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Analysis of the driving task and the role of lane departure warnings

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A.M. Rook and J.H. Hogema

SUMMARY

Purpose: Advanced Driver Assistance Systems (ADAS) are beginning to penetrate the market. The Dutch Ministry of Transport, Public Works and Water Management is conducting a Field Operational Test focussing on Lane Departure Warning Assistance (LDWA) systems. This report is the result of the Workpackage GEN1: "Analyses of the driving task and the role of lane departure warnings". The aim is to develop a theoretical model of lane keeping and steering as part of the driving task, including the role of lane departure warnings. This will help to generalise and qualify the findings from the other work packages.
Method: A literature survey was conducted, focussing on models of human vehicle control and on empirical research of actual driving behaviour.
Results: Most of the models of human vehicle control found in the literature are based on models derived from (optimal) control theory. They typically cover (or try to cover) the range of normal operation of vehicle control. Phenomena as accidents or unintended lane departures are not in their scope. The role of LDWA can be seen as complementary to the *observation/prediction* and *decision* functions from the so-called Supervisory Driver Model. When these functions from the driver model fail to produce the required steering actions, the warning by an LDWA can trigger the decision to initiate observation as well as control actions.
Factors that influence the lateral control task can be grouped in external factors (wind, lane width, curves and traffic) and internal, driver-state related factors (drowsiness, fatigue, inalertness). With respect to the external factors, drivers typically increase their control effort and/or adjust their behaviour (e.g. reduce their speed on narrower lanes) to compensate for reduced margins. If the external conditions are such that the driver is operating at the limits of his ability as a controller, the LDWA is not expected to have any contribution.
Inalertness in the driving task can be caused by (1) drowsiness or fatigue, (2) distraction by the environment, and (3) secondary tasks. Drowsiness has been shown to degrade driving performance, reduce safety margins in terms of TLC, and increase the occurrence of lane departures. For secondary tasks, the situation is sometimes different in the sense that drivers are sometimes found to adjust their driving behaviour, thus possibly maintaining a constant safety level, and in some occasions lateral control by the driver actually improved when adding a secondary task. Still, in other studies secondary tasks did lead to degrading control behaviour and reduced margins.
Conclusions: Few models are geared to address driving behaviour in relation to lane departure warning. The most suitable model is the Supervisory Driver Model (SDM). The role of LDWA can be seen as complementary to the observation/prediction and decision blocks of the SDM. When these functions from the driver model fail to produce the required steering actions, the warning by an LDWA can trigger the decision to initiate observation as well as control actions.
The largest potential for LDWA in avoiding imminent lane departures is expected when the driver fails to produce the required steering actions due to a temporarily degraded driver state by fatigue, drowsiness or distraction.

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TNO Technische Menskunde
Soesterberg

Analyse van de rijtaak en de rol van waarschuwingen bij lijnoverschrijdingen

A.M. Rook en J.H. Hogema

SAMENVATTING

Vraagstelling: Advanced Driver Assistance Systems (ADAS) staan op het punt om door te breken. Het Ministerie van Verkeer en Waterstaat voert een Field Operational Test uit, gericht op systemen die een waarschuwing geven wanneer een lijnoverschrijding dreigt plaats te vinden (Lane Departure Warning Assistance, LDWA). Dit rapport is het resultaat van Werkpakket GEN1, dat zich richt op een analyse van de rijtaak en de rol van *lane departure warnings*. Het doel is om een theoretisch model te ontwikkelen voor het koershouden, inclusief de rol van lane departure warnings. Hiermee zullen de bevindingen uit andere werkpakketten in perspectief geplaatst kunnen worden.
Werkwijze: Er is een literatuurstudie uitgevoerd, gericht op modellen van de mens als voertuigbestuurder en gericht op empirisch onderzoek naar werkelijk rijgedrag.
Resultaten: De meeste modellen van menselijk bestuurdersgedrag zijn gebaseerd op modellen afkomstig uit de (optimale) regeltheorie. Het bereik dat deze modellen (trachten te) bestrijken is het normale besturen. Fenomenen als ongevallen of onbedoelde rijstrookwisselingen vallen buiten het werkgebied. De rol van LDWA kan worden gezien als complementair aan de observatie/predictie en de beslissings-functies uit het zogenaamde Supervisory Driver Model. Wanneer deze functies uit het bestuurdersmodel niet de benodigde stuurinput genereren zal de waarschuwing van een LDWA nieuwe waarnemingen en stuuracties van de bestuurder kunnen initiëren.
Factoren die de laterale regeltaak beïnvloeden kunnen worden onderverdeeld in externe factoren (wind, rijstrookbreedte, bochten, verkeer) en interne, bestuurders-gerelateerde factoren (vermoeidheid, slaperigheid, onoplettendheid). Bij de externe factoren verhogen bestuurders hun inspanning en/of passen ze hun gedrag aan (bijvoorbeeld snelheidsverlaging bij versmalde rijstroken) om te compenseren voor gereduceerde marges. Wanneer de externe condities zodanig zijn dat de bestuurder op de grenzen van zijn kunnen opereert wordt niet verwacht dat een LDWA zal helpen.
Onoplettendheid kan worden veroorzaakt door (1) vermoeidheid/slaperigheid, (2) afleiding vanuit de omgeving, en (3) neventaken. Van slaperigheid is gebleken dat het de rijprestatie aantast, veiligheidsmarges in termen van TLC reduceert, en het aantal rijstrookoverschrijdingen doet toenemen. Bij neventaken is de situatie soms anders aangezien bestuurders soms hun rijgedrag aanpassen, wat het veiligheidsniveau gelijk zou kunnen houden; in sommige gevallen verbeterde het koershoudgedrag zelfs wanneer een neventaak werd toegevoegd. Echter, in diverse andere studies leidden neventaken tot een verslechtering van het rijgedrag en tot een afname van beschikbare marges.
Conclusies: Slechts weinig modellen zijn geschikt voor het weergeven van rijgedrag in relatie tot *lane departure warnings*. Het meest geschikt is het Supervisory Driver Model (SDM). De rol van LDWA kan complementair worden beschouwd aan het observatie/predictie- en het beslissingsblok uit het SDM. Wanneer deze functies uit het bestuurdersmodel falen om de vereiste stuurbewegingen te produceren kan een waarschuwing van de LDWA een nieuwe waarnemings- en regelactie initiëren.
De grootste waarde van LDWA voor het voorkomen van lijnoverschrijdingen wordt verwacht wanneer de bestuurder niet de vereiste stuuracties uitvoert ten gevolge van een tijdelijk gedegradeerde toestand door slaperigheid, vermoeidheid of afleiding.

1 INTRODUCTION

Advanced Driver Assistance Systems (ADAS) are beginning to penetrate the market. Applications such as Adaptive Cruise Control and Lane Departure Warning Assistant (LDWA) are now commercially available, not only for high-performance cars, but also for medium class cars such as the Fiat Stilo, Nissan Primera and heavy trucks such as the DAF XF and the Mercedes Actros. Earlier research predicts a significant reduction of the number of incidents (read accidents). Unfortunately, no sufficient statistical data is available to show this reduction.

1.1 Traffic accidents

In The Netherlands, approximately 1100 traffic related deaths and 12000 severe casualties are reported annually (Schermers, 2000). An overview of Dutch police reports indicates that in 1999, 57 fatalities and 979 severely injured casualties occurred in single vehicle accidents (e.g., drifting off the road) in The Netherlands. Of these accidents, steering errors were considered to be major contributing factors in 33 and 603 cases, respectively. In the same year, side wipe accidents (i.e., accidents between two vehicle driving in the same driving direction, between two vehicles crossing, merging, or turning) claimed 401 fatalities and 5438 severely injured casualties. Here, the number of cases where steering errors were reported as a major contribution were 64 and 1047, respectively (Schermers, 2000).

Although the findings for America could well differ from the situation in The Netherlands, because of differences in driver and vehicle population, and traffic and road characteristics, it may be interesting to consider accident data from the USA. A statistical review of the 1992 American databases indicates that run-off-road crashes are the most common of crash types within the USA. They account for 20% of all police reported crashes, and over 41% of all in-vehicle fatalities.

These statistical databases give reason to research systems that have potential to reduce the number of run-off-road related accidents. In an earlier study Pomerleau et al. (1999) investigated the potential of Intelligent Vehicle Highway Systems (IVHS) countermeasures to avoid run-off-road collisions. They concluded that the fraction of all run-off-road crashes that could be prevented by LDWA (assuming it is functioning all the time and in all vehicles) was:

- 14% for passenger cars
- 33% for heavy trucks.

1.2 The research project

The Dutch Ministry of Transport, Public Works and Water Management has recognised the potential and relevance of ADAS and is planning a sequence of Field Operational Tests (FOTs). The first of these FOTs is aimed at systems that provide lateral support, in particular LDWA systems. During the LDWA FOTs, three types of LDWA systems will be installed in a fleet of about 40 heavy-goods vehicles. These systems have the potential of a considerable contribution to traffic safety, but there are still a lot of uncertainties. The important issue of how much of the potential effect can be expected in practice, needs to be thoroughly explored through research. In order to understand the impact of these LDWA systems, the Ministry of Transport, Public Works and Water Management has formulated a research framework. After submitting a research proposal for this framework, a consortium consisting of TNO, ITS (University of Nijmegen), ARCADIS, University of Berkeley (PATH) and the University of Minnesota are now conducting the resulting research project. The project consists of eight Workpackages, as shown in Figure 1.

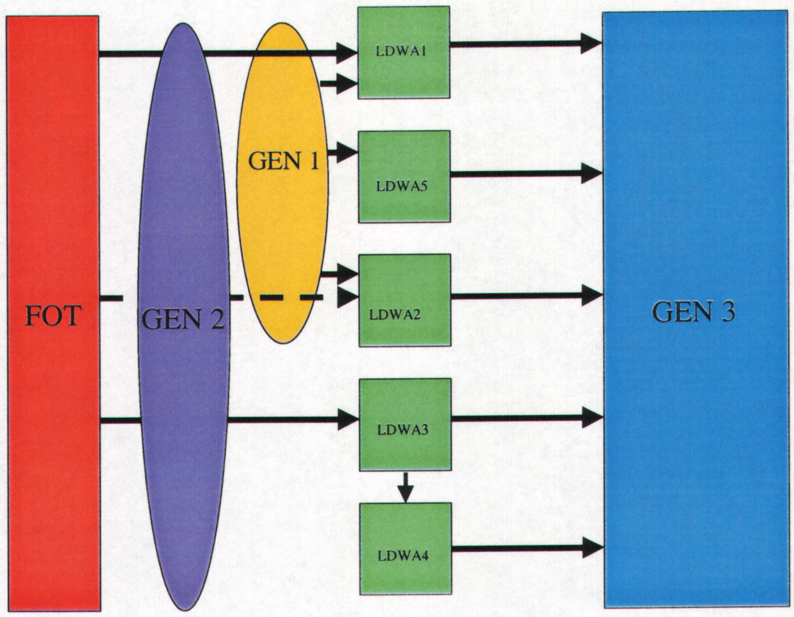

Figure 1 Flow diagram of the coherence among the workpackages.

These Workpackages have the following content:

- GEN1 Analysis of the driving task and the role of lane departure warnings
- LDWA1 Behavioural effects in Field Operational Test
- LDWA2 Effects of LDWA on traffic flow
- LDWA3 Acceptance of LDWA
- LDWA4 Infra-structural consequences of LDWA
- LDWA5 Relation of LDWA with narrow lanes
- GEN2 Service desk
- GEN3 Integration of results

This report consists the product of the GEN1 Workpackage. The work includes a literature survey, analysis of the driving task and the role of lane departure warnings. This workpackage has the aim to develop a theoretical model of lane keeping and steering as part of the driving task, including the role of lane departure warnings. This will help to generalise and qualify the findings from the other work packages.

Lane keeping is a basic driving task, mainly performed at the control level. It is clear that steering errors will regularly be made. It is, however, essential to investigate the cause of such errors. The focus of this work package is to develop an understanding of the complex nature of accidents related to lane keeping and steering behaviour.

Lateral support systems can be categorised as followed.

- *Lane departure warning* systems assist the driver in avoiding lane departures by warning him when he is about to depart (unintentionally) from his lane. The warning can be auditory, visual, haptic or tactile.

- *Lane keeping* systems have a wider range of operation: these systems actively support the driver in the steering task. These systems function on a continuous basis, and not only when the vehicle is about to depart unintentionally from its lane.

The focus of the project – and hence of this report – is on the first category only.

1.3 Outline of this report

The first task of the literature study was to find out what aspects are related to lane keeping and LDWA and address these aspects to a model, which also includes lane keeping and LDWA. Chapter 2 gives an overview of factors, which possibly affect the lateral steering task. This chapter concludes with a discussion whether LDWA could play any role in relation to the particular factors. In Chapter 3 *models of human vehicle control* are discussed in relation to the factors, which affect the steering task. Also the role of LDWA is discussed. Chapter 4, literature that specifically addresses LDWA and driving behaviour is discussed. Finally, the combined result of these elements is presented in Chapter 5.

2 CAUSAL FACTORS IN RUN-OFF-ROAD ACCIDENTS

2.1 Introduction

To be able to evaluate (or build) driver models, which incorporate the relation between LDWA and the driving task, it is necessary to have an overview of the elements which the model should contain. Therefore the driving task and driving behaviour should be defined in some more detail. Driving behaviour in relation to the lateral control task is considered to be dependent on the following items: driver state, road configuration, vehicle state (vehicle stability and dynamics) weather conditions (crosswind) and traffic. These items can be grouped in internal and external factors.

- Internal Factors: driver state
- External Factors: road configuration, vehicle state, weather conditions and traffic

It is acceptable to consider that the (in-)stability and dynamics of modern vehicles have a relatively small contribution to lane departures; therefore the vehicle state will not be taken into consideration. Vehicle speed, which is also a vehicle state, will be discussed implicitly in the sections of this chapter. In contrast, driver states do have quite a large contribution to run-off-road related accidents. Distraction, drowsiness and fatigue are important phenomena, which have to be considered. Furthermore, other traffic is considered to have large effects on lane keeping behaviour. This is not discussed in this report, because no relevant literature was found on this subject. It is expected that implicit results will be found in the FOTs.

Before describing factors that possibly affect the lane keeping task, a brief explanation of this task and an often used quantitative measure for this task will be given. When performing a straight lane-keeping task, drivers deliberately neglect path errors. After a certain amount of time, but before crossing the lane edge, drivers correct these path errors.

The Time to Line Crossing (TLC) is defined, at each instant, as the time necessary for any part of the vehicle to reach the shoulder line if the driver does not change current course, speed, or acceleration (Godthelp, 1984). TLC is a quantitative measure for the quality of driving behaviour, in which vehicle movements and control behaviour are integrated and where vehicle and roadway characteristics are simultaneously taken into account. As such, TLC is appropriate to describe driving behaviour on straight roads and in curves, and to optimise vehicle- and roadway-characteristics.

2.2 Internal factors

The driver state can be explained as the ability of a driver to drive a car. Assuming that drivers do have a drivers-license and are in principle able to drive a car, the ability to drive a car is strongly related to the level of alertness. Vlakveld and Van Raamsdonk (2002) distinguished the following categories of alertness:

- One is alert, but distracted by external matters that are not related to the driving task.
- One is alert, but pays attention to tasks which are not related to the driving task and is aware of this fact.
- One is alert, but keeps one's mind on other things and is therefore not attentive to road traffic. (internal distraction)
- One is not alert, because of fatigue or drowsiness and is therefore not able to be attentive to the driving task.

The relation between these categories of alertness and traffic accidents follows from Table 1. This table shows the percentages of causal factors involved in Run-Off-Road accidents in the USA. The first four categories are related to driver attention.

Table 1 Primary causes of Run-Off-Road crashes for cars and heavy trucks from 1992 (Pomerleau et al., 1999).

Primary Causal Factor	Passenger car	Heavy truck
Driver inattention	12.7 %	12.4 %
Driver fell asleep	6.9 %	42.7 %
Driver intoxicated	10.9 %	1.1 %
Driver passed out	1.5 %	1.1 %
Evasive manoeuvre	15.4 %	9.0 %
Lost directional control	16.0 %	6.7 %
Vehicle failure	3.7 %	5.6 %
Vehicle speed	32.1 %	22.5 %
Vision obscured	--	1.1 %

The large percentage for the category: 'driver fell asleep' for heavy trucks is remarkable. Although regulations with regard to driving hours and the way these are monitored in the USA most likely differ from the regulations in The Netherlands and Europe, still the factor 'driver fell asleep' is considered to be one of the most important factors. This is confirmed by results described in an EU-Report (ETSC, 2001). In this report the role of driver fatigue in commercial road transport crashes is described. Driver fatigue is a significant factor in approximately 20% of commercial road transport crashes in Europe. Drivers are usually aware of their drowsiness state and may have experienced driving in that condition. 50% of long haul truck drivers report they have fallen asleep at the wheel (at least) once. Similar findings were presented by Van Ouwerkerk (1986). He performed a study among 650 truck drivers in The Netherlands. When asked whether they had ever blanked-out or dropped off for a moment in their career, 60% answered "yes". The results of these studies in Europe and in The Netherlands in particular are quite comparable with the situation in the USA. In a telephone survey of 1000 drivers in New York state (McCartt, Ribner, Pack and Hammer, 1995), 55% of the drivers responded that they have been driving in a drowsy state within the last year at least once.

Intoxicated drivers of heavy trucks seem to contribute for a small percentage to the number of accidents. Intoxication has a negative effect on alertness, but will not be discussed in detail. The adaptive model discussed in chapter 3 includes intoxication. Driver inattention is discussed in Section 2.2.1. This section discusses inattention through distraction and dual tasks. Section 2.2.2 discusses fatigue and drowsiness in relation to lane keeping.

2.2.1 Distraction and secondary tasks

In a recent (2001) traffic safety research project, a random sample of Dutch car drivers was asked to complete a questionnaire (Vlakveld & Van Raamsdonk, 2002). Of all respondents who reported being involved in an accident during the previous 12 months, about 10% stated that distraction was a major factor involved in the occurrence of the accident. In these figures, accidents caused by fatigue are not included. However, these data do not indicate what proportion of these accidents could be addressed to lateral steering errors and what to longitudinal errors.

Drivers may be considered to be able to select the right radio channel or to make a quick telephone call while driving. So what is the problem with performing these secondary tasks while driving? It may be interesting to know what really happens when distracted. In case of secondary tasks drivers know they are less alert. In several studies it was found that drivers who knew they were less alert (in case of secondary tasks) compensated by reducing their speed. However lane keeping performance still decreased in most cases. The following studies will illustrate these findings.

De Waard, Brookhuis and Hernandez-Gress (2001) conducted a driving simulator study, in which 20 drivers drove in two conditions, once under normal driving conditions and once while distracted by using a phone. In the 'distracted' condition, results showed a deterioration in driver performance on different vehicle parameters. The standard deviation of the lateral position (SDLP) increased from 0.22 to 0.29 meters due to the phone task, which means a decreased steering performance. The number of lane departures increased by a factor of three, which also indicates to a decreased steering performance. The driving speed reduced by an average of 5 km/h, which indicates to compensation. A similar trend was observed by Blaauw (1984) and Van Winsum (1996).

Hogema and Veltman (2002) did not find a difference in steering performance, but they did find a reduction in driving speed in their field study. They conducted a field study with an instrumented vehicle, where subjects drove with and without a cognitive secondary task (the Continuous Memory Task). On the contrary, Reed and Green (1999) found several performance decrements when using a mobile telephone while driving (higher mean lateral speed, higher standard deviations of accelerator position and speed). Alm and Nilsson (1995) found no compensation at all. They conducted a driving simulator experiment in the VTI driving simulator to study effects of using a mobile telephone on driving behaviour. They found that their mobile telephone task had a negative effect upon the drivers' choice reaction time, and that the effect was more pronounced for the elderly drivers. The subjects did *not* compensate for their increased reaction time by increasing their headway during the phone task.

A lot of divergent results showing compensation or no compensation, and decreased steering performance or not. Overall one can conclude that distraction has a negative effect on driving performance in general and most likely on steering performance. But Brookhuis, De Vries, and De Waard (1991) found an increased steering performance. They conducted a field experiment with an instrumented vehicle to study effects of using a mobile telephone. They found that on a motorway with light traffic conditions and the subject instructed to maintain a fixed speed of 95 km/h in the right lane, the SDLP *decreased* during the telephone task. An explanation could be that the task alerted the driver who had a mental underload due to a boring motorway (environment). Similar results were found by simulator experiments carried out by Tenkink (1990). He carried out a set of driving simulator experiments that included speed choice (free speed choice vs. fixed speed) and an additional task (with/without) as factors. The additional task consisted of a Continuous Memory Task (CMT), with various modalities for the stimulus presentation: auditory, visual in-car, or visual along the road. Adding an auditory secondary task resulted in a speed reduction of about 8%. In the condition with a fixed speed, subjects could not compensate for the additional load of the CMT by reducing speed, and consequently the performance on the CMT became worse than when only performing the CMT. Furthermore, under the fixed speed condition, the proportion of power of the steering control input in the higher frequency band (>0.4 Hz) was higher with than without the auditory task, which indicated a higher steering effort. In the free speed condition, this effect was not found, possibly due to the reduced driving speed. The reduction in speed due to the lane width reduction was not influenced by the additional task. Contrary to what might be expected, lateral control (in terms of SDLP) improved when adding the CMT. Similar findings were reported by Blaauw (1984). Explanations (explicit or implicit) from these authors are an increase of attention for the lateral control task, or a change in control strategy.

An interesting study performed by Wikman, Nieminen and Summala (1998), found interesting differences between novices an experienced drivers and the way they allocate their attention and glance behaviour. They found that experienced drivers allocate their attention more adequately than novices do. While executing several in-car tasks (changing an audio cassette, dialling a mobile phone, tuning the radio) driving behaviour and viewing behaviour were registered in an instrumented vehicle. Results showed that the glance duration of the novices showed a larger variance, due to a greater percentage of short, possible ineffective, and long, risky glances. None of the experienced drivers took glances longer than 3 s during the in-car task, but 29% of the novices did. The novices' long glances were also associated with larger lateral displacements of the car. Drivers took longer glances on a four-lane motorway than on a two-lane highway, which supports the notion that drivers accommodate their glances to the time margins dictated by different traffic situations. However a difference is found between novices and experts in the level of accomodation.

2.2.2 Fatigue and drowsiness

Similar to distraction, fatigue and drowsiness have a large contribution to run-off-road accidents. Also similar to distraction is that fatigued and drowsy drivers fail in making or timing a decision related to the driving task. ADAS seem to have large potential to contribute positively to this timing. Knipling, Wang and Kanianthra (1996) stated that 80% of drowsy driver crashes are single-vehicle roadway departures or collision with parked vehicles. The results of a large scale interview (McCartt, Rohrbaugh, Hammer & Fuller, 2000) indicate that an LDWA may have large potential to support the driver when he's drowsy or falls asleep behind the steering wheel. McCartt et al. (2000) interviewed 593 long distance truck drivers at rest areas in the USA. 47% of them reported to have fallen asleep at the wheel once and 25% reported to have fallen asleep at the wheel in the past year. Six underlying independent factors seemed to contribute to the occurrence of falling asleep: greater daytime sleepiness; more arduous schedules (fewer off-duty hours plus more hours overall); older, more experienced drivers; shorter, poorer sleeping conditions en route; symptoms of sleep disorder; greater tendency to night time drowsy driving. Falling asleep was also associated with not having been alerted by driving over shoulder rumble strips. Interesting is that 56% replied "yes" to the question "did driving over rumble strips ever alert you while driving off the road due to drowsiness?" It is considered to be acceptable that rumble strips are very well comparable to an LDWA.

It may be helpful to analyse what effects drowsiness and fatigue potentially have on the driving task. Results of earlier studies on fatigued drivers are described in the following. Tracking tasks are measures of perceptual-motor ability which are analogous to steering a vehicle (Moskowitz, 1973). An alert vigilant driver smoothly tracks the road geometry by making many fine steering adjustments. A fatigued driver, however, makes fewer fine adjustments and is forced to make more compensatory tracking responses. These coarse variations in lateral displacement often lead to an obvious meandering steering pattern (Seko, Kataoko, & Senoo, 1986). Van Winsum, Brookhuis and De Waard (2000) found that lane boundary crossings due to drowsiness are characterised by little steering activity. These incidents are generally characterised by gradual drifting towards the lane boundary with low lateral velocity. These results already indicate that there is a negative effect of drowsiness on the steering performance and this is confirmed by a driving simulator study by Verwey and Zaidel (1997). In this simulator study (in The Netherlands) subjects drove at night for 135 min. on a rural road with light traffic. Runs were conducted in three shifts, starting at 23:00, 01:30, and 04:00, respectively. The combination of lack of sleep and a long, monotonous night drive produced a demanding task that became more difficult in the second and third shift, and as time went on during each shift. A total of 16 out of 26 drivers became so drowsy, tired and/or bored that they left their lane.

2.3 External factors

The external factors are determined by the environment, in which the driver operates. The following study shows some results, which indicate the dependency of driving behaviour on this environment. Pomerleau et al. (1999) found that run-off-road crashes in the USA occur most often:

- on straight roads (76%)
- on rural or suburban roads (75%)
- on dry roads (62%) and in good weather (73%)

The external factors, which are discussed in this section are road configurations and weather conditions.

2.3.1 Lane width

In the international literature, a lot of research has been reported on the relation between lane width and driving speed. A review of this literature by Tenkink (1989) showed that driving speed decreases as lane width decreases. This can be interpreted as a task load compensating mechanism: a task load increase (due to a lane with reduction) is compensated by a task load decrease (by choosing a lower driving speed).

However, it has to be noted that the reduction of driving speed also depends upon the way in which the lane width has been reduced. Tenkink (1989) carried out a field experiment to investigate the effect of lane width with various types of obstacles as edge markers: road surface reflectors, cones, and work zone panels. When margins are reduced, the speed reduction depends on the obstacle type: the more an obstacle is seen as a threat, the higher the reduction in driving speed.

The standard deviation of the lateral position (SDLP), when determined for one driver/vehicle over a certain period, is an indication of the extent to which the vehicle sways in its lane. The relation between lane width and SDLP has been investigated extensively. The results show that the SDLP typically decreases as the lane width decreases. In other words, on narrower lanes drivers sway less than on broader lanes (see, e.g., Riemersma, 1987; Tenkink, 1990; Martens & Brookhuis, 1998). There are several explanations for this phenomenon, for instance the extra effort allocated to the steering task or changes in steering strategy (McLean & Hoffmann, 1972), the improvement of visual information for lateral control when the edge markings are closer, and the reduction of speed.

According to McLean and Hoffmann (1972), for moderate lane widths and speeds, drivers appear to use a strategy of dominantly controlling the path or heading angle of the car such that it will not deviate too close to a lane boundary. This control is mainly carried out at frequencies of 0.1 to 0.3 Hz. Under extreme conditions of narrow lane width and high speed, drivers find it necessary to change their steering strategy to one that appears to involve direct control of lateral error. A higher frequency control action, at or near the natural frequency of the vehicle, is apparently used for fine angular control.

Based on such qualitative changes on control behaviour, the proportion of high frequency (> 0.3 or > 0.4 Hz) steering control movements (HFA: High Frequency Area) has been defined (e.g., Blaauw, 1984). HFA typically increases with increasing speed and decreasing lane width, that is, increases as the driving situation becomes tighter (Blaauw, 1984).

An experiment by Käppler and Godthelp (1990) showed that when driving at a fixed speed, TLC measures reduce with decreasing lane width. This is in line with the expectations. According to Van Winsum's adaptive driver behaviour model (Van Winsum, 1996), this TLC reduction will cause the driver to reduce speed. Indeed various authors (Tenkink, 1989, Martens & Brookhuis, 1998) reported a speed reduction on narrower lanes, but they still found lower TLC values on narrower lanes. Apparently, the speed reduction was not sufficient to maintain a constant TLC_{min}.

2.3.2 Curves

Vehicle control in negotiating curves involves anticipatory steering, i.e., the steering action is initiated before the actual entrance of the curve is entered (Godthelp, 1986). The anticipatory steering action can be regarded as the result of a process with three major stages, i.e., (i) perception of the curve, resulting in an estimate of the curvature, (ii) translation of the estimated curvature into a desired steering wheel angle, and (iii) a motor control process to transform the desired steering position into manual action. In addition to this anticipatory steering process, a compensatory control mechanism is considered to add steering corrections based on instantaneously perceived path errors. This two-component steering behaviour is in line with the two-level model from Donges (1978) (see Section 3.2.1).

Given the driving speed, the radius of the curve and some vehicle parameters, the steady-state steering wheel angle required to negotiate the curve can be calculated. Thus, the error of the anticipatory steering process can be studied by comparing the actual anticipatory steering wheel angle with the required steady-state steering wheel angle. Several authors reported a suggestively linear relationship between the steering error and the required steering angle (Godthelp, 1985; Godthelp, 1986; Van Winsum, 1996). Under a fixed-speed paradigm, Godthelp (1986) found that sharper curves lead to lower TLCs. In the experiment by Van Winsum (1996), subjects could adjust their speed, and smaller curve radii resulted in the choice of a lower speed. Here, the minimum TLCs during curve negotiation were not affected by radius. This suggests that drivers compensate for larger steering errors by choosing a lower speed, such that a constant minimum TLC is maintained. This confirms the ideas of Summala (1988) and Rumar (1988) that drivers control safety margins that can be operationalized as distance- or time-related measures. The TLC can be considered as a safety margin, controlled by the drivers' speed choice. From the Van Winsum (1996) study it also followed that speed choice and steering performance are both intimately related in negotiating curves. The quality of steering performance was related to driving experience. Steering performance, speed choice, and minimum TLC were consistent within drivers, for example drivers consistently have a certain level of steering performance during curve negotiation. Drivers with poorer steering performance drove slower, such that although their steering errors were larger, no significant relations of speed and steering errors with TLC were found.

2.3.3 Crosswind

Disturbance due to crosswind can be divided into:

- natural wind fluctuations (wind gusts), and
- disturbances that occur at specific locations (either stationary objects alongside the infrastructure, or moving objects, especially other traffic)

For an overtaking manoeuvre, the most critical condition in terms of crosswind effects occurs for a vehicle passing through the wake on the leeward side of another vehicle (Heffley, 1973).
This manoeuvre was investigated in a field experiment on the Moerdijkbrug in the Netherlands (Elink Schuurman, 1984; Wouters, 1984). The structure of the bridge and its surroundings did not

cause disturbances of the wind pattern. Therefore, there was no sudden turbulence that could have disturbed the lateral driving task. The lateral position of a VW van was measured when driven at a speed of 100 km/h, and then passed through the wake on the leeward side of a truck driving at 80 km/h. The amplitude of the lateral deviation due to the sudden wind disturbance was typically about 0.8 m (where it should be noted that the VW van used in the experiment is very susceptible to crosswind).

In another study (Elink Schuurman, 1988), a VW van was driven on the 'Oosterscheldekering' dam in the Netherlands, at a speed of approximately 80 km/h. The largest crosswind-induced sudden change in lateral position was in the order of magnitude of 0.20 – 0.25 m. However, the lateral displacements at the start or end of the bridge were approximately 70% larger, especially due to sudden changes in wind direction.

The overall effect of crosswind on a vehicle's motion can be expressed as a force that acts on the vehicle's pressure point. The location of this pressure point in relation to the location of the vehicle's centre of gravity determines the nature of the effect of crosswind disturbance: merely a lateral acceleration, or also a yaw component.
Looking at differences in susceptibility among vehicle categories, it can be stated that (Elink Schuurman, & De Vos, 1992):

- Passenger cars are not very susceptible to crosswind
- Vans constitute the most susceptible category, due to a large side area, a relatively small mass and a high aerodynamic coefficient for yaw movement.
- The crosswind disturbance for trucks is relatively small, especially in terms of yaw motion. Wind forces are high due to the large areas involved, but the resulting moment is relatively small due to the location of the pressure point. For trucks, rollover due to crosswind is a potential problem that must be taken into account, but this is, of course, beyond the scope of LDWA.

An increase of driving speed typically results in a reduction of vehicle stability, due to a reduction in the vehicle's natural frequency and damping factors in the transfer functions.
In terms of frequency responses, a literature review by Lemaire (1975) showed that cars are most sensitive to disturbances below 1 Hz. For drivers, the area above 0.2 Hz is difficult. Thus, the most difficult frequency range is from 0.2 to 1 Hz.

The behaviour of a car driver in crosswind condition has been modelled by Weir and McRuer (1973). This model was applied by Elink Schuurman (1984) on the data gathered on the Moerdijkbrug. The model predictions of the maximum lateral deviation were in the same order of magnitude as the experimental results (i.e., around 0.8 m). For small path deviations, the model gave a slight underestimate, whereas for large path deflections, the model gave an overestimate. This was explained by the notion that drivers, in contrast to the model, adjust their control effort to the driving situation.

In control-theoretical terms, crosswind can be considered as an external disturbance on the system to be controlled. Anticipation of natural wind fluctuations by the controller/driver is impossible; for fluctuations around specific objects, anticipation may be possible for the driver up to a certain extent. For an LDWA, anticipation of this disturbance is not possible. It is expected that wind gusts strong enough to cause a vehicle to leave its lane will give sufficient cues to the driver (visual as well as haptic), even without an LDWA.

2.4 Conclusion and discussion

Due to distraction, fatigue and drowsiness, drivers can fail to make the required control actions. The considered decisions and actions are mainly at the control level. For example the decision to adjust speed, lateral position or heading. The effects on safety mainly depend on the duration until drivers resume the control task. Experienced drivers know how to regulate this process and keep their safety margins constant relatively well. Novices, however, are generally not able to regulate this as well. ADAS are expected to have great potential in these situations.

On some road configuration lane keeping demands a lot of effort from the driver, for example in situations with narrow lane widths and curves. In these cases the driver is typically aware of the potential lane departures and allocates a lot of attention to correct steering errors. LDWA systems are not expected to prevent lane departures in such situations.

The effect of crosswind on lane departures strongly depends on the speed and direction of the crosswind, the dimensions of the vehicle and the position of point of gravity. At the moment a wind gust occurs and causes path deviations, the driver probably pays a lot of attention to correct these deviations. An LDWA has low potential to support the driving task in this particular case.

An LDWA has most potential to decrease the number of run-off-road accidents caused by degraded driver states. In these cases, the system triggers the driver to resume the steering task. In case of narrow lane widths, curves and crosswind, the driver is expected to pay a lot of attention to his driving task. In these situations, the driver probably knows when he makes a lane departure, and it may even be possible that warning has unwanted effects. The drivers may start to ignore the signal, get irritated and turn the system off, or the warning could even distract the driver.

3 MODELS OF HUMAN VEHICLE CONTROL

The results discussed in the previous chapter form a basis for modelling the lane keeping task in relation to LDWA. A perfect model should contain all of these factors, which are considered to be relevant. The four most commonly used models will be discussed concerning the usefulness in modelling the application of ADAS and in particular LDWA. If necessary these models will be adjusted to be able to include the relevant factors discussed in the previous chapter. Before the four models are introduced, in Section 3.1 the driving task will be explained in more detail. Section 3.2 describes the four models and discusses them for the mentioned factors and for LDWA. Section 3.3 gives some concluding remarks.

3.1 The driving task

Before modelling the driving task, it should be analysed first in more detail. The pure driving task (i.e., only vehicle control) should be considered as a combination of a lateral control task and a longitudinal driving task. It is important to use the word combination, because of the interference between both tasks. In the context of lane departures it is obvious that most emphasis will be on the lateral driving task. Another important classification of driving behaviour and the driving task in general consists of the different levels of the driving task. For example, planning a trip and performing an avoidance manoeuvre both are parts of the driving task, but they are of a completely different level. One is long-term planning, whereas the avoidance manoeuvre is an example of local guidance.
Michon (1985) classified driving behaviour in the following levels:

- The strategic level defines the general planning of a trip, including modal and route choice (both before and during the trip).
- The manoeuvring or tactical level deals with the directly prevailing circumstances and involves lane change manoeuvres, overtaking, obstacle avoidance, etc.
- Finally, the control level deals with the control of speed and headway, as well as lane keeping. Here, the driver uses the primary vehicle controls (steering wheel, pedals, and gear) in order to carry out the intended manoeuvres.

In the context of LDWA especially the control level is relevant, because at this level the straight lane-keeping task is performed. Krendel and McRuer (1960, 1968) distinguished three levels of control for the lateral driving task. These levels differ in potential for prediction of future values (in this context lateral position and heading):

- Compensatory level: At 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 crosswind gusts, following an unfamiliar road in heavy fog.
- Pursuit level: Driver's uncertainty can be decreased by information about future values of the variables (perceptual anticipation). The strategies at this level are closed-loop in combination with prediction control, e.g., preview of the road to be followed.
- Precognitive level: At 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.

Human steering behaviour can be characterised by a certain amount of error tolerance (in contrast to a simple control model that assumes control reaction to even the smallest of path deviations).

Several approaches have been used in models to incorporate error tolerance (e.g., by including dead zones or hysteresis; see Godthelp, 1984, for an overview).

In reality, driving a vehicle is a typical multi-task situation. The driver not only has to deal with the driving task itself, but possibly also with other aspects that may be more or less relevant for the actual driving task. Obvious examples are conversations with passengers, dealing with in-car equipment (e.g., stereo, navigation systems, telephone), etc. Dealing with ADAS (setting, monitoring, and reacting to) should be considered here as well. Associated with each of these tasks is a certain amount of *workload*. At the same time, the driving task often has a *self-paced* character. Therefore, as the driving situation becomes more demanding, a driver may increase the total effort invested in the driving and other tasks, and/or may reduce the workload by reducing the driving speed. The following section describes four models from three different points of view.

3.2 Driver Models

The models described in this section show different approaches of the driving task. These approaches make it possible to analyse the driving task on different ways and in different levels. The basic control models emphasise the control task under the assumption that the driver has full attention to this task. The Supervisory and the Integrated Driver Model include external events and dual tasks. Finally, the adaptation model is discussed in which driver states and learned associations are included.

3.2.1 Basic Control Model (I)

In the literature, many models for human vehicle control have been presented using modelling techniques from classical control engineering as the basis (i.e. by means of transfer functions to relate the input signals to output signals of the various components). A representative example is the model presented by Weir and McRuer (1973), which is shown in Figure 2.

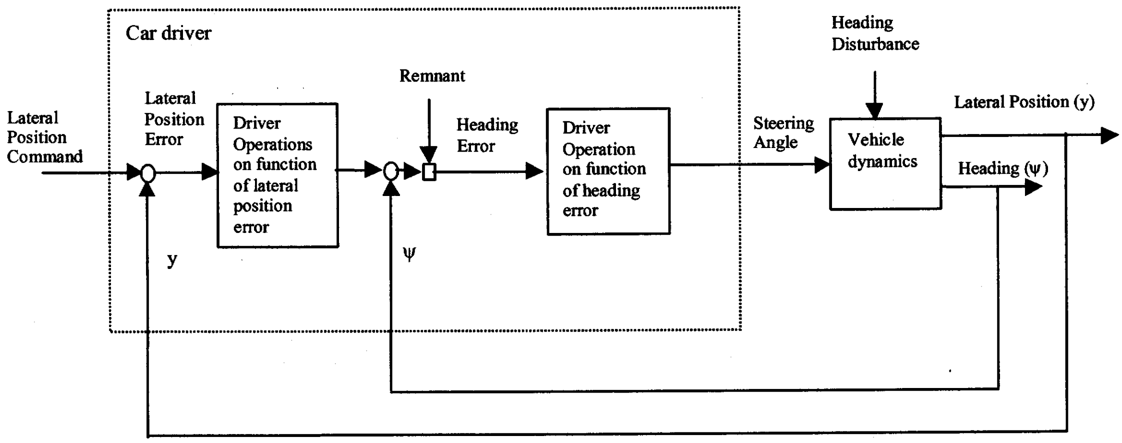

Figure 2 Block diagram Car driver – Vehicle for a describing function (from Weir & McRuer, 1973).

It is hypothesised that the car driver prefers a certain lateral position. This Lateral Position Command is arbitrary within his lane in the absence of vertical elements and other traffic. When this preferred lateral position deviates from his current lateral position (y), the driver perceives a certain lateral error and determines a preferred heading to reduce this error. The difference between the preferred heading and the current heading is the heading error. The heading error is the actual measure for the driver to determine a steering angle. The steering angle is the input for the vehicle. The dynamic system of the vehicle not only has the steering angle as input, but also the external inputs like wind gusts and roughness of the road. The output of the vehicle dynamics system is the lateral position on the lane and the heading. Thus, the model consists of two nested control loops: a fast inner loop that controls the yaw angle, and a slower outer loop that controls the lateral deviation.

The theory on which the dynamics of this model is based is the McRuer cross-over model (McRuer, & Jex, 1967), originally developed in an aeronautical context, but proven to apply in general to human control of a dynamic system. The basic notion of this theory is that the human controller tries to emulate the ideal characteristics of an ideal system, i.e. an integrator. The driver adjusts his dynamic characteristics to the system to be controlled in such a manner that the overall closed-loop system is well behaved. Inherent limitations of the human operator (reaction time, neuro-muscular dynamics) can be taken into account to a certain extent.

Considering this control model in the context of LDWA, one can conclude that the model is hardly applicable. The control model describes the driving task only at the control level and assumes that drivers are fully attentive to the driving task. The model is especially useful for quantitative analyses of driving performance. With this model it is possible to evaluate some external factors, in particular disturbances (as crosswind). This is all quantitative and unfortunately it still assumes that the driver is fully attentive to the driving task.

3.2.2 Basic Control Model (II)

A derivative of the Basic Control Model in the previous section combines open- and closed loop precognitive, pursuit and compensatory control structures (McRuer, Allen, Weir, & Klein, 1977). Figure 3 describes directional guidance and control operations. It was founded primarily on the analytical and empirical bases of manual control theory as applied to automobile driving. The elements within the driver section are seldom, if ever, all present simultaneously. Yet each block is required for some task or other to permit the model to serve as a reasonable facsimile of actual driver behavioural patterns.

The driver is not so easily considered mathematically. As the operative element in the system, he adapts and manipulates his dynamic characteristics to satisfy the key guidance and control requirements for the driver/vehicle system. The guidance and control requirements for lateral path control are:

1. To select appropriate pathway and tolerances.
2. To establish and maintain the automobile on the specified pathway
3. To reduce path errors to threshold levels in a stable, well damped, and rapidly responding manner.
4. To maintain the established path in the presence of disturbances such as crosswinds, roadway fluctuations and vehicle-centred disturbances.

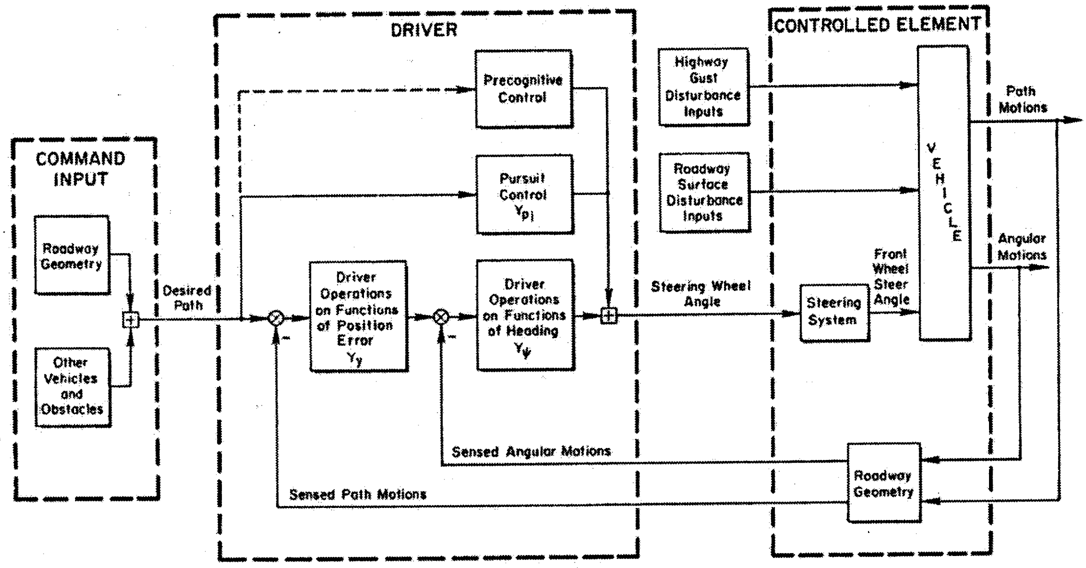

Figure 3 Topology of the driver/vehicle system combining open- and closed loop precognitive, pursuit and compensatory control structures (source: McRuer, Allen, Weir, & Klein, 1977).

This basic control model is actually an elaboration of the previous discussed basic control model. Therefore it has a little more potential to apply in modelling LDWA and driving behaviour. Still, only few external factors can be evaluated by this model, for example different kinds of disturbances. The Command Input of the model offers the possibility to use different road configurations. The difference (and advantage) with the previous model is that it is more detailed. This gives a better view on what part of the model is responsible for what factor (or variable). In general the model still consists of a human controller, which is the driver and a controlled element, which consists of the vehicle-road-system. Another difference compared to the previous control model is that the human controller is elaborated and offers the possibility to apply different levels of control. The levels of control are explained in Section 3.1.

The most important disadvantage of both control models is that they do not offer a possibility to include LDWA in the control loop. This means that the models don not give any insight in the relation between LDWA and the earlier mentioned external factors.

3.2.3 Supervisory Driver Model

Most driving studies related to car and road design, e.g. vehicle dynamics, crosswind effects or curve layout, have been limited to situations in which drivers are fully attentive to the control of one singular task (Blaauw, 1984). As mentioned in Section 2.1, driving a road vehicle is a typical multi-task situation. In Blaauw (1984), the Supervisory Driver Model (SDM) is introduced. It can explicitly address the specific multitask aspects of driving. This model is based on the concepts of the Optimal Control Model (Baron & Kleinman; 1969) and the Optimal Control Decision Model (Kok & Van Wijk, 1978).

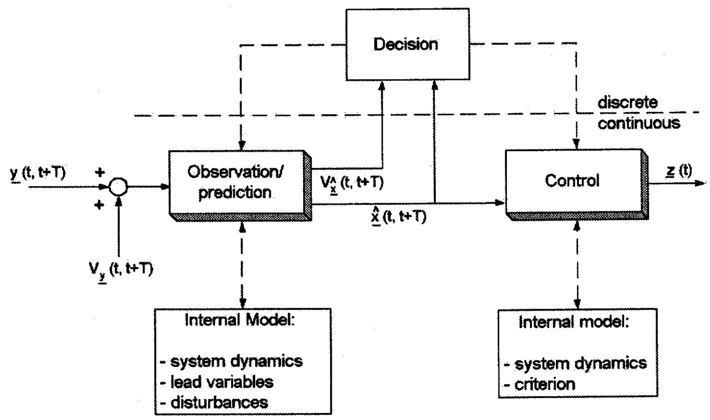

Figure 4 Structure of the Supervisory Driver Model.

The structure of the model is shown in
Figure 4. The model consists of two continuous blocks: an *observation/prediction* block, that transforms perceptual cues into state estimates, and a *control* block, which transforms these estimates into control actions. The third main block is a discrete *decision* block as a representation of supervisory activities. Decisions for new observations and control actions are based on the driver's estimates in combination with the uncertainties associated with these estimates. Drivers decide to make new observations of perceptual cues whenever the corresponding uncertainties are too high, and/or when the estimate reaches a critical level.

A typical experiment (Blaauw, 1984) conducted in relation to this model focussed on how driver's control strategy is affected by driving skill and demands. In the experiment described, the drivers' possibilities to obtain visual information on lateral control were minimised. Drivers were instructed to scan the off-road environment actively and to mention details of what was seen. In this way foveal and peripheral information on 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 could obtain visual information continuously. Effects of task demands and driving skill were analysed by lateral performance in terms of the mean and 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. The experiment 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 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.

The SDM has a totally different approach to the driving task. The model as presented in figure 4 does not show a lot of detail, but was elaborated in much more detail. An important advantage of the SDM is that it offers the possibility to include the LDWA. The consequence of including LDWA is that the initially quantitative model, can only be considered qualitative. Accepting this consequence one could in a relatively straightforward manner add an LDWA-block. The input for the LDWA is the same input as for the continuous prediction/observation block. Similar as the prediction/observation block, the LDWA transforms the input into state estimates. In case of inalertness there is a failure in the observation/prediction block or the decision block. In this case the LDWA also makes a decision whether a control action is necessary. If so, the output is discrete and is an input (trigger) to the discrete decision block. The input triggers to make a decision to perform new observations and predictions.

3.2.4 Integrated Driver Model

Levison and Cramer (1995) presented their Integrated Driver Model (IDM), which was developed to predict driver behaviour and system performance when an automobile driver performs concurrent steering and auxiliary in-vehicle tasks. The first main component is a procedural model that deals with the in-vehicle tasks, task selection, and attention allocation. Various generic activities are included, e.g., reading a message, listening to a message, and carrying out elementary monitoring and control tasks. The second component deals with the actual steering control of the vehicle, using an approach based on Optimal Control Theory.
The model predictions were compared with empirically observed trends. The following trends were correctly predicted by the model:

- Compared to single-task driving, steering performance degrades when an auxiliary task is introduced.
- Increasing the difficulty of the driving task in a multi-task environment results in more attention to the driving task and worse steering performance.
- Contrary to expectations, when attention-sharing between driving and an auxiliary task is relatively frequent, steering performance is slightly better during intervals when attention is paid to the auxiliary task than to the driving task possibly due to overcompensation.
-

The IDM allows one to predict continuous steering performance as visual attention is intermittently diverted from the roadway to one or more monitoring diverted from the roadway to one or more monitoring locations associated with the auxiliary in-vehicle tasks. The IDM uses penalty functions, which are computed to determine which task(s) the driver should attend to next whenever two or more tasks are competing for attention and the driver is at stage where attention can be shifted (1.e., the driver is not committed to continuing the current task). If two tasks are selected for concurrent attention, the penalty functions are also used for apportioning cognitive attention between the two tasks.

In the first instance the IDM seems to contain a lot of possibilities for modelling the internal, the external factors and the LDWA. Unfortunately, this is not so easy. The IDM is emphasised on the relation between the auxiliary task and the driving task. Furthermore, an underlying assumption for the IDM is that the operators are sufficiently well-trained and motivated to perform in a near-optimal manner subject to system goals and limitations. This implicates that the driver has full attention for selecting the 'right' task. In the IDM it may not be possible to find a logical place for the LDWA, which does not mean that the model is not useful. It may be possible to integrate LDWA into the several components of IDM. Probably it would affect the penalty functions, because drivers rely on the LDWA, which may result in a shift of attention.

The actual point in modelling LDWA in driving behaviour is not the secondary task in specific, but the consequence, which is inalertness. Therefore the IDM does not seem to have any surplus value compared to the SDM.

3.2.5 Adaptive Model

Van Winsum (1996) formulated a model that focussed on adaptation processes in driving behaviour (see Figure 5). The adaptation model states that several factors affect operational performance. For example, temporary states, induced by alcohol and marijuana, affect psycho-motor abilities, which in turn affect operational performance. Also, vehicle related factors, situational factors and driving experience may affect operational performance in accordance with the adaptive control models.

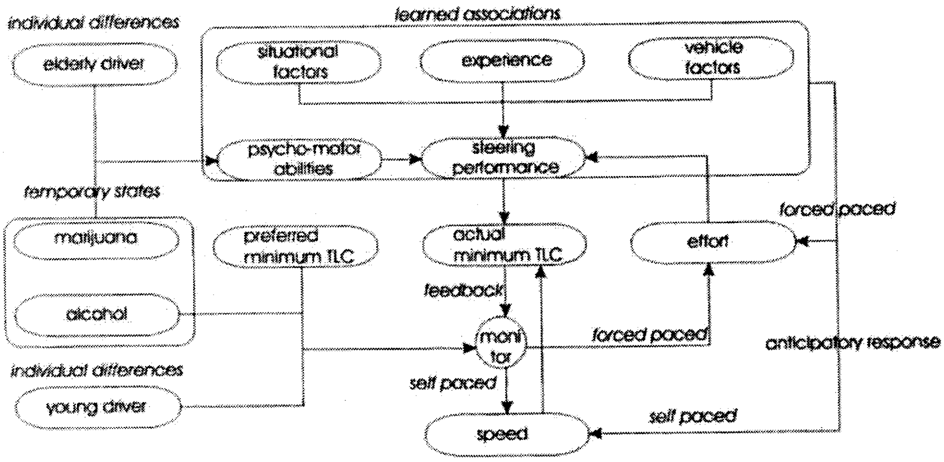

Figure 5 Adaptation model of car driving for the lateral control task (Van Winsum, 1996).

The adaptation mechanism in the model is based on safety margins, which for the lateral control task is operationalised as TLC. Drivers appear to be able to estimate the TLC in lateral control tasks, and there is evidence that TLC plays an important role in steering control. If local minima of the minimum values of TLC are too small, they can be increased by choosing a lower driving speed. Thus, speed adaptations allow control of a TLC-based safety margin.

Several factors related to operational performance, vehicle characteristics, environment and behaviour on the tactical level affect these time-based safety margins. TLC is affected by vehicle dynamics and dimensions, steering behaviour, speed, road width and curve radius.

The adaptation model seems to include most of the internal and external factors when the following considerations are taken into account.

- Alcohol and fatigue has similar effects on the driving task (Ryder et al., 1981).
- Situational factors are for example road configurations and weather conditions.
- Vehicle factors are the vehicle dynamics.

Inalertness by distraction and secondary tasks are not explicitly represented, but the left side of the model gives quite a complete representation of the driver state. Unfortunately, the adaptation model does not have very logical points of contact for the LDWA. This makes the adaptation model less suitable for modelling of LDWA and driving behaviour.

3.3 Discussion

Most of the models described here attempt to cover the range of normal operations in vehicle control. However, modelling driving behaviour up to the level of a calibrated and validated model of 'accident' or 'lane departure' is far from trivial.

When a driver model produces an 'accident', the question is whether the processes involved in an accident have been adequately modelled, or whether the model has reached a state beyond its intended range of use. Many scientists focussed their studies on modelling human vehicle control, but none of them included ADAS in their models.

The role of LDWA can be seen as complementary to the *observation/prediction* and *decision* blocks from the SDM. When these functions from the driver model fail to produce the required steering actions, the warning by an LDWA can trigger the decision to initiate observation as well as control actions. The consequence of including LDWA is that the model can not be considered quantitative anymore.

Furthermore can be concluded that the four discussed models are applicable in one way or another, because they all include one or more of the internal and external factors. The first discussed basic control model is the least applicable model. The second basic control model includes some external factors and is best applicable for analysing the steering task. Unfortunately, there is no relation with the LDWA. The adaptation model includes almost all internal and external factors, but again the relation with the LDWA is not present. The IDM is emphasised to the relation between secondary tasks and the driving task and including the LDWA in this model, if possible, is very complex. As concluded before, the qualitative considered SDM has most potential for modelling the LDWA and driving behaviour.

4 LDWA AND DRIVING BEHAVIOUR

This chapter focuses on empirical research that investigated how driving behaviour is influenced by LDWA.

Pomerleau et al. (1999) stated that there are distinct differences between the lane-keeping behaviour of passenger car drivers and heavy truck drivers. Most notably, heavy trucks leave their lane frequently, though briefly. Drivers of passenger cars tend to control their lane position much more carefully on narrow country roads than on freeways. So, the performance requirements for an LDWA are different for trucks and passenger vehicles, primarily because of the significantly different vehicle dynamics and driver lane-keeping characteristics (which are related). Thus, it may be necessary to tailor warning criteria to different vehicle and driver types, to different roadway types (shoulder width and curvature), and to different operating conditions (speed, weather).

Renner and Mehring (1997) specifically regarded LDWA as a countermeasure for inattention and drowsiness. They evaluated an LDWA based on a TLC criterion, using an auditory warning (imitating a rumble strip, including the directional information). No quantitative results are presented, but it was stated that the warning triggered a "quick and safe response" from the driver to recover the vehicle position.

Suzuki, Soma, Hiramatsu and Kurosawa (2000) presented an LDWA design based on a TLC criterion, and studied suitable warning thresholds. Looking for a TLC threshold that was low enough to avoid annoying false alarms yet high enough to allow for the successful avoidance of a lane departure in a critical situation, they found a threshold of 1 s.

Rudin-Brown and Noy (2002) investigated behavioural adaptation to lane departure warnings. They tested how drivers reacted to an LDWA using a driving simulator and through on-the-road-tests. The accuracy of the system was manipulated as an experimental variable. The accurate version functioned correctly, i.e., had no misses or false alarms. The inaccurate system produced a false alarm every seven minutes, and produced a miss on every third warning. The LDWS generated a rumble-strip sound every time the vehicle came within 22 cm of either lane boundary. It was found that drivers who drove with an *accurate* LDWA deviated less within the lane than drivers driving without the system. This effect persisted when they were driving with an *inaccurate* LDWA afterwards. Also those drivers who only experienced an *inaccurate* LDWA deviated less in their lanes, but were not as good as the *accurate* LDWA drivers. This effect demonstrates that the presence of an inaccurate system also has the potential to improve lane-keeping performance. It was also found that driver's beliefs concerning an in-vehicle system's accuracy persevere and extend to future exposures, regardless of the system's actual performance. This could result in over-relying on the system to keep them alerted and, in case the system failed to do this, with negative consequences for road safety.

In terms of the driver's personality, it was found that drivers with an external locus of control (i.e., drivers believe they can not do anything about external forces) as opposed to internal locus of control (where a person believes that s/he is able to act in order to influence the positive outcome and who score low on the sensation seeking scale), were more likely to report to trust the LDWA. The highly trusting drivers were the only ones in the experiment who made complete lane departures when the system failed to warn.

The authors concluded that while LDWA appeared to have positive effects in terms of lane-keeping behaviour, caution needs to be exercised when promoting the use of such systems, because of drivers' possible over-reliance to keep them oriented to the driving task.

Enkelmann (2001) proposed to use a fixed distance to the edge line as a warning criterion. He introduced two thresholds for low and high driver activity, respectively. Under low steering activity conditions, it is assumed that the driver might become inattentive easily. Thus, warnings are given earlier by using a virtual lane with reduced width. High steering activity indicates actions of an attentive driver, e.g. evasive manoeuvres. Warnings in these cases might disturb the driver and are therefore suppressed. Warnings are also suppressed when the driver is using the indicator and/or the brakes. However, evaluation results were not obtained.

In conclusion, very little information on effects of LDWA has been found in the literature. Most publications on LDWA focus on the technology involved. Several warning strategies have been reported (TLC, distance), but the effect of the warning strategy on driver behaviour or acceptance has not been investigated. Several papers address (implicitly or explicitly) the accuracy of the system in terms of false alarms and misses, and the trade-off between these categories. Only in one study, the accuracy of the system was manipulated as an experimental variable. The results showed that LDWA had positive effects on lane-keeping behaviour, but also that drivers could become over-reliant on the system.

5 DISCUSSION AND CONCLUSIONS

Developing a calibrated and validated driver model up to the level of 'accident' or 'lane departure' is far from trivial. Earlier models have been developed (1) to analyse the control task, (2) to analyse the driving task as a supervisory task, (3) a combination of the control and auxiliary tasks and (4) to analyse adaptation of the driver. These models describe the driving task on different levels, and therefore it is hardly possible to include them in one model. In Section 5.1 of this final chapter an overview is given of what role an LDWA is expected to play in lane keeping and related accidents. In Section 5.2 it is discussed in what way driver models cover these expectations. Furthermore it is discussed what effects of an LDWA could be expected in relation to the other worckpackages of the LDWA FOT.

5.1 Expectations

Factors that influence the lateral control task can be grouped into internal (drowsiness, fatigue, and secondary tasks) and external factors (wind, lane width, curves and traffic). The internal factors were defined as the driver state and are mainly related to inalertness or inattentiveness. Inattentiveness to the driving task can be caused by (1) drowsiness or fatigue, (2) distraction by the environment, and (3) secondary tasks. An LDWA has the potential to reduce unintended lane crossings, especially in these cases. Factors like fatigue or drowsiness have been shown to degrade driving performance, reduce safety margins in terms of TLC, and increase the occurrence of lane departures. This clearly illustrates the potential of LDWA. For distraction and secondary tasks, the situation is sometimes different in the sense that drivers are sometimes found to adjust their driving behaviour, thus possibly maintaining a constant safety level; in some occasions lateral control by the driver actually improved when adding a secondary task. Still, in other studies secondary tasks did lead to degrading control behaviour and reduced margins. In this category, LDWA has the potential to reduce unintended lane crossings.

With respect to the external factors, research has shown that drivers typically increase their control effort and/or adjust their behaviour (e.g. reduce their speed on narrower lanes) to compensate for reducing margins. TLC has been shown to play a role in these processes. If the external conditions are such that the driver is operating at the limits of his ability as a controller the LDWA is hardly expected to contribute to the drivers' performance.

Crosswind can under certain circumstances lead to lateral disturbances strong enough to cause lane departures. A driver may be able to anticipate up to a certain extent for some types of wind disturbance. However, for an LDWA, anticipation to this disturbance is not possible at all. The LDWA will only be able to detect the problem once the vehicle's motion has been disturbed to such an extent that a lane departure is imminent. It is expected that wind gusts strong enough to cause a vehicle to leave its lane will give sufficient cues to the driver (visual as well as haptic), even without an LDWA. Thus, the LDWA is not expected to improve crosswind situations.

Empirical results on the effect of LDWA on driving behaviour are still rare. Most of the publications focus on a technical description or on the warning strategy. There are some indications that while an LDWA appears to have positive effects in terms of lane-keeping behaviour, there may be a drawback in drivers' possible over-reliance on the system to keep them oriented to the driving task.

5.2 Behavioural model

Most of the models that were reviewed cover (or try to cover) the range of normal operation of vehicle control. Phenomena as accidents or unintended lane departures may be substantial when regarding them from accident statistics, but for an individual driver, they occur infrequently.
Therefore, modelling driving behaviour up to the level of a calibrated and validated model and up to the level of rare situations such as 'accidents' or 'lane departures' is far from trivial. This finding is in line with Reid (1983), who reviewed driver steering behaviour models for their suitability for accident statistics research, and concluded that "none of the new driver models surveyed have been sufficiently well-validated to serve as an accident investigation tool without further development". Thus, when a driver model produces an 'accident' or 'lane departure', the question is whether the processes involved in an accident or lane departure have been adequately modelled, or whether the model has reached a state beyond its intended range of use.

Some of the models (the Supervisory Driver Model, SDM, and the Integrated Driver Model, IDM) do take into account the notion that a driver is not continuously involved in observation and control. The Integrated Driver Model explicitly addresses auxiliary tasks in addition to the actual steering task. Individual differences and especially temporary states (fatigue, drowsiness, distraction) are often incorporated in experimental research on driving behaviour or workload. However, in driver models, especially the factor fatigue/drowsiness is hardly covered explicitly. This also holds for the SDM and IDM.

As a conceptual model to understand effects of LDWA, the Supervisory Driver Model (Blaauw, 1984) can be used. Even though states such as inattention or drowsiness are not explicitly covered by this model, it can be stated qualitatively, that they will affect the quality of all main elements (observation/prediction, control, and decision making), and thus also affect the frequency of decisions to restart observations or control actions. In this sense, the role of LDWA can be seen as complementary to the *observation/prediction* and *decision* elements. When these functions from the driver model fail to produce the required steering actions, the warning by an LDWA can trigger the decision to initiate observation as well as control actions.

In conclusion, the largest potential for LDWA in avoiding imminent lane departures is expected when the driver fails to produce the required steering actions due to a temporarily degraded driver alert state.

LIST OF ABBREVIATIONS

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
CMT	Continuous Memory Task
FOT	Field Operational Test
IDM	Integrated Driver Model
IVHS	Intelligent Vehicle Highway Systems
LDWA	Lane Departure Warning Assistance
SDLP	standard deviation of the lateral position
SDM	Supervisory Driver Model
TLC	Time to Line Crossing

REFERENCES

Alm, H., & Nilsson, L. (1995). The effects of a mobile telephone task on driver behaviour in a car following situation. *Accident Analysis & Prevention, 27* (5), 707-715.

Baron, S., & Kleinman, D. L. (1969). The human as an optimal controller and information processor. *IEEE transactions on man-machine systems, MMS-10* (1), 9-17.

Blaauw, G. J. (1984). *Car driving as a supervisory control task* (PhD Thesis). Soesterberg, The Netherlands: Institute for Perception TNO.

Brookhuis, K. A., de Vries, G., & de Waard, D. (1991). The effects of mobile telephoning on driving performance. *Accident Analysis & Prevention, 23* (4), 309-316.

Donges, E. (1978). A two-level model of driver steering behavior. *Human Factors, 20* (6), 691-707.

ETSC (2001). *The Role of Driver Fatigue in Commercial Road Transport Crashes.* Brussels: European Transport Safety Council.

Elink Schuurman, R. (1984). *De metingen t.b.v. de evaluatie van het windwaarschuwingssysteem Moerdijkbrug* (report 700460409). Delft, The Netherlands: TNO Road Vehicles Research Institute.

Elink Schuurman, R. (1988). *Verkennende metingen windhinder Oosterscheldekering* (TNO-report 740830001). Delft, The Netherlands: TNO Road Vehicles Research Institute.

Elink Schuurman, R., & Vos, A. P. de (1992). *Consult met betrekking tot de windhinder op de Westerschelde Oeververbinding* (Report 92.OR.VD.027.1/RES). Delft, The Netherlands: TNO Road Vehicles Research Institute.

Enkelmann, W. (2001). Video-based driver assistance - from basic functions to applications. *International Journal of Computer Vision, 45* (3), 201-221.

Godthelp, J. (1984). *Studies on human vehicle control* (PhD Thesis). Soesterberg, The Netherlands: Institute for Perception TNO.

Godthelp, J. (1985). Precognitive control: open- and closed loop steering in a lane changing maneuver. *Ergonomics, 28,* 1419-1438.

Godthelp, J. (1986). Vehicle control during curve driving. *Human Factors, 28* (2), 211-221.

Heffley, R. K. (1973). Aerodynamics of passenger vehicles in close proximity to trucks and busses. *SAE Paper 730235*, Warrendale: Society of Automotive Engineers, Inc.

Hogema, J. H., & Veltman, J. A. (2002). *Werkbelasting en rijgedrag tijdens duisternis: eerste veldexperiment* [Workload and driving behaviour: first field experiment] (TNO-report TM-02-C046). Soesterberg, The Netherlands: TNO Human Factors.

Knipling, R. R., Wang, J. S. & Kanianthra, J. N. (1996). Current NHTSA drowsy driver R&D. *15th international technical conference on the Enhanced Safety of Vehicles (ESV).* Paper no 96-S2-W-14.

Kok, J. J., & Van Wijk, R. A. (1978). *Evaluation of models describing human operator control of slowly responding systems.* (PhD thesis). Delft: Delft University Press.

Krendel, E. S., & McRuer, D. T. (1960). A servomechanisms approach to skill development. *Journal of the Franklin Institute, 269* (1), 24-42.

Krendel, E. S., & McRuer, D. T. (1968). Psychological and physiological skill development - a control engineering model. *Proceedings of the 4th Annual Conference on Manual Control,* University of Michigan, Ann Arbor, 275-288.

Käppler, W.-D., & Godthelp, J. (1990). *Design and use of the two-level sequential judgement scale in the identification of vehicle handling criteria: I. Instrumented car experiments on straight lane driving* (Report FAT 79). Wachtberg, Germany: Forschungsinstitut für

Anthropotechnik. Also Report IZF 1990 B-13, Soesterberg, The Netherlands, TNO Institute for Perception.

Lemaire, P. (1975). *De invloed van zijwind op het dynamische gedrag, de responsie en de prestatie van het systeem bestuurder/voertuig. Fase 1A: literatuurstudie* (project nr 744001). Delft, The Netherlands: TNO Road Vehicles Research Institute.

Levison, W. H., & Cramer, N. L. (1995). *Description of the integrated driver model* (FHWA-RD-94-092). McLean, Virginia: Federal Highway Administration.

Martens, M. H., & Brookhuis, K. H. (1998). *4-0 en 3-1 contraflow-systemen; effecten op rijgedrag* [4-0 and 3-1 contraflow systems: effects on traffic safety] (Report TM-98-C049). Soesterberg, The Netherlands: TNO Human Factors Research Institute.

McCartt, A. T., Ribner, S. A., Pack, A. I., & Hammer, M. C. (1995). The scope and nature of the drowsy driving problem in New York state. *Proceedings of the 39th Annual Meeting of the Association for the advancement of automotive medicine,* Chicago, IL: October 1995.

McCartt, A. T., Rohrbaugh, J. W., Hammer, M. C., & Fuller, S. Z. (2000). Factors associated with falling asleep at the wheel among long-distance truck drivers. *Accident Analysis and Prevention, 32* (4), 493-504.

McLean, J. R., & Hoffmann, E. R. (1972). The effects of lane width on driver steering control and performance. *Proceedings of the Australian Road Research Board Sixth Conference, 6* (3), 418-440.

McRuer, D. T., & Jex, H. R. (1967). A review of quasi-linear pilot models. *IEEE Transactions on Human Factors in Electronics, HFE-8* (3), 231-249.

McRuer, D. T., Allen, R. W., Weir, D. H., & Klein, R. H. (1977). New results in driver steering control models. *Human Factors, 19* (4), 381-397.

Michon, J. A. (1985). A critical view of driver behaviour models: What do we know, what should we do? In L.A. Evans and R.C. Schwing (Eds.), *Human behaviour and traffic safety* (pp. 487-525). New York: Plenum Press.

Moskowitz, H., (1973). Laboratory studies of the effects of alcohol on some variables related to driving. *J. Safety Res., 5,* 185-189.

Pomerleau, D., Jochem, T., Thorpe, C., Batavia, P., Pape, D., Hadden, J., McMillan, N., Brown, N. & Everson, J. (1999). *Run-off-road collision avoidance using IVHS countermeasures. Final report* (Report DOT HS 809 170). US department of transportation. Nation Highway Traffic Safety Administration.

Reed, M. P., & Green, P. A. (1999). Comparison of driving performance on-road and in a low-cost simulator using a concurrent telephone dialling task. *Ergonomics, 42* (8), 1015-1037.

Reid, L. D. (1983). A survey of recent driver steering behavior models suited to accident studies *Accident Analysis & Prevention, 15* (1), 23-40.

Renner, G., & Mehring, S. (1997). Lane departure and drowsiness --two major accident causes one safety system. *Proceedings of the 4th world congress on Intelligent Transport Systems.* Berlin, October 1997.

Riemersma, J. B. J. (1987). *Visual cues in straight road driving* (PhD thesis). Groningen, The Netherlands: Rijksuniversiteit Groningen.

Rudin-Brown, C. M., & Noy, Y.I. (2002). An investigation of behavioural adaptation to lane departure warnings *Proceedings of the 81st Annual Meeting of the Transportation Research Board*, Paper Number 02-2454. January 13-17, Washington, D.C.

Rumar, K. (1988). Collective risk but individual safety. *Ergonomics, 31,* 507-518.

Ryder, J. M., Malin, S. A. & Kinsley, C. H. (1981). *The effects of Fatigue and Alcohol on Highway Safety* (DOT-HS-805-854). Washington D.C: National Highway Traffic Safety Administration.

Schermers, G. (2000). *Advanced Driver Assistance (ADA) systemen. Perspectief verkeersveiligheid* (Rapport AVV-BG/CBS). Rotterdam: Adviesdienst Verkeer en Vervoer.

Seko, Y., Kataoko, S. & Senoo, T. (1986). Analysis of driving behaviour under a reduced state of alertness. *International Journal of Vehicle Design, 7,* 318-330.

Summala, H. (1988). Risk control is not risk adjustment: the zero risk theory of driver behaviour and its implications. *Ergonomics, 31,* 491-506.

Suzuki, K., Soma, H., Hiramatsu, K., & Kurosawa, R. (2000). The experimental analysis of time to departure for the design of lane departure warning systems. *Proceedings of the 7th world congress on Intelligent Transport Systems.* Torino, November 6-9, 2000.

Tenkink, E. (1989). *De invloed van wegbreedte en obstakeldreiging op snelheids- en koersgedrag* [The effect of roadwidth and obstacles on speed- and course behaviour] (Report IZF-89-C4). Soesterberg, The Netherlands: TNO Institute for Perception.

Tenkink, E. (1990). *Effecten van wegbreedte en een additionele taak op rijsnelheid en stuurgedrag* [The effect of road width and an additional task on speed and lateral control in car driving] (Report IZF-90-C27). Soesterberg, The Netherlands: TNO Institute for Perception.

Van Ouwerkerk (1986). *Relationship between Road Transport Working Conditions, Fatigue, Health and Traffic Safety.* Groningen, The Netherlands: Traffic Research Centre, University of Groningen.

Verwey, W. B., & Zaidel, D. M. (1997). *Predicting drowsiness accidents from personal attributes, eye blinks, and ongoing driving behaviour* (Report TNO-TM 1997 B 09). Soesterberg, The Netherlands: TNO Human Factors Research Institute.

Vlakveld, W. P., & Van Raamsdonk, M. (2002). *Aandacht en afleiding in het verkeer* (report 21 May). Rotterdam, The Netherlands: Adviesdienst Verkeer en Vervoer.

Waard, D. de, Brookhuis, K. A., & Hernandez-Gress, N. (2001). The feasibility of detecting phone-use related driver distraction. *International Journal of Vehicle Design, 26* (1 Special Issue SI), 85-95.

Weir, D. H., & McRuer, D. T. (1973). Measurement and interpretation of driver steering behaviour and performance. *SAE Paper 730098.* Warrendale: Society of Automotive Engineers, Inc.

Wikman, A.-S., Nieminen, T. & Summala, H. (1998). Driving experience and time-sharing during in-car tasks on roads of different width. *Ergonomics, 41* (3), 358-372.

Winsum, W. van (1996). *From adaptive control to adaptive driver behaviour* (PhD thesis). Haren, The Netherlands: Traffic Research Centre, University of Groningen.

Winsum, W. van, Brookhuis, K. A., & Waard, D. de (2000). A comparison of different ways to approximate time-to-line crossings (TLC) during car driving. *Accident Analysis & Prevention, 32* (2000), 47-56.

Wouters, P. I. J. (1984). *De evaluatie van het windwaarschuwingssysteem Moerdijkbrug. Conclusies en aanbevelingen* (rapport SWOV R-84-31). Leidschendam, The Netherlands: Stichting Wetenschappelijk Onderzoek Verkeersveiligheid.

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