angle	rad
δ_w	front wheel steering angle	rad
Δ	inclination angle	rad
$\bar{\Delta}$	mean inclination angle	rad

ψ	heading angle	rad
$\dot{\psi}$	yaw rate	rad/s
τ_1	time constant	s
τ_2	time constant	s
ω_r	yaw rate natural frequency	rad/s

Abbreviations

ANOVA	ANalysis Of VAriance
c.g.	centre of gravity
FFT	Fast Fourier Transform
OCM	Optimal Control Model
OCDM	Optimal Control Decision Model
S.D.	Standard Deviation
SDM	Supervisory Driver Model
TLC	Time to Line Crossing
VPS	Vanishing Point of Straight road

CURRICULUM VITAE

The author was born in 1948 in The Hague. He graduated from High School, HBS-B at the Dalton Lyceum in The Hague in 1965. He studied mechanical engineering at the Delft University of Technology, where he specialised in man-machine systems at the Laboratory for Measurement and Control. After obtaining his engineering degree in 1971, he joined the Traffic Behaviour Research Group at the Institute for Perception TNO, Soesterberg. Research projects were conducted in the area of driver vehicle control, road and vehicle ergonomics, and simulation. In 1984 he was appointed as Head Vehicle Properties at Volvo Car BV, Helmond.