From adaptive control to adaptive driver behaviour

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Proefschrift

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Chapter 1

1. Introduction

During the last decade the field of driver behaviour modeling has suffered from a lack of progress. This has been attributed to a number of different causes, the most important one being the preoccupation in traffic psychology with accidents and accident causation (Ranney, 1994). As a result it has never been clear whether driver theories should explain accidents or everyday driving. Several authors have stressed that the actual traffic situations instead of accident analysis should be the main focus and that driver theories should explain everyday driving instead of accidents (for example Rumar, 1988).

The second factor behind the lack of progress in driver modeling is the fact that the motivational models which are dominant today have failed to generate testable hypotheses (Ranney, 1994) mainly because of the confusion between individual and aggregate levels of analysis (Michon, 1989). Also, the continuing debate concerning the validity of the risk homeostasis theory has stalled progress.

Michon (1985) has attributed the lack of progress in driver behaviour modeling to the failure to incorporate the results from the 'cognitive revolution' in psychology. He divided the task of car driving into three levels of skills and control: strategic (planning), tactical (maneuvering) and operational (control). On the strategic level, trip planning and the selection of trip goals and route occur. On the tactical level, sometimes referred to as the maneuvering level, the driver negotiates prevailing circumstances. It includes maneuvers such as obstacle avoidance, gap acceptance, overtaking, choice of headway during car-following and speed choice. The operational level relates to direct lateral and longitudinal vehicle control. Michon postulated that a comprehensive model of driving should take these levels into account, and specify the relations between them. However, all existing models have focused almost exclusively on one level. Ranney (1994) regarded the hierarchical control structure between these levels as one of the most significant developments in the field of driver modeling. It forms a basis for the development of modern driver behaviour theories.

Huguenin (1988) saw the abundance of determinants and factors that operate simultaneously as the cause for the lack of a general theoretical basis or a comprehensive model of driver behaviour which has resulted in several theories that apply only to a limited problem domain.

The causes for the limited progress in driver modeling referred to by Ranney, Michon and Huguenin converge in the problem of 'human behaviour feedback' which has puzzled many traffic safety researchers during the last decade and triggered fierce discussions about the effects of safety measures. This issue of the apparently unpredictable human behaviour effects following road safety measures was explored by Evans (1985). He compared the expected safety effects with the actual safety changes in 26 studies and found evidence of changes greater than expected, as expected, smaller than expected, no safety change and perverse effects (safety change opposite in sign to expected). Evans concluded that no behavioural model was available to predict effects of changes in the road-vehicle-driver system. The same issue was referred to as 'behavioural adaptation' instead of 'human behaviour feedback' in a report of the OECD (1990). Behavioural adaptation was defined as "those behaviours which may occur following the introduction of changes to the road-vehicle-user system and which are not consistent with the initial purpose of the change …”. Because behavioural adaptation may strongly affect the success or failure of road safety measures, collection of driver behaviour data is at least as important as accident data. Accident and fatality data do not contribute as much to an understanding of the process that produced them as driver behavior data because they are only a summary or a final result of a complicated process.

The effects of 'human behaviour feedback' as defined by Evans and of 'behavioural adaptation' as defined in the OECD report are limited to changes related to the road and the vehicle. For example, in the OECD report a number of studies are referred to that present evidence of increases in speed if lane width or shoulder width is increased while accidents are reduced. Also, the presence of edge lines has been associated with speed increases and accident reductions. However, in chapter 2 evidence will be presented that adaptation is a much more general phenomenon that can be observed in the fields of individual differences, transient states, effects of age and so on. At present no theory is able to predict or explain the changes in behaviour after the introduction of a road safety measure, although several theories have claimed to explain some of the effects. The theory that has been associated most often with the 'human feedback effects' is Wilde's risk homeostasis theory (Wilde, 1982). The most important reason for the fierce discussions evoked by this theory centers around the explanation it provides for the 'human feedback effects'. The emotional discussions over the reasons for this phenomenon and surrounding any attempt at theory development have incapacitated the progress in driver modeling.

In chapter 2 a model of driving behaviour is developed in which the process of adaptation plays a dominant role. Although the meaning of the term adaptation in this thesis differs from its meaning in the OECD report, the underlying process is thought to be the same. In both cases behaviour on the tactical level is changed as a function of some factor. 'Behavioural adaptation' as defined in the OECD report results in a smaller safety benefit than expected after the introduction of a safety measure, because behaviour becomes more 'risky'. This is sometimes referred to as 'negative adaptation': drivers choose a higher speed or follow at a smaller headway. It is often assumed that the number of traffic accidents would have been reduced more if behaviour had remained constant. In contrast, adaptation as described in this thesis sometimes may result in a process in which system safety increases because behaviour becomes less 'risky', in the sense that drivers sometimes choose a lower speed or follow at a larger headway in response to some factors. It is then assumed that both effects on behaviour are two sides of the same coin.

Most driver models can be characterized by an emphasis on either individual differences or on situational factors and are limited in scope to either the tactical level or the operational level. The emphasis on either of these is in part determined by historical reasons. A comprehensive driver model should be able to handle both individual differences and situational factors as well as the operational and the tactical level of car driving behaviour. In this, several factors related to the driver, the vehicle and the road-environment have to be incorporated into a comprehensive framework.

The purpose of the present study is to construct and validate a model of driving behaviour in which these requirements are met, starting from a discussion of existing theories and models of driving behaviour in chapter 2. The essence of the model that is derived in the course of the next chapter is that human drivers operate at different levels simultaneously. Several factors affect the quality of operational performance. These factors may be related to individual differences in perceptual-motor ability affected by age or to temporary state-related effects induced by marijuana or alcohol. But situational factors such as sight distance may also affect operational performance. The main point discussed in chapter 2 is that both individual and situational factors that affect performance on the operational level will ultimately result in an adaptation of behaviour on the tactical level and in some cases also on the strategic level. Therefore the model is referred to as the adaptation model of car driving behaviour. In chapter 2 evidence is presented that adaptation of behaviour on the tactical level to changes in performance on the operational level may be crucial from a safety point of view. Accident involvement appears to be highest in cases where adaptation fails. This makes the study of the process of adaptation not only important from a scientific point of view but also from a traffic safety point of view.

Outline of the study. Chapter 2 serves as a theoretical section and discusses a number of driver models from the perspective of adaptation. A general model of driver behaviour is presented that emphasizes the interactions between the operational and the tactical level of the car driving task. The skill models, motivational models and adaptive control models are analyzed in terms of their emphasis on either the operational or tactical level and situational factors or individual differences. During this discussion a number of central problems in traffic psychology is examined in detail. The problem of the elderly driver is analyzed in terms of individual differences in perceptual-motor abilities. The effects of alcohol and drugs (marijuana) are analyzed in terms of state-related factors that result in a transient degradation of operational performance. The problem of the young male driver is associated with motivational factors and discussed in terms of the motivational models. Paragraph 2.5 connects the operational and the tactical levels of behaviour with the concept of safety margins, and makes the adaptation model more explicit for the lateral and the longitudinal driving control tasks. Paragraph 2.6 serves as a link between the theoretical model and six experiments that were performed to test a number of elements from the adaptation model. In these experiments one important aspect of the adaptation model is examined in detail: the extent to which individual differences in behaviour on the tactical level are related to individual differences in operational performance and perceptual-motor skills.

The experiments were performed in the TRC driving simulator. Chapter 3 discusses this research instrument and the contribution of the author to its development in more detail. Two car driving tasks, negotiating curves and car-following, are studied in the chapters that follow.

Experiment 1 analyzes the driver task of curve negotiation and this is discussed in chapter 4. It focuses on the relation between steering performance and speed choice in curves with different radii. The car-following task and its relation with braking performance is examined in the experiments 2 to 6. These are discussed in the chapters 5, 6, 7, 8 and 9 respectively.

The general results from the six experiments and the relevance for the adaptation model are discussed in chapter 10, together with a number of general conclusions and some next steps.

Chapter 2

2. Models of driving behaviour

2.1 Introduction

A wide range of models of driving behaviour has been described in the literature that typically emphasize a specific aspect of car driving. Some models emphasize operational performance while others stress the importance of behaviour on the tactical level. Also, some models focus on individual differences while others emphasize situational factors. The number of serious attempts at categorization of driver behaviour models is limited. The problem is that the categorizations are almost always too limited, exclude important models or are wrong according to the advocates of some models. However, an important attempt is the one proposed by Michon (1985). Michon has made a distinction between taxonomic and functional driver behaviour models. Taxonomic models are inventories of facts while functional models specify relations between components. The best known example of a taxonomic model is the task analysis of the driving task developed by McKnight and Adams (1970). This task analysis specifies the driving task in terms of behaviour requirements (for a distinction between several types of task analyses, see Hackman, 1969). This means that it describes what the driver *should* do. The task analysis of McKnight and Adams is not aimed at understanding driver behaviour or at describing how the driver actually drives. Given the purpose of driver education, this is not surprising. However, since it is not aimed at understanding driver behaviour, it is not discussed here.

In the sixties, the early concept of accident proneness was replaced by studies of individual differences in accident involvement that focused on psychological abilities. Together, these studies have become known as the skill model. The term 'skill model' is actually a misnomer, because the model centers around psychological abilities instead of skills. The use of the word 'skill' suggests that the model focuses on car driving performance while in fact psychological abilities are tested and correlated with accident involvement. Proponents of this model assume a relation between psychological abilities and car driving skills but generally fail to test this relation explicitly. Still, because of the general use of the term in traffic psychology, skill model is used in this thesis. Situational factors were hardly given any consideration in this approach. The dependent variable has been accident involvement instead of actual car driving behaviour. The studies in the tradition of accident proneness and differential accident involvement belong to the taxonomic models and focus on individual differences measured by psychological ability tests.

Individual differences are also stressed in studies on the effects of aging. Since elderly road users differ in car driving performance from younger drivers and are assumed to suffer from skill degradation having an effect on accident involvement, the studies on this issue are grouped under the heading of the skill model in this thesis. However, it must be stressed that these studies differ strongly from the correlation approach of the differential accident involvement studies. Also, behaviour on the strategic and the tactical level of car driving is explicitly incorporated.

The effects of temporary states induced by alcohol and drugs are assumed to affect car driving skills. Traditionally, studies on the effects of temporary states are not part of the skill model if this is envisaged as being equivalent to the correlation approach. Also, the focus is neither on individual differences nor on situational factors. Since temporary states may be seen as within-subjects manipulations of skill level they may give some insights in the workings of skill level on driver behaviour. This is why studies on the effects of temporary states are discussed under the heading of skill models in the present thesis.

Michon (1985) has categorized the motivational models as functional models. In most motivational models the emphasis is on risk. Since they have been introduced to a certain extent as a reaction to the skill model, the emphasis is on situational factors instead of individual differences. Skills and abilities are not regarded as important in motivational models and behaviour on the operational level has a low priority in this approach, or as Näätanen and Summala (1976) put it: "crucial to traffic safety is what the driver actually will do in any given situation, rather than his maximum level of performance and the environmental demands". Motivational models mainly study behaviour on the tactical level, especially speed choice. Although individual differences have a low priority in motivational models, young (male) drivers are regarded as a subgroup of the driving population that deserves special attention because of their high accident involvement rate. Studies of the young male driver are grouped under the heading of motivational models, since in the literature motivational factors are emphasized in the behaviour of the young driver.

The adaptive control models, also categorized as functional models by Michon (1985), focus on behaviour on the operational level and especially on steering behaviour. Individual differences are ignored while effects of situational and vehicle-related factors on operational behaviour are emphasized.

In the next paragraphs, and especially in the paragraphs 2.2.2 and 2.2.3, a number of experimental studies on driver behaviour are discussed. However, it is not intended to give a comprehensive review. The results of studies on driver behaviour are merely referred to as illustrative examples for the model of driver behavior that is developed during the course of the next paragraphs.

2.2 Skill models

From accident proneness to differential accident involvement.

The concept of accident proneness has been in vogue from the 1920s up until the 1960s, and played an important role in theories of driver behaviour. McKenna (1983) presented a conceptual analysis of accident proneness. The idea was that some individuals are more liable to be involved in accidents than others. The statistical techniques that have been applied to resolve this issue have given rise to substantial controversy. One of the problems mentioned by McKenna is that differential accident liability can always be attributed to differences in exposure to risk. Moreover, the lack of a clear definition of accident proneness has resulted in confusion. Several meanings have been assigned to the concept of accident proneness. Some have understood it as that most accidents are caused by a few people. This is associated with the definition of accident proneness as a disproportionate involvement in accidents in a statistical sense. However, the mere randomness of accidents suggests that some people have been involved in more accidents than others because of 'bad luck'. Others have regarded it as an individual property, or as a personality characteristic or disposition leading to a disproportional accident involvement. In that case accident proneness is a trait. However, the connection between these (personality) characteristics and actual car driving behaviour resulting in a higher accident involvement is unclear.

McKenna (1982) proposed the differential accident involvement approach as an alternative to the concept of accident proneness because this would offer a better theoretical understanding of the psychological abilities and characteristics associated with human error. Further advantages of this approach are that it does not suffer from the moral and emotional connotations associated with accident proneness, and that it is based on psychological testing instead of statistical modeling. The differential accident involvement approach evaluates the contribution of psychological abilities instead of personality factors to accident involvement. Although this approach has become known as an important representative of the so-called skill model, it is important to note that it is not driving skill as such that is being evaluated but psychological abilities that are assumed to be related to driving skills. Efforts were made to identify the psychological abilities critical to safe car driving. A substantial amount of research was devoted to the study of correlations between performance on perceptual-motor tasks that were assumed to measure abilities required for safe driving on the one hand and accidents on the other hand.

Unfortunately, because this approach is purely correlational, the nature of the relation between psychological abilities and accident involvement is not made explicit at all. The existence of such a relation is assumed on intuitive grounds and based on face validity. Because the process controlling this assumed relation was not investigated, the effects of psychological abilities on operational driving performance and on behaviour on the tactical level have not been examined. Therefore, accident involvement has been the only dependent variable in this line of research. The results were generally disappointing. A small overview of some of the extensive relevant literature gives the following results:

Vision is generally accepted as being of central importance in driving. Yet correlations between several visual performance tests such as static acuity, dynamic acuity, visual field, glare recovery and recognition on the one hand and accident rate on the other, are typically lower than 0.05 (Rumar, 1988).

The psychological test that has probably been studied most often in relation to accident involvement is the embedded figures test (EFT) of Witkin. This test measures the cognitive style of 'field independence' and it requires that a simple form is found within a background. The EFT has been presented as predicting accident rate. Mihal and Barrett (1976) reported a correlation of 0.24 between EFT performance and accident involvement. Loo (1978) obtained a correlation of 0.42 with self-reported accident rate. However, Harano (1970) found a correlation of only 0.001 and McKenna et al. (1986) found a non-significant correlation of 0.19 between EFT performance and accident rate. Also, Quimby and Watts (1981) failed to obtain a significant correlation with accident involvement.

Other psychological tests, such as the dichotic listening test, Stroop test and reaction time tests also have been reported to be poorly related to accident involvement (McKenna et al., 1986; Quimby and Watts, 1981).

Noordzij (1990) reviewed the German literature on individual differences and accident liability. Performance measures on a wide range of tests failed to predict safe driving in any of the reviewed studies. Some studies even reported relations contrary to the expected direction, such that better performance in the laboratory and on the road was associated with poorer accident histories.

McKenna et al. (1986) gave two explanations for the low correlations. The reliability of accident scores is low when these are obtained over only a few years. This makes it impossible to obtain high correlations between accident rate and test performance. Furthermore, accident rate probably reflects different psychological abilities that cannot be captured in a limited number of tests. Häkkinen (1979) demonstrated that the reliability of accident scores increases by lengthening the time over which accidents are measured. He argued that the lack of significant relations between test scores and accident involvement in so many studies was caused by short exposure periods and poor control of environmental risk. Häkkinen studied accident involvement of professional bus and streetcar drivers and found significant differences between safe drivers and accident involved drivers on a number of psychological tests measuring, for example, eye-hand coordination, choice reaction time and psychomotor personality factors. The correlations were over 0.40. The study of Häkkinen has often been referred to a evidence for the skill model, and it is one of the few studies that supports the model.

In summary, psychological abilities assumed to be related to driving skills have proven to be unrelated to accident involvement, except perhaps for professional drivers. Summala (1985) explained the results of Häkkinens' study by the forced-paced nature of the driving task for this group of drivers. The task of professional bus drivers is paced by time-schedules and differs from the task of private drivers who are able to decrease the speed, overtake less often or avoid bad conditions. The explanation suggested in this thesis is that the driver adapts behaviour on the tactical level to the level of operational performance if the driving task is self-paced. This prevents a higher accident involvement for drivers with poorer psycho-motor abilities. This ofcourse assumes that drivers with poorer psycho-motor abilities are characterized by poorer operational performance. However, when the task is forced-paced adaptation is not possible. Unfortunately, the effects of psycho-motor abilities on operational performance and on tactical behaviour, such as speed choice, have not been studied, thus making it impossible to prove the existence of such an adaptive mechanism from the data presented so far. There is however evidence that adaptive processes play an important role in accident causation of elderly drivers, who suffer from age-related performance decrements and in some transient state-related performance decrements. In that case the term compensation is applied instead of adaptation.

Individual differences in skill: the elderly driver.

It is well documented that older drivers have to cope with declining vision and exhibit poorer performance on a wide range of tests of perceptual and motor ability and response speed (see for example Ysander and Herner, 1976). Ranney and Pulling (1990) found that older drivers (74-83 years of age) score lower on laboratory tasks requiring rapid switching of attention. Rackoff and Mourant (1979) reported poorer performance of older drivers on motor tests and especially on the embedded figures test.

Yet the accident rate of elderly drivers is lower than expected on the basis of the skill model, although the fatality amongst elderly drivers is quite high due to their physical frailness (Evans, 1988; Brouwer, 1989). Hakamies-Blomqvist (1994) found that older drivers had fewer accidents at nighttime and under bad weather and road-surface conditions compared to younger drivers. Older drivers were also less often in a hurry, alcohol intoxicated or distracted by non-driving activities compared to younger drivers. These results were interpreted as evidence that older drivers avoid more difficult conditions. Ranney and Pulling (1990) reported that complex traffic situations pose problems for elderly drivers. They are more often involved in multiple vehicle intersection accidents, while they are less involved in single-vehicle accidents. They questioned the idea that older drivers have higher accident rates than middle-aged drivers. Although drivers over 65 make up 11.2% of the driving population in the United States, they are involved in only 7% of all accidents. A study of Cerelli (1989) was cited reporting that drivers over 75 have a crash involvement rate that is 2.5 times lower than that of drivers aged 40, and 5 times lower than that of 20 year old drivers. According to Brouwer and Ponds (1994) the fatality risk for drivers of age 70 is about three times as high compared to drivers at age 20, due to physical changes such as osteoporosis and decreased cardio-vascular efficiency resulting in an increased physical vulnerability. Correction for this increased vulnerability gives a better impression of actual accident involvement of older drivers compared to younger drivers. Application of this correction factor resulted in almost equal casualty risks for 35 and 70 year old drivers in the Netherlands in the eighties. Evans (1988) also found that when correcting for increased vulnerability, fatalities for older drivers are less than for male drivers under 20.

The results suggest that, although older drivers suffer from decreased performance on most tests of psycho-motor and attentional abilities, their accident risk is not dramatically different from drivers of other age groups. In situations with high time-pressure and situations beyond the control of the driver accident risk appears to increase for older drivers. A possible cause for this phenomenon may be found in the distinction between self-paced and forced-paced driving situations. When the driving task is self-paced, the situation allows the driver to compensate for performance deficits. However, compensation is impossible in forced-paced situations. In that case the driver is subjected to higher levels of time-pressure. The results may then be explained in terms of a process of adaptation: older drivers may compensate for their degradations of psycho-motor abilities by changing their behaviour both at the strategic level and the tactical level. There are a number of research findings in support of adaptive mechanisms.

The ultimate decision at the strategic level is to give up driving. Kosnik et al. (1990) found that older drivers who had recently given up driving reported more visual problems compared to older drivers who had not given up driving. The results suggested that older drivers are aware of their visual deficits and that this awareness influenced decisions about driving. At the strategic level decisions are also made regarding the time of driving. Planek and Fowler (1971) and Ysander and Herner (1976) found that older drivers avoided driving in the dark, on icy roads and in unknown cities more than younger drivers. According to these authors, self-selection seems to be a factor of great importance when judging the traffic safety risks of elderly drivers. Older drivers also may compensate for their age-related impairments by limiting their driving and avoiding risky situations and rush hours (Ranney and Pulling, 1990). In addition to this, there is some evidence in support of compensation at the tactical level. Ranney and Pulling found that older drivers drive slower compared to younger drivers. This was also reported by Rackoff and Mourant (1979). They cited the studies of Case et al. (1970) and Rackoff (1974) in which it was found that the vehicle speed of older drivers, in an instrumented vehicle, was about ten percent less than the speed of younger drivers. The tendency of older drivers to drive at lower speeds was also referred to by Rumar (1987). The proportion of accidents where speed is below average increases as a function of age.

Variations in skill as a function of temporary states.

Both the consumption of marijuana and alcohol result in temporary state changes. This is generally assumed to temporarily affect perceptual-motor abilities. Because of this, the literature on temporary states is discussed under the heading of the skill model, although it must be stressed that in practice this field of research is treated as a separate problem domain, while the results of these studies are normally not related to a specific driving model. The line of reasoning in this thesis is that marijuana and alcohol may effect psycho-motor abilities which may affect operational driving performance. The factors marijuana and alcohol may be considered as a natural experiment in which perceptual-motor abilities are manipulated within the driver. This then offers interesting opportunities to study the effects on tactical behaviour and the relation with accident involvement. The effects of this within-subjects manipulation on driving skills and driving behaviour may then give important information about the workings of the process of adaptation.

Marijuana. Moskowitz (1985) reviewed a large number of studies on the effects of marijuana on psychological abilities. In reaction time experiments neither the speed of initial detection nor the speed of responding appears to be affected by marijuana, although the frequently reported increase of RT variability suggests that attentional mechanisms are impaired by marijuana. Tracking is significantly affected by marijuana. Also, perceptual functions and vigilance are negatively affected by this drug.

However, based on a review of a number of epidemiological studies, Moskowitz (1985) concluded that there is little evidence for an increased risk of accident involvement under marijuana. Robbe (1994) reviewed the epidemiological literature as well and concluded that some people do drive after cannabis use and that drivers involved in accidents often show the drug's presence. However, because alcohol has been a severe confounding factor in all surveys of accident-involved drivers, the independent contribution of marijuana to accidents remains unclear.

The effects of marijuana on driving behaviour has been examined in many experiments. According to Robbe (1994), the foremost impression one gains from reviewing the literature is that no clear relationship has been demonstrated between marijuana and either seriously impaired driving performance or the risk of accident involvement. Smiley (1986) compared simulator and on-road studies of marijuana effects on car driving performance. In simulator studies with realistic car dynamics and in interactive simulators strong effects of marijuana on operational performance were found. In a study of Smiley et al. (1981) in an interactive driving simulator variability of velocity and lateral position increased during curve negotiation and while following cars and in windgusts. Variability of headway and lateral position while following cars also increased under marijuana. However, a larger headway was chosen during car-following under marijuana. In a study by Stein et al. (1983) with an interactive simulator, performance effects of marijuana were examined in a number of driving tasks such as car control during windgusts, curve following and lane changes. Although there were effects on steering performance, mean driving speed was lower under marijuana.

Several other studies have presented behavioural evidence suggesting that drivers may adapt their tactical behaviour to deteriorated operational performance by choosing a lower speed or by increasing headway in car-following. In an on-road study by Caswell (1977) drivers under marijuana drove more slowly. In an on-road study by Smiley et al. (1986) the effects of marijuana on several tasks such as car-following, curve following, open road driving, emergency decision making and obstacle avoidance were measured. Marijuana only had a few effects, but it significantly increased headway in the car-following task. Smiley (1986) concluded that all studies indicate that when the driver under marijuana has the possibility to choose a lower speed, there are no effects on lane position control while speed is reduced. Stein (1986) studied the effects of marijuana on driving behaviour in a number of driving tasks in a simulator. A dose dependent effect of marijuana on speed was found; drivers decreased speed more with higher doses. In a task requiring the driver to compensate for random wind gusts, a strong effect of marijuana was found on mean speed and speed variability. Drivers were also required to control speed and steering during the negotiation of curves. Again, marijuana decreased speed. The speed reduction was also found in an obstacle avoidance task. No effects of marijuana on steering behaviour were found.

Robbe (1994) performed three on-road experiments in which the effect of marijuana on car driving was examined. In a study with driving on a restricted highway it was found that marijuana affected steering performance as indicated by an increased standard deviation of lateral position (SDLP). Subjects were instructed to maintain a constant speed of 90 km/h, or less if they felt incapable of driving safely at that speed. The greater the dose, the harder the subjects attempted to compensate as indicated by perceived effort and increased heart rate. Despite the instruction, there was a small reduction in mean speed under marijuana. Drivers rated the quality of their own driving performance lower with higher doses, suggesting that they were aware of the effects of marijuana.

In another experiment, Robbe (1994) had subjects drive on a highway with other traffic under the instruction to maintain a speed of 95 km/h. This also involved a car-following test in which subjects were instructed to maintain a 50 meter headway. A marijuana dose-dependent increase in SDLP was found and a decrease in speed under marijuana. Also, under marijuana headway increased although the increase was highest with the smallest dose. Reaction time to speed changes in the preceding vehicle increased under marijuana. However, reaction time was confounded with headway, such that RT increased with increased headway.

In a third experiment, Robbe (1994) examined the effects of marijuana in a city driving task. Driving performance was evaluated by trained observers (driving instructor). No effects of marijuana were found on driving performance. Under marijuana it took more time to complete the circuit, suggesting a lower speed, although this was not significant. Drivers under marijuana perceived their driving quality as poorer compared to placebo and perceived their effort as higher.

In conclusion, the studies of the effects of marijuana suggest that, firstly, it affects perceptual and psycho-motor skills, secondly, it affects performance on the operational level, and thirdly, it affects behaviour on the tactical level, especially when the task is self-paced. Evidence was presented that the drivers are aware of performance decrements under marijuana. It may be hypothesized that the perception of feedback of these performance decrements is a necessary prerequisite for such a compensation strategy. However, the nature of the perception of feedback, whether it is conscious or unconscious, is at present unclear. When the task is self-paced instead of prescribed by the experimenter (by instructing the subject to maintain a fixed speed), effects of marijuana on operational performance may be limited due to compensation for decreased skills: when drivers are allowed to choose their speed, effects of marijuana on steering behaviour are generally absent, while effects on steering behaviour are found when speed is prescribed by the experimenter. This compensation mechanism may explain why epidemiological studies have been unable to find a relation between marijuana and accident involvement.

Alcohol. A substantial part of the literature on accidents and driver behaviour concerns the effects of alcohol. The effects of alcohol on performance are well documented for a large number of tests. Only a few examples are given here. Moskowitz and Robinson (1986) reviewed the literature on the effects of alcohol on task performance. They analyzed the results of 178 studies that fulfilled regular methodological criteria. Forty-five percent of the studies indicated impairment at 0.04% BAC (blood alcohol concentration) or less. The majority of studies reported impairment at below 0.07% BAC. Impairments were found in tracking, divided attention, information processing, eye movements and psycho-motor skills, especially in tasks requiring skilled motor performance and coordination. Divided attention deteriorated already at very low BAC levels. Signal detection, visual search and recognition tasks also showed impairments at low BAC levels. Kennedy et al. (1989) measured the effect of BAC level on performance in a battery of nine tests measuring motor speed, symbol manipulation/reasoning, cognitive processing speed and speed of response selection. Performance on eight out of nine tests was strongly and monotonously affected by BAC.

Evans (1991) estimated that 47% of fatal accidents, 20% of injuries and 10% of property damage are attributable to alcohol. This means that alcohol contributes importantly to traffic accidents with the contribution increasing as crash severity increases. Evans (1989) concluded that eliminating alcohol would reduce traffic fatalities in the United States by 47±4 percent. Guthrie and Linnoila (1986), suggested that epidemiological studies indicate a disproportionate number of alcohol related fatal crashes involving young male drivers below 24 years of age. The majority of alcohol related accidents occur during the weekend, especially at evening hours, and in summer. According to Smiley (1989), alcohol is involved in 62 percent of all fatal single vehicle accidents.

There is also overwhelming evidence that alcohol affects operational driving performance. Louwerens et al. (1986) studied the effects of four doses of alcohol in a task where subjects were required to drive with a constant speed of 90 km/h with a constant lateral position between the right lane boundaries. Standard deviation of lateral position (SDLP) increased in a dose dependent manner as a function of alcohol. The subjective assessment of driving performance by the driver correlated poorly with SDLP and BAC level. This suggests that drivers were unaware of performance decrements under alcohol. In a simulator study with several driving tasks, Stein (1986) found that alcohol increased the number of accidents. Also, in a task requiring the driver to compensate for windgusts while following a winding road, steering behaviour was significantly affected by alcohol, and lane position variability was increased under alcohol. No effects of alcohol on mean speed were found, although speed variability increased under alcohol. Stein and Allen (1986) reported the results of an experiment that aimed to unravel the effects of alcohol on performance and risk taking. This is important because the effect of alcohol on accident involvement has often been attributed to an increase in deliberate risk taking. The effects of alcohol on driver behaviour was studied in a driving simulator and on a closed course. Both methods gave essentially the same results. Alcohol increased speed variability and the number of times the speed limit was exceeded. As drivers were well aware of the speed limit and the probability of detection, and since speed feedback was available both visually and aurally, the increased variability suggested decrements in the driver's perception and/or speedometer monitoring. Also the frequency of running red lights was increased by alcohol. The subjective probability of running a red traffic light was affected by alcohol while risk acceptance was not affected by alcohol. Stein and Allen saw these results as evidence that the driver's perception of speed and distance was impaired by alcohol, and that the drivers were unaware of this impairment. They concluded that the locus of effect of alcohol on risk taking is on the perceptual level instead of the risk acceptance level. Wilde et al. (1989) investigated the effect of BAC on performance on a response timing task and a general knowledge quiz. The findings did not support the hypothesis that alcohol increases deliberate risk taking. A significant increase in overconfidence in the cognitive task was observed under alcohol, but overconfidence and risk taking were not correlated.

In an on-road study by Caswell (1977) drivers performed several tasks such as overtaking, driving on straight road sections and curves and through narrow gaps while responding to road signals, traffic signals and auditory signals in a subsidiary task. Alcohol resulted in increased speeds and poorer tracking performance. In an on-road study of Smiley et al. (1986), alcohol at 0.05% BAC was associated with significantly higher speed on straight roads and in curves. Also, alcohol decreased the number of peripheral stimuli detected. According to Smiley (1986), in three of the four studies reviewed, where effects of alcohol on speed were recorded, alcohol was associated with an increase in speed while it significantly affected steering performance in a number of studies (Smiley, 1989). In a study of Hansteen et al. (1976), alcohol increased the number of cones hit and the amount of 'rough vehicle handling' while it increased speed. Robbe (1994) tested the effect of alcohol on driving performance during city driving. Alcohol decreased performance in 'vehicle handling' and 'action in traffic', while speed was increased. Subjects thought, however, that they had driven as well as following placebo and there was no effect of alcohol on effort invested in the driving task.

In summary, alcohol strongly affects perceptual and psycho-motor skills as well as performance on the operational level of car driving. At the same time, alcohol increases speed. In this the effect of alcohol is opposite to the effect of marijuana. It may then be hypothesized that a lack of compensation for impairments in performance is the cause for the very strong role of alcohol in accident involvement. Evidence was presented that suggests that drivers are unaware of performance decrements under alcohol. This may be somehow related to the absence of compensatory speed changes and effort.

Conclusions and consequences for the present model.

Correlation studies in the tradition of the differential accident involvement approach have been unable to demonstrate a relation between psycho-motor abilities and accident involvement, with the possible exception of professional drivers. This may be explained by the self-paced nature of the driving task for private drivers which allows compensation for poorer skills, such that effects of psycho-motor abilities on accident involvement are decreased. Because the driving task for professional drivers is often controlled by time schedules and fixed driving times and routes, their task is more of a forced-paced nature. In the differential accident involvement approach a relation between psycho-motor abilities and driving performance was assumed instead of tested and driving behaviour on both the operational and the tactical level typically was not examined by this approach.

The effects of individual differences in psycho-motor abilities on behaviour on the strategic and the tactical level was illustrated by the case of the elderly driver. Accident involvement of the elderly driver is much lower than expected from the skill model. A possible cause for this may be that behaviour on the strategic level and the tactical level is adapted to poorer psycho-motor abilies of elderly drivers, in the sense that these drivers often refrain from driving in the dark, under bad weather conditions and so on, and that they drive with lower speeds.

Variations of skill within the driver as a function of temporary states were illustrated by examining the effects of marijuana and alcohol. These studies have supplied strong evidence for effects on psycho-motor abilities and operational performance, together with effects on tactical behaviour. Evidence was presented that supports the hypothesis that effects of marijuana on accident involvement are tempered because of compensation of behaviour on the tactical level for degradations of perceptual-motor abilities and operational performance under marijuana, and that the driver perceives the feedback of poorer operational performance. Alcohol also strongly affects perceptual-motor abilities but the driver appears to be unable to perceive this. This may explain why the driver does not compensate behaviour on the tactical level which may be the cause for a strongly increased accident risk. The results are consistent with the idea that behaviour on the tactical level is adapted by decreasing speed or increasing headway when feedback of operational performance decrements is perceived by the driver.

The results presented so far, are summarized in figure 1 as a first attempt to describe a model of driver adaptation. Individual differences in psycho-motor abilities, for example as a function of age, and effects of temporary states induced by marijuana or alcohol on these abilities affect operational car driving performance.

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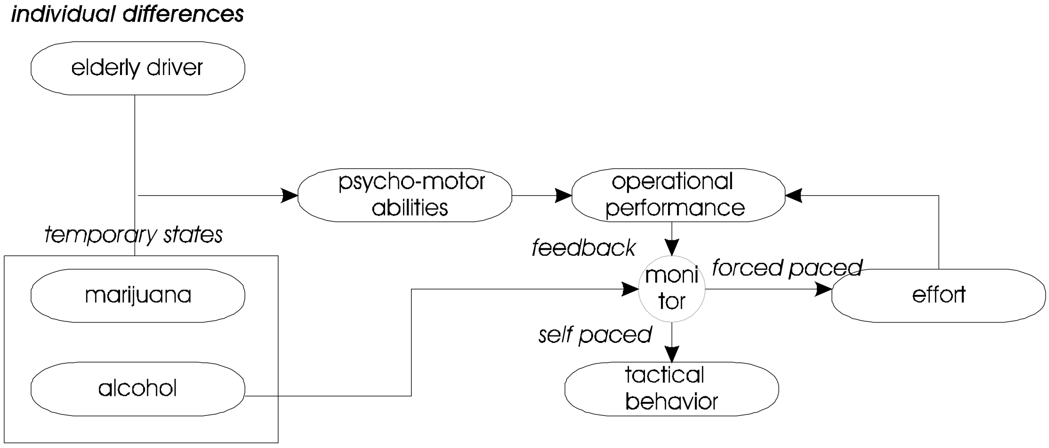

Figure 1. Model of driver adaptation, derived from the discussion of skill models

Normally, these effects are monitored by the driver and the driver perceives the feedback of these effects, although this may be inhibited by alcohol. Two kinds of adaptation may occur. Either behaviour on the tactical level is adapted to compensate for decreased operational performance, if driving is self-paced. If driving is not self-paced the driver may also increase effort to improve operational performance or, alternatively, the driver may adapt behaviour on the strategic level by deciding to give up driving for a while or altogether, or by avoiding driving in bad conditions.

Thus far, only the effects of poorer operational performance have been examined, resulting mainly in decreased speeds. The reverse, better performance resulting in increased speed has not been examined. However, in the motivational models, discussed in the next paragraph, it is argued that behaviour on the tactical level, such as higher speed or smaller headway during car-following, are the result of motivational factors instead of improved performance.

2.3 Motivational models of car driving

During the seventies driver behaviour modeling shifted to motivational approaches as alternatives for the skill model. The main reason for the rise of motivational models was the rejection of accident proneness as an explanatory concept and the disappointing results of the differential accident involvement approach (Summala, 1985; Näätänen and Summala, 1974). The fact that increasing driver skills and decreasing environmental demands did not result in increased traffic safety in a straightforward manner was attributed to the self-paced nature of the driving task in which the driver is able to control task difficulty. The emphasis of the motivational models on transient or situational factors came as a response to the individual difference approach of the skill model (Ranney, 1994). The actual behaviour of the driver in any given traffic situation was given more importance than the maximum level of performance. The motivational models that emerged in the seventies were based to a large extent on a few articles, written in the sixties, that stressed the self-paced nature of the driving task. Taylor (1964) claimed that galvanic skin response (GSR) per unit of time was constant. He regarded GSR as a measure for subjective risk and hypothesized that the driver adjusts the level of risk taking to keep emotional responses on a constant level. In this view, speed was adjusted to keep subjective risk on a constant level. This notion of compensation by adjusting speed differs from compensation as discussed in previous paragraphs. Taylor (and the motivational models in general) conjectured that speed was adjusted to compensate for subjective risk, while the viewpoint expressed in previous paragraphs suggests that speed is adjusted to compensate for degradations or improvements in operational performance. Both viewpoints stress the importance of the self-paced nature of the driving task. The Risk Homeostasis Theory of Wilde can be seen as a descendant of the principle formulated by Taylor. Cownie and Calderwood (1966) argued that accidents are the product of a simple closed-loop process in which feedback from the consequences of driver actions and decisions play an important role. They emphasized the importance of finding a good balance between motivating and inhibitory forces of positive and negative motivating events. This viewpoint has played an important role in the model of Näätänen and Summala.

Motivational models of driver behaviour have become synonymous with models of risk taking. The most important variants are Wilde's Risk Homeostasis Theory, Näätänen and Summala's Zero Risk Model and Fuller's Threat Avoidance Model. The relation between motivations other than risk taking and driving behaviour has been examined in a limited number of studies, for example French et al. (1993), Rothengatter and de Bruin (1986) and Rothengatter (1988). French et al. (1993) investigated the relation between decision-making style, driving style and accident rates. The results of this study do not give an indication how behaviour on the tactical level is affected by motivational factors. Speed is described as an aspect of driving style together with more motivational concepts such as social resistance and deviance. This indicates that the concept of "driving style" is not clearly defined since it mixes overt behavioural manifestations with covert motivational constructs. Because of this it is difficult to integrate with other approaches discussed in this thesis. Rothengatter and de Bruin (1986) and Rothengatter (1988) examined the relation between speed choice and motivational factors within the framework of Fishbein and Ajzen's model of reasoned action. It was found that speed choice is determined by four motivational factors: pleasure in driving, risk, travel time and costs. Pleasure in driving proved to be the strongest determining factor of speed choice, such that the subjects with the highest speed scored highest on pleasure in driving. However, pleasure in driving was also related to the top speed of the vehicle and thus to vehicle characteristics: drivers of high performance cars scored higher on pleasure in driving compared to drivers of low performance cars. This was explained by suggesting that drivers with more pleasure in driving, as a characteristic of the person, are more inclined to buy high performance cars. However, the reverse could also be true: drivers of high performance cars may enjoy driving fast more than drivers of low performance cars because the car allows better control at higher speeds. This issue should be considered in further studies.

Risk Homeostasis Theory.

Risk compensation models propose a general compensatory mechanism whereby drivers adjust their driving (e.g. speed) to establish a balance between what happens on the road and their level of accepted subjective risk. Wilde's Risk Homeostasis Theory (RHT) is based on the assumption that the level of accepted subjective risk is a relatively stable personal parameter. An important implication is that drivers will nullify the effects of safety improvements by driving faster or behaving less cautious in general. This has resulted in considerable controversy. RHT (see for example Wilde, 1982), previously known as risk compensation theory (for example Wilde, 1976), consists in fact of two models; an individual model of driver behaviour and an aggregate model that relates driver behaviour to accident rate. In the individual model the driver is assumed to have a target level of risk that represents the amount of accident risk the driver accepts. This is continuously compared to the perceived level of risk which is an estimate of the accident risk in the immediate future. The perceived level of risk is determined by the vehicle path, the road environment and paths of other road users (the stimulus situation) and anticipations regarding the development of the stimulus situation in time. When there is a discrepancy between perceived risk and target level of risk the driver makes a behavioural change, either in the direction of reducing the level of risk if perceived risk is larger than target level of risk, or in the direction of increasing the level of risk if the reverse is true. This results in a homeostatic process in which the driver aims to match the perceived level of risk with the constant target level of risk.

The name 'risk homeostasis' theory is, however, essentially derived from the aggregate model, see figure 2. Again, drivers compare the perceived level of risk with the target level, resulting in adjustment actions. Aggregated over all road users over a given time span, these adjustment actions will produce the rate of accident frequency and severity. This has a lagged feedback on perceived risk. Decreased accident rates then decrease perceived risk after some time, resulting in adjustment actions that increase accident risk in a homeostatic way. The only factor that affects accident risk then is the target level of risk. In the aggregate model, skills play some role, although improvements in skills are unlikely to have a lasting effect on accident frequency and severity (Wilde, 1981). Perceptual skills determine the extent to which subjective risk corresponds to objective risk. It is important to note here that Wilde does not think that improving risk perception skills will improve traffic safety. Decision skills refer to the drivers' ability to bring about the desired adjustment, while vehicle handling skills determine the extent to which the planned actions are executed properly. In the individual model of risk compensation skills only have a modest influence on perceived level of risk and on the transformation of sensory input. Thus, the concept of skill, as discussed previously, plays no role in Wilde's theory. Individual differences are restricted to individual differences in motivational states that may affect the target level of risk.

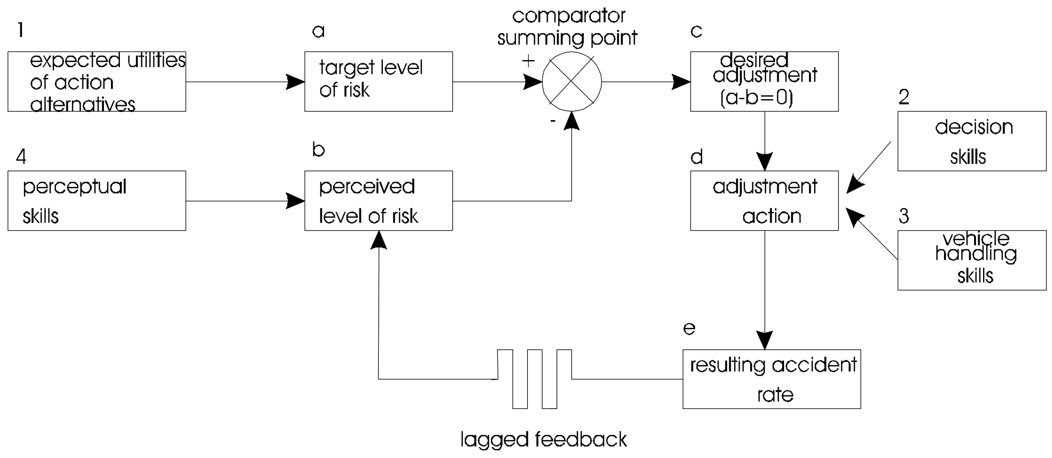

Figure 2. Aggregate model of Risk Homeostasis Theory (from Wilde, 1982).

The effects of motivations on choice of time-headway (THW) during car-following has been studied by Heino et al. (1992). Drivers were classified as sensation seekers or sensation avoiders depending on their scores on personality inventories. It was expected that sensation seekers seek more risk and are thus characterized by a higher level of target risk. It was found that sensation seekers followed at a smaller THW which is associated with higher objective risk by several authors. However, Heino found that this smaller THW was not associated with a higher subjective risk. It appeared then that both sensation groups accepted the same level of risk, and thus did not differ in target level of risk, but for sensation seekers this perceived level of risk was achieved at a smaller THW compared to sensation avoiders.

Meanwhile the discussions concerning the validity of RHT have gone on for years. Evidence provided by Wilde supporting RHT has been refuted by various counterexamples (for example, McKenna, 1982; Evans, 1985). Even more controversy has arisen over Wilde's hypothesis that safety improvements will not work unless it affects the target level of risk (McKenna, 1988). The ability of drivers to monitor accident risk has been questioned and the assertion that drivers experience or accept risk has been challenged (for example, Evans, 1991). The plausibility of seeking some level of risk has been seriously doubted and according to several authors drivers seek the lowest possible, or zero, level of risk.

Zero Risk Theory.

Näätänen and Summala (1974, 1976) have presented a model of the driver's decision making that has become known as the zero-risk theory. In this model motivational factors such as subjective risk, other motivations and vigilance determine driver decision-making and behaviour, see figure 3. The subjective risk monitor is a crucial element in this model. It was conceptualized as a monitor that generates subjective risk or fear depending on the experienced risk in the present or expected traffic situation. Activation of subjective risk inhibits ongoing behaviour in the sense that it results in behaviour such as slowing down. It also has an inhibitory effect on subsequent behaviour in the sense that drivers learn to behave more cautiously in similar situations. However, most of the time subjective risk equals zero. Other motivations provide an excitatory component resulting in increased speed. These other motives are affected by personality factors such as aggressiveness and the state of mind of the driver. Several changes in the traffic environment may affect subjective risk. Drivers may drive faster or overtake other cars more frequently before subjective risk is experienced. The best traffic safety measures are those that decrease objective risk but increase subjective risk.

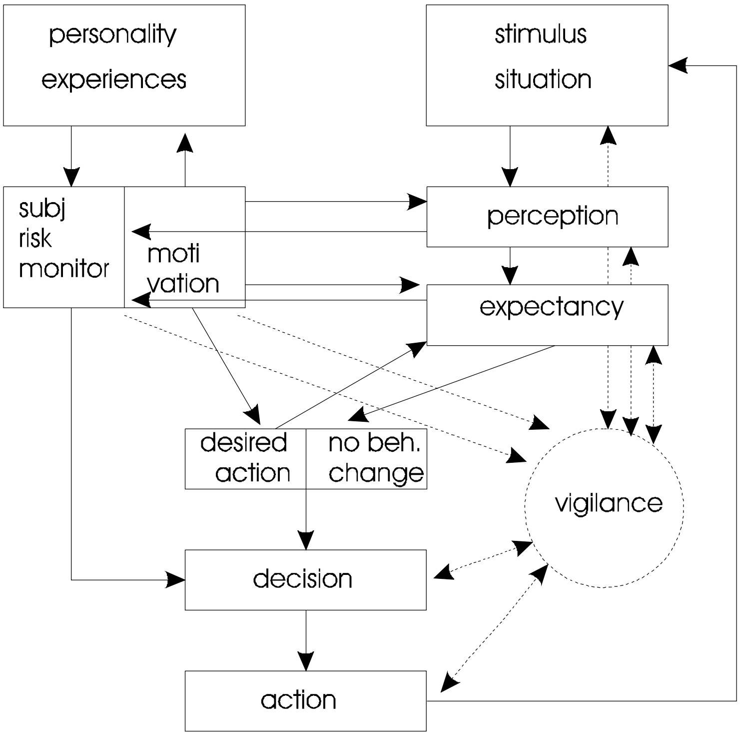

Figure 3. The zero-risk model of Näätänen and Summala (from Näätänen and Summala, 1976).

An important difference with the risk homeostasis theory is that in the zero-risk theory the driver is assumed to accept no risk at all, that is, the target level of risk is zero. Näätänen and Summala state on the one hand that subjective risk is an important determinant of driver behaviour (as an inhibitory factor) while on the other hand most of the time subjective risk equals zero. Fuller formulated his Threat Avoidance Model, to be discussed later, partly in response to this inconsistency. In later publications by Summala (1985, 1988) the concept of subjective risk was more or less abandoned as an explanatory factor in driver behaviour: it is not risk that the driver attempts to control, but instead, drivers control and maintain safety margins, since normally the driver gives no consideration to risk (Summala, 1988). The concept of subjective risk should be reserved for 'arm-chair estimates' of the risks of, for example, traffic scenes shown to subjects for research purposes (Summala, 1988). He stated that the output of the subjective risk monitor was meant to represent a fear response resulting from the perception or expectation of loss of control over the car or of being on a collision course (Summala, 1986). The concept of 'perceived loss of control' thus replaced the continuous control of subjective risk. Taylor (1976) postulated that subjective risk is equivalent to the perception of loss of control. The relative unimportance of subjective risk in the zero-risk theory was further exemplified by Summala by his observation that as drivers become more experienced driving becomes more automated and feelings of uncertainty or fear related to perceived loss of control decrease because confidence in control skills increases. He regarded the fact that drivers are not very well able to take account of the objective variance in the traffic system as the most important point of the zero-risk theory. The second main point is that different kinds of motives push drivers towards higher speeds and if the traffic system provides (environmental) opportunities to satisfy these motives, drivers are inclined to use them. This is not risk compensation but merely the result of a tendency for satisfaction of motives. Examples of such motives are that high speed as such is motivating and higher speeds mean shorter travel times. Also the conservation of effort is seen as an important motive resulting in a reluctance to slow down. Speed also provides outlets for many other 'extra motives' such as the motive to demonstrate driver skills to peers. In order to improve traffic safety, drivers should be prevented to satisfy their motives by introducing speed limits.

Thus, the zero-risk theory has undergone significant changes in time. The role of the inhibitory forces associated with subjective risk has diminished while the excitatory motivational components are emphasized more strongly. Also, the concept of safety margins has replaced the concept of subjective risk and 'perceived loss of control' has become an important factor in the control of safety margins. Although this is not stated explicitly by Summala, loss of control is strongly related to performance on the operational level. Because safety margins appear to be underlying controlling variables of driver behaviour, different subtasks such as lane keeping, car-following, curve negotiation, gap acceptance and overtaking should be analyzed in more detail (Summala, 1988). The concept of safety margin will be discussed later.

Yet, a large number of studies have focused on one aspect of the early version of the zero-risk model: the assumption of a discrepancy between subjective and objective risk. A threshold for risk perception is assumed, and risk compensation occurs only if this threshold is exceeded. Below this threshold subjective risk is experienced as zero. The idea then became in vogue that risk perception may be distorted as a function of several factors such as age or driving experience. Most studies on risk perception have focused on the young driver and these will be reviewed later.

Threat Avoidance Model.

Although the Threat Avoidance Model of Fuller is typically classified as a motivational theory it is actually more a theory of learning applied to car driving. Fuller (1984) has formulated his threat avoidance model of driving behaviour partly in an attempt to solve two problems associated with the zero-risk theory. The first problem was the dissociation between subjective and objective risk in the zero-risk model. The second problem was that subjective risk reactions constitute an important determinant of decision making while at the same time the driver feels no subjective risk most of the time. Since the experience of subjective risk is aversive drivers are motivated to escape from situations that elicit subjective risk or to avoid those situations. Thus, subjective risk reactions are important determinants of behaviour assuming that drivers are able to anticipate and make appropriate adjustments to upcoming hazards. If driving consists to a large extent of learned avoidance reactions drivers will rarely experience any subjective risk at all.

Figure 4 gives a representation of the model. Because, in general, the driver's own actions determine whether or not interactions with the road environment will be punishing, stimuli in the road environment have an aversive potential. A discriminative stimulus is some precursor of a potential aversive stimulus which has been learned by association. Several consequences are experienced as aversive. These may be very common consequences such as loss of self-pacing in the driving task and a state of high arousal, or less common consequences such as loss of vehicle control, physical injury, material damage, loss of self esteem and so on. The driver then is motivated to prevent these negative consequences and not just to avoid the experience of subjective risk. The discriminative stimulus is a function of the drivers' perception of speed, the road environment and skill. It is an integration of these features projected into the future. For example, the combination of a particular speed, a curve that is approached and an estimate of present vehicle handling skills determine together whether this constitutes a discriminative stimulus. When perceived capability is a primary factor underlying the discriminative stimulus some compensatory response is generated that may consist of raising the performance level or some behavioural adjustment such as lowering the speed or increasing headway during car-following. It is then important to note that the issue of feedback and compensation is solved in Fuller's model by assuming behavioural anticipatory avoidance responses to a discriminative stimulus. A delayed avoidance response may occur if the anticipatory avoidance response is inadequate. If there is a discriminative stimulus, the probability of an anticipatory avoidance response or a non-avoidance response is both determined by the subjective probability of expected threat and by the rewards and punishments of the response alternatives. If no discriminative stimulus is detected then either no threat is realized or a threat occurs demanding a delayed avoidance response of the driver.

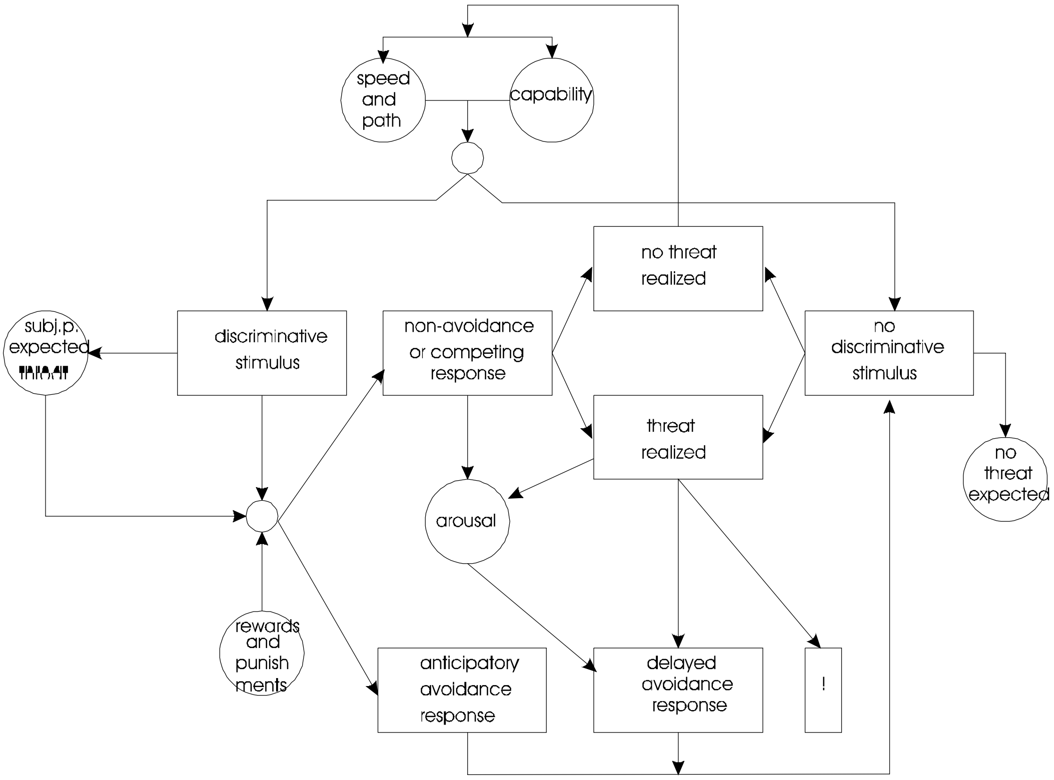

Figure 4. Fuller's threat avoidance model (from Fuller, 1984).

This may occur because of perceptual errors, inadequate learning to recognize a discriminative stimulus, unpredictable behaviour of other road users or sudden mechanical failure. If the driver makes no anticipatory avoidance response a delayed avoidance response represents an escape from an aversive stimulus. Learner drivers are more likely to make delayed avoidance rather than anticipatory avoidance responses than experienced drivers because they have not yet developed associations between discriminative and potential aversive stimuli. The higher accident involvement of young drivers was explained by this lack of associations, while Näätänen and Summala (1976) attributed the high accident involvement of young drivers to the relative strength of 'extra motives' in this group, such as the desire to drive at high speeds.

Based on this framework, Fuller suggested that there may be drivers who are predominantly anticipatory avoidance responders while others are predominantly delayed avoidance responders. This may then be related to individual differences in the ability to detect hazards. This ability has been referred to as 'hazard cognition' by several authors and it is believed to be related to accident involvement of young and inexperienced drivers.

Individual differences in motivations: the young driver.

Young drivers, especially males, from 18 to 24 are dramatically more often involved in accidents compared to drivers of other age groups (Evans, 1991). This overinvolvement of young male drivers in the accident statistics is one of the most consistently observed phenomena in traffic throughout the world. A confounding factor is that young drivers usually are the least experienced. Simpson (1986) stated that the reason for the high involvement of young drivers in vehicle accidents, even when exposure to risk is controlled for, is not clear. While young people from 16 to 24 years of age represent 17% of the Canadian population, they account for 31% of all traffic fatalities, 33% of all traffic injuries and 58% of all driver fatalities in Canada. Because risk is usually applied as an explanatory concept for the high accident involvement of young drivers, studies on this issue are discussed here.

The meanings of the risk-related concepts will be discussed first as they are applied in the case of the young driver. Risk-taking is something which is usually inferred from observation of behaviour (Saad, 1989). Traffic researchers often assume that high speed and close following carry a higher objective risk. Drivers who display such behaviours are then assumed to take more risks. Jonah (1986) has given several examples of higher risk-taking in young drivers. Young drivers have been reported to drive at higher speeds (for example Wasielewski, 1984; Soliday, 1974), although the correlation between speed and age is generally very low. Also, younger drivers have been reported to follow at smaller headways (Evans and Wasielewski, 1983). This behaviour associated by a number of researchers with higher risk taking in young drivers, is often seen as evidence that young drivers either deliberately seek more risk or accept a higher target level of risk, and thus have a higher risk acceptance or risk utility, or have a deficient risk perception, i.e. they fail to see the risk involved with such behaviours. The former concept is associated with Wilde's model while the latter is more closely associated with the models of Näätänen and Summala and Fuller. Both concepts have been used as expressions of subjective risk. One of the problems with risk research centers around the conceptual vagueness of the term 'subjective risk'. It is not always clear whether it refers to a failure to perceive the potential danger (hazard perception), to an underestimation of the probability of a certain event (subjective estimation of objective risk), to the driver's poor appreciation of his or her ability to cope with the situation, or to attitudes and motives regarding safety (risk acceptance) (Saad, 1989). Haight (1986) argued that the only valid meaning of the term 'risk' refers to empirical probability or expected cost. In that case risk is a statistical concept referring to the outcome of behaviour on a highly aggregated level. In such a view there is little room for terms such as subjective risk, risk perception or risk acceptance. Another problem associated with some risk research is the circularity in reasoning. The explanation for behaviour associated with a higher objective risk, resulting in more accidents, is that drivers deliberately want a higher objective risk or fail to see the objective risk involved. So the behaviour to be explained is explained in terms of the outcomes of precisely the same behaviour.

The high accident involvement of young drivers has often been attributed to poorer risk perception, resulting in a larger discrepancy between subjective risk and objective risk for young male drivers. Jonah (1986) stated that, even though young drivers may perceive as much risk while driving as older drivers and thus do not deliberately seek more risk, they may be more confident in their ability to avoid an accident. In Jonah's review, risk perception was meant to reflect the subjective estimation of objective risk. He presented some evidence that younger drivers had poorer risk perceptions in the sense that they estimated objective risk lower compared to other age groups. However, it is not clear what this means. Basically, the subjects were asked about their knowledge of statistical facts over which even traffic researchers are still debating. Wilde's model is the only risk model that assumes that knowledge of drivers concerning statistical accident risk affects behaviour. It has been objected by many authors that it is highly unlikely that drivers are aware of accident statistics or that these play any role in driving behaviour. Finn and Bragg (1986) also measured subjective risk or risk perception as the estimation of objective risk as a statistical phenomenon by asking questions such as 'how many people were killed in traffic accidents in Massachusetts last year'. Although it was found that young drivers see driving as more dangerous when general questions about accident risk were asked, and they recognize that their age group is at greater risk of accident involvement compared to other age groups, they see their own chances to be involved in an accident as lower compared to their own age group and older drivers when specific questions about their own risk are asked. Finn and

Bragg saw this as evidence that young drivers differ from older drivers in lower risk perception and not in risk acceptance and that risk perception, or at least seeing less risk in driving situations compared to older male drivers, may account for the high accident involvement of young male drivers. Bragg and Finn (1982) found that specific behaviours such as speeding and tailgating were perceived as less risky by young drivers. They hypothesized that the lower perception of risk in young drivers may be attributable to the greater confidence in their skill or belief in their ability to handle a particular hazardous situation. Risk perception was thus connected with confidence in driver skills.

Matthews and Moran (1986) assessed the relationship between perceived skill and perceived risk. In their study young (18-25) and middle-aged (35-50) male drivers completed a questionnaire on accident risk and driving ability and gave subjective ratings of risk to videotaped traffic situations. Young drivers gave lower ratings of accident risk for driving situations which demanded fast reflexes or substantial vehicle handling skills. They rated their own risk of an accident and driving abilities as being the same as for older drivers. However, they saw their peers as being significantly more at risk and as having poorer abilities than themselves. The data suggested that risk perception is strongly related to perceived ability. Spolander (1982) found that drivers with three years of experience judged themselves to have better driving skills compared to other drivers. The drivers who gave the highest ratings on skill also reported faster driving.

Brown and Groeger (1988) distinguished two inputs to the process of risk perception: information on potential hazards in the traffic environment and information on the joint abilities of driver and vehicle to prevent that hazard potential being transformed into actual accident outcomes. Risk perception is the detection of any shortfall in the ability to avoid realizing the potential of immediate task and environmental hazards.

This short review makes clear that the concept of risk perception has more than one meaning which makes the interpretation of results from these studies difficult. On the other hand, subjective risk has been linked more and more with (perceived) driving skills. This suggests that, at least in the mind of the driver, subjective risk really means fear of loss of control, as was suggested during the discussion of the zero-risk theory.

In another line or research, the high accident involvement rate of especially young male drivers has been associated with the use of alcohol and drugs as a lifestyle-related phenomenon. Although as many as 50% of fatally injured young drivers have been found to be positive for alcohol, this is slightly lower than the frequency for older drivers. Also, it has become clear from surveys that drinking and driving is widespread among younger drivers although they had typically consumed less alcohol than older drivers. In alcohol related crashes younger drivers tend to have lower BACs than older drivers (Simpson, 1986). Yet, the high accident involvement among young drivers has been attributed to risky driving behaviour as an aspect of adolescent lifestyle that is embedded in the same set of personality and behaviour aspects as other kinds of adolescent problem behaviour such as delinquency, problem drinking and illegal drug use and smoking (Jessor, 1986). Also, Beirness and Simpson (1986) found that accident involved young drivers score higher on thrill and sensation seeking, alcohol consumption and frequency of drinking while they score lower on traditional values and usage of seat belts. In short then, some authors believe that the high accident involvement of young, and especially male, drivers is a lifestyle related phenomenon resulting in a higher deliberate risk acceptance or higher target level of risk, using the terminology of Wilde. But in that case it would be expected that a higher percentage of accident involved young drivers are positive on alcohol and have higher BAC levels compared to older drivers. This obviously is not the case.

It has frequently been reported that the relative risk of becoming involved in a fatal accident rises faster as a function of BAC level for younger drivers compared to older drivers (Simpson, 1986; Kretschmer-Bäumel and Kroj, 1986). In other words, with increases in the amount of alcohol consumed, the accident risk increases for all age groups, but much more rapidly for the young. Although the typical explanation for this has been the relative inexperience of young drivers with alcohol, driving and the combination of these, there is no scientific evidence that inexperience with drinking and/or driving is the cause for the stronger impact of alcohol on accident rate for the young (Simpson, 1986; Mayhew et al. 1986). Although the reason for the interaction between age and BAC level on accident involvement is not clear, it suggests that both factors share a common locus of effect, in the sense that the factor that causes the higher accident rate of young drivers is aggravated by alcohol. In the discussion of the effects of alcohol it was suggested that the lack of compensation for impaired performance may be the cause for the large role of alcohol in accident causation. Evidence was presented that drivers are unaware of performance decrements under alcohol which is possibly the cause for the absence of compensatory speed changes and effort. From the same perspective it may be suggested that young and inexperienced drivers have not yet learned to recognize the effects of situational factors on their performance and thus fail to compensate for these effects resulting in speeds that are too high for the circumstances.

Conclusions and consequences for the present model.

In the literature on risk perception it is often suggested that young drivers are more involved in accidents because the discrepancy between subjective risk and objective risk is higher in this group. The reason proposed in a number of studies is that young drivers tend to overestimate their own abilities, although the overestimation of one's abilities appears to be a general phenomenon for all age groups. A drawback of studies on young drivers is that the problem is often examined without simultaneously measuring operational and tactical behaviour. Following the line of reasoning of this thesis, it may be hypothesized that the high accident involvement of young drivers is caused by a failure of young drivers to adapt their speed, or tactical behaviour in general, to the traffic situation, because they overestimate their ability to cope with hazardous situations and fail in the perception of feedback of operational performance decrements induced by traffic situations, vehicle characteristics or environmental variations in general. The interaction between BAC level and age on accident involvement may then be suggestive of a common locus of effect for both the factors alcohol and young drivers. However, it must be stressed that the lack of studies that have examined explicitly the operational and tactical behaviour of young drivers prevents firm conclusions.

From the discussion of the motivational models, a second version of the model of driver adaptation is presented in figure 5.

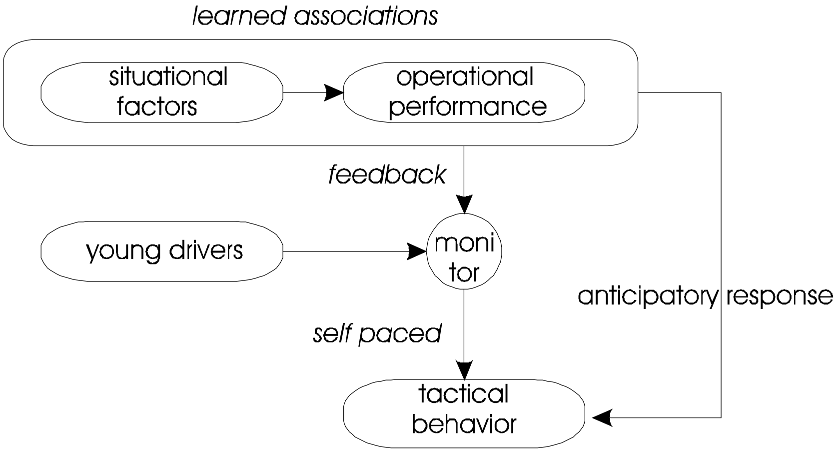

Figure 5. Model of driver adaptation, derived from the discussion of motivational models.

Various situational factors may affect operational performance resulting in a sense of 'loss of control'. In general, this effect is monitored, although for young drivers monitoring or recognition of these effects on operational performance may be hampered in some way. Associations between situational factors and the monitored effects on operational performance are formed that result in adaptations of behaviour on the tactical level (anticipatory avoidance responses, according to Fuller). There also is a direct effect of performance monitoring on tactical behaviour. The effects of age on accident involvement may also be explained in terms of fewer associations between situational effects and operational performance because of limited experience, resulting in fewer anticipatory avoidance responses. However, the comments made on the young driver are highly hypothetical and need to be verified by more rigorous experimentation.

2.4 Adaptive control models

The adaptive control models, referred to by Michon (1985), deal primarily with the operational level of car driving behaviour. These models have been inspired by the principle of adaptive control in which the human operator adapts his control behaviour to the characteristics of the system to be controlled. This concept resembles the use of the term adaptation in this thesis. An important difference lies in the behavioural level at which this process of adaptation occurs: in adaptive control models adaptation occurs on the operational level while in the model of adaptation discussed in this thesis adaptation occurs primarily on the tactical level.

Michon (1985) distinguished between two different classes of adaptive control models; the servo-control models and the information flow control models. The first class is primarily concerned with manual control in the context of signals that are continuous in time, while the second involves discrete decisions. In practice, the distinction has somewhat vanished, resulting in hybrid models. Servo-control models consider driving as a continuous tracking task. These models have been applied to operational performance of steering on straight roads and curves and to obstacle avoidance maneuvers. Input signals are transformed by transfer functions into a vehicle output. Transfer functions represent both driver and vehicle dynamics and contain lead components to account for preview or anticipation of the driver and lag components representing driver and vehicle inertia.

Young (1969) discussed a number of different types of adaptation to the system to be controlled. Input adaptation refers to the ability of the operator to detect familiar or repeated patterns in the input and track these in a predictive or open loop fashion. The adaptive control models applied to the driver task mainly refer to input adaptation. The best known is the STI model described by McRuer et al. (1977). One variant of this model, see figure 6, refers to compensatory steering control on straight roads. In this model the driver is assumed to act as a regulator against external disturbances that arise from wind and road surface effects. Thus, operational performance is continuously adapted to system disturbances and vehicle characteristics. The steering wheel output is determined by transfer functions while the visual inputs to the model are lateral position and vehicle heading errors. In the ‘input adaptation’ models the predictable aspects of the steering task, such as the required steering angle as determined by the road curvature, are described as precognitive tracking while the random components in the input signal are handled by compensatory tracking. Another important type of adaptation is referred to as controlled element adaptation. This occurs when the operator changes his control strategy as an adaptation to changes in the dynamics of the system. If a driver normally drives a sedan but changes to a sports car he has to adapt his steering behaviour to the different steering ratio. In general, any change in vehicle characteristics or vehicle dynamics requires some form of controlled element adaptation. In chapter 4 an experiment on steering during curve negotiation is discussed. In the introduction of chapter 4 it is stated that required steering wheel angle during curve negotiation is determined by curve radius and by speed. Speed then changes the dynamics of the system to be controlled and requires an adaptation of steering wheel angle as a form of controlled element adaptation. In that sense speed is considered as a ‘property’ of the system to be controlled instead of a form of operator adaptation on its own. In the adaptive control models, the operator is described as someone who responds to the task-characteristics instead of someone who actively creates the task. However, because the driving task is self-paced most of the time, the behaviour of the driver affects the dynamics of the task.

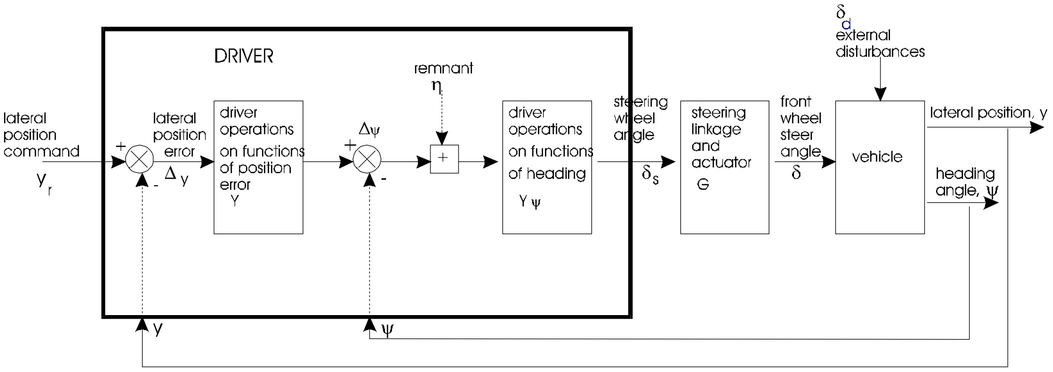

Figure 6. STI compensatory steering model (from Reid, 1983).

Some properties of the adaptive control models.

A consistent feature in attempts to validate these models with human drivers is that subjects are instructed to drive with a fixed speed, thereby excluding possible effects of tactical behaviour on operational performance. Also, the parameters that are found using human drivers often apply to only one situation. Variation in speeds and curve radii will affect the parameters of the models (see for example Donges, 1978). It is argued here that operational performance and behaviour on the tactical level are interdependent and should both be incorporated into a single model.

There are a large number of examples that suggest that speed is used to compensate for detrimental effects of various task-related and situational factors on operational steering performance. For example, Good and Baxter (1986) used the STI model to study steering performance as a function of roadway delineation. The quality of steering was expressed, among other things, by the remnant that accounts for that part of the manual control output that is uncorrelated with the input. A smaller remnant then indicates better steering performance. Wider edge lines resulted in a smaller remnant because of improved vehicle guidance. However, wider edge lines also resulted in higher speed. Also, day time driving resulted in better steering performance and higher speed compared to night time driving. Thus, it appears that factors that improve steering performance result in higher speeds. However, the effects on speed are not accounted for by the model and are considered undesirable artifacts.

Tenkink (1988) studied the effects of sight distances of 27, 37 and 183 meters with fixed speeds. Standarddeviation of lateral position (SDLP) increased with higher fixed speeds over all sight distances with steeper increases for smaller sight distances. A smaller sight distance resulted in a larger SDLP at a given speed. Lowering sight distance thus deteriorated steering performance and this was aggravated with higher speeds. However, if drivers were allowed to choose their own speed, reductions in sight distance resulted in the choice of lower speeds while SDLP was maintained on a relatively constant level, except for very short sight distances of 27 meters where speed was not reduced enough to prevent an increase in SDLP. According to Tenkink, a safety margin based on time may have caused the speed reduction under reduced sight distance, because the speed-distance curve appeared to approach a line through the origin, with a slope corresponding to a minimum time of 1.2 seconds for driving on straight roads. Harms (1993) also studied the effect of reduced sight distance on speed choice and lane keeping. She found that reduced sight distance resulted in the choice of a lower speed, while SDLP was unaffected, even with the shortest sight distance of 30 meters. She suggested that the speed reduction had prevented a deterioration of lateral control performance as a function of sight distance.

These studies suggest that situational factors that affect operational steering performance are compensated for by speed choice if task conditions are self-paced. If drivers are not given the opportunity to adapt behaviour on the tactical level they are forced to improve behaviour on the operational level, and it is under these conditions that the adaptive control models are normally tested.

In most adaptive control models lateral position deviations, heading angle and anticipated curvature are treated as the input variables that are continuously transformed into a steering wheel angle. The validity of the input variables and the assumption of continuous minimization of errors has been challenged by a number of authors. Riemersma (1987) performed a number of experiments to find the visual cues that are used by the driver in steering control. He found that control of lateral position alone is not sufficient for lane keeping in straight road driving and that heading angle is not directly used as an input variable in steering control, in contrast to the assumption of adaptive control models.

Blaauw (1984) studied the multitasking aspects of car driving. A monitoring function was assumed to supervise manual control associated with steering and speed control on the operational level. Because of a supervisory function, perceptual and control actions are not executed continuously, in contrast to the assumption of the adaptive control models, thus allowing free time in-between control actions. Experienced drivers adjusted their steering control better to increased task demands invoked by driving with a constant speed or night time driving compared to inexperienced drivers. Also, in self-paced conditions where drivers were free to choose their own speed, increasing task demands by occlusion or night time driving resulted in the choice of lower speeds.

Godthelp (1984) questioned the assumption of the adaptive control models that the driver behaves in a closed-loop error-correction mode in which continuous attention is allocated to the steering task. He applied the Time-to-Line-Crossing (TLC) as a measure that reflects the time available for the driver before a correcting steering action is needed to prevent a lane boundary exceedence. The amount of time the driver voluntarily refrains from using visual feedback (occlusion time) corresponded closely with TLC values. This means that when the driver has less time available to postpone correcting steering actions, a request for visual feedback is made sooner. This implies that the driver is aware of the time available and that correcting steering actions are generated when some TLC criterion has been reached. Drivers chose occlusion times of about 40% of the available time, irrespective of speed. Also, if steering corrections during the occlusion interval were larger, the driver requested visual feedback sooner, suggesting awareness of the driver's own steering behaviour and a compensatory effect on visual sampling. When, in Godthelp (1984), drivers were asked to switch to error-correction when vehicle motion could still comfortably be corrected to prevent a crossing of the lane boundary, it appeared that drivers chose a strategy where TLC on the moment of steering correction was about constant over different (fixed) speeds. This constancy of TLC over speed was obtained without occlusion, while the strategy of requesting visual feedback when 40% of available time was reached occurred under occlusion. This difference was explained as a result of the degree of uncertainty regarding the vehicle trajectory. Thus, Godthelp found strong evidence that steering control is not continuous, that drivers are sensitive to TLC and that TLC information is used in steering control.

The relation between vehicle dynamics and operational behaviour constitutes an important aspect of adaptive control models. Godthelp and Käppler (1988) found that changing the vehicle characteristics to heavy understeering resulted in increased steering control effort but similar lateral control performance, as evidenced from TLC control performance, compared to a normally understeered car, because drivers were able to develop an accurate internal representation of the vehicle dynamics. In both normal and heavy understeered cars the accepted occlusion times were about 40% of available time, independent of (fixed) speed. This suggests that drivers adapt their visual information intake and steering behaviour to the dynamic characteristics of the vehicle such that the same strategy is maintained. From the results of Godthelp and Käppler it may be inferred that drivers are sensitive to vehicle handling properties and change their operational behaviour as a function of this if the driver is required to drive with a fixed speed. This may be considered as an example of controlled element adaptation and thus as an example of adaptation of operational behaviour. A number of other studies have revealed effects of vehicle characteristics on tactical driver behaviour. Rumar et al. (1976) studied the effects of studded tires on speed choice in curves. Drivers with studded tires drove faster compared to drivers with unstudded tires in icy road conditions. This did not result in lower safety, since the 'safety margin', defined as the difference between real and critical lateral acceleration, was larger with studded tires. Summala and Merisalo (1980) also found that drivers with studded tires chose higher speeds in curves in low-friction conditions and that the safety margin was greater for drivers with studded tires in slippery conditions. The higher speeds with studded tires in low friction conditions may be regarded as an adaptation of tactical behaviour to the increased friction coefficient induced by studded tires. Also, the acceleration capability of cars has been shown to affect behaviour. Evans and Herman (1976) found that drivers accepted smaller gaps with oncoming cars while negotiating intersections if the acceleration capability of the car was higher. However, the physical safety margin was not negatively affected by acceleration capability. Also, newer cars used higher levels of deceleration compared to older cars when they stopped at signalized intersections (Evans and Rothery, 1976). This was explained as a possible adaptation of behaviour (on the tactical level) to compensate for reduced mechanical conditions in older vehicles. Evans and Wasielewski (1983) found that drivers of newer cars and cars with intermediate mass followed with a smaller time-headway. This may also be the result of better deceleration capabilities of newer cars. Evans (1991) postulated that improved braking and vehicle handling characteristics result in increased speeds, closer following and higher speeds in curves. When safety changes are invisible to the user as may be the case with seat belts and increased crashworthiness, there is no evidence of any measurable human behaviour feedback. A similar point was made by Lund and O'Neill (1986). Design changes that reduce the likelihood of a crash do have an effect on behaviour. They stated that how a car is driven depends on feedback to the driver about the car's handling characteristics. Vehicle-related factors may then affect both operational and tactical driver behaviour depending on the visibility of the feedback.

Conclusions and consequences for the present model.

Adaptive control models study the effects of system characteristics on operational behaviour without establishing a link with behaviour on the tactical level. Also, adaptive control models assume that continuous attention is being allocated to the steering task resulting in continuous error correction.

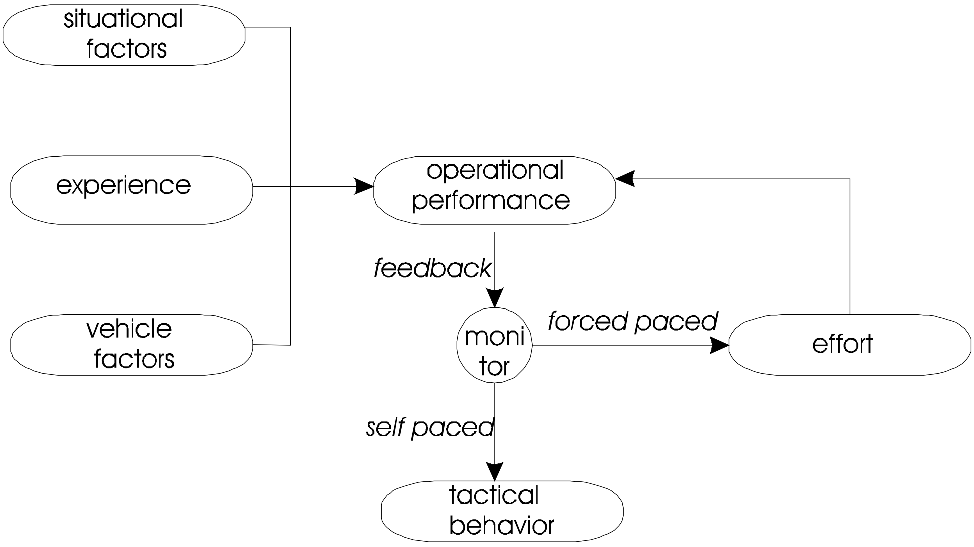

Figure 7. Model of driver adaptation, derived from the discussion of adaptive control models and related research.

Under forced paced conditions effects of vehicle characteristics and situational factors generally affect operational behaviour as is predicted by the adaptive control models. However, car driving is a self-paced task most of the time and it is under these conditions that speed reductions generally occur, possibly as an attempt to compensate for effects on operational performance. Evidence was presented that a time-based variable, TLC, is used by the driver as a criterion for generating corrective steering actions. TLC is determined by operational steering performance, vehicle characteristics, speed and lane width. Effects of situational and vehicle-related factors on steering performance and vehicle dynamics may then be compensated for by a speed reduction, such that a constant safety margin is maintained.

From the discussion of the adaptive control models, a third version of the model of driver adaptation is presented in figure 7. Various situational factors, driving experience and vehicle characteristics affect operational performance. This effect is monitored and adapted for either via allocation of effort in order to improve operational performance, or via an effect on behaviour on the tactical level.

2.5 Connecting operational and tactical behaviour: a driving model based on safety margins

The adaptation model as it emerges from the discussion of the literature on driver models and driving behaviour is presented in figure 8. This model states that several factors affect operational performance. For example, temporary states, induced by alcohol or marijuana, affect psycho-motor abilities while psycho-motor abilities affect operational performance. Also, vehicle related factors situational factors and driving experience may affect operational performance in accordance with the adaptive control models. The effects on operational performance are perceived via a feedback loop by the driver, although alcohol and young age may inhibit this. If driving is self-paced, the driver adjusts behaviour on the tactical level by either increasing speed or decreasing headway during car-following if operational performance is improved, or by decreasing speed or increasing headway if operational performance deteriorates. If there are no opportunities to adapt behaviour on the tactical level, i.e. when the driving task is forced-paced, the driver may elect in allocate more effort to increase operational performance. Adaptation of tactical behaviour or effort allocation does not only occur as a response to momentary changes, but also in the form of an anticipatory response. This response is the result of learned associations between various factors and effects on operational performance allowing an adaptation of tactical behaviour in the absence of an effect on operational performance. For example, if the driver has learned the effects of rain on road friction and on operational steering performance, he may already choose a lower speed before these effects are actually experienced during a particular period of rain

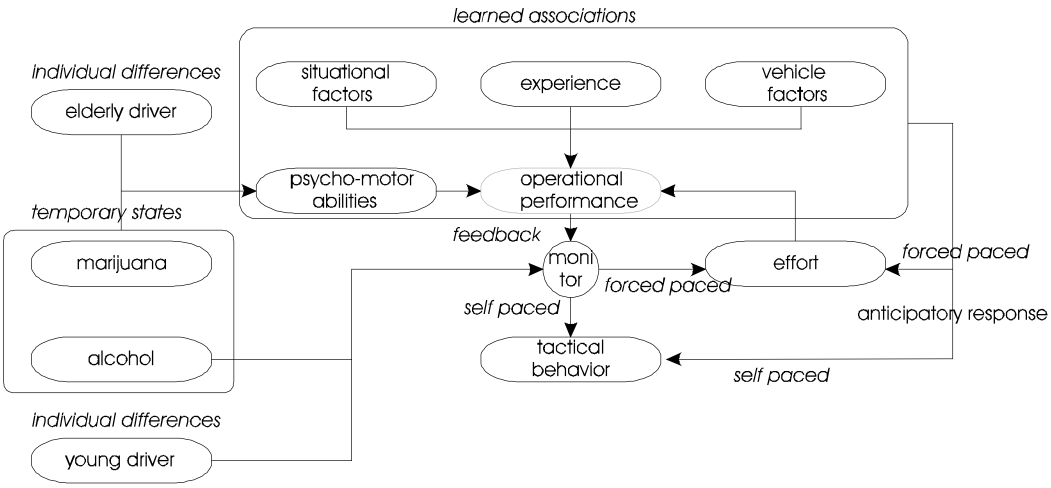

Figure 8. Adaptation model of car driving.

However, the mechanisms by which this process works are still unclear. The extent to which speed is adapted cannot be predicted because of the lack of a unitary measure that incorporates both behaviour on the operational level and the tactical level. An organizing principle may be found in the operation of safety margins. Earlier it was mentioned that, according to Summala (1985), drivers maintain safety margins and that this process should be analyzed in more detail in subtasks such as lane keeping, car-following, curve negotiation, gap acceptance and overtaking. Rumar (1988) shares the point of view that drivers control safety margins instead of risk. He proposed that a safety margin may be operationally defined as an area of safe driving around the car, equivalent to the old idea of the subjective dynamic field that expands in front of the car if speed is increased (Gibson and Crook, referred to by Rumar, 1988). Safety margins can be operationally defined as distance or time related measures (Summala, 1988), although they have also been described in other terms such as a difference between actual and critical lateral acceleration. Summala has mentioned the time-to-line-crossing (TLC) and time-to-collision (TTC) as examples of safety margins.

Operational control in car driving is usually separated into lateral control and longitudinal control. Lateral control refers to keeping the car within the lane boundaries or to steering away from objects that block the path of the vehicle. Longitudinal control refers to activities related to the control of speed, such as braking and use of accelerator and clutch. It is proposed here that the driver uses TLC as a safety margin during lateral control, while TTC, or more generally time-to-object (TTO), is used as a safety margin during longitudinal control. Ofcourse, TLC is the same as TTO to either of the lane boundaries. Thus, safety margins are proposed to represent time-related measures. This has a number of advantages. Because driving is a dynamic task in which the driver and other traffic participants move with varying speeds, time may be used as a relatively constant parameter that can be controlled by means of tactical adaptations of speed or headway. In addition to this, there is abundant evidence that humans are very well equipped to perceive time to static and dynamic objects in dynamic situations.

Lee (1976) argued that drivers are able to control braking based on time-to-collision (TTC) information from the optic flow field (visual angle divided by the angular velocity). This would enable the driver to judge the moment to start braking and to control the braking process. The ability to use TTC information and the actual use of this information has been established in a number of studies, referred to in subsequent chapters on car-following and braking. Van der Horst (1990) showed that time-to-intersection (TTI) is used by the driver in the decision when to start braking as well as in the control of braking. The TTI at which the driver starts braking appeared to be rather constant over speed. In stopping for a stationary object the minimum TTC during the approach was also about constant over different approach speeds. This suggests that time-to-object may be used as a safety margin the driver is not willing to exceed in longitudinal control tasks. Behavioural manifestations of adaptation on the tactical level in longitudinal control tasks are adaptation of speed and of time-headway during car-following. It may be argued that poorer performance in operational control increases the chance that a TTO safety margin is exceeded. In approaching a stationary object such as a traffic light, for which the driver has to stop, the driver may decrease his speed earlier in order to compensate for this. During car-following, the driver may choose a larger time-headway. This allows more time to react if the lead vehicle decelerates and thus minimizes the chance that a critical TTC is exceeded.

As was already mentioned in the previous paragraph, 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 TLC is too small, it can be increased by choosing a lower 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, steering performance, speed, road width and curve radius. TTC is affected by braking characteristics of the vehicle, braking performance of the driver, initial headway, and behaviour of the lead vehicle. Thus, these measures of safety margin integrate many different aspects of the driving task, such as operational performance and tactical behaviour, and may be regarded as good candidates for the unitary measures that serve as an organizing principle in the model presented here.

The general idea underlying the adaptation model is that any factor that affects operational performance may result in adaptation of behaviour on the tactical level, if the driving task is self-paced and if the driver is able to perceive these effects on operational performance. In this, feedback of the effects on operational performance may have a direct effect on tactical behaviour. For example, windgusts affect operational performance which, if detected by the driver, result in the choice of a lower speed. Alternatively, feedback effects may result in learned associations of the effects of various factors on operational performance, resulting in anticipatory adaptation responses. If, for example, the driver detects a fog bank in the direction of the vehicle path, he may already decrease speed, although the effect of fog on operational performance has not been experienced yet. The speed reduction then is an anticipatory adaptation response resulting from associations learned in the past between fog and effects on operational performance. If the driving task is not fully self-paced, the driver may elect to increase effort in order to improve operational performance. Time-based safety margins are proposed as the regulating mechanisms of behavioural adaptation. The strategies involved in this are a matter of further experimentation.

In the experimental section of this thesis two driving tasks, curve negotiation and car-following, are analyzed in more detail. Curve negotiation is essentially a lateral control task, while car-following is predominantly a longitudinal control task. Figure 9 presents a model for lateral control tasks. Figure 10 does the same for the longitudinal control tasks of car-following. Both models are almost identical, although they differ in the kinds of safety margins and behavioural adaptations.

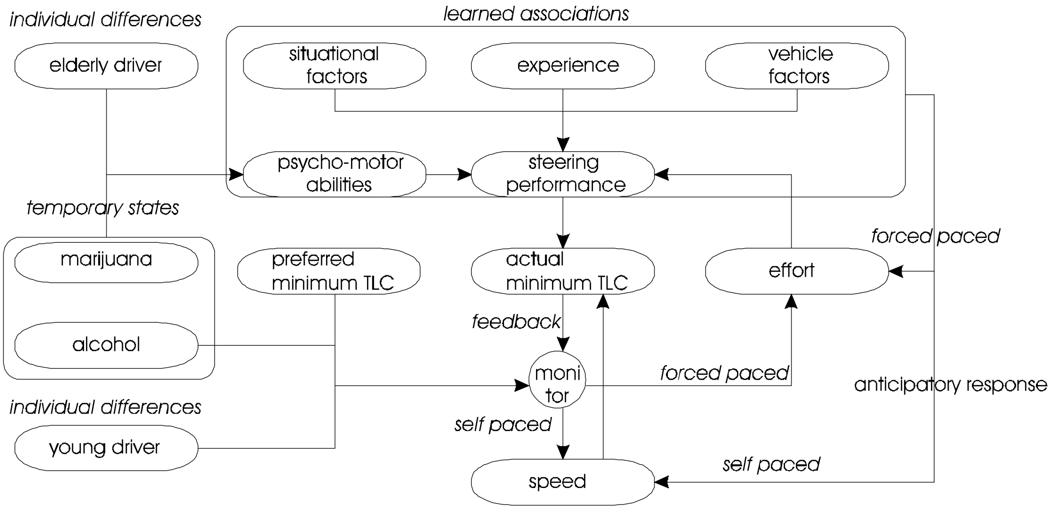

Figure 9. Model for the lateral control task.

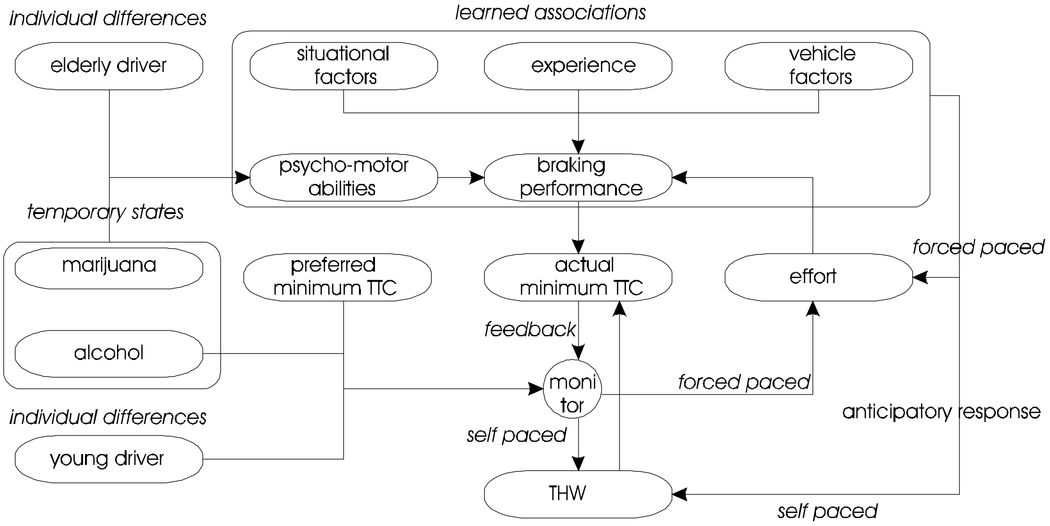

Figure 10. Model for the longitudinal control task of car-following.

2.6 Experimental validation of the model: research questions

Two different car driving tasks, negotiating curves and car-following, are studied in detail in the chapters that follow. The goal of the six experiments discussed in the chapters 4 to 9 is to examine one aspect of the present model: the prediction that individual differences in operational performance affect behaviour on the tactical level.

In experiment 1 the driver task of curve negotiation is analyzed. It focuses on the relation between steering performance and speed choice in curves with different radii. Drivers differ in steering performance in that some drivers consistently commit larger steering errors than others. Curve radius is manipulated as an situational factor that affects operational performance. In general, steering errors are larger in curves with smaller radii. It is then investigated how speed is affected by curve radius and by individual differences in steering competence as an adaptative response to steering performance. Drivers already decrease speed before the curve is entered and, thus, before the effect of radius on steering performance is experienced. The adaptation of speed then is assumed to be an anticipatory adaptation response that has been learned by experience in curve negotiation. Time-to-line-crossing (TLC) is used as a safety margin and it is explored whether this safety margin is affected by curve radius and steering competence.

In the experiments 2 to 6 the longitudinal control task of car-following is analyzed. It is examined whether choice of time-headway (THW), as behaviour on the tactical level, is affected by operational braking performance. During car-following, the driver has to take account of the possibility that the driver of the lead vehicle might brake. However, the driver never knows when the lead vehicle will brake, and if it does, how hard it will brake and for how long. It is then assumed that the driver has learned the quality of his or her own braking performance from previous experiences and that this results in a preference for a specific THW. THW is the time available to the driver to reach the same level of deceleration as the lead vehicle in case it brakes, without becoming involved in a collision. Braking performance is assumed to affect the time required to reach the same level of deceleration as the lead vehicle. Adaptation of THW may then be regarded as a tuning of available time to required time that is determined by braking performance.

In experiment 2 it is investigated whether choice of THW is related to the ability to brake as fast as possible in situations where the driver knows that the lead vehicle will brake and the level of deceleration at which it will brake. In this experiment the locus of effect of differences in braking performance is examined as well.

In experiments 3 and 4 it is examined whether choice of THW is constant over different speeds and whether individual differences in choice of THW are consistent. In experiment 3 the role of time-to-collision (TTC) on the moment the lead vehicle starts to brake is examined in detail. More specifically, it is tested whether the sensitivity of the braking response to TTC information differs as a function of preferred THW. In experiment 4 the process of braking itself is examined in more detail and a model of braking is presented starting from modern theories of perceptual-motor performance. The process of braking is separated into three sequential phases: a reaction time (RT) phase, an open-loop phase covering the initial motor response, and a closed-loop phase during which visual feedback is used to control the process of braking. It is tested whether TTC on the moment the driver detects the braking of the lead vehicle affects the early motor phase (open-loop component) of the braking process and whether the motor response differs as a function of preferred THW in unexpected emergency braking situations.

In the experiments 5 and 6 it is tested explicitly whether short followers differ from long followers in the open- and closed loop phases of the braking response by manipulating both phases. However, in experiment 5 specific task-related factors induced startle responses and vigilance effects requiring some methodological changes in the final experiment. In experiment 6 the level of deceleration of the lead vehicle is manipulated. This affects the TTC on the moment the driver detects the deceleration of the lead vehicle and this procedure aims to manipulate the duration of the open-loop response. It is tested whether the open-loop response of short followers is more strongly affected by this manipulation compared to long followers. This would support the idea that the sensitivity of the motor response to TTC information differs as a function of preferred THW, and thus, that short followers differ in operational performance from long followers. It is also examined whether preferred THW is related to differences in performance in other tasks that require a fast dynamic perception-response coupling as a test of the hypothesis that preferred THW is related to perceptual-motor abilities that are more general than braking performance.

Chapter 3

3. Instrumentation: the driving simulator

3.1. Background

The preparation of the experiments discussed in this thesis required a substantial amount of software design and implementation for the TRC driving simulator. A full description of the functionality and implementation of the simulator is beyond the scope of this chapter. The reader is referred to other documents for more detail and background (for example Van Wolffelaar & Van Winsum, 1992; Van Wolffelaar & Van Winsum, 1994). [edit WvW: For a modern version of the software, see http://www.rijschool-simulator.nl/driving-simulator.html]

The driving simulator of the Traffic Research Center (TRC) was developed as an instrument for behavioural research of driving. The GIDS project in which the TRC was involved at that time required a simulation testbed for mathematical driving modeling. Because of the dynamic complexities of driver tasks in multi-vehicle traffic, a dynamic traffic simulation was required as a test tool (Van Winsum and Van Wolffelaar, 1993). The objective of GIDS, an acronym for Generic Intelligent Driver Support, was 'to determine the requirements and design standards for a class of intelligent co-driver (GIDS) systems that are maximally consistent with the performance requirements and performance capabilities of the human driver.' (Michon and Smiley (1993). A prototype system was developed as a demonstrator for the essential features of the GIDS concept. One of the functions of the GIDS system was to compare required driving behaviour with actual behaviour. Required behaviour was modeled for a number of driving tasks and implemented in a computer system (Van Winsum, 1991; McLoughlin et al., 1993). It was decided at that time to design and implement a dynamic traffic simulation model and connect this with the driving simulator under development. From that moment the driving simulator evolved as a dynamic driving simulator with an interacting traffic world that could be connected to the GIDS system to serve as a test bed. After this, the simulator was also used as a testbed for other external driver support systems.

However, most importantly, the simulator is an instrument for the study of driver behaviour. Because it is used by researchers with very different questions and requirements, flexibility in software design has been considered to be important. This was accomplished by using the object-oriented computer language C++, and a multi-purpose UNIX machine instead of a single purpose dedicated simulation machine. To further increase flexibility for the researchers and to facilitate the design and testing of the experiments reported in this thesis, a fourth generation simulation language, SSL (Scenario Specification Language), was developed for the specification of experiments, together with a specification language (NSL, Network Specification Language) and software tools for roadnetwork creation. Data-sampling and data-processing facilities were added to facilitate experimentation.

3.2 The structure of the simulator

The simulator is composed of a number of software and hardware components that are connected via interfaces. The 'conventional' driving simulator consists of a physical car mockup, a car model implemented in software and a graphics system, together with a static road network environment. A dynamic traffic environment is added to this. The structure of these components as well as the object relations are shown in figure 1. In this figure several types of relations can be seen. An "is-a" relation specifies that a certain object type is a subtype of an other more abstract object type. For example, a BMW-car is some kind of car. This means that it inherits the functionality of the more abstract object type car. A "has-a" relation specifies that a certain objects has another object as a member. For example, a car has a traverser. The heavy printed arrows specify the direction of the flow of information. For example, there is an information flow from the object roadnet to the object sensor. This means that a sensor requests information from a certain instantiation of the object roadnet.

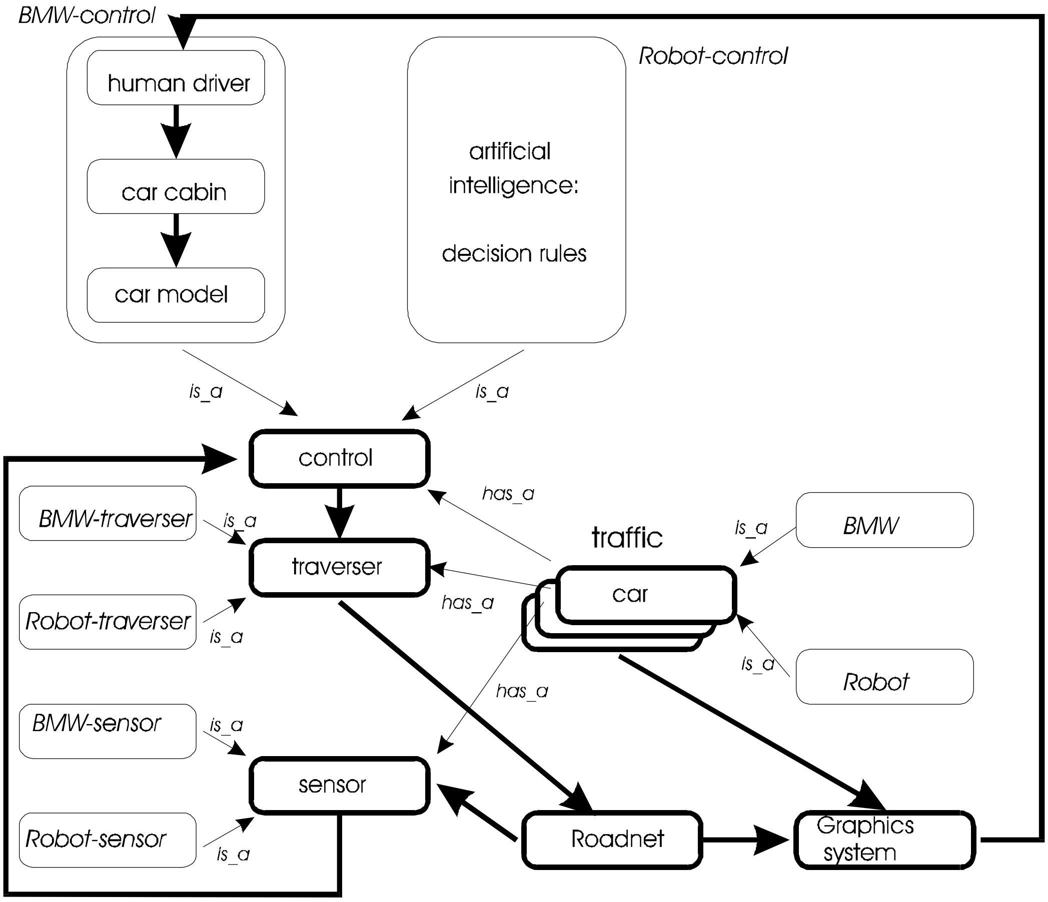

Figure 1. Logical structure of components of the driving simulator and relations between objects.

In addition to this, a number of facilities related to data-sampling and processing and experimental control are added to the simulator.

Car cabin. The steering wheel, clutch, gear, accelerator, brake and indicators of the car (a BMW 518) are connected to a Silicon Graphics Skywriter 340VGXT computer (IRIS). Electromotors and other electronic appliances are built in the car to excert forces on the pedals and steering wheel and to send data on the steering wheel, accelerator pedal, brake pedal and indicators to the IRIS computer for further processing by the car model.

Car model. The IRIS computer processes these signals in a separate process referred to as the car model. The car model is described in more detail in Spaargaren (1994). It computes the longitudinal and lateral speed and acceleration that are the result of physical characteristics of the car and the input from the car cabin. From this the new coordinate position in the artificial world the car is driving in is computed. The output of the car model is used by the car traverser and by the graphics system. The traverser constitutes the link with the dynamic traffic process while the graphics system presents the output of the full system in a real-time visual format to the driver.

Graphics system. On a projection screen, placed in front, to the left and to the right of the driver, an image of the outside world from the perspective of the driver with a horizontal angle of 150 degrees is projected by three graphical videoprojectors that are controlled by the graphics software. Images are presented with a rate of 15 to 20 frames per second, resulting in a suggestion of smooth movement. The visual objects are buildings, roads, traffic signs, traffic lights and other vehicles.

In addition to this, the sound of the engine, wind and tires is presented by means of a digital soundsampler receiving input from the simulator computer.

Logical network (Roadnet). The logical network is the static environment in which the simulator car and traffic operate. The static environment consists of a database with a network of roads, traffic signs, traffic lights and buildings. This database is used for the visualization of the environment by the graphics system and by the artificially intelligent traffic to evaluate the present situation. The database can be generated in two ways:
- by NSL (Network Specification Language). This is a user specification language, created for the TRC simulator (Van Winsum, SSL/NSL specification release 1.2, 1994), by which a network of roads can be specified as an ASCII text. This text is processed by an NSL interpreter program that generates a road network database that is used by the simulator (Van Winsum, 1994, NSL scanner/ parser/interpreter computer program).
- by means of an interactive graphical program written in C++/OSF Motif (Van Winsum, 1993, program WORLDED). The user can specify a network of roads by means of click and point operations. The output of the NSL interpreter can also be used as input for this program to visualize and change the network.

The network consists of a structure of three base tables: a table with intersections, a table with paths and a table with segments. An intersection is a point in the network coordinate system with 1..n, {n >= 1}, outgoing paths. Coordinates are in meters. The following relations hold:

> - n = 1: the intersection forms a terminal point in the network. If cars approach this intersection they cannot proceed beyond the intersection and provisions are made to ensure that the car turns around in the opposite direction as soon as the intersection is reached. The intersection has no physical layout and has the appearance of an ending road. The implication is that it is not possible for cars to move off the logical world.
> - n = 2: the intersection is a virtual intersection in the sense that it has no specific layout and is not treated as an intersection by the traffic. The only purpose of creating such an intersection is for the convenience of the network constructor.
> - n > 2: the intersection has more than two branches.
>
> An intersection is of a certain type (f.i. a roundabout), it can be controlled by traffic lights with a certain control strategy, and it contains a list of references to outgoing paths. This list is ordered such that the path connections to the intersections are counterclockwise. In addition to this the intersection contains information about the layout, which is used by the graphics system and by the traffic.

A path is a logical connection between two intersections and always has one direction. It must start at one intersection A and end at one intersection B, where A may be equal to B. If A=B then the path is logically a circular path. All paths have precisely one path in the opposite direction, referred to as a counterpath. It has a list of references to segments with 1..n elements, {n>=1} . This list is ordered such that the segments are in successive order. A path also contains information on right-of-way at the intersection at the end of the path, whether entry into this path is allowed, a reference to a traffic light at the end of the path if there is one, and information on buildings on the right side of the segments on the path.

To every path an ordered list with references to cars is attached. This list is ordered such that it reflects the order of the cars on the path and it may be empty. Cars can be added or removed at any time during the simulation process. In this way the simulator car and the computer controlled cars are connected to the static environment. Because every car is an object in the software-engineering conception that it has its own functions and data-structures, every car performs its own administration of detailed position (coordinates, distances from the last intersection and from the edge of the road etc.) in relation to the logical network.

The concept of path corresponds to the terminology of graph theory. Using that terminology, intersections are nodes.

The combination of nodes and paths may be described as a directed graph with the following properties:

- Suppose the network is represented as the graph G=(P,Z), with P being the set of intersections or nodes and Z being the set of ordered relations between the intersections, then P = {0..n} with n > 0. The fact that all intersections are member of a set ensures that all members occur once. The number of the intersections are in successive order. A set of intersections is, for example, {0,1,2,3}, meaning that there are 4 intersections. The set {0,1,3,4} is incorrect because the number 2 is missing.
- Z contains the relations between two nodes A and B, for example {{1,2}, {1,3}, {1,1}}. If {A, B} is a member of Z then {B,A} is also a member. This shows that all paths have a counterpath. A road can be traveled in two directions and this is the reason that every path has a counterpath. If only one-way traffic is allowed there are still two paths because physically it is possible to enter a one-way street into the wrong direction although legally it is not allowed.
- The fact that Z is described as a set suggests that the member {A,B} may occur only once. This restriction has been abandoned for practical purposes. There may be more than one instantiation of the relation {A,B}. In that sense Z is not a set but a collection. This restriction was loosened because sometimes there is more than one road between two intersections.
- A further restriction to the graph specification is that all nodes must occur in at least one relation, that is, a node that is fully unconnected is not allowed.

A segment is represented as a line through the middle of a roadpiece. It can be either straight or curved and is undirected. Segments are members of ordered lists connected to a path and the ordered list must contain al least one segment. A segment must be a member of one and only one ordered list. Segments represent the physical layout of the road, while a path represents the logical presence of a road. The direction depends on the path the segment is in. If the segment is straight the two end points are given in coordinates. If it is curved the segment contains the necessary information on the curvature, such as the radius, the centerpoint of the arc etc. A segment has a certain lane-width. At present only two-lane segments are allowed.

Traffic signs, buildings and traffic lights are connected to the network and have a certain position, angle, and type. Within the simulator program this roadnet representation is implemented as the separate object class in the roadnet module (Van Winsum, 1992, computer program class c_roadnet, roadnet.c). This object performs its own administration and can be queried from outside via an interface.

The following is an example of a definition of a simple network with NSL.

```
Define Inter[0] {
  X := 100; Y:= 100;
}

Define Segment[0] {
  Type   := Straight;
  StartX := Inter[0].X;
  StartY := Inter[0].Y
  Length := 100;
  Angle  := 90;
}
```

In this definition a straight road of 100 meters with an absolute angle of 90 degrees is created, starting at coordinate position [100, 100]. Paths are added automatically by the system. Since this definition of a network would result in a path without an end node, the system creates an end node (intersection number 1). Since the lane-width is not specified, the segment is assigned the default lane-width of 3 meters by the NSL system. In this case the NSL interpreter creates 2 intersections, 2 paths and 1 segment, no traffic signs, traffic lights or buildings. NSL contains a number of geometric transformation methods and rules to assists the user and to make it easier to build the network.

Traffic. Traffic consists of a list of cars that may be controlled by a human driver (the simulator car) or by an artificially intelligent 'driver'. Every car has a number of properties, such as a length, a width, a wheel-base and so on and a number of objects that are needed for driving in the logical world. These objects are a traverser, a sensor and a decision (control) mechanism. In the case of a human-controlled car the decision mechanisms is of course the human driver who, together with the car model, determines the movement of the car. In the case of a computer controlled car the decision mechanism is composed of a set of decision rules. Traffic is implemented in the simulator program as a separate object container class (Van Winsum, 1992, computer program class c_traffic, traffic.c). It contains all kinds of methods for adding or removing cars from a traffic list. The class traffic contains references to cars which may be very different in type. The mechanisms of late binding and virtual classes and inheritance, which are properties of the object-oriented methodology used, ensure that in the future all kinds of other moving objects such as pedestrians and bicyclists may be added to traffic. Every car has its own instantiation of a traverser, sensor and control object. These objects also may be of different types. For example, a human controlled car (the simulator car) would need a somewhat different traverser than a computer controlled car or maybe a pedestrian.

In the case of a human driver, the output of the car model, i.e. the speed and the angle of lateral displacement, are input for the traverser. For computer-controlled cars, the output of the artificially intelligent decision mechanism is the input for the traverser. The traverser calculates the lateral position (with respect to the right side of the road), the longitudinal displacement with respect to the road, it connects the car to the network of roads, checks which path is selected if the car is on an intersection and performs a number of other checks to maintain the position of the car accurate with respect to other traffic. It uses deadreckoning techniques in this process. The traverser is the interface between traffic and the road network and it also connects the simulator car with the interactive traffic world. The traverser is implemented as a separate object class in the simulator program, such that every car has a reference to its own instantiation of a traverser object (Van Winsum, 1992, computer program class, c_traverser, travers.c)

The sensor is an object that really consists of a set of sensors. Both the human controlled car and the computer controlled cars have a sensor object but they use it differently. In general, the sensor is used to 'look' into the network. In this way every car, including the simulator car, can evaluate the present type of road and curvature, evaluate the distance and speed of traffic in front etc. This means that the sensor is an interface between the network and the car in that it requests information from the network. The human controlled car uses this information for data storage purposes and to give input to driver support systems. The computer controlled cars use this information for the decisions they are required to make concerning their speed and course. Sensor is implemented as a separate object class in the simulator program (Van Winsum, 1992, computer program class c_sensor, sensor.c). Every car has a reference to its own instantiation of a sensor object.

The control mechanism for the human driver is the human information processing system that uses visual information received via the graphics system, to exert the controls in the car cabin. These car control signals are processed by the car model. The output of the car model is used to update the graphics and as input for the traverser that connects the simulator car to the network. The control mechanism of the computer controlled cars consists of a set of decision rules. Every computer controlled car has rules for different driver tasks on the tactical level. These tasks are related to curve negotiation, car-following, overtaking, negotiating intersections, speed choice on straight roads and processing road sign information. The car evaluates which tasks are presently performed and computes a required speed and lateral position. Since multiple tasks can be performed at the same time, a decision mechanism selects the appropriate speed and lateral position together with the required acceleration and wheel-angle to reach this state, after all tasks have been evaluated for the present car . This results in a natural and human-like behaviour that contributes in an important way to the fidelity of the simulator. For computer controlled robot cars the artificial intelligence is implemented in a separate object class in the simulator program (Van Winsum, 1992, computer program class c_control, control.c).

3.3 Data collection and processing

A large quantity of performance data can be collected with any sampling frequency. Examples are time-to-collision, time-to-intersection, time-to-line crossing, lateral position, speed, acceleration, brake force and so on. The user creates an ASCII text with keywords that specify the sample frequency and the data to sample with that frequency. The data are then sampled during a simulation run and stored into a binary file. The real-time handling of data-storage during a simulator run is controlled by a separate object class c_data that is implemented in the simulator program (Van Winsum, 1992, computer program class c_data, newdata.c).

After a simulator run the data can be visualized and preprocessed with a graphical program written in C++ and X-windows/OSF motif (Van Winsum, 1994, program DATAPROC).

For the experiments described in this thesis the real-time sampling of time-based information was required. The variables used are TTC (time-to-collision), TLC (time-to-line crossing) and THW (time-headway during car-following). These measures are defined and implemented as follows:

- THW is defined as D/u
for u > 0, else THW = infinite (undefined)
with D = bumper to bumper distance in meters along the path between
the simulator car and the lead vehicle, and
u = speed of simulator car in m/s

- TTC is defined as $D/(u - u_{lead})$
for $(u - u_{lead}) > 0$, else TTC = infinite (undefined)
with u_{lead} = speed of lead vehicle in m/s

- TLC is calculated differently depending on whether the car is on a straight road or in a curve.
In general, TLC = DLC/u,
for u > 0, else TLC = infinite (undefined)
with DLC = distance to line crossing along the vehicle path and
u = speed of simulator car in m/s.

DLC is solved goniometrically using the cosine rule. Normally, the car is not driving in a straight line but it alternates between curves to left and to right. The radius of the vehicle path is calculated using the coordinates of the centerpoint of the curve the car is driving. This centerpoint is calculated as the point where the perpendicular lines through the frontwheel and the rearwheel, with slipangles added to the wheelangles, intersect. *Rv*, the vehicle radius, is then computed as the distance between the center of gravity of the car and the centerpoint of the vehicle curve. Rv_1 then is the distance between the front (left or right) wheel and the centerpoint of the vehicle curve. *TLC* then measures the time until either the left or right front wheel crosses the left or right lane boundary, given the current vehicle path and speed.

First the case for straight roads is described if the vehicle makes a left turning curve, see figure 2. *DLC* is computed as $a * Rv_1$. Since Rv_1 is known, only a has to be computed, using the cosine rule.

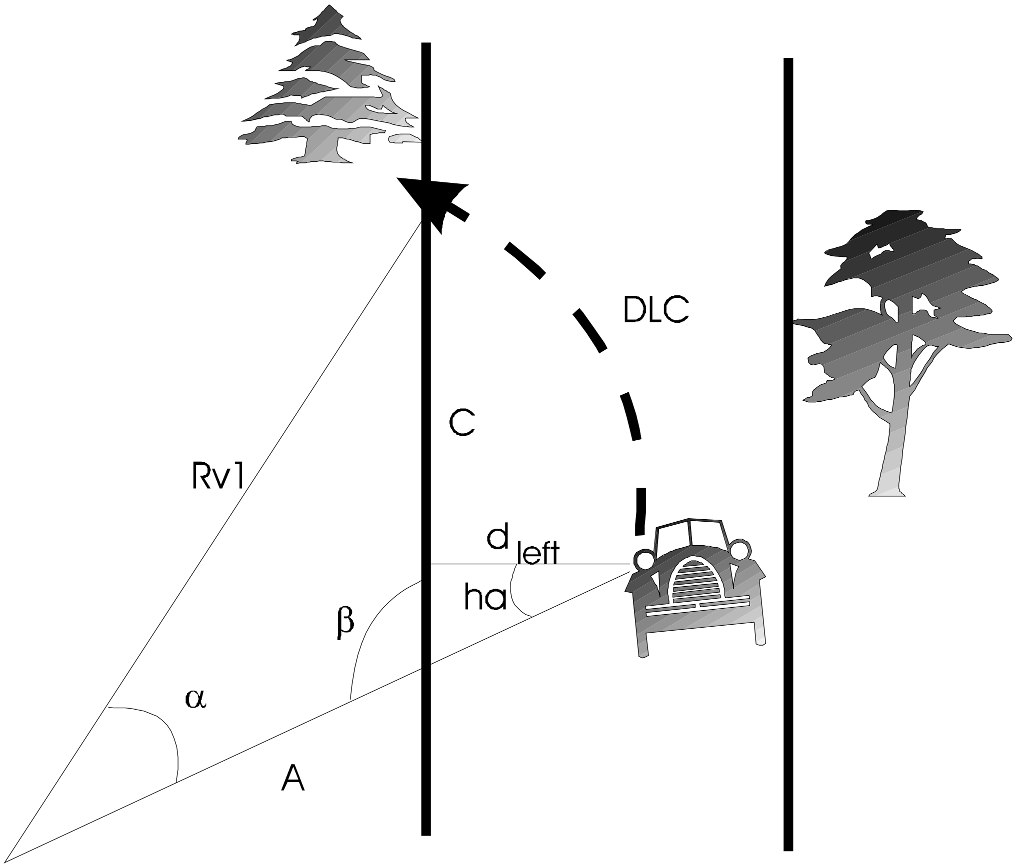

Figure 2. Determination of the length of the arc DLC for driving on straight roadsections.

- The length of the linepiece *A* is computed as $Rv1-(d_{left}/\cos(ha))$, with d_{left} being the distance between the left frontwheel and the lane boundary (in a line perpendicular on the road) and *ha* the angle between the line perpendicular on the road and the line from the front wheel to the centerpoint of the vehicle curve.
- The length of the linepiece *C* is computed as $(2*A*\cos(ß)+\sqrt{((2*A*\cos(ß))^2-4*(A^2-Rv_1^2))})/2$

Then $\alpha = \arccos((A^2 + Rv_1^2 - C^2)/(2*A*C))$

and $DLC = \alpha*Rv_1$

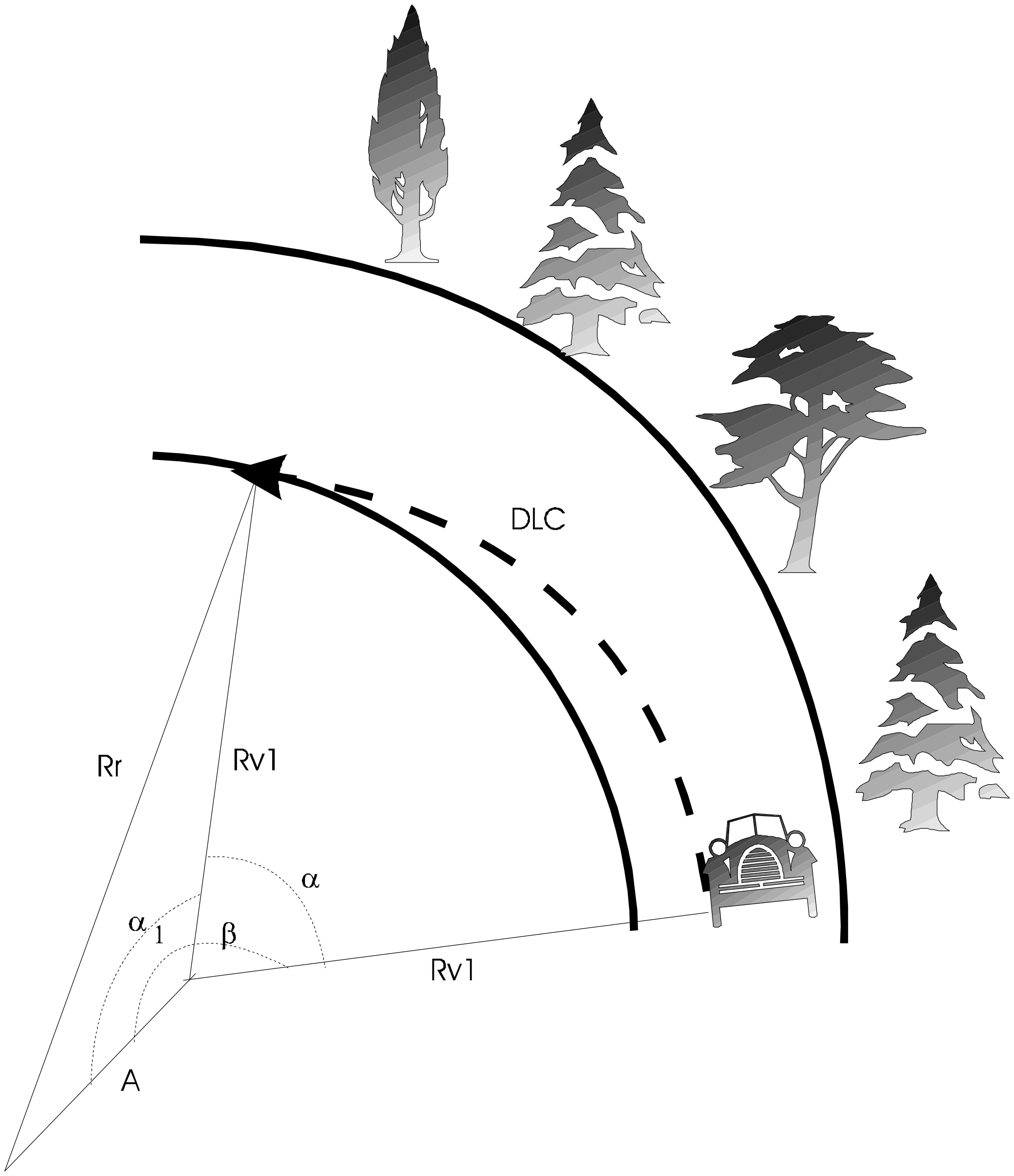

Figure 3. Determination of the length of the arc DLC for driving on curved roadsections.

Figure 3 shows the situation for determining the TLC while the car is negotiating a road curve. Again, *DLC* is determined as $a*Rv_1$. In this case a is computed differently.

- The length of linepiece *A* represents the distance between the centerpoint of the roadcurve and the centerpoint of the vehicle curve.
- Angle *ß* is computed as the angle difference between the line from the centerpoint of the vehicle curve to the centerpoint of the roadcurve and the line from the centerpoint of the vehicle curve to the left front wheel (if the vehicle turns towards the inner lane boundary).
- Angle a_1 is computed as $\arccos((A^2 + Rv_1^2 - Rr^2)/(2*A*Rv_1))$
- α= ß - α_1 and DLC = $\alpha*Rv_1$

In addition to this, vehicle control information was required for the experiments. The position of the accelerator pedal, expressed as a percentage pressed, the position of the brake pedal and the force excerted by the foot on the braking pedal were used in the studies on car-following, while steering wheel angle was used in the study on steering performance and curve negotiation. The results of these control actions, such as speed, acceleration, heading angle and lateral position, were sampled and processed as well.

For every experiment automatic data processing programs were written to extract and process the required data. These data were then transformed into a format suitable for processing by SPSS.

3.4 Scenario Specification Language (SSL)

SSL is a user specification language that was defined and implemented as a tool for specification and design of experiments. It contains most of the functionality of the simulator. A description of SSL then essentially gives a description of the functionality of the TRC simulator. For a full specification of the language the reader is referred to the SSL/NSL specification document (Van Winsum, 1994).

An ASCII file with SSL commands is analyzed by a scanner and parser module during initialization of the simulator program and syntactical errors are reported to the user. (Van Winsum, 1994, SSL scanner/parser/interpreter modules). If no syntactical errors are found, the SSL commands are converted to an internal data-structure that is interpreted in real-time by the SSL-interpreter during execution of the simulation process. Since the simulation process is a dynamic process in which the state is determined by SSL specifications, the human driver, the behaviour of traffic and by the process operator who interacts with the computer via the user interface, the course of events is not deterministic. However, SSL commands can be used to force identical situations for all subjects in an experiment. Since SSL commands are often conditional, the state of the traffic world can be queried and events can be triggered if some condition is true or false.

Scenarios are defined in a SSL text file. A scenario is a predefined list of situations with a start and an end condition: the scenario starts when the start condition is fulfilled and terminates when the end condition is fulfilled. A scenario may involve 0..n cars, referred to as participants, in addition to the simulator car. A participant is a car that performs conditional actions. A scenario may be used for controlling traffic and traffic lights, for indicating when data must be stored, for communication with the driver with spoken or written messages, for sending messages to other devices, and so on. SSL is not exclusively a language for specification of traffic situations during an experiment. It also may be used for rapid prototyping of driver support systems, for creating test situations and for debugging. It is important to note that SSL is often used to override default settings and default behaviour. For example, if a computer-controlled car is created with SSL, the car follows its own rules unless specified differently with SSL.

The following is an example of an SSL description.

```
Define Scen[1] {
  Var { time; }
  Start {
     When ( Part[MainTarget].LeadCar != Absent and
          Part[MainTarget].DisToLeadCar < 50 );
     Scen[].NrTimes := 1;   time := runtime();
  }
  End {
     When ( runtime() - time > 20 );
  }
  Define Part[1] {
    Start {
       Part[].CarNr  := Part[MainTarget].LeadCar;
       Part[].MaxVelocity := 50/3.6;
    }
    End {
       Part[].MaxVelocity := 100/3.6;
```

```
    }
  }
}
```

This scenario specifies that if there is a lead vehicle and the distance to it is less than 50 meters then this lead vehicle starts to drive with a maximum speed of 50 km/h during 20 seconds. After 20 seconds (at the end of the scenario) this vehicle pulls up to a speed of 100 km/h.

SSL files contain the full script for an experiment and are thus complete specifications of an experiment. This ensures repeatability and detailed documentation of experiments. Since researchers are able to make their own SSL script files they can design and test experiments with a minimal dependency on technical staff and computer programmers.

3.5 The use of the simulator in the experiments

The driving simulator offers a number of advantages compared to studying driver behaviour on the road.

1) The sensors of the simulator car and of other cars used in the car-following experiments contain important information that is much harder to obtain with current technology in a real world test situation. This information is vital as input for the control of experiments and data-sampling. For the experiment on curve driving the measurement of TLC information during curve negotiation would be very hard to obtain in real world driving. A simulator is the only practical way to obtain complex measures such as the TLC in curves. Although time-to-collision information may be obtained during on-road experiments it is measured more practically and efficiently in the simulator.
2) All kinds of situations can be generated and tested that would be very hard or impossible to generate in the real world. In the curve negotiation experiment the drivers are required to negotiate a number of different road curves with a specific lane width and radii. Roads with the precise characteristics required by this experiment are very hard to find in the real world. During the car-following experiments the lead vehicle was sometimes required to drive with a certain fixed time-headway in front of the simulator car. This would be difficult to establish in on-road experiments.
3) The responses of drivers to maneuvers too dangerous to be tested in real world driving can easily be tested in the simulator. This is especially important in the car-following and braking experiments discussed in the chapters 5 to 9.
4) Situations can be brought under experimental control. This is important for the comparability of the results since all subjects have encountered precisely the same situations. In on-road experiments traffic density and weather conditions are hard to control. In this respect a simulator has important advantages compared to real world experiments.

In the experiments performed in the context of this thesis, the time-based safety margins TLC and TTC play an important role. The perception of TTC has been studied in a large number of experiments (see chapter 6). These studies have given strong support for the idea that TTC information is extracted from the optic flow field. The expansion of the image on the retina gives sufficient information for the extraction of TTC information without requiring the driver to assess speed or distance information. Since the graphical properties of optical perspective, visual angle and optical expansion rate are the same in the TRC simulator as in real world driving, there is reason to assume that the driving simulator is suitable for the type of research discussed in the chapters 5 to 9. An important prerequisite for a smooth optic expansion is a high graphical frame rate. In order to obtain a high frame rate, the visual scenes in all experiments are limited to the essential components while substantial effort has been invested in the design of fast algorithms for traffic handling and experimental control.

Chapter 4

4. EXPERIMENT 1: Speed Choice and Steering Behaviour in Curve Driving

Accepted for publication by *Human Factors*, co-author Hans Godthelp

The relation between speed choice and steering performance during curve negotiation was studied in a driving simulator. The hypothesis was that curve radius and steering competence both affect steering error during curve driving resulting in compensatory speed choice. In this, the control of safety margins was assumed to operate as a regulatory mechanism. Smaller curve radii resulted in a larger required steering wheel angle while steering error increased linearly with required steering wheel angle. This was compensated for by choosing a lower speed, such that the time-to-line crossing to the inner-lane boundary was constant over all curve radii examined. Steering competence was measured during straight road driving. Poorer steering competence also resulted in larger steering errors that were compensated for by choosing a lower speed such that the safety margin to the inner-lane boundary was unaffected by steering competence.

4.1 Introduction

Car driving behaviour in curves may be regarded as an interesting case where steering, as an example of operational performance, is intimately related to behaviour on the tactical level, in this case the choice of speed as a function of curve radius. The distinction between the operational and the tactical level of car driving behaviour has been made by several authors (c.f. Michon, 1985) and might form a fruitful basis for the development of modern driver behaviour theories (see c.f. Ranney, 1994). Until now, studies of car driving behaviour in curves have focused either exclusively on speed choice or on steering behaviour while no attempts have been made to integrate these two lines of research.

A consistent finding in studies on speed choice in curves is that speed has a curvilinear relation with curve radius (see c.f. Kanellaidis et al., 1990) and an inverse relation with lateral acceleration. This means that with smaller radii speed is lower but lateral acceleration is higher compared to larger radii (c.f. McLean, 1981). Sometimes an inverse linear relation is reported (Ritchie et al., 1968) while other studies have found an inverse non-linear relation between speed and lateral acceleration (Herrin and Neuhardt,1974; Macura, 1984). These results have encouraged the idea that lateral acceleration is used by drivers as a cue in speed choice in which a smaller lateral acceleration is accepted as a safety margin at higher speeds (and thus larger radii).

In studies of steering behaviour during curve negotiation, speed is usually held constant. Donges (1978) presented a two-level steering control model that incorporated negotiating curves. Anticipatory open-loop control starts with a steering action some time before the curve is entered followed by a steering-wheel angle maximum, δ_{sa}, in the curve. Then a period of stationary curve driving begins during which the driver generates correcting steering actions in a compensatory closed-loop mode. In a survey of models of steering behaviour Reid (1983) argued that driver models should incorporate both lane tracking and speed control. In Donges' model the parameters estimated to fit the model on experimental data were influenced by vehicle speed and confounded with road curvature. Curve radius and speed during curve negotiation affect required operational performance because both factors affect the required steering-wheel angle. Godthelp (1986) described this phenomenon as follows: the required steering-wheel angle for a particular curve can roughly be characterized as $\delta_{sr} = GL(1+Ku^2)/R_r$. In this, δ_{sr} represents required steering-wheel angle, R_r the road radius in meters, G the steer-to-wheel ratio, L the wheel base, K a vehicle related stability factor and u represents longitudinal speed in m/s. For any given speed, required steering-wheel angle then increases with smaller radii, but for a given radius it increases with higher speed, if K is larger than zero, which is the case for a normal understeered car.

If the steering-wheel angle during curve negotiation matches the required steering-wheel angle perfectly, speed is only restricted by an upper limit where the vehicle starts skidding. The speed at which this occurs is generally much higher than actual speed in curves. The hypothesis of the present study is that steering errors play an important role in speed choice, such that speed is adapted to operational performance. There is some evidence that steering errors increase linearly with required steering-wheel angle, see c.f. Godthelp (1985, 1986). Since negotiating curves with a smaller radius requires a larger steering-wheel angle, the implication is that steering error is larger in curves with smaller radii compared to wider curves. If steering error is a linear function of required steering-wheel angle, the fraction defined as steering error divided by required steering-wheel angle should be constant over radii.

There is also evidence that steering error is affected by steering competence. Cavallo et al. (1988) found that, under visual occlusion, experienced drivers estimated the correct required steering-wheel angle better than inexperienced drivers. Also, experienced drivers exhibited less variation in steering-wheel amplitude during closed-loop control compared to inexperienced drivers. These results suggest that experienced drivers generate smaller steering errors.

If the driver compensates for larger steering errors induced by smaller radii or poorer steering competence by choosing a lower speed, some regulating mechanism or safety margin is required that determines how speed is adapted. It is suggested here that the time-to-line crossing (TLC), developed by Godthelp et al. (1984), is such a safety margin. TLC represents the time available for a driver until the moment at which any part of the vehicle reaches one of the lane boundaries. In a study of Godthelp (1988) drivers were instructed to generate correcting steering actions when vehicle heading could still comfortably be corrected to prevent a crossing of the lane boundary. Drivers made a corrective steering action at a constant TLC irrespective of vehicle speed.

The model on the relation between speed choice and steering performance may then be summarized as follows. Required steering-wheel angle is determined by curve radius and speed, while steering error is determined by required steering-wheel angle and steering competence. It is assumed that the driver has learned the effect of curve radius and speed on required steering-wheel angle and on steering error from previous experiences. Also, it is assumed that steering error is consistent and the driver is aware of his or her steering competence. When the driver approaches a curve, both radius and steering competence cause an anticipatory adjustment of speed, much like the anticipatory avoidance response in the threat avoidance model of Fuller (1984), in which the effects of radius and steering competence on steering error are traded off with speed such that the safety margin TLC remains constant and independent of radius and steering competence. Although mathematically TLC is determined by steering error as well as speed, the higher steering errors associated with smaller radii and poorer steering competence are assumed to result in lower speeds because of the constancy of preferred TLC as a guiding principle. This principle will then result in low or non-significant correlations of speed and steering error with TLC. The relation between lateral acceleration and speed is then assumed to be a by-product of this mechanism.

In the experiment steering competence was measured separately during straight road driving. Road radius was manipulated within-subjects with radii of 40, 80, 120 and 160 meters. Originally, lane-width was manipulated within-subjects as well, since lane-width was expected to affect TLC. However, the effects of lane-width are not reported since these are not of crucial importance to the issue addressed here. Also, subjects used only a part of the lane-width because they drove relatively close to the inner lane boundary. This counteracted possible effects of lane-width on TLC and speed choice. There is also evidence in the literature that drivers use the inner lane boundary as a reference for vehicle guidance, see c.f. Shinar et al. (1980), McDonald and Ellis (1975), Cohen and Studach (1977). Therefore, only TLC and steering behaviour data towards the inner lane boundary are reported in the present article.

4.2 Method

Apparatus. The experiment was performed in the Traffic Research Centre (TRC) fixed-based driving simulator. It consists of a car (BMW 518) with a steering wheel, clutch, gear, accelerator, brake and indicators connected to a

Silicon Graphics Skywriter 340VGXT computer. A car model converts driver control actions into a displacement in space. On a 2 x 2.5 meter projection screen, placed in front of the car mockup, an image of the outside world with a horizontal angle of 50 degrees is projected by a graphical videoprojector, controlled by the 3D-graphics software. Images are presented with a rate of 15 to 20 frames per second, resulting in a suggestion of smooth movement. The visual objects are buildings, roads, traffic signs, traffic lights and artificially intelligent traffic. The sound of the engine, wind and tires is presented by means of a digital soundsampler receiving input from the simulator computer. The simulator is described in more detail elsewhere (Van Wolffelaar & Van Winsum, 1992 and Van Winsum & Van Wolffelaar, 1993).

Procedure. A circuit of two-lane roads with a lane-width of either 3.0, 3.5 or 4.0 meters was used. Roads had delineation with broken center lines and continuous edge lines. Four left-turning curves with 90 degrees angle and radii of 40, 80, 120 and 160 meters were separated by straight road segments. After completing a questionnaire on driving experience and age, subjects practiced driving in the simulator for ten minutes. They were instructed to choose their own preferred speed but to adapt the speed for curves as they normally would and to stay in the right lane. There were three trials, one for every lane-width. Each trial consisted of five roundtrips. This means that in every trial all four curves were negotiated five times. The three trials are treated as multiple measurements here.

Data registration and analysis. Sample measurements (10 Hz) were taken on speed (m/s), lateral position, steering-wheel angle (degrees), TLC (seconds), and steering error (degrees).

The steering integral ($I\delta_s$) during straight road driving was used as a measure for steering competence. This was computed as follows. The steering-wheel signal was divided into periods where the steering wheel was turned to left and periods where it was turned to right (relative to the zero angle). For every period the amplitude was integrated over time and these integrals were averaged resulting in $I\delta_s$. Thus, this measure is affected by both steering-wheel amplitude and frequency. A smaller steering integral represents better steering performance. Steering error in curves, δ_{se}, was defined as the difference between the actual steering-wheel angle and required steering-wheel angle (δ_s - δ_{sr}).

Figure 1 presents a time-history of steering error and TLC during curve negotiation. The curve is entered at time 0. Positive values of steering error and TLC represent steering to the inner lane boundary (left) while negative values represent steering to the outer lane boundary (right). The steering error fluctuates around zero. If steering error is zero then the steering-wheel angle equals the required steering-wheel angle. The open-loop phase ends when the maximum steering-wheel angle, δ_{sa} is reached. In Figure 1 this is indicated by the first maximum for δ_{se}. This is followed by closed-loop steering control during which deviations from the required steering error are minimized by the driver.

The following variables were analyzed:

- The steering error δ_{se} on the moment δ_{sa} is reached. This represents the steering error during the open-loop phase.
- The required steering-wheel angle δ_{sr}. This was measured as the steering-wheel angle on the moment that steering error was zero just before δ_{sa} was reached.
- The steering error ratio, computed as δ_{se}/δ_{sr}. This ratio is a measure for the relative steering error.
- The steering error integral, $I\delta_{se}$, during the closed-loop phase. This was computed as the average integral of all periods where the steering error was directed toward the inner lane boundary.
- The minimum TLC's to the inner lane boundary, TLC_{min} during the closed-loop phase. These were determined and averaged for every radius/trial combination.
- The minimum speed during curve negotiation. This was determined and averaged for every radius/trial combination.

The effects of radius were analyzed with repeated measurements analysis of variance. The effects of steering competence were analyzed with correlation and regression analyses. The confidence level for significance was set at p□0.05.

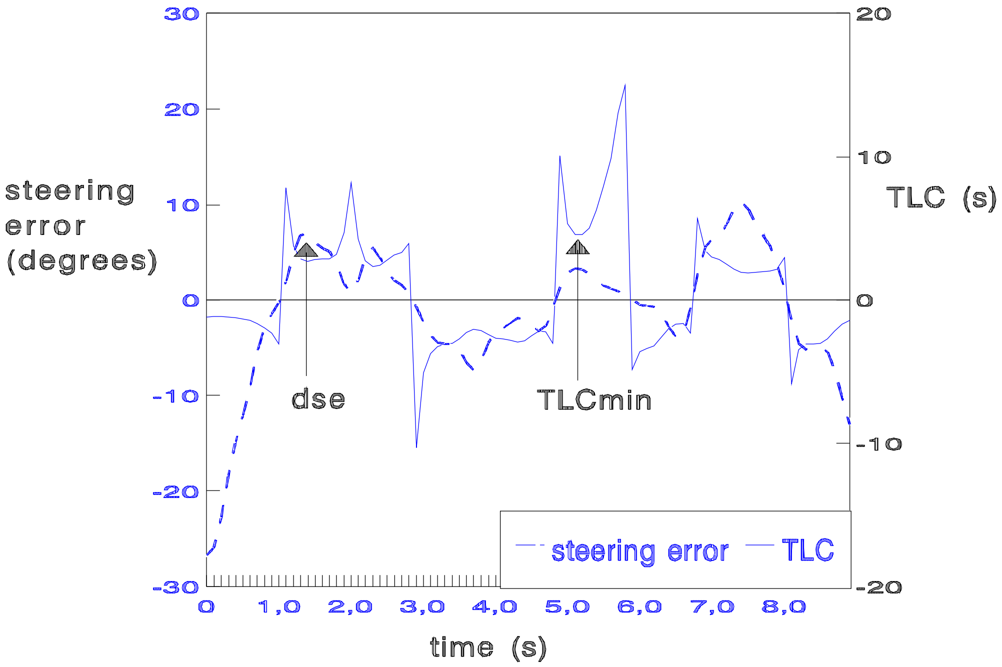

Figure 1. Steering error and TLC time-history during curve negotiation.

Subjects. 16 subjects, 8 male and 8 female, participated in the experiment. The average age was 34 years (sd. 6.3, range 22-47). They were licensed drivers for 12 years on average (sd. 6.3, range 2-27). The average annual kilometrage was 10594 (sd. 8267, range 1500-30000).

4.3 Results

The correlation between steering integral $I\delta_s$ and drivers' total kilometrage was -0.62 ($p<0.01$). This means that more experienced drivers steered more accurately on straight road segments.

The minimum speed during curve negotiation was significantly affected by radius (F(3,15)= 58.17, $p<0.01$). Required steering-wheel angle (δ_{sr}) was significantly affected by radius (F(3,15)=188.24, $p<0.01$) as was the steering error (δ_{se}) during the open-loop phase (F(3,15)=28.28, $p<0.01$) and the steering error integral ($I\delta_{se}$) during the closed-loop phase (F(3.15)=14.29, $p<0.01$). The effect of radius on steering error ratio was not statistically significant. Also, the effect of radius on the minimum TLC (TLC_{min}) during the closed-loop phase was not significant. The averages of these dependent variables as a function of radius are presented in Table 1.

Table 1. Averages of dependent variables as a function of radius

	Radius (m)			
Dependent variable	40	80	120	160
speed (m/s)	11.23	14.92	17.58	17.99
required angle (degrees)	121.44	74.64	56.56	43.47
steering error:				
-open loop (degrees)	14.20	7.47	5.54	4.75
-closed loop (integral)	14.02	6.55	5.26	4.67
steering error ratio	0.12	0.10	0.10	0.11
minimum TLC (s)	2.52	2.70	2.89	2.79

It can be seen that a smaller radius resulted in a larger required steering-wheel angle, larger steering errors and a lower speed. However, TLC and the steering error ratio were constant over all radii. Both steering errors during the open and closed-loop phases were affected by radius in the same manner.

Table 2. Standardized alpha coefficients of dependent variables

Dependent variable	standardized alpha
Speed	0.93
required angle	0.91
steering error:	
-open loop	0.88
-closed loop	0.86
steering error ratio	0.91
minimum TLC	0.90

In order to test effects of individual differences in steering competence on dependent variables it is required that these variables are consistent within the driver. In that case, it is justified to average over all measurements (4 radii x 3 repetitions). In that way, the effect of radius is canceled while the effect of individual differences is preserved. The reliability, or consistency, of the dependent variables was tested with the standardized alpha coefficient. This represents the estimated square of the correlation of scores on a collection of items, in this case the 12 measurements, with true scores (Nunnally, 1978). For basic research a reliability of 0.80 is generally regarded as a satisfactory level.

Table 2 presents the standardized alpha coefficients for all dependent variables. It can be seen that all variables are reliable and most alpha's are higher than 0.90. The minimum speed, TLC, steering errors, required steering-wheel angle and steering error ratio were averaged over radii and repetitions. Figure 2 presents the results of multiple regression analyses. Only significant partial regression coefficients are displayed.

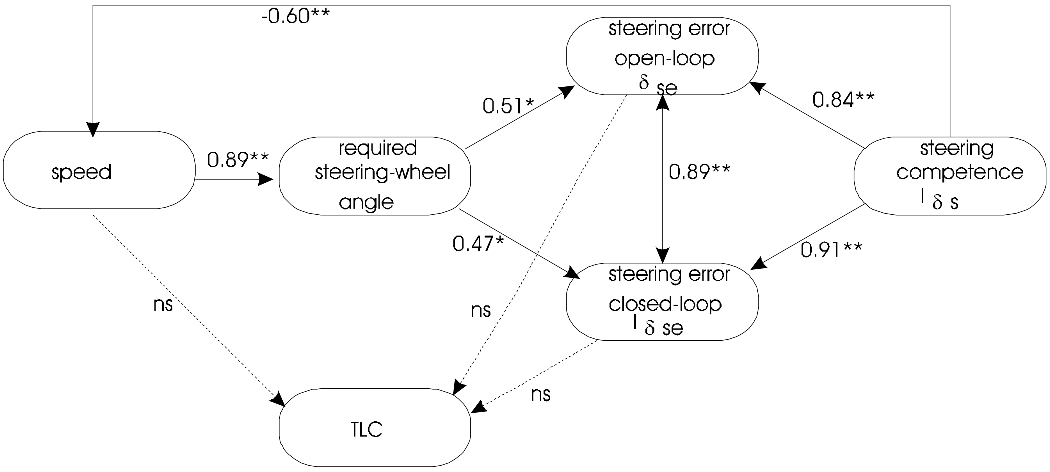

Figure 2. Path diagram with partial regression coefficients.
*=p<0.05, **=p<0.01, ns=not significant.

It can be seen that the measures for steering errors in the open-loop and the closed-loop phase are strongly intercorrelated, indicating that they measure the same phenomenon. Steering error is determined by required steering-wheel angle, while there is no direct path from speed to steering error. Required steering-wheel angle is strongly determined by speed. In addition to this, steering error is strongly determined by steering competence (Iδ_s). But while a higher steering competence results in lower steering error it also results in higher speed. Because steering competence is an intermediary factor, there is no effect of speed or steering error on TLC. Also, there is no path from steering competence to TLC. This suggests that subjects with poorer steering performance maintain the same safety margin as subjects with better steering performance, and that they choose a lower speed in order to maintain that safety margin. The correlation between Iδ_s and the steering error ratio was 0.74 (p<0.01).

4.4 Discussion and conclusions

The effects of curve radius as a road design factor and steering competence as an individual driver characteristic on speed choice in curves were studied from the perspective that effects on operational performance are compensated for on the tactical level. The implied mechanism in the case of curve negotiation is that both curve radius and steering competence affect steering errors on the operational level. In this, the preferred TLC was assumed to be a regulating mechanism that determines how speed is controlled in order to compensate for larger steering errors. Since TLC is mathematically determined by speed and steering error, higher steering errors can be compensated for by choosing a lower speed such that TLC is unaffected by radius or steering competence. The results supported this model. It was found that both required steering-wheel angle and steering error during the open and closed-loop phases increase with smaller radii, but that the relative steering error, defined as steering error divided by required steering-wheel angle, is constant over radii. This strongly suggests that steering error is linearly related to required steering-wheel angle and is consistent with the results of Godthelp (1985, 1986). Smaller radii resulted in the choice of a lower speed, but the minimum TLC's during curve negotiation were not affected by radius. This suggests that larger steering errors are compensated for by choosing a lower speed such that a constant minimum TLC is maintained. This finding 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 as a safety margin then is controlled by the drivers' speed choice. The results suggest that speed choice and steering performance are both intimately related in negotiating curves.

In this study, individual differences in steering competence strongly determined speed choice and steering performance in curves. Steering competence was measured with the steering integral during straight road driving. A larger steering integral is an indication of poorer steering performance. The quality of steering performance was related to driving experience. Steering performance, speed choice and minimum TLC were consistent within drivers during curve negotiation. Steering error was determined both by steering competence and by required steering-wheel angle while required steering-wheel angle was determined by speed. This confirms the model discussed in the introduction. Because drivers with poorer steering performance drove slower, while their steering errors were larger, no significant relations of speed and steering errors with TLC were found. This suggests that drivers with poorer steering competence compensated their larger steering errors, which decreased TLC, by choosing a lower speed, which increased TLC. Since steering competence did not affect TLC, it can not be concluded that drivers with poorer steering competence were less safe drivers. Steering error ratio correlated significantly with steering-competence as measured by the steering integral. The strong effect of steering competence on the steering errors during curve negotiation suggests that the steering integral is a good indicator for the quality of steering performance and that steering performance is consistent within the driver.

Based on the finding that steering error is a linear function of required steering-wheel angle and on the constancy of the minimum TLC to the inner lane boundary, the speed in curves as a function of radius was calculated using a mathematical model. From this, lateral acceleration was computed. Lateral acceleration proved to be an inverse function of speed as a by-product of the presented driver strategy.

Thus it appears that both radius as a road design element and steering competence as a driver characteristic exercise their influence on driving behaviour in the same manner. Both affect operational performance resulting in an adaptation of behaviour on the tactical level in an attempt to control safety margins. This is of theoretical significance for driving modeling in general since it suggests that effects of various factors related to the vehicle, weather, road, traffic, temporary states and the driver on behaviour on the tactical level (c.f. speed choice) may exercise their influence via an effect on operational performance. Most driver models are exclusively directed at either the operational or the tactical level. However, it is suggested that the relation between operational performance and behaviour on the tactical level should be a fundamental element in driver modeling.

Chapter 5

5. EXPERIMENT 2: Preferred time-headway in car-following and operational skills in expected braking reactions

In a simulator experiment the relation between preferred time-headway in steady-state car-following and operational competence in braking reactions was studied. The hypothesis that drivers with smaller preferred time-headways are able to react faster or generate a faster motor response per se was not confirmed. Also, no evidence was found for differences in perceptual processes related to the detection of braking by the lead vehicle between short followers and drivers with a larger preferred time-headway. The results suggest that short followers generate a faster motor response when there is some uncertainty concerning the level and duration of deceleration of the lead vehicle in case it brakes. The results suggest that short followers differ from long followers in the ability to transform visual feedback to a required motor response. However, the presence of brake lights is required for the relation between operational performance and choice of time-headway to hold, possibly because a change in feedback requirements, i.e. the absence of brake lights, is more detrimental for skilled performers.

5.1 Introduction

Choice of time-headway (THW) in car-following has been associated with task-related factors and with factors related to temporary state in a number of studies. The results of these studies may be explained in terms of an adaptation of choice of THW to perceived performance decrements in operational skills related to braking. The importance of task-related factors appears from the studies of Fuller (1981) and Brookhuis et al. (1991). Fuller (1981) studied THW of truck drivers. During the late shift, consisting mainly of driving in the dark, time-headway was significantly larger than during day time driving. Fuller explained this as an effect of visual conditions. Brookhuis et al. (1991) reported an increase in THW when using a car telephone while driving. The effects on THW may be explained as a result of awareness of the effects of task demands on the ability to detect a deceleration of a lead vehicle resulting in an adaptation of THW to compensate for this. A number of other studies have shown that choice of time-headway is sensitive to temporary states. Fuller (1984) reported a time-on-task effect on THW for older truck drivers in the late shift. After seven hours of driving, THW increased quite strongly, accompanied by verbal reports of performance decrements, drowsiness and exhaustion. In an experiment reported by Smiley et al. (1981) in an interactive driving simulator, marijuana resulted in increased headway during car-following. Smiley et al. (1986) again found that marijuana significantly increased headway in a car-following task. Smiley et al. (1985) reported that marijuana increased headway while alcohol decreased headway. These results strongly suggest effects of temporary states such as fatigue or states induced by marijuana and alcohol on preferred THW; fatigue and marijuana increase preferred THW, which may be a reflection of an adaptation of THW to perceived adverse effects on the braking response, whereas alcohol decreases preferred THW, possibly because drivers overestimate their braking competence under alcohol.

The effects of task-related factors and transient states refer to intra-individual differences. The results suggest a process of adaptation of THW to changes in operational competence which is influenced by task-related and state-related factors. From the same perspective, inter-individual differences in following behaviour, may be related to inter-individual differences in operational level competence, such that preferred THW is adapted to limitations in braking-related competence. These limitations in braking competence may be determined by specific skills required for optimal braking performance. In that case drivers may adapt time-headway to their braking skills such that the time available to reach the same level of deceleration as the lead vehicle in case it brakes matches the time needed by the driver to reach this level of deceleration. The former is equivalent to the momentary time-headway. The latter may be related to braking related skills of the driver. Extrapolated to the more general case, behaviour on the tactical level is assumed to be adapted to operational skills. The same reasoning was applied to speed choice in curves by Van Winsum and Godthelp (1996). They found a strong relation between choice of speed in curves and steering performance on straight roads, such that drivers adapt the speed in curves to their steering competence. An important research question then focuses on finding the relevant skills that discriminate drivers with different preferred time-headways.

In the normal case of braking for a decelerating lead vehicle, the driver adjusts the timing and intensity of the braking response to the criticality at the moment of detection of a deceleration of the lead vehicle and the development of criticality in time. In this, TTC information is assumed to plays an important role (e.g. Van der Horst, 1990; Cavallo et al., 1986; Cavallo and Laurent, 1988; Lee, 1976), although it is not clear how TTC information affects the braking response. However, when the driver is instructed to brake as fast as possible as soon as a deceleration of the lead vehicle is detected, the timing and intensity of braking are expected to depend on the limits of perceptual and motor skills instead of TTC information.

The dominant view in studies of braking has been that perceptual limitations, instead of response mechanisms, are responsible for rear-end collisions. In the literature braking skill is generally studied as the ability to brake as fast as possible instead of the ability to tune the timing and intensity of braking to the dynamic requirements of the situation. This is somewhat surprising given the ecological desirability to brake with a velocity and intensity that matches the requirements of the situation. In the literature, brake reaction time (BRT), or alternatively, perception-response time is used as an index for braking performance. This is defined as the interval between the onset of the stimulus, usually the brake lights of the lead vehicle, and the moment the foot touches the brake. BRT differs from reaction time (RT) as it is normally applied in experimental psychology. RT for a decelerating lead vehicle is measured as the interval between the moment the lead vehicle starts to decelerate and the moment the foot is retracted from the accelerator pedal. Although BRT includes reaction time, it covers the time to move the foot from the accelerator to the brake pedal as well. A reduction of BRT has been proposed as a means to reduce the number of rear-end collisions. Experiments that were aimed at finding factors that decrease BRT have been carried out for years (see for example McKnight and Shinar, 1992). For this purpose, center high-mounted stop lamps (CHMSL) have become standard equipment in passenger cars in the United States, although the evidence for actual reductions in BRT by these lamps is limited (McKnight and Shinar, 1992, Sivak et al., 1981). There is however some evidence that CHMSL reduces the number of rear-end accidents (see for instance Rausch et al., 1982). Thus, the scientific answer to the assumed perceptual limitations in braking has been to decrease the detection time by technical means. Other factors have been found that affect BRT as well. Johansson and Rumar (1971) found that BRT to anticipated events is faster than for unexpected events. Olson and Sivak (1986) reported an average BRT to expected stimuli of about 0.7 s. while it was about 1.1 s. to unexpected stimuli. The expectancy effect was also reported by Sivak (1987). The nature of the stimulus affects BRT as well. In car-following situations BRT is faster compared to other situations such as the detection of a stationary police car (Sivak, 1987). Furthermore, distance headway has a substantial effect on BRT (see for instance Brookhuis and De Waard, 1994, McKnight and Shinar, 1992 and Sivak et al., 1981).

From an adaptation perspective, perceptual skills related to the detection of a deceleration of the lead vehicle may be a determining factor for choice of time-headway. In that case a relation is expected between preferred THW and reaction time. The reaction time interval consists of a series of information-processing stages. The additive factor method, introduced by Sternberg (1969), assumes that these processing stages are serial and that the duration of these stages are independent. It is a method for studying the locus of effect of differences in RT. Several task variables are known to affect RT via effects on specific information-processing stages. According to the additive factor method, if two task variables interact in their effect on RT a common processing stage is involved. Additive effects of two task variables on RT are indicative of separate effects on different processing stages. In this chapter, the additive factors method is used to determine whether differences in RT as a function of preferred THW are caused by differences in the input side or the output side of the information-processing chain. Figure 1 shows the successive information-processing stages that are assumed to determine RT.

Stimulus degradation is known to affect the stimulus encoding stage on the input or perception side of information-processing (Sanders, 1990, Frowein, 1981). In braking for a decelerating lead vehicle, the absence of brake lights (BL) may be regarded as a severe form of stimulus degradation. Alternatively, differences in RT may have a locus of effect on the output or response preparation side of the information-processing chain. Time uncertainty, manipulated by means of presentation of a warning signal (WS) in advance of stimulus presentation is known to affect the output or motor side of the information-processing chain. Sanders (1980a) and Frowein (1981) reported additive effects of time uncertainty and stimulus degradation. This indicates that different information-processing stages are affected by signal quality and time uncertainty. Sanders (1980b) reported an interaction between time uncertainty and instructed muscle tension on RT. This suggest that the factor WS affects the motor-adjustment stage.

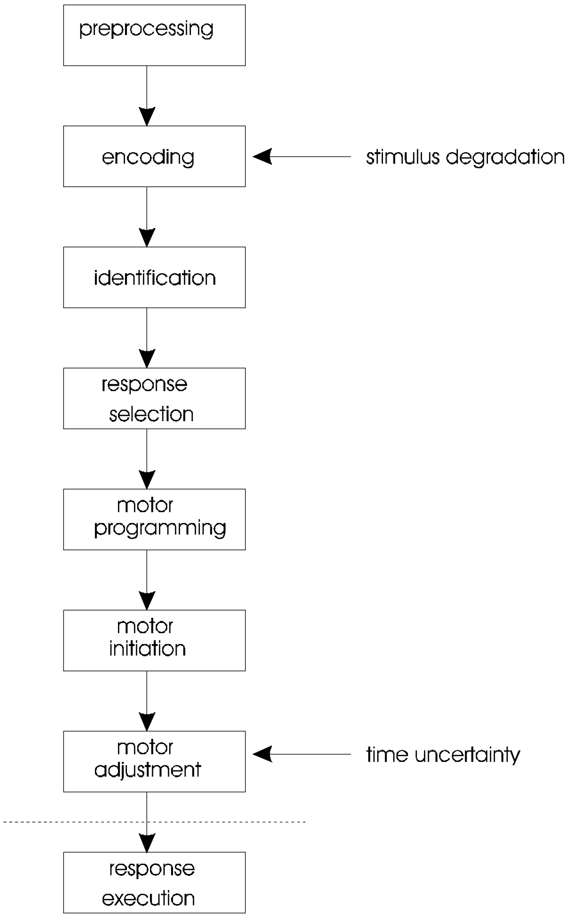

Figure 1. Information-processing stages during the reaction time interval
as discussed by Frowein (1981)

Also, Spijkers (1989) reported an interaction between time uncertainty and response specificity suggesting an effect of time uncertainty, or WS, on motor adjustment. Motor adjustment represents the stage where the state of motor readiness is modulated by straining the muscles.

The additive factor method has not only been applied to the study of information-processing stages, it has also been used to study individual differences related to, for example, dementia (Jolles, 1985) and hyperactivity in children (Spijkers and Curfs, 1986). This is important since the present study uses the additive factor method to explore information-processing factors underlying individual differences in behaviour.

In summary, if short followers differ in RT from drivers who follow with a larger THW, the reasons for differences in RT may be located on the input and/or output side of the information-processing chain. It can then be tested whether short followers differ from drivers with a larger preferred THW in the stimulus encoding stage with the BL manipulation. If drivers with a larger preferred THW are less efficient or slower in stimulus encoding, stimulus degradation is predicted to result in a relatively larger effect on RT for these drivers. Thus, differences in stimulus encoding as a function of preferred THW expresses itself as an interaction between preferred THW and the BL manipulation on RT. This would mean that differences in RT as a function of preferred THW are caused by faster detection by short followers of a deceleration of the lead vehicle. Alternatively, an interaction between preferred THW and the WS manipulation on RT such that RT of short followers is less affected by the WS manipulation than the RT of drivers with larger preferred THW, would suggest that short followers reach the state of required motor readiness faster. In that case, differences in RT are related to response mechanisms instead of perceptual mechanisms.

Choice of time-headway may also be related to the speed at which the driver is able to move the foot. In that case choice of time-headway may be an adaptation to individual differences in motor speed. However, the additive factor method has never been successfully applied to the motor phases of response execution. This means that there is not sufficient reason to apply this method to the examination of motor execution during the braking response. Also, there are no theoretical predictions for the effects of WS and BL on the duration of the motor phases that follow the RT interval when the subjects are required to brake as fast as possible.

In summary, the following questions are examined in the present experiment :

1) Is preferred time-headway related to differences in reaction speed to a deceleration of the lead vehicle, and if so, are the differences located on the perceptual or the response side of the information-processing chain.
2) Is preferred time-headway related to skills involved in motor execution.

The experiment was performed in an interactive simulator. This allows full control over the behaviour of the lead vehicle and accurate on-line measurement of time-related variables.

5.2 Method

Apparatus. The experiment was performed in the driving simulator of the Traffic Research Centre (TRC). This fixed-based simulator consists of two integrated subsystems. The first subsystem is a conventional simulator composed of a car (a BMW 518) with a steering wheel, clutch, gear, accelerator, brake and indicators connected to a Silicon Graphics Skywriter 340VGXT computer. A car model converts driver control actions into a displacement in space. On a projection screen, placed in front, to the left and to the right of the subject, an image of the outside world from the perspective of the driver with a horizontal angle of 150 degrees is projected by three graphical videoprojectors, controlled by the graphics software of the simulator. Images are presented with a rate of 15 to 20 frames per second, resulting in a suggestion of smooth movement. The visual objects are buildings, roads, traffic signs, traffic lights and other vehicles. The sound of the engine, wind and tires is presented by means of a digital soundsampler receiving input from the simulator computer.

The second subsystem consists of a dynamic traffic simulation with interacting artificially intelligent cars. For experimental purposes different traffic situations can be simulated. The simulator is described in more detail elsewhere (Van Wolffelaar & Van Winsum, 1992 and Van Winsum & Van Wolffelaar, 1993).

Procedure. The experiment was preceded by another one in which the same subjects had been driving in the simulator for about one hour. Instructions were delivered in writing. Preferred time-headway was measured as follows. Subjects were instructed to drive 80 km/h where possible and to follow the lead vehicle at the distance they would choose in real traffic. A lead vehicle in front of the simulator car controlled its speed such that a THW of 1 second was maintained. After a while the lead vehicle started to maintain a constant speed of 80 km/h and the subject was required to choose the preferred THW. As soon as the preferred THW was reached the subject pressed a button. Time-headway, calculated as distance headway divided by the speed of the simulator car in m/s, at the moment the button was pressed was used as a measure for preferred time-headway (THW_{pref}).

After this, braking performance was measured. Four trials were executed successively. A trial consisted of braking with the instruction to brake as fast as possible followed by braking with the instruction to brake normally. Only the results of braking responses with the instruction to brake as fast as possible are reported here. Subjects were requested to drive with a constant speed of 80 km/h and not to exceed the lane boundaries. Speed (in km/h) was continuously projected on the screen in front, allowing subjects to monitor the behaviour of the lead vehicle. The lead vehicle maintained a constant time-headway of 1 second. After a while, i.e. about 1 minute, it braked to a full stop with a deceleration of 6 m/s^2. In two trials, a warning signal (WS) was presented 1 second before the lead vehicle braked, while in the other two trials no WS was presented. A WS consisted of three stars projected on the screen during 1 second. Subjects were told a WS indicated that the lead vehicle might brake after 1 s. They were requested not to release the right foot from the accelerator until they were sure that the lead vehicle actually braked. The lead vehicle only braked when the accelerator position was not more than 5% less than 1 second before. This means that braking of the lead vehicle never occurred while the S was releasing the foot from the accelerator pedal. In two trials the lead vehicle carried brake lights during braking, while in the other two trials the brake lights were switched off. This constitutes the BL manipulation. The trials were administered in four different orders (see table 1). Subjects were randomly assigned to one of these orders with the restriction that the same number of subjects were represented in each order of trials.

Table 1. Order of trials. ! means not

	Order			
	1	2	3	4
A	WS- BL	WS-!BL	!WS- BL	!WS-!BL
B	WS-!BL	WS- BL	!WS-!BL	!WS- BL
C	!WS- BL	!WS-!BL	WS- BL	WS-!BL
D	!WS-!BL	!WS- BL	WS-!BL	WS- BL

Data collection and analysis. Speed, distance-headway, time-headway, accelerator- and brake position were sampled with a frequency of 10 Hz. Reactions to braking of the lead vehicle were stored in an event file. These events were monitored with a frequency of 50 Hz. The following events were stored:

- 1) time of presentation of WS
- 2) time of braking of lead vehicle (t_0)
- 3) time at which accelerator position was decreased >= 5% since 2 (t_{acc})
- 4) time at which brake pedal position was >= 5% (t_{br})
- 5) time at which a brake maximum was reached (t_{maxbr})
- 6) value of brake maximum (MAXBR)

Reaction time (RT) was calculated as 3-2. Movement time (MT) was calculated as 5-3. MT was recoded as a missing value when there was more than one brake peak in a trial. The occurrence of more than one brake peak indicates that the subject braked, retreated the foot, and pushed the brake again. This indicates that the instruction to brake as fast as possible was not followed and it occurred in two subjects.

The effects of WS and BL on RT and MT were tested with an analysis of variance repeated measurement design. Preferred time-headway was treated as a between-subjects factor.

Subjects. 78 subjects participated in the experiment, 38 were male and 40 were female. 40 subjects were younger than 25 years of age, and 38 were older, but not older than 40. The average number of years the subjects were licensed to drive a car was 7.38 (sd. 4.87), total kilometrage was 88600 km (sd. 134355) on average, while the average annual kilometrage was 11786 (sd. 14794).

5.3 Results

Three groups (THW_{pref} groups) of equal size were created from the distribution of preferred time-headway. The group 'short' followers includes the subjects with smallest preferred time-headway, the group 'medium' followers contains subjects in the middle range of preferred time-headway, while the group with highest preferred time-headway are the 'long' followers. The average time-headways of these groups can be seen in table 2.

Table 2. Average time-headway

group	THW	n
short	1.58	26
medium	2.13	26
long	3.16	26

The effects of THW_{pref} groups on RT and MT are listed in table 3.

Table 3. Effects of THW_{pref} groups on RT and MT, df between brackets.

variable	F	p
RT	0.25 (75,2)	0.790
MT	0.75 (72,2)	0.477

Short followers did not exhibit a faster RT than drivers with a larger preferred time-headway. Also the duration of the movement phase of braking (MT) was not significantly affected by THW_{pref} groups..

The effects of WS and BL on RT are shown in figure 2. There was a significant main effect of WS on RT (F(79,1)=45.91, p<0.001). The effect of BL on RT was statistically significant as well (F(79,1)= 290.41, p<0.001). The interaction was not significant (F(79,1)=2.18, p=0.144). WS and BL had additive effects on RT in the expected direction.

The effects of WS and BL on MT are presented in figure 3. WS had a significant main effect on MT (F(76,1)=12.50, p<0.001). The effect of BL was not significant (F(76,1)=0.21, p<0.646). The interaction was not significant (F(76,1)=0.49, p<0.487).

The interactions with THW_{pref} group are listed in table 4.

Table 4. Interactions of THW_{pref} group with WS and BL.

variable	effect	F	p
RT	THW_{pref}xWS	0.00 (75,2)	1.000
	THW_{pref}xBL	0.02 (75,2)	0.985
	THW_{pref}xWSxBL	0.35 (75,2)	0.708
MT	THW_{pref}xWS	1.64 (72,2)	0.200
	THW_{pref}xBL	4.31 (72,2)	0.017
	THW_{pref}xWSxBL	0.63 (72,2)	0.537

The interactions of WS and BL with $\mathrm{THW}_{\mathrm{pref}}$ groups on RT were not significant. Thus, no evidence was found for differences between short followers and drivers with a larger preferred THW in the stimulus encoding and motor-adjustment stages. The interaction between $\mathrm{THW}_{\mathrm{pref}}$ and BL on MT was significant. This interaction was analyzed in more detail. MT of the two extreme $\mathrm{THW}_{\mathrm{pref}}$ groups (short and long followers) were compared for the BL and non-BL trials separately. MT during BL trials was significantly faster for short followers compared to long followers ($F(49,1)=4.17$, $p<0.05$). During non-BL trials MT was not significantly different for short and long followers however ($F(49,1)=0.72$, $p=0.401$), see figure 4. This means that only in trials in which the brake lights were switched on short followers moved their foot faster to the maximum level compared to long followers. Post-hoc analyses revealed that the $\mathrm{THW}_{\mathrm{pref}}$ x BL interaction on MT was mainly caused by an effect of preferred THW on MT for the first braking trials in which the lead vehicle carried brake lights. The results of regression analyses with MT as a dependent variable and preferred THW as an independent variable are listed in table 5, for BL and non-BL trials separately. It can be seen that only for first trials in which the brake lights on the lead vehicle were switched on MT was a function of preferred THW, such that drivers with a smaller preferred THW moved their foot faster from the accelerator pedal to the brake maximum.

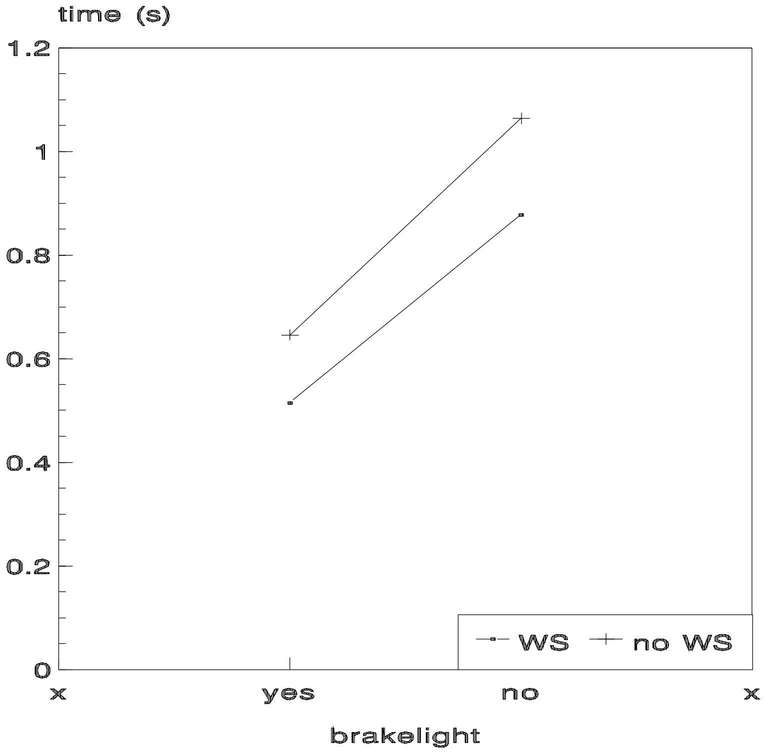

Figure 2. RT as a function of WS and BL.

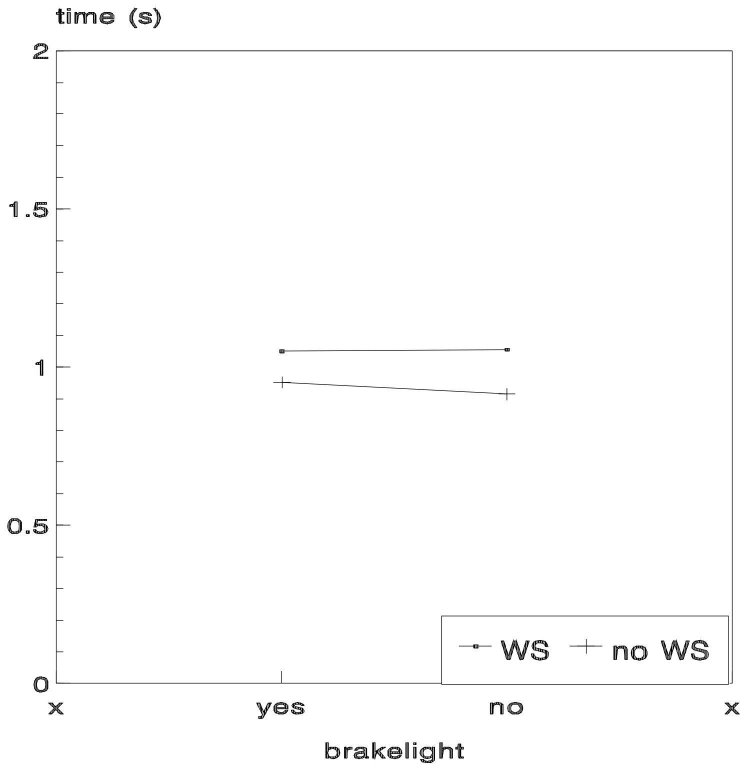

Figure 3. MT as a function of WS and BL.

Table 5. Effects of regression analyses of THW_{pref} on MT for trial orders 1, 2, 3 and 4 and for BL and non-BL trials separately (df between brackets).

	Order	Beta	F
BL trials			
	1	0.50	12.67 (38,1) **
	2	0.02	0.02 (34,1)
	3	0.29	3.59 (40,1)
	4	-0.29	3.08 (34,1)
non-BL trials			
	1	-0.18	1.06 (33,1)
	2	0.18	1.41 (40,1)
	3	-0.17	0.96 (34,1)
	4	-0.11	0.49 (40,1)

** = $p < 0.01$; * = $p < 0.05$

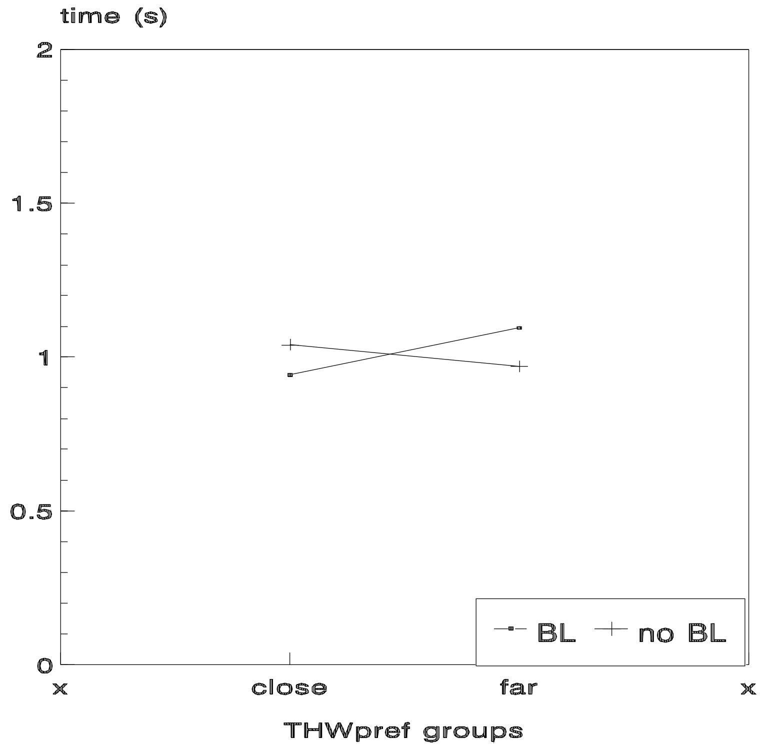

Figure 4. Average MT for short and long followers, for BL and non-BL trials.

It was tested whether this had caused the THW_{pref} x BL interaction to become significant. The THW_{pref} x BL interaction was examined for the last two trials (3 and 4) only. This interaction was not significant (F(75,2)=2.18, p=0.120), while the THW_{pref} x BL interaction was significant for the first two trials (1 and 2) only (F(72,2)=4.52, $p<0.05$).

5.4 Discussion and conclusions

The experiment was performed in an interactive driving simulator. Drivers were subjected to a number of scenarios in which the lead vehicle braked sharply from 80 km/h until it came to a full stop. The lead vehicle started to brake at a time-headway of 1 second. Subjects were instructed to brake as fast as possible as soon as the deceleration of the lead vehicle was detected. Subjects knew in advance that the lead vehicle would brake. Presentation of a warning signal (on/off) and application of brake lights on the lead vehicle (on/off) were administered in a within-subjects design, resulting in four braking conditions.

The theoretical perspective of the present study was that drivers adapt time-headway to their braking skills in such a way that the time available to reach the same level of deceleration as the lead vehicle in case it brakes matches the time needed by the driver to reach this level of deceleration. Individual differences in choice of time-headway are then expected to be related to individual differences in braking skills. Braking for a lead vehicle requires a number of skills varying from perceptual skills needed for a fast detection of decelerations of the lead vehicle to perceptual-motor skills involved in tuning the motor response to visual input. This study was aimed at finding the relevant skills related to choice of time-headway during car-following.

In the literature on braking perceptual mechanisms, such as the estimation of time-to-collision and the detection of deceleration of a lead vehicle, are emphasized as important skills. Also, the ability to initiate braking as fast as possible is seen as an important factor in rear-end collisions. Starting from the existing literature, it was investigated whether choice of time-headway is related to the ability to initiate braking as fast as possible. Using the logic of the additive factor method the locus of effect for differences in reaction time was examined. The stimulus encoding stage of the information-processing chain was manipulated by switching the brake lights of the lead vehicle on or off. This resembles a manipulation of the factor stimulus degradation. The motor-adjustment stage was manipulated by the presence or absence of a warning signal 1 second in advance of stimulus presentation (deceleration of the lead vehicle). The presentation of a warning signal affects time uncertainty, a factor that is known to affect the motor-adjustment stage. The manipulations both had statistically significant additive effects on reaction time. This confirms the results reported in the experimental psychological literature that different stages are selectively affected by these two manipulations. However, no significant effect of preferred time-headway was found on reaction time. Also, no significant interactions of preferred time-headway with either the brake lights or the warning signal manipulations were found on reaction time. This indicates that choice of time-headway is not related to reaction time. It also indicates that choice of time-headway is not related to the speed at which a deceleration is detected or to the speed at which the state of motor-readiness is reached.

The results on movement time (MT) revealed a different pattern. The factor warning signal had a significant effect on movement time; presentation of a warning signal resulted in a larger movement time. This result is difficult to explain. Generally, in laboratory experiments no effects of time uncertainty on movement time are found (see f.i. Frowein, 1981). A possible explanation is that the absence of a warning signal resulted in a longer reaction time and thus a higher criticality at the moment the motor response was initiated. This required the subjects to speed up the motor response. However, the absence of a significant effect of the factor brake lights on movement time makes this explanation highly unlikely because the brake lights manipulation had much stronger effects on reaction time. If there are effects of criticality on movement, the manipulation of brake lights is expected to have a greater effect on movement time than the warning signal manipulation. This obviously was not the case. Also, since the subjects were instructed to brake as fast as possible, criticality effects were not expected. There was no significant effect of preferred time-headway on movement time. This means that there is no evidence that short followers differ from drivers with a larger preferred time-headway in the ability to generate a faster motor response per se. However, the interaction between preferred time-headway and the brake lights manipulation on movement time was significant. Only when the lead vehicle carried brake lights, short followers moved their foot faster to the brake maximum than drivers with a larger preferred time-headway. The relation between preferred time-headway and movement time was absent when the lead vehicle did not carry brake lights. This is partly consistent with the results reported by Marteniuk et al. (1988) in a study of motor learning. They found that as the performer is more skilled in the execution of a motor task, changing the feedback conditions strongly interferes with motor execution. The absence of brake lights may be regarded as a strong change in feedback conditions, since the brake lights of the lead vehicle are an important cue for the driver in braking. Post-hoc analysis revealed that the interaction of preferred time-headway with the brake light manipulation on movement time was mainly caused by a trial order effect. In the first braking maneuver there was a strong effect of preferred time-headway on movement time, only if brake lights of the lead vehicle were switched on during braking. This effect was absent in later braking maneuvers. The first braking maneuver differs in one important aspect from later braking trials. During later braking trials the subjects knew the level of deceleration of the lead vehicle and the duration of its deceleration, while this information was not available to the driver during the first braking trial. This suggests that preferred time-headway is related to the skill to transfer visual feedback to a required motor response. During the first trial visual feedback had to be interpreted during the course of braking, while during later trials the required motor response was known even before the response was generated. This means that for later trials a standard learned fast response could be generated while in the first trial the transformation of visual feedback to the motor-response may have played some role. This suggests that the differences in response execution speed as a function of preferred time-headway are restricted to braking situations characterized by uncertainty concerning the braking by the lead vehicle, the required deceleration and the duration of braking, as is the case in normal car-following situations.

Chapter 6

6. EXPERIMENT 3: Choice of time-headway in car-following and the role of time-to-collision information in braking

published in *Ergonomics*, 1996, 39(4), 579-592, co-author Adriaan Heino

Time-headway (THW) during car-following and braking response were studied in a driving simulator from the perspective that behaviour on the tactical level (e.g. choice of THW) may be linked to operational competence of vehicle control (e.g. braking) via a process of adaptation. Time-headway was consistent within drivers and constant over a range of speeds. Since time-headway represents the time available to the driver to reach the same level of deceleration as the lead vehicle in case it brakes, it was studied whether choice of time-headway was related to skills underlying braking performance. The initiation and control of braking were both affected by time-to-collision (TTC) at the moment the lead vehicle started to brake. This strongly supported the idea that time-to-collision information is used for judging the moment to start braking and in the control of braking. No evidence was found that short followers differ from long followers in the ability to accurately perceive TTC. There was however evidence that short followers are better able to program the intensity of braking to required levels. Also, short followers tuned the control of braking better to the development of criticality in time during the braking process. It was concluded that short followers may differ from long followers in programming and execution of the braking response.

6.1 Introduction

Close car-following has been associated with traffic accident involvement. Rear-end collisions accounted for about 24% of all accidents involving two or more vehicles in the U.S.A in 1990 (McGehee et al., 1992). These accidents are usually attributed to maintaining insufficiently long headways and/or to inattentive driving resulting in responding too late to a deceleration of a vehicle in front. In the literature, headway is expressed either as distance headway (DHW) or as time headway (THW) (Fuller, 1981). DHW is the bumper to bumper distance between the lead vehicle and the following vehicle. THW is the time interval between two vehicles in car-following, calculated as DHW divided by the speed (in m/s) of the following vehicle. When the following and the lead vehicle drive at the same speed (steady-state following), THW represents the time available to the driver of the following vehicle to reach the same level of deceleration as the lead vehicle in case it brakes. This available time is independent of speed. A faster braking response is then required with a smaller THW. Also, the control of braking is more critical in that case. In this article, the THW during steady-state car-following will be referred to as THW_{pref} (preferred time headway).

Evans and Wasielewski (1982) found that drivers with a larger THW_{pref} had a history of fewer traffic violations and traffic accidents. However, the same authors also argued that accident involvement did not have a reliable relation with THW_{pref} by itself (Evans and Wasielewski, 1983). Especially younger drivers employed smaller THW's, as did drivers of newer cars and of vehicles with medium mass.

Several factors have been identified that influence choice of THW. Choice of THW has been associated with personality factors by some authors. Sensation seeking as a personality trait is assumed to be related to risky behaviour (Zuckerman, 1979). For example, Zuckerman and Neeb (1980) found a positive correlation between the sensation seeking score and reported driving speed, whereas Heino et al. (1992), using a realistic car-following task, reported a smaller THW_{pref} for sensation seekers than for sensation avoiders. Ota (1994) studied car-following behaviour in relation to personality traits. He suggested social maladjustment as an important factor in choice of THW, although correlations between THW and personality test scores were not significant.

Other authors have stressed the importance of task-related factors with regard to THW_{pref}. Fuller (1981) studied THW of truck drivers in convoy situations. During the late shift, covering a large period of driving in the dark, THW_{pref} was significantly larger than during daytime driving. This was explained as an effect of visual conditions. Brookhuis et al. (1991) reported an increase in THW when using a car telephone while driving, which can be regarded as an additional task competing for attention. This suggests the driver is aware of effects of task demands on the ability to detect a deceleration of a lead vehicle and adapts THW accordingly.

Choice of THW also has been associated with temporary state-related factors. Fuller (1984) reported a time-on-task effect on THW for older truck drivers in the late shift. After seven hours of driving, THW increased quite strongly, accompanied by verbal reports of performance decrements, drowsiness and exhaustion. In an experiment reported by Smiley et al. (1981) in an interactive driving simulator, marijuana resulted in increased headways during car-following. Smiley et al. (1986) studied the effect of marijuana on several car-driving tasks on the road. Again marijuana significantly increased headway in a car-following task. In another simulator study, Smiley et al. (1985) found that marijuana increased headway while alcohol decreased headway. These results strongly suggest effects of temporary states such as fatigue or states induced by marijuana and alcohol on THW_{pref}; fatigue and marijuana increase THW_{pref} which may be a reflection of an adaptation of THW to adverse effects on the brake reaction, whereas alcohol decreases THW_{pref}, possibly because drivers overestimate their braking competence under alcohol.

The effects of task-related factors and transient states refer to intra-individual differences. The results strongly suggest a process of adaptation of THW to changes in operational level competence which is influenced by task-related and state-related factors. From the same perspective, inter-individual differences in following behaviour, may be related to inter-individual differences in operational level competence, such that THW_{pref} is adapted to limitations in braking-related competence. These limitations in braking competence may then be determined by specific skills required for optimal braking performance. For this to be the case, THW_{pref} must be consistent within the individual driver, while it differs between drivers as a function of operational skill. Since THW_{pref} represents the ultimate reaction time in case of a deceleration by the lead vehicle, THW_{pref} must be invariant over speed. However, in spite of years of research into car-following it is still not clear whether this time headway constancy holds over speed and whether it is consistent within drivers.

Fuller (1986) reanalyzed the results of previous car-following experiments and found negative correlations between speed and THW. Following distance increased with speed but not enough to maintain THW at a constant level. However, the conditions resulting in different speeds varied widely. High speeds were associated with rural open-road conditions with low traffic density and the absence of junctions, pedestrians and other hazards. Low speeds, on the other hand were associated with opposite conditions. Conditions that resulted in lower speeds, and an accompanying larger THW_{pref}, were characterized by multiple tasks competing for attention, possibly resulting in performance decrements in braking. Ota (1994) studied THW while drivers were required to drive with a speed of 50, 60 or 80 km/h and follow under different instructions such as 'follow at a comfortable distance' and 'follow at a minimum safe distance'. No effects of speed on THW were found while instruction significantly affected choice of THW. This suggests that THW_{pref} is constant over different speeds.

In the present study, an important hypothesis is that THW_{pref} is constant over speed and consistent within the driver. In order to test consistency of THW_{pref} and constancy over speed, it is required that, besides speed, all other factors that might affect braking performance are constant.

According to Lee (1976) drivers are able to control braking based on time-to-collision (TTC) information from the optic flow field (visual angle divided by the angular velocity). This would enable the driver to judge the moment to start braking and to control the braking process. The initiation of braking includes the timing of releasing the accelerator pedal after a deceleration of the lead vehicle has been detected as well as the interval between release of the accelerator pedal and the moment the foot touches the brake pedal. The control of braking includes braking intensity and the interval between the moment the brake is touched and the moment the maximum brake pressure is reached. Brake reaction time (BRT) is usually measured as the interval between the onset of the stimulus, such as the brake lights of the lead vehicle, and the moment the brake is touched. Therefore, BRT is an important measure for the initiation of braking. BRT to anticipated events is faster than to unexpected events (Johansson and Rumar, 1971) and the DHW at the moment the lead vehicle brakes has a strong effect on BRT (Brookhuis and De Waard, 1994; McKnight and Shinar, 1992;, Sivak et al., 1981). An important skill that has been associated with the initiation of braking relates to the perception of time-to-collision (TTC). TTC is defined as the time required for two vehicles to collide if they continue at their present speed and on the same path (see Van der Horst, 1990). TTC is computed as DHW/V_r, where V_r is the relative velocity or speed difference which must be larger than zero. While the ability to accurately perceive TTC is often mentioned as an important factor for judging the moment to start braking, studies that related TTC to actual braking are scarce. However, Van der Horst (1990) reported evidence that both the decision to start braking and the control of braking are based on TTC information available from the optic flow field. If TTC is an important factor in the initiation of braking, a relation is expected between the TTC at the moment the lead vehicles starts to brake (TTC_{t0}) and BRT. Since TTC_{t0} is an index for criticality, it is expected that BRT is faster if criticality is higher, i.e. when TTC_{t0} is smaller. A consistent finding in the literature is an underestimation of TTC, especially at higher TTC's. Schiff and Detwiler (1979) found substantial individual differences in the ability to give accurate judgments of TTC and an average underestimation of TTC of 39%. McLeod and Ross (1983) found that men gave higher and more accurate judgments than women. They reported an underestimation of TTC of 42%. Cavallo et al. (1986) found that experienced drivers produced better estimates of TTC than inexperienced drivers. They reported a general underestimation of 35%. Hoffmann and Mortimer (1994) found that both estimated TTC and standard deviation of estimated TTC were linearly related to actual TTC. They reported an underestimation of TTC of 20% on average, while other studies typically report an underestimation of around 40%. This better performance in TTC estimation was attributed by Hoffmann and Mortimer to the fact that in their experiment both vehicles were in motion, while other experiments typically measured estimated TTC to a static object. The studies on TTC estimation give substantive evidence for underestimation of TTC and for individual differences in the ability to accurately estimate TTC. Differences in ability to accurately estimate TTC are assumed to be expressed in the initiation of braking. BRT of drivers with better TTC estimation skills is assumed to covary more with TTC_{t0} than BRT of less skilled drivers. This is because better skilled drivers are more sensitive to variations in TTC_{t0}. A hypothesis in the present study is that THW_{pref} is related to sensitivity of the initiation of braking to TTC information. Drivers who are more sensitive to TTC are then better able to judge the moment to start braking, while drivers who are less sensitive to TTC information run a higher risk of starting to brake too late. This might result in a larger safety margin and thus a higher THW_{pref} for these drivers.

Drivers may not only differ in the initiation of the braking response but also in the control of braking. Van der Horst (1990) studied the control of braking by the maximum deceleration reached by the driver (DEC_{max}), the minimum TTC reached during braking (TTC_{min}), and the time difference between the moment of TTC_{min} (t_{TTCmin}) and the moment of DEC_{max} (t_{DECmax}). TTC_{min} describes how imminent a collision has been during the braking process. According to Van der Horst, t_{DECmax} gives an indication of the moment the driver knows a collision will be avoided. During the time before t_{TTCmin} is reached, TTC is still decreasing resulting in increasing criticality. If t_{DECmax} occurs some time before t_{TTCmin}, criticality is still increasing at the moment the driver already relaxes the deceleration. If t_{DECmax} occurs some time after t_{TTCmin} is reached the driver keeps increasing the deceleration when it is no longer necessary. A close relation in time between t_{DECmax} and t_{TTCmin} then suggests a more efficient control of braking, where the control of braking is better tuned to the development of criticality in time. In the present experiment it will be examined whether THW_{pref} is related to braking control as indicated by these measures. In addition to this, the maximum percentage brake pressed (MAXBR), and the interval between touching the brakepedal and the moment the brake pedal is pressed to the maximum value are measured. Furthermore, it will be examined whether the intensity of the braking reaction, measured by MAXBR, is more sensitive to TTC at the moment the lead vehicle starts to brake for short followers compared to long followers. A higher sensitivity of the intensity of braking to TTC_{t0} suggests that the braking response is more adapted to criticality at the moment the driver detects the braking of the lead vehicle.

In summary, the following hypotheses will be tested in the present experiment.

1) Preferred time-headway is constant over different speeds.
2) Preferred time-headway is consistent within individual drivers, but differs between drivers.

3) The initiation of braking, measured by BRT, is more strongly related to TTC at the moment the lead vehicle starts to brake for short followers compared to long followers. This is assumed to be related to differences in the ability to perceive TTC information.
4) Preferred time-headway is related to the intensity of braking and quality of braking control. The intensity of braking is measured by MAXBR while the quality of braking control is measured by the sensitivity of the braking intensity to criticality (as measured by TTC) and by the time difference between t_{TTCmin} and t_{DECmax}.

6.2 Method

Apparatus. The driving simulator of the Traffic Research Centre (TRC) was used for the present experiment. This fixed-based simulator consists of two integrated subsystems. The first subsystem is a conventional simulator composed of a car (a BMW 518) with a steering wheel, clutch, gear, accelerator, brake and indicators connected to a Silicon Graphics Skywriter 340VGXT computer. A car model converts driver control actions into a displacement is space. On a 2 x 2.5 meter projectionscreen, placed in front of the car mockup, an image of the outside world with a horizontal angle of 50 degrees is projected by a graphical videoprojector, controlled by the graphics software. Images are presented with a rate of 15 to 20 frames per second, resulting in a suggestion of smooth movement. The visual objects are buildings, roads, traffic signs, traffic lights and other vehicles. The sound of the engine, wind and tires is presented by means of a digital soundsampler receiving input from the simulator computer.

The second subsystem consists of a dynamic traffic simulation with interacting artificially intelligent cars. For experimental purposes different traffic situations can be simulated. The simulator is described in more detail elsewhere (Van Wolffelaar & Van Winsum, 1992 and Van Winsum & Van Wolffelaar, 1993). De Waard et al. (1994) reported a significant correlation (r=0.67) between THW measured in this simulator and ratings of preferred headway on a photo-preference test. In this test subjects rated preferred headway from a series of photographs with a view of a lead vehicle through the windscreen on a motorway. This supports the validity of this simulator for measuring car-following behaviour. Also, TTC has been reported to be directly available from the optic flow field without requiring speed and distance estimation. Since visual angle and angular velocity are identical in the simulator and in real world driving, this simulator was assumed to be a valid instrument for estimation of TTC.

Procedure. The circuit was made of two-lane roads with a lane-width of 3 meters. All roads had delineation with broken center lines and closed edge lines. Sideroads connected with an angle of 45 degrees to the main road, allowing other vehicle to merge in front of the simulator car and leave the main road. The length of the circuit was 7600 meter.

Before the experiment started, subjects completed a questionnaire on driving experience and age. After this, subjects were instructed to drive as if they had to reach their destination as soon as possible, without overtaking other vehicles, to drive safely and to respect the speed limit of 80 km/h. The experiment started after a ten minutes practice drive.

The experiment consisted of two parts, separated by a 15 minutes break. During the first part choice of headway was measured as a function of speed. Lead vehicles drove with a constant velocity of either 40, 50, 60 or 70 km/h. These different speeds are referred to as 'speed conditions'. Subjects were required to drive around the circuit twice. The first drive around the circuit was used to familiarize subjects with other traffic. Vehicles merged in front of the simulator car, controlling their speed such that when the simulator car was 50 meter from the intersection, the lead vehicle was 100 meters in front of the simulator car.

During the second part of the experiment braking behaviour was measured. Vehicles merged in front of the simulator car in the same way as described above. Lead vehicles drove with a constant speed of either 60 or 50 km/h, resulting in two 'braking conditions'. As soon as the lead vehicle was 50 meter in front of the simulator car (t_0), it decelerated with -2 m/s², with its brakelights on, to a speed 20 km/h below the initial cruise speed. As soon as the simulator car reached this speed (40 of 30 km/h) the lead vehicle pulled up again. The two braking conditions (50 vs 60 km/h) were used to study within-subjects differences in braking as a function of TTC_{t0}.

***Data registration and analysis*.** Speed of the simulator car (V) and lead vehicle (V_{lead}) in m/s, distance headway (DHW) in meters, acceleration in m/s² and brake pedal signal expressed as percentage pressed were sampled with a frequency of 10 Hz. THW was calculated as DHW/V. TTC was calculated as DHW/Vr, with Vr being the relative speed ($V-V_{lead}$). Average THW was computed from the moment the simulator car and the lead vehicle drove with the same speed until the lead vehicle left the main road. THW_{pref} was computed as the average THW over the four speed conditions.

In the second part of the experiment t_0 represents the moment a DHW of 50 meters was reached. On t_0 the lead vehicle started to brake. TTC_{t0} represents the TTC on t_0. BRT was computed as t_{br} - t_0, where t_{br} refers to the moment the brake pedal was pressed more than 5%. TTC_{br} represents TTC on t_{br}. On t_{maxbr} the maximum brake pressure, MAXBR, was reached. TTC_{maxbr} represents TTC on t_{maxbr}. Brake control movement time, (BCMT) was calculated as t_{maxbr}-t_{br}. The moment the maximum deceleration, DEC_{max}, was reached is indicated as t_{DECmax}. The moment the minimum TTC, TTC_{min}, was reached is indicated as t_{TTCmin}. The absolute time difference between the moment of maximum deceleration and the moment of minimum TTC was computed as ABS(t_{DECmax}-t_{TTCmin}) and is referred to as t_{dif}. Figure 1 shows a time history of braking, together with a number of dependent variables.

Analysis of covariance was applied to test differences in sensitivity to TTC as a function of THW_{pref}. For this, differences between the two braking conditions were studied to test whether braking-related variables covaried with TTC. The difference in TTC_{t0} between braking condition 60 (lead vehicle braked from 60 to 40 km/h) and braking condition 50 (lead vehicle braked from 50 to 30 km/h) is expressed as δTTC_{t0}. The differences in MAXBR and BRT between these two conditions are expressed as δMAXBR and δBRT. The regression coefficient of δBRT and δMAXBR on $\delta TTCt_0$ is an indicator for the sensitivity of BRT and MAXBR to $TTCt_0$. Higher sensitivity is expressed as a steeper slope (larger coefficient of regression). Analysis of covariance was used to test differences in slope as a function of THW_{pref}.

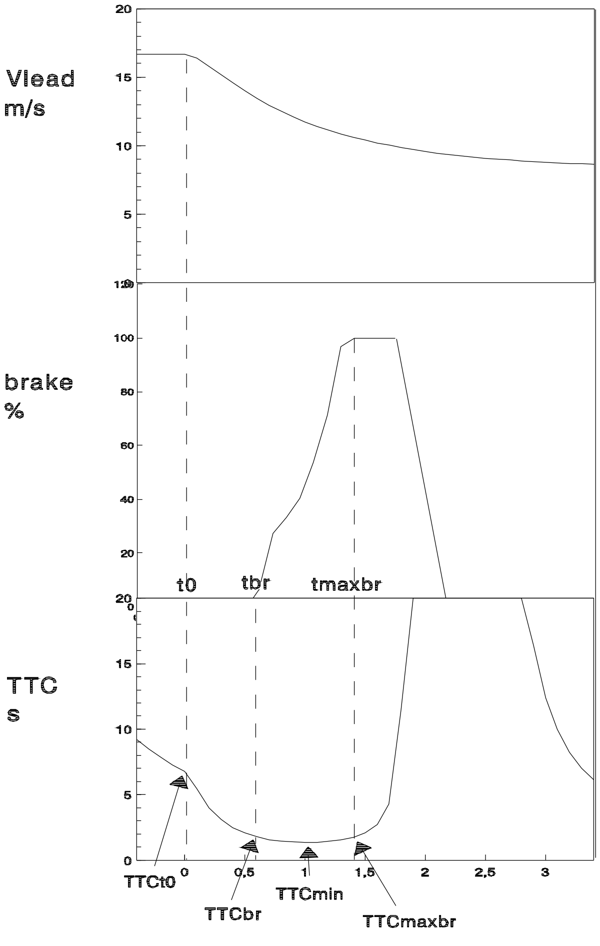

Figure 1. Time-history of braking and dependent variables.

Effects of THW_{pref} and braking conditions on dependent variables were tested with repeated measurements multivariate analysis of variance (MANOVA) with braking condition as a within-subjects factor.

Subjects. Fifty-four male subjects participated in the experiment. The average age was 29 years (sd. 8.12, range 19-48) with 65% of the subjects being younger than 30 years of ages. They had held a driving license for 9 years on average (range 1-29).

6.3 Results

Stability of THW_{pref}. THW was not significantly affected by speed of the lead vehicle ($F(135,3)= 1.27$, $p>=0.2$-5), see figure 2. This supported the hypothesis that THW is constant over speed.

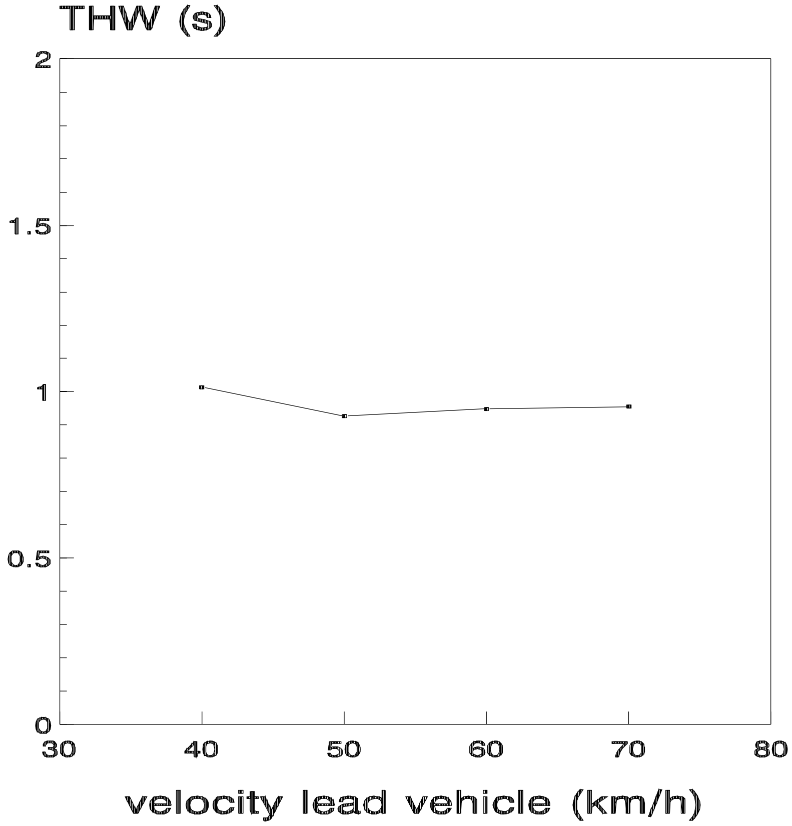

Figure 2. THW as a function of speed.

A high correlation between THW's in the four speed conditions suggests consistent following behaviour. THW's in all speed conditions were significantly correlated ($p < 0.001$), as shown in table 1. Additional evidence for consistency in following behaviour was obtained by considering each THW as an "item" in a (4-item) "following behaviour" test (Hendrickx, 1991). The test's reliability index (Cronbach's alpha) was found to be as high as 0.91. This was taken as evidence that all THW's were an expression of a subjects' general THW_{pref}.

Table 1. Correlation matrix for THW's in the four speed conditions

	THW50	THW60	THW70
THW50	0.69**		
THW60	0.76**	0.63**	
THW70	0.67**	0.69**	0.60**

(** indicates $p < 0.001$).
THWxx : THW = time headway, xx = speed (km/h) of lead vehicle

These results supported the hypothesis that THW is consistent within drivers, but differs between drivers. For further analysis, the average THW over the four speed conditions was computed as THW_{pref}. Based on the frequency distribution of THW_{pref}, three groups of equal size were created. These groups are referred to as 'THW_{pref} groups'. These groups served as a between-subjects factor in subsequent analyses. Four subjects were not included because they failed to reach a stable THW in the 70 km/h condition. Table 2 shows number of subjects, average THW and standard deviation of THW for the THW_{pref} groups.

Table 2. Size, mean THW and sd of THW for THW_{pref} groups

THW_{pref} group	N	mean THW(s)	sd of THW
short	17	0.67	0.19
medium	16	1.08	0.09
long	17	1.52	0.27

Braking responses. Two additional subjects failed to display a clear brake response in one of the two braking conditions. Therefore, the total number of subjects in the analyses was 48.

Figure 3 shows the time history of TTC for the three THW_{pref} groups in both braking conditions. Four datapoints are displayed. The first point represents TTC_{t0}, the second TTC_{br}, the third TTC_{min} and the fourth TTC_{maxbr}. The time interval between TTC_{t0} and TTC_{br} represents BRT, while the time interval between TTC_{br} and TTC_{maxbr} represents brake control movement time (BCMT).

The initiation of braking. Table 3 gives the MANOVA effects of THW_{pref} group and braking condition on variables related to the initiation of braking.

TTC_{t0} and TTC_{br} were significantly smaller, while the relative speed (Vr) at t_0 and t_{br} was significantly larger for subjects with a smaller THW_{pref}. At t_0 long followers already had lowered their speed to a greater extent than short followers. BRT was not significantly different for short followers compared to long followers.

Table 3. Effects of THW_{pref} group and braking condition on variables related to the initiation of braking (F-statistics)

	Effect		
Dependent	THW_{pref} group	Braking con.	interaction
TTC_{t0}	8.57**	0.16	0.52
TTC_{br}	18.05**	0.59	1.14
Vr_{t0}	15.83**	6.79**	1.90
Vr_{br}	24.72**	8.07**	1.26
BRT	0.62	20.57**	1.01

THW$_{pref}$ group effect : df = 45,2;
Braking condition effect : df = 45,1;
Interaction effect: df= 45,2
** = $p < 0.01$

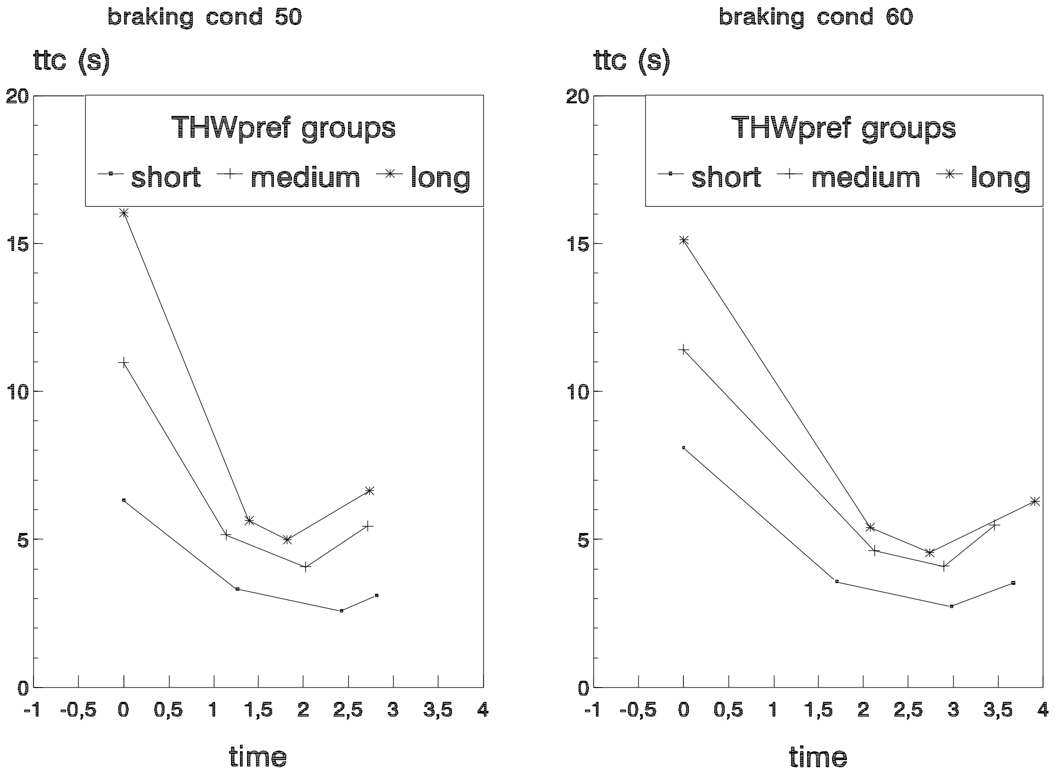

Figure 3. Time history of TTC as a function of THW$_{pref}$ groups for braking condition 50 (left) and braking condition 60 (right).

Braking condition had a significant effect on BRT. BRT was faster in the condition where the lead vehicle decelerated from 50 to 30 km/h. This was accompanied by a larger relative velocity on t_0 and t_{br} in this condition. None of the interactions were significant.

Table 4 presents the correlations of BRT with TTC$_{t0}$ and TTC$_{br}$.

Table 4. Correlation of BRT with TTC in braking condition 50 and 60

	Condition 50	Condition 60
TTC$_{t0}$	0.66**	0.61**
TTC$_{br}$	0.01	-0.21

** = $p < 0.01$

The correlations of BRT with TTC$_{t0}$ were highly significant. The correlations of BRT with TTC$_{br}$ were not significant. Thus, BRT decreased as TTC$_{t0}$ decreased for both braking conditions. This was taken as evidence that the initiation of braking, indicated by BRT, was sensitive to TTC information as an index for criticality. The significant effect of THW_{pref} group on TTC_{t0} and the absence of a significant effect of THW_{pref} on BRT suggests the TTC criterion for initiating the braking response is lower for short followers.

One of the hypotheses was that the initiation of braking was more sensitive to TTC for short followers compared to long followers. Sensitivity was expressed as the extent to which BRT covaries with TTC_{t0}. Analysis of covariance revealed that δBRT was dependent on δTTC_{t0} (F(42,1) = 14.77, p<0.001). This means that, within Ss, a smaller TTC_{t0} resulted in a faster BRT. Since δBRT was computed as the difference between BRT's in the two braking conditions, the effect of braking condition on BRT is partly explained by within-subjects differences in TTC_{t0}. Thus, the initiation of the braking response was very sensitive to between-subjects as well as within-subjects variations of TTC at t_0. The slope of the regression of δBRT on δTTC_{t0} represents the sensitivity of BRT for TTC_{t0}. The magnitude of the slope as well as the correlation coefficients are shown in table 5 for the three THW_{pref} groups. Although the correlation and regression coefficients suggest a stronger relation between δBRT and δTTCt0 for short followers, this was not confirmed by analysis of covariance because the interaction with THW_{pref} groups was not significant (F(42,2)=1.62, p=0.210). Thus, the hypothesis that short followers are more sensitive to TTC information in the initiation of the braking response was not confirmed.

Table 5. Correlation and sensitivity of BRT to TTCt0

THW_{pref} group	R	coefficient of regression
short	0.72**	0.19
medium	0.63**	0.12
long	0.51*	0.06

** = p < 0.01; * = p < 0.05

The control of braking. Table 6 shows the effects of THW_{pref} group and braking condition on variables related to the control of braking.

Table 6. Effects of THW_{pref} group and braking condition on variables related to the control of braking (F-statistics)

	Effect		
Dependent	THW_{pref} group	Braking con.	interaction
TTC_{min}	18.78**	0.30	1.23
TTC_{maxbr}	16.13**	0.01	0.51
BCMT	0.86	2.01	2.19
MAXBR	6.24**	7.12**	0.33
DEC_{max}	4.54*	2.49	0.02
t_{dif}	3.88*	0.75	0.09

THW_{pref} group effect : df = 45,2
Braking con. effect : df = 45,1
interaction effect : df = 45,2
** = p < 0.01; * = p < 0.05

The minimum TTC during braking (TTC_{min}) was significantly smaller for short followers, as was the TTC at the moment the brake was pressed to the maximum (TTC_{maxbr}). Short followers generated a more intense brake reaction than long followers : MAXBR was significantly larger for short followers. Also DEC_{max} was larger for short followers. This supported the hypothesis that short followers differ from long followers in the intensity of the braking response. BCMT, the time within which the brake maximum was reached, was not affected by THW_{pref} groups.

The absolute time difference between t_{DECmax} and t_{TTCmin}, t_{dif}, was seen as an indicator for the efficiency of braking control. There was a significant effect of THW_{pref} group on this measure. T_{dif} was smaller for short followers compared to long followers, see figure 4. This supported the hypothesis that short followers differ from long followers in the quality of braking control.

In order to test the sensitivity of the intensity of braking to criticality, an analysis of covariance was performed on δMAXBR (differences in MAXBR between the two braking conditions) as a function of δTTC_{t0} (differences in TTC_{t0} between the two braking conditions), with THW_{pref} group as a between-subjects factor. A smaller TTC_{t0} generally resulted in a larger MAXBR (F(42,1)=22.37, p=0.000). This means that the intensity of the braking reaction strongly depended on TTC_{t0}. The interaction with THW_{pref} group was significant as well (F(42,2) = 4.63, p=0.015). In table 7 it can be seen that MAXBR decreases more as a function of TTC_{t0} for short followers compared to long followers. The differences in slope indicate that the intensity of the braking response is more sensitive to TTC_{t0} for drivers with a smaller THW_{pref}, although the correlations between δMAXBR and δTTCt0 are comparable for the three groups.

This again supported the hypothesis that short followers differ from long followers in the quality of braking control.

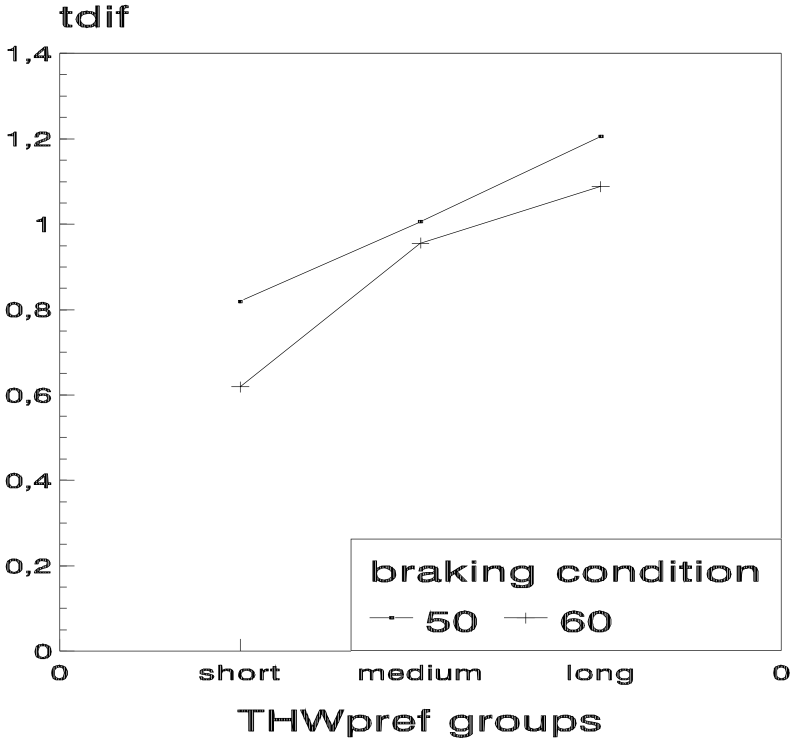

Figure 4. Difference between t_{TTCmin} and t_{DECmax} as a function of THW_{pref} groups and braking condition.

Table 7. Correlation and sensitivity of MAXBR to TTCt0

THW_{pref} group	R	coefficient of regression
short	-0.69**	-6.52
medium	-0.57*	-3.13
long	-0.58*	-1.13

** = $p < 0.01$; * = $p < 0.05$

6.4 Discussion and conclusions

The hypothesis that THW_{pref} is consistent within the driver and the hypothesis of constancy of THW_{pref} over speed during steady-state car-following were confirmed for the range of speeds examined in the present experiment. The brake reaction of drivers was analyzed in order to investigate whether differences in THW_{pref} during steady-state car-following are related to differences in braking performance and underlying skills. Since THW during steady-state following represents the time available to the driver to give an appropriate braking response in case the lead vehicle decelerates, THW may be the result of an adaptation of the driver to individual differences in braking competence. Braking performance was assumed to be related to the ability to perceive time-to-collision (TTC) and the ability to generate an efficient braking response, depending on the criticality of the situation. The initiation of braking, as measured by brake-reaction time (BRT) was strongly related to TTC at the moment the lead vehicle started to brake (TTC_{t0}) and thus to criticality. This strong relation was apparent between subjects as well as within subjects. This conforms with the suggestion in the literature that TTC information is used by the driver to judge the moment to start braking. However, drivers with a smaller THW_{pref} during steady-state following start to brake at a lower TTC, i.e. when the criticality is higher. This suggests a different TTC criterion for the initiation of braking, depending on preferred time-headway. Although the initiation of braking was very sensitive to TTC information, there were no differences between short followers and long followers in sensitivity of BRT to TTC_{t0}. Thus, the hypothesis that differences in THW_{pref} during steady-state following are related to the ability to accurately perceive TTC was not confirmed since a differential ability related to TTC perception was assumed to be expressed in BRT.

The minimum TTC during braking was smaller for short followers. This indicates that a collision was more imminent for short followers than for long followers. There were however differences in the control of braking. Firstly, short followers pressed the brake pedal to a higher maximum, resulting in a larger deceleration. Secondly, for short followers the intensity of the braking response was more strongly dependent on the criticality at the moment the lead vehicle started to brake. This suggests that the intensity of braking is at least partly programmed before response execution and confirms the suggestion in the literature that TTC information is used in the control of braking. Short followers are then better able to program this response to the appropriate level, depending on criticality. However, at the moment the lead vehicle starts to decelerate, the driver does not know how strong it will decelerate and for how long. Therefore, visual feedback during the braking maneuver is important for continuously adapting the braking response to the required level. The programmed braking intensity may then have to be adjusted to another level depending on the development of criticality in time. The moment of maximum deceleration (t_{DECmax}) was assumed to indicate when the driver knows a collision will be avoided. A closer correspondence in time with the moment of minimal TTC (t_{TTCmin}) suggests a better ability to adjust the control of braking to requirements. In this respect, the third difference was found between short en long followers. For short followers the absolute difference between t_{DECmax} and t_{TTCmin} was smaller, indicating a more efficient braking control where the timing and intensity of braking is better tuned to the development of criticality in time during the braking process.

These results suggest differences in skills related to the response programming and response execution of braking between short and long followers. On the other hand, the absolute levels of TTC_{t0} were different between

THW_{pref} groups. An alternative explanation may then be that short followers had to generate more efficient braking responses that were better tuned to criticality because criticality was higher for them to begin with. In other words, they may have been forced to perform better. Also, since TTC during the braking process was lower for short followers, and, as discussed in the introduction, the estimation of TTC is more accurate for smaller TTC's, the differences between short and long followers in braking control may have been caused by a more accurate estimation of TTC by short followers. In both cases, however, the sensitivity of BRT to TTC_{t0} is expected to be higher too for short followers. Since this was not the case, the evidence presented suggests differences in skills related to the programming of the intensity of braking and the control of braking between short and long followers.

Chapter 7

7. EXPERIMENT 4: Time-headway in car-following and operational performance during unexpected braking

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The relation between choice of time-headway during car-following and the quality of braking skills was studied in a driving simulator. The theoretical perspective was that individual differences in behaviour on the tactical level may be related to skills on the operational level of the driving task via a process of adaptation. In a sample of 16 young and middle-aged experienced drivers independent assessments were made of preferred time-headway and braking skill. Starting from modern theories of visual-motor learning, braking skill was analyzed in terms of a reaction time component, an open-loop visual-motor component, and a closed-loop visual-motor component involving the precise adjustment of braking (timing and force) to the situation. The efficiency of the visual-motor component of braking was a strong and significant predictor of time-headway in such a way that more efficient braking indicated a shorter preferred time-headway. This result appears to support the adaptation theory on an individual level.

7.1 Introduction

For many years it has been realized that individuals who have very good driving skills in the sense of great fluency and agility in performing the basic driving tasks of visual orientation and vehicular control, are not necessarily safe drivers (Williams and O'Neill, 1974; Evans, 1991). Traffic safety depends on what the driver will do in a given situation and not on the maximum level of performance (Näätanen and Summala, 1976) or, as Evans (1991) puts it, what is crucial is not how the driver can drive but how the driver does drive. The failure of driver skill models in explaining accident involvement has been attributed to various adaptive mechanisms. For example, drivers with poor skills might compensate by driving slower, or, the other way around, very skilled drivers might tend to drive very fast. Because traditional skill models do not incorporate such compensatory mechanisms they are not suitable for assessing and understanding individual differences in the safety of traffic behaviour.

A solution to this problem may be the application of the hierarchical framework discussed by Michon (1985) to driving behaviour (Ranney, 1994). In this framework driving is viewed as a hierarchically organized set of tasks on the strategic, tactical and operational level. On the strategic level trip planning and the selection of trip goals and route occur. The tactical level includes, for instance, choice of speed on straight roads and in curves and choice of headway in car-following. Steering and controlling the timing and intensity of braking are activities on the operational level. Traditionally the study of driving skill was aimed as the efficiency of performance on the operational level. However, in this article the importance of the interrelation between behaviour on the operational and the tactical level is stressed. In this framework the adaptation problem may be understood as a compensation on the tactical and strategic levels of the driving task for individual differences in skills on the operational level (Brouwer et al., 1988). This adaptation theory has been used as an explanation for the relatively safe driving records of functionally impaired drivers. The link with driver safety now becomes clear. Driver safety may be defined in terms of the relationship between operational level skills and choices and preferences on the tactical level.

Recently, Van Winsum and Heino (1996) found some evidence with regard to the relationship between individual differences in operational level skills and tactical behaviour which appears to fit an adaptation theory on the individual level. In a study on time-headway in car-following, they found evidence for a relationship between braking skill and choice of time-headway. Since time-headway (THW), defined as the time interval between two vehicles in car-following, represents the time available to reach the same level of deceleration as the lead vehicle in case it brakes, they studied whether choice of THW is related to time-critical skills underlying braking performance. THW was constant over the range of speeds studied. Drivers were consistent in their choice of THW, evidencing systematic individual differences in choice of THW during car-following. The results suggested differences in skills related to the motor control of braking as a function of preferred time-headway. What was lacking in this study was a specific model of the braking skills so that it was difficult to pinpoint in which respect drivers with short THW differed from those with long THW. In the present study a model for the decomposition of perceptual-motor processes in braking is proposed and individual differences in the efficiency of such processes are related to the choice of time-headway in a free field situation.

Braking for a decelerating lead vehicle requires substantial perceptual-motor skills because of the dynamic task environment. Lee and his co-workers have shown in a number of publications that a perceptual variable, named tau, which is the inverse of the expansion of the retinal image, is used in action. This variable directly specifies time-to-contact in dynamic situations. Thus, perception is assumed to guide action and this relation between tau and action has been established in a number of different tasks such as long jumpers running up to a take-off board (Lee et al., 1982) and jumping up to hit a falling ball (Lee et al., 1983). Also, Bootsma and Van Wieringen (1988) found that time-to-contact plays an important role in the guidance of actions of an experienced table tennis player. In car driving and braking the equivalent of time-to-contact is time-to-collision (TTC). Lee (1976) suggested that TTC information is used by the driver in the initiation and control of braking. Van Winsum and Heino found that the initiation and control of braking for a decelerating lead vehicle was very sensitive to TTC information. The timing of the initiation of the braking response was equally sensitive to TTC for short followers and long followers. However, short followers were more efficient in the control of braking, braked harder and adjusted the intensity of braking better to the criticality (as measured by TTC) at the moment the lead vehicle started to decelerate, compared to long followers. So, it appeared that the difference between the short and long followers was in the execution of the motor response.

Substantial individual differences in the ability to accurately estimate TTC have been reported in the literature (for instance see Schiff and Detwiler, 1979). A general finding is that TTC is underestimated with a constant proportion. TTC estimation is more accurate for smaller TTC's, see for instance, McLeod and Ross (1983), Cavallo et. al (1986), Hoffmann and Mortimer (1994). Given this evidence, the results of Van Winsum and Heino could have been affected by the fact that the TTC at the moment the lead vehicle started to brake (t_0) was smaller for short followers although the distance at t_0 was the same for all subjects. This was caused by a higher speed on average for short followers on t_0. Theoretically, short followers were thus in a position to estimate TTC more accurately. In addition, since TTC was smaller for short followers they may have been forced to brake harder and more accurately. In order to control for effects of differential criticality and accuracy of TTC estimation, all drivers will be subjected to the same high level of criticality in the present study.

In dynamic situations such as braking for a decelerating lead vehicle, following the initial reaction of releasing the accelerator, the motor response is assumed to consist of two phases, i.e. an open-loop and a closed-loop phase. We attempt to separately assess these three processes by analyzing the braking response in terms of Reaction time (RT), the Brake Initiation Movement Time (BIMT) and the Brake Control Movement Time (BCMT) (see Figure 1). Starting from the adaptation theory we expect that the quality of these processes is related to preferred time-headway: specifically we hypothesize that preferred time-headway (behaviour on the tactical level) can be predicted from the BIMT and the BCMT (performance on the operational level). To be able to assess the reliability of preferred THW as an indicator of a stable individual characteristic, it is measured at four different speeds. It is expected that the results of Van Winsum and Heino concerning the consistency of THW and the constancy of THW over speed will be replicated.

Reaction time (RT) represents the interval between stimulus presentation and movement initiation. Several information processing stages including response selection and response preparation, together called motor programming, occur within this interval. Motor programming time, as a part of RT, is assumed to be related to temporal complexity and organization of the movement to be executed, but not with physical task dimensions such as distance (Kerr, 1978). This suggests that the time associated with parameter setting for a generalized motor program does not vary for different parameter values. Thus, TTC is not expected to affect RT because TTC is assumed to determine the speed parameter value for the generalized motor program.

The Brake Initiation Movement Time (BIMT) is used to operationally define the open-loop phase under the control of the generalized motor program for braking of which the speed parameter is set by TTC information. During this phase the influence of feedback is absent. Because of the time characteristics of the braking response the open-loop phase is defined here as the interval between the moment the driver withdraws the foot from the accelerator pedal and the moment the brake pedal is touched. The duration of this phase is then assumed to be dependent on TTC at the moment the driver detects the deceleration of the lead vehicle or at the moment the driver decides to brake.

Error detection and error correction are assumed to take place during the closed-loop phase, operationally defined here as the Brake Control Movement Time (BCMT). This is the interval between the moment the brake pedal is touched and the moment the brake maximum is reached. Since the environmental goal of the movement is to avoid a collision and to keep sufficient distance to the lead vehicle, TTC information is possibly used during this feedback process. According to Hayes and Marteniuk (1976) movement control complexity can be viewed as the information load imposed on the performer by the necessity to detect and correct movement errors. For more skilled operators movement time decreases because of a decrease in the number of movement corrections (Keele, 1968). During the closed-loop phase of the braking response, movement time is then expected to be related to the number of movement corrections.

7.2 Method

Subjects. Sixteen (8 male, 8 female) subjects participated in the experiment. The average age was 33.6 years (sd. 6.1, range 22-47). They had held a driving license on average for 11.6 years (range 2-27). The average annual kilometrage was approximately 10083 kilometers (range 1500-30000).

Apparatus. The experiment was performed in the Traffic Research Centre (TRC) fixed-based driving simulator. It consists of a car (BMW 518) with a steering wheel, clutch, gear, accelerator, brake and indicators connected to a Silicon Graphics Skywriter 340VGXT computer. A car model converts driver control actions into a displacement in space. On a 2 x 2.5 meter projection screen, placed in front of the car mockup, an image of the outside world with a horizontal angle of 50 degrees is projected by a graphical videoprojector, controlled by the 3D-graphics software. Images are presented with a rate of 15 to 20 frames per second, resulting in a suggestion of smooth movement. The visual objects are buildings, roads, traffic signs, traffic lights and artificially intelligent traffic. The sound of the engine, wind and tires is presented by means of a digital soundsampler receiving input from the simulator computer. The simulator is described in more detail elsewhere (Van Wolffelaar & Van Winsum, 1992 and Van Winsum & Van Wolffelaar, 1993).

Procedure. A circuit of two-lane roads (lane-width 3 meters) with broken center lines and continuous edge lines was used. Since the subjects had participated in another simulator experiment not involving car-following prior to the present experiment, they were already sufficiently practiced. First, preferred time-headway was measured as a function of different speeds. Subjects were instructed not to overtake other vehicles, to respect the speed limit of 80 km/h and to follow other vehicles at a safe distance. While driving, the subjects approached vehicles that were parked on the right shoulder. At a distance of 200 meter these vehicles accelerated to a fixed cruising speed and merged in front of the simulator car. There were four of these trials that differed in the cruising speed of the lead vehicles. The order of speeds was 60, 40, 70 and 50 km/h for all subjects (speed condition). In every trial, time-headway was measured during 5 minutes.

After this, a vehicle, driving with a speed of 60 km/h, was approached. Prompted by the experimenter the subjects were asked to rate the danger of the present headway on a scale from 1 to 5. Then they were requested to drive a bit closer and again asked to give a rating. This continued until a time-headway of 0.6 seconds was reached. At that moment the lead vehicle suddenly decelerated unexpectedly from 60 km/h to 30 km/h with a deceleration of 6 m/s². This constitutes the braking condition. The aim of this procedure was to ascertain a fixed time headway at the moment the lead vehicle started to brake for all subjects.

Data registration and analysis. Speed, brake and accelerator pedal signal (percentage pressed), distance-headway, time-headway and time-to-collision were sampled with a frequency of 10 Hz. Average THW was computed, for the four trials in the speed condition, from the moment the simulator car reached the same velocity as the lead vehicle until the lead vehicle left the road. THW's were averaged over the four speed trials to compute preferred time-headway (THW_{pref}). The effect of speed on THW was tested with multivariate analysis of variance with repeated measurements.

Figure 1 shows the time-history of braking together with a number of dependent variables. In the braking condition, t_0 represents the moment a THW of 0.6 was reached. On t_0 the lead vehicle started to brake. The moment the accelerator pedal was 5% less than the position on t_0 represents t_{acc}. Reaction time (RT) was calculated as the interval between t_0 and t_{acc}. The moment the brake pedal was pressed more than 5% is indicated as t_{br}. The interval between t_{acc} and t_{br} represents the open-loop phase of the movement and is referred to as brake initiation movement time (BIMT). The moment the maximum brake position was reached is indicated by t_{maxbr}. The duration of the closed-loop phase, brake control movement time (BCMT), was computed as the interval between t_{br} and t_{maxbr}. Movement time (MT) was computed as the sum of BIMT and BCMT. TTC on t_{acc} is referred to as TTC_{acc}.

During the closed-loop phase the brake pedal is pressed. A typical time-history of this is presented in figure 2. It shows the percentage at which the brake pedal is pressed together with the velocity of pressing the brake pedal and acceleration of brake pedal signal as a function of time. The number of decelerations in this signal reflect the number of movement (speed) corrections. The effect of driver reactions to braking by the lead vehicle on THW_{pref} were tested with multiple regression analysis.

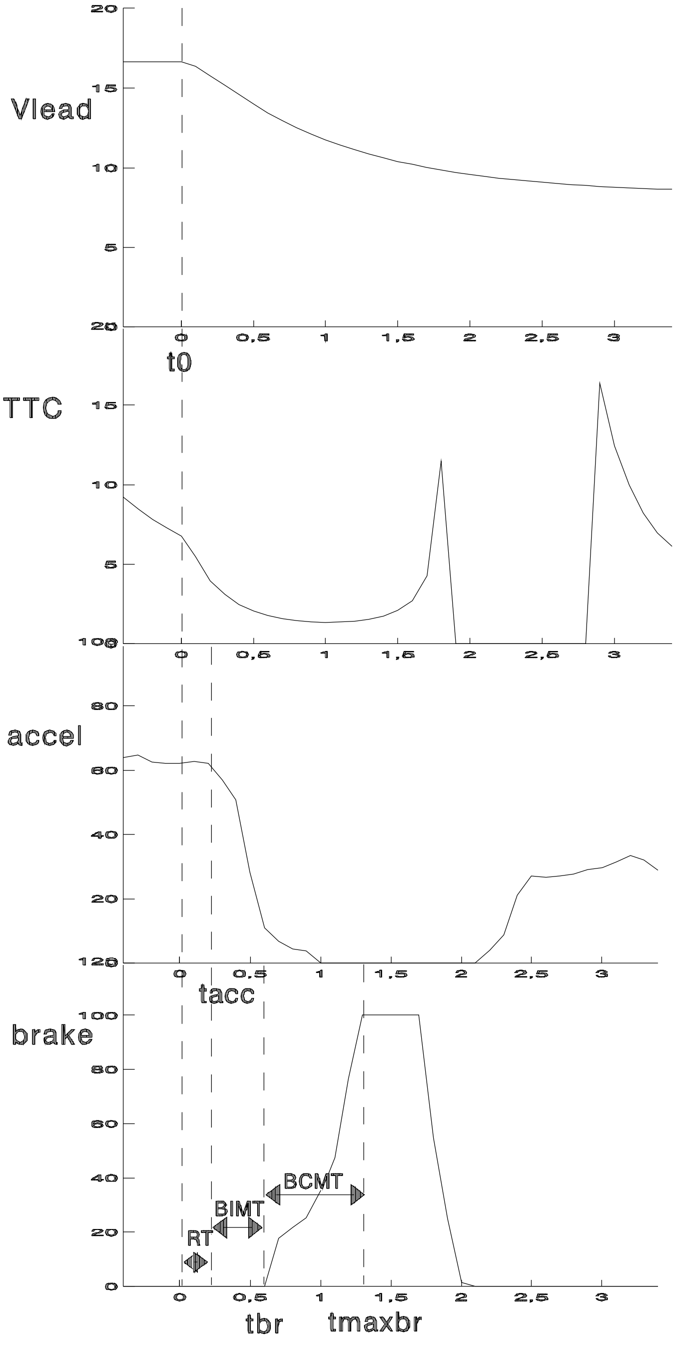

Figure 1. Time-history of the braking maneuver. Vlead represents speed of lead vehicle in m/s, accel represents accelerator pedal position.

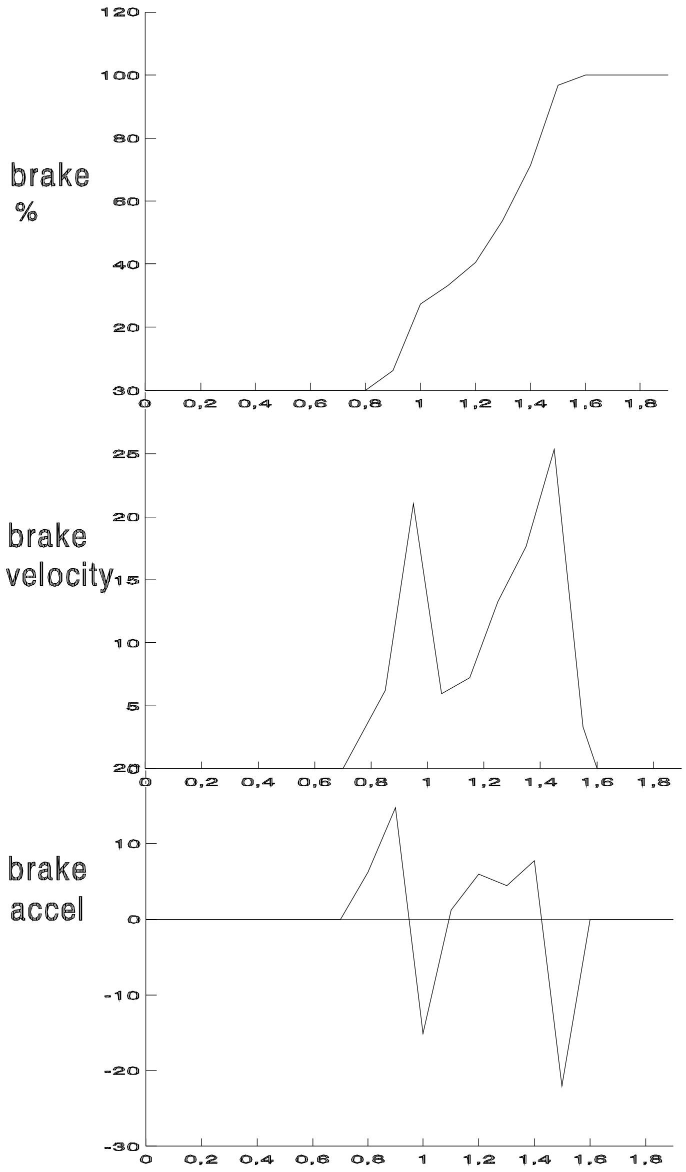

Figure 2. Brake pedal signal, velocity and acceleration of braking as a function of time during the closed-loop phase.

7.3 Results

Before testing the main hypothesis a preliminary assessment is made of the reliability of THW_{pref}.

Reliability of preferred THW. THW was not significantly affected by the speed of the lead vehicle (F(3,15)=1.20, p>=0.352), whereas distance headway significantly increased with speed (F(3,15)=20.20, p<0.0001). This means that THW was constant over speed. The test's reliability index (Cronbach's alpha) for the four measurements of THW over different speeds was 0.89, while the standardized alpha was 0.90. This was taken as evidence that all THW's are an expression of a subjects' general preferred THW. THW_{pref} was computed as the average THW over the four speed trials.

The correlations of THW_{pref} with annual kilometrage and number of years licensed were not statistically significant (R=0.13 resp. -0.02). This means that preferred time-headway was not related to driving experience. Also, none of the braking-related variables correlated significantly with driving experience.

The relationship between preferred THW and braking skill. It is first tested whether the duration of the open-loop phase is determined by TTC after the RT interval and whether the duration of the closed-loop phase is affected by the number of movement corrections as predicted by the braking model presented in the introduction. The regression coefficients (Beta weights) are presented in table 1.

Table 1. Effects of regression analyses of TTC_{acc} and movement corrections on the duration of the open-loop (BIMT) and closed-loop (BCMT) phases.

Dependent	Independent	R(=Beta)	F
BIMT	TTC_{acc}	0.81	27.11 **
BCMT	nr corr	0.83	30.09 **

nr corr = number of movement corrections

** = p < 0.01;

From inspection of table 1 it appears that the duration of the open-loop phase was strongly determined by TTC at the moment the accelerator was released. The duration of the closed-loop phase was strongly determined by the number of movement corrections. This confirms the model of braking discussed in the introduction.

It was then tested whether operational braking performance affected choice of time-headway. For this the regressions of RT, BIMT and BCMT on THW_{pref} were analyzed, controlling for the effects of TTC_{acc} and number of movement corrections. In this way the direct effects the independent variables on THW_{pref} could be established. Table 2 lists the effects of RT, BIMT and BCMT on THW_{pref}. This table should be read as follows. The first column lists the dependent variable. The second column lists the independent variables in order of inclusion in the regression equation. R represents multiple correlation after addition of the independent variable, and F represents the accompanying F statistic for the whole regression equation. Beta and T represent the Beta weight and t value when all dependent variables are included in the equation.

Table 2. Effects of multiple regression analyses of brake-related times on THW_{pref}.

Dep	Indep	R	F	Beta	T
THW_{pref}	RT	0.31	1.50	-0.31	-1.23N.S.
THW_{pref}	BIMT	0.53	5.37	1.12	3.25**

	TTC_{acc}	0.68	5.64	-0.74	-2.13*
THW_{pref}	BCMT	0.49	4.39	0.49	2.09*
	nr corr	additional contribution too small for inclusion			
THW_{pref}	MT	0.67	11.24	0.67	3.35**

* = $p < 0.05$; ** = $p < 0.01$; N.S. = not significant

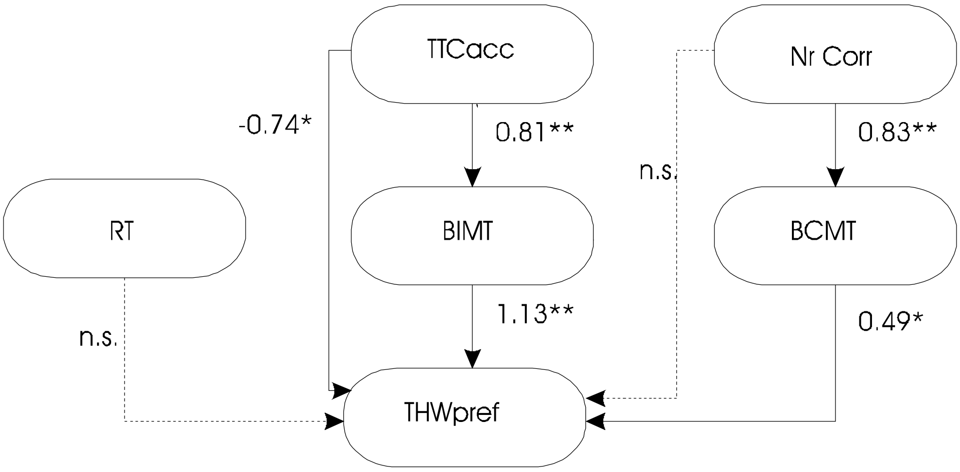

Figure 3. Path diagram with partial regression coefficients.
*=$p< 0.05$, **=$p< 0.01$, ns=not significant.

There was no significant effect of RT on THW_{pref}. The effect of BIMT on THW_{pref}, with TTC_{acc} controlled for, was statistically significant. This means that subjects with a faster open-loop motor reaction preferred a smaller THW. This was not simply caused by a smaller TTC_{acc} for subjects with a smaller THW_{pref}, since there also was a significant direct effect of TTC_{acc} on THW_{pref} indicating that drivers with a larger TTC_{acc} tended to have a smaller preferred time-headway. The effect of BCMT on THW_{pref} also was statistically significant. There was no significant direct effect of number of movement corrections on preferred time-headway. This means that the faster closed-loop motor response of drivers with a smaller preferred time-headway was caused by a smaller number of movement corrections. The effects of total movement time (MT) on THW_{pref} also was statistically significant. The path diagram of dependent variables on preferred time-headway is presented in figure 3.

7.4 Discussion and conclusions

The hypothesis that preferred time-headway is consistent within the driver and constant over different speeds during steady-state car-following was confirmed for the range of speeds (40, 50, 60, 70 km/h) examined in the present experiment. This replicates the results of Van Winsum and Heino (1996).

Reaction time, i.e. the difference between the moment the lead vehicle started braking and the moment the accelerator was released, was not related to preferred time-headway. This confirms the results of Van Winsum and Heino that short followers do not differ from long followers in perceptual mechanisms related to time-to-collision (TTC) detection. The open-loop phase of the motor response was very sensitive to TTC, and especially to TTC at the moment the foot was released from the accelerator pedal. This suggests that as soon as the driver detects the deceleration of the lead vehicle, the speed parameter of the generalized motor program is set as a function of TTC.

Drivers who moved their foot faster to the brake pedal had a smaller preferred time-headway. The direct effect of TTC at the moment the accelerator was released on preferred time-headway indicates that the effect of the duration of the open-loop phase on preferred time-headway was not caused by a smaller TTC for short followers. This suggests that drivers with a smaller preferred time-headway program the movement speed of the foot to a higher level than drivers with a longer preferred time-headway. This suggests differences in the transformation of perceptual information into the adjustment of the speed parameter.

The duration of the closed-loop phase of the motor response was strongly related to the number of movement corrections. This confirms the expectations, discussed in the introduction, of separate influences on the duration of the open-loop and the closed-loop phases. Subjects who moved their foot faster to the maximum during the closed-loop phase and who exhibited fewer movement corrections had a smaller preferred time-headway. This suggests a higher skill level in these subjects. Subjects with a larger preferred time-headway appear to be more uncertain about the required braking response.

An important result in the present experiment was the strong effect of total movement time on preferred time-headway. This strengthens the conclusion that short and long followers differ in both the open- and closed-loop phases of movement. Short followers may be more sensitive to the task requirements in emergency braking situations. Short and long followers differ in the efficiency of the control of braking. This was also found in Van Winsum and Heino, but there results could have been affected by differences in absolute levels of TTC between drivers with different preferred time-headway.

Together, the results suggest that individual differences in choice of time-headway are related to individual difference in braking performance. This supports the hypothesis that drivers adapt their tactical level behaviour to their operational skill level. However, the mechanism could also be the other way around: Short followers may have had more opportunities to acquire emergency braking skills, simply because they had to brake hard more often. It can be argued that this would be particularly the case in relatively inexperienced drivers. A very experienced driver, even when being a long follower, will probably have experienced a substantial number of emergency stops anyway. Also experience in other situations may count, e.g. for stationary objects such as traffic lights. Braking for stationary objects also requires a tuning of the braking response to perceptual information. In the present study, none of the braking related variables were affected by driving experience. This does not support the idea that short followers have learned to brake more efficiently because they have been exposed to critical encounters more often. However, this is not enough evidence to rule out the alternative hypothesis and this issue will have to return in future research.

Chapter 8

8. EXPERIMENT 5: The effects of deceleration on braking reactions as a function of preferred time-headway

The manoeuvre of braking for a decelerating lead vehicle was separated into three sequential processes that were manipulated independently. The initial time-headway to the lead vehicle at the moment it started to decelerate affected reaction time. Primary deceleration of the lead vehicle manipulated the duration of the open-loop phase. From the moment the driver touched the brake pedal, the deceleration of the lead vehicle was changed. This secondary deceleration was assumed to affect the closed-loop phase of braking. The hypothesis was that drivers who prefer a small time-headway during car-following (short followers) differ from drivers who prefer to follow at a large time-headway (long followers) in both the open- and closed-loop phases. In that case an interaction is expected between following group (short vs. long followers) and primary deceleration on the duration of the open-loop phase and between following group and secondary deceleration on the duration of the closed-loop phase, the maximum brake force exerted and the number of movement corrections. In general terms, these predictions could not be confirmed. The lack of confirmation of the hypothesis is explained in terms of task characteristics that resulted in startle reactions and vigilance effects.

8.1 Introduction

A number of studies of car driving have shown that behaviour on the tactical level such as speed choice and choice of time-headway in car-following is sensitive to a variety of factors that affect operational performance. For example, marijuana affects operational car driving performance while it also results in driving with a lower speed and in choosing a larger time-headway (THW) during car-following (Smiley, et al., 1981; Smiley et al., 1985; Smiley et al., 1987). Time-on-task results in the choice of a larger time-headway during car-following, accompanied by verbal reports of performance decrements, drowsiness and exhaustion (Fuller, 1981). Brookhuis et al. (1991) reported an increase in THW when using a car telephone while driving. These findings suggest that behaviour on the tactical level is used by the driver to compensate for effects on operational performance. For the case of car-following this means that any factor that may lead to performance decrements in braking for lead vehicles may result in a compensatory increase of time-headway. From the same perspective it was studied whether individual differences in preferred THW are related to individual differences in braking performance in a number of experiments (Van Winsum, 1996; Van Winsum and Heino, 1996; Van Winsum and Brouwer, 1996). In Van Winsum and Heino (1996) and Van Winsum and Brouwer (1996) preferred THW proved to be consistent within the driver. This means that drivers are consistently short or long followers and, thus, that individual differences in THW are consistent.

In Van Winsum (1996) it was found that, under the instruction to brake as fast as possible as soon as a deceleration of the lead vehicle was detected, reaction time and motor-response times are not different between short and long followers. Also, no evidence was found for differences in the information processing stages of stimulus encoding of a braking lead vehicle and motor adjustment. However, when the driver did not know the deceleration of the lead vehicle in advance, short followers generated a faster motor response, i.e. they moved the foot faster from the accelerator pedal to the maximum brake position when the lead vehicle decelerated. This suggests that short followers differ from drivers with a larger preferred THW in the transformation of visual feedback to a required motor response.

In Van Winsum and Heino (1996) it was found that the initiation and control of braking are both affected by time-to-collision (TTC) at the moment the lead vehicle starts to brake. This suggests that TTC information is used for judging the moment to start braking and in the control of braking. No evidence was found for differences between short followers and long followers in the ability to accurately perceive TTC. However, short followers were better able to program the intensity of braking to required levels and tuned the control of braking better to the development of criticality in time during the braking process. It was concluded that short followers may differ from long followers in programming and execution of the braking response as a function of TTC information.

Van Winsum and Brouwer (1996) analyzed the braking response in terms of three sequential phases in the braking process. The first phase consists of the interval between the moment the lead vehicle starts braking and the moment the driver releases the accelerator pedal. This is measured by the reaction time (RT). The second phase consists of the open-loop ballistic motor response. It is measured as the interval between the moment the accelerator pedal is released and the moment the brake pedal is touched and referred to as Brake Initiation Movement Time (BIMT). The third phase is a closed-loop motor response during which visual feedback is used to control the braking response while braking. The duration of the open-loop phase was strongly determined by the TTC at the moment the accelerator pedal was released, while the duration of the closed-loop phase was strongly determined by the number of movement corrections in the brake pedal signal. It was found that short followers exhibited a faster open-loop motor response which was not caused by a smaller TTC at detection time. Also, short followers generated a faster closed-loop response which was caused by fewer movement corrections. These results again supported the hypothesis that short followers differ from long followers in the efficiency of programming and execution of the braking response.

According to Van Winsum and Brouwer (1996), the duration of the three phases is affected by different factors. The RT interval is assumed to be affected by the THW at the moment the lead vehicle starts braking. This means that RT is expected to be faster if the momentary time-headway at the moment the lead vehicle starts to decelerate is smaller. The open-loop interval (BIMT) is assumed to be affected by the primary deceleration of the lead vehicle. If the lead vehicle decelerates more strongly, TTC at detection time is smaller resulting in a faster open-loop response. The closed-loop interval (BCMT) is affected by the number of movement corrections. If the deceleration of the lead vehicle changes after the subject's braking response has started, the speed and intensity of the braking response has to be changed, based on visual feedback. This means that a change in the level of deceleration after the braking response has started (secondary deceleration) is assumed to result in more movement corrections and thus affects the duration of the closed-loop phase. If short followers differ from long followers in both the open- and closed loop phases, then an interaction is expected between following group (short vs. long followers) and primary deceleration on BIMT and between following group and secondary deceleration on BCMT, the maximum brake force exerted and the number of movement corrections. These hypotheses are tested in the present experiment.

8.2 Method

Subjects. Twenty-two subjects participated in the experiment. The subjects were selected from the TRC database by the following procedure. First a preselection was made on the basis of age and driving experience. Only subjects between 25 and 40 years of age with a minimum driving experience of 10000 km that were known not to be susceptible to simulator sickness were preselected from the database, resulting in 150 persons. These were send a small photo-preference test that measures preferred THW. This test consisted of 6 numbered photographs with scenes of a lead vehicle on a highway at different distances in front of the car. The preselected subjects were required to fill out on a form the number of the photograph that best matched the THW chosen by the subject while driving with a speed of 110 km/h on a highway and to return the form if they were interested in participating in the experiment. This test procedure has been shown to result in a reliable estimate of preferred time-headway during car-following on the road (Heino et al., 1992). From the returned forms, 11 subjects with a small preferred THW and 11 subjects with a larger preferred THW were invited for participation in the experiment. Subjects with a preferred photo number of less than or equal to 3 were assigned to the group of 'short followers'. Subjects who preferred photo number 5 or 6 were assigned to the group of 'long followers', see table 1. These two groups are referred to as '$\mathrm{THW}_{\mathrm{pref}}$ groups'.

Table 1. Relation between photo number and headway on the photo preference test and number of subjects. DHW=distance-headway in meters, THW=time-headway in seconds.

Photo number	DHW	THW	number of subjects
1	6	0.20	0
2	11	0.36	2
3	25	0.81	9
4	33	1.08	0
5	45	1.47	4
6	65	2.13	7

Apparatus. The experiment was performed in the driving simulator of the Traffic Research Centre (TRC). This fixed-based simulator consists of two integrated subsystems. The first subsystem is a conventional simulator composed of a car (a BMW 518) with a steering wheel, clutch, gear, accelerator, brake and indicators connected to a Silicon Graphics Skywriter 340VGXT computer. A car model converts driver control actions into a displacement in space. On a projection screen, placed in front, to the left and to the right of the subject, an image of the outside world from the perspective of the driver with a horizontal angle of 150 degrees is projected by three graphical videoprojectors, controlled by the graphics software of the simulator. Images are presented with a rate of 15 to 20 frames per second, resulting in a suggestion of smooth movement. The visual objects are buildings, roads, traffic signs, traffic lights and other vehicles. The sound of the engine, wind and tires is presented by means of a digital soundsampler receiving input from the simulator computer.

The second subsystem consists of a dynamic traffic simulation with interacting artificially intelligent cars. For experimental purposes different traffic situations can be simulated. The simulator is described in more detail elsewhere (Van Wolffelaar & Van Winsum, 1992 and Van Winsum & Van Wolffelaar, 1993).

Procedure. The circuit was made of two-lane roads with a lane-width of 3 m., and straight road sections alternated with left-turning curved road sections. All roads had delineation with broken center lines and closed edge lines. Before the experiment started subjects practiced braking several times by approaching a traffic light that turned on red after a certain time-to-intersection was exceeded. This required the subjects to come to a full stop. After this, preferred time-headway was measured by the following procedure. The subject was instructed to drive with a fixed speed of 100 km/h, while continuously being overtaken by other cars. One of these cars merged in front of the subject and adopted a time-headway of 2 s. The subject was asked to rate on a scale from 1 to 10 how well the present THW resembled the THW normally adopted by the subject in similar situations on the road. If THW was too small it was increased with 0.5 s. If THW was too large it was decreased by 0.5 s. After this the subject was again asked for a rating. This continued until a definite peak was found in the subject's rated THW, i.e. until the preferred THW was found. After this the braking trials started. The subject was instructed to drive with a constant speed of 100 km/h, to stay in the right lane and to avoid a collision with a lead vehicle in case it braked. While driving, the subject was overtaken by another vehicle every 5 seconds on average. The lead vehicle merged in front of the lead vehicle and started to drive at a fixed THW of either 0.8 or 1.2 seconds (THW condition). After a stable THW was reached it either pulled up again or it braked from 100 to 60 km/h. Braking occurred on average once in every 5 minutes. The lead vehicle applied either a deceleration of 3 or 6 m/s² (initial deceleration). After the subject touched the brake in response to the lead vehicle, the deceleration of the lead vehicle changed either to 3 or 6 m/s² (secondary deceleration), resulting in the following deceleration patterns for both THW conditions (0.8 vs. 1.2 s.): 3 to 3 m/s², 3 to 6 m/s², 6 to 3 m/s² and 6 to 6 m/s². Thus, the driver was subjected to a total of 8 braking trails, that were counterbalanced.

Data collection and analysis. During the braking trials the following data were sampled with a frequency of 50 Hz.: speed of the simulator car and the lead vehicle in m/s, accelerator pedal position, brake pedal position and force excerted in Nm, acceleration in m/s², time-to-collision (TTC) and bumper to bumper distance from the lead vehicle. At t_0 the lead vehicle started to brake.

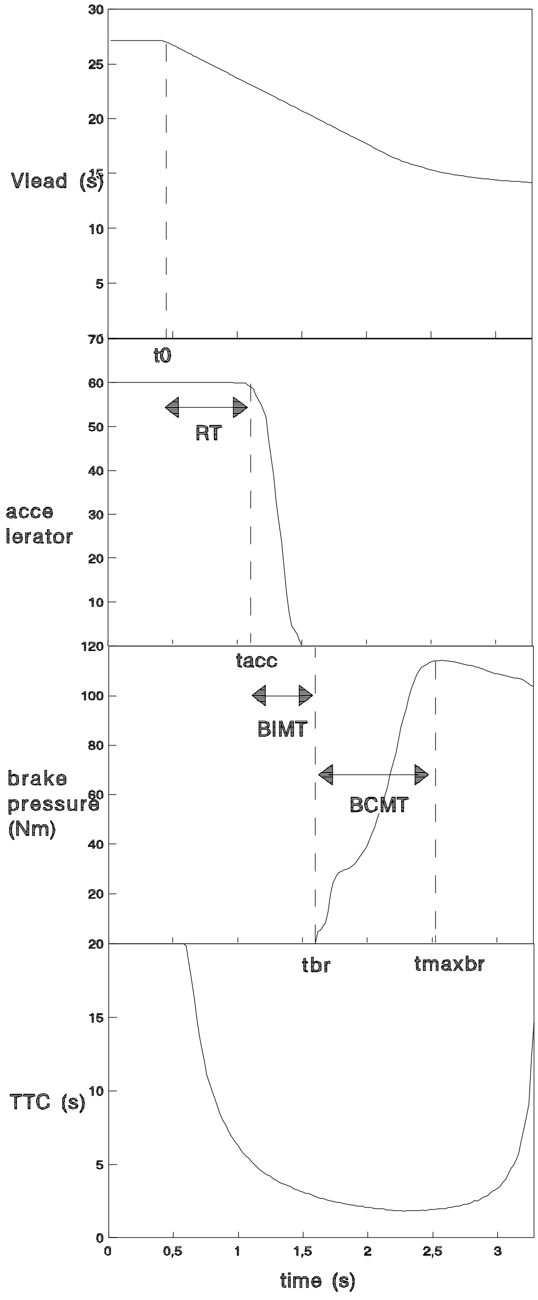

Figure 1. Time history of braking and dependent variables.

The moment the accelerator pedal position was less then 4% after t_0 was registered as t_{acc}, and RT was computed as t_{acc}-t_0. The moment after t_{acc} at which the brake pedal force was more than 3 Nm, was registered as tbr (the moment the brake pedal was touched). BIMT (Brake Initiation Movement Time, or the open-loop ballistic response) was computed as t_{br}-t_{acc}. The maximum brake force was detected on-line and the moment this was reached was registered as t_{maxbr}. BCMT (Brake Control Movement Time, or the closed-loop braking response) was computed as t_{maxbr}-t_{br}. The maximum brake force excerted, MAXBRFO, was stored as well. During the closed-loop phase a number of decelerations typically occur in the brake pedal signal. These decelerations reflect movement velocity corrections. The number of decelerations in the brake pedal signal (NRCOR) was analyzed, together with the maximum deceleration (DEC_{max}) of the simulator car, the minimum TTC (TTC_{min}) and the minimum distance to the lead vehicle (DIS_{min}) during the braking maneuver. In previous studies, the TTC on the moment the driver initiates braking, that is, TTC on t_{acc} (TTC_{tacc}) has proven to be an important variable controlling subsequent phases in the braking process. For this reason TTC_{tacc} was analyzed as well. The time-history of braking can be seen in figure 1.

The dependent variables were analyzed with repeated measures analysis of variance with THW, initial deceleration and secondary deceleration as within-subjects factors, and THW-group as a between-subjects factor.

8.3 Results

Characteristics of THW_{pref} groups. Table 2 presents the results of analysis of variance and the averages of THW as measured in the simulator, age, number of years licensed and kilometrage per year as a function of THW_{pref} groups.

Table 2. Statistical effects and averages of THW as measured in the simulator, age, number of years licensed and kilometrage per year as a function of THW_{pref} groups.

Dependent variable	F(22,1)	short	long
THW simulator	34.24**	1.5	2.9
Age	0.03	31.6	31.3
Years licensed	0.65	12.8	11.3
Annual kilometrage	5.30*	28084	13227

** = $p<0.01$; * = $p< 0.05$.

There was a strongly significant difference between THW_{pref} groups on the preferred THW as measured in the simulator. This supports the validity of the simulator for measuring car-following behaviour. There were no significant differences in age or number of years licensed to drive a car between short and long followers, but short followers drove significantly more kilometers per year.

Effects of manipulations. Table 3 lists the main effects of the manipulations on the dependent variables. The averages of RT, BIMT, BCMT, MAXBRFO and NRCOR as a function of the manipulations are shown in table 4. RT was significantly affected by the factor THW (0.8 vs. 1.2 s): a smaller THW at which the lead vehicle started to brake resulted in a smaller RT. BIMT was both affected by THW and by initial deceleration: a smaller THW and a larger initial deceleration both resulted in a smaller BIMT. These effects match the significant effects of THW and initial deceleration on TTC_{tacc}.

Table 3. Main effects of manipulations on dependent variables. ** = $p<0.01$; * = $p< 0.05$, dec-1 represents primary deceleration and dec-2 secondary deceleration.

Dependent	Independent	F(21,2)
RT	THW	8.44 **
	dec-1	0.57
	dec-2	3.63
BIMT	THW	20.06 **
	dec-1	17.68 **

	dec-2	0.19
BCMT	THW	0.11
	dec-1	19.23 **
	dec-2	0.73
MAXBRFO	THW	26.83 **
	dec-1	41.68 **
	dec-2	71.64 **
NRCOR	THW	0.04
	dec-1	7.65 *
	dec-2	7.65 *
TTC_{min}	THW	14.89 **
	dec-1	77.23 **
	dec-2	35.13 **
DEC_{max}	THW	17.43 **
	dec-1	65.31 **
	dec-2	57.20 **
DIS_{min}	THW	81.40 **
	dec-1	80.23 **
	dec-2	9.02 **
TTC_{tacc}	THW	15.69 **
	dec-1	160.42 **
	dec-2	0.86

Thus, if criticality, measured by TTC_{tacc}, is higher the open-loop ballistic motor response is faster. The duration of the closed-loop phase, BCMT, was only significantly affected by initial deceleration, but not by THW or secondary deceleration: a larger initial deceleration resulted in a smaller BCMT. The maximum force, MAXBRFO, excerted on the brake pedal was significantly affected by all independent factors. Thus, a higher secondary deceleration, after the brake pedal was touched, resulted in a higher maximum brake force instead of a faster BCMT. The number of decelerations in the brake pedal signal (NRCOR) was both affected by initial and secondary deceleration. A larger initial and secondary deceleration both resulted in fewer decelerations in the brake pedal signal.

Table 4. Averages as a function of the manipulated factors time-headway on which lead vehicle starts to decelerate, initial deceleration and secondary deceleration. RT, BIMT and BCMT in seconds, MAXBRFO in Nm. dec-1 represents primary deceleration and dec-2 secondary deceleration.

THW	0.8				1.2			
dec_1	3		6		3		6	
dec_2	3	6	3	6	3	6	3	6
RT	0.73	0.79	0.74	0.88	0.91	1.05	0.91	0.83
BIMT	0.63	0.73	0.49	0.50	0.98	0.89	0.66	0.58
BMCT	1.64	1.50	1.13	1.16	1.43	1.69	1.09	1.30
MAXBRFO	51.68	113.22	103.91	218.22	48.26	87.21	80.24	98.21
NRCOR	3.68	2.77	3.09	2.32	3.73	3.05	2.73	2.55

This indicates that this variable basically measures the necessity to move the pedal straight to the maximum without hesitation. Finally, a smaller initial THW resulted in a smaller minimum TTC, a larger deceleration and a smaller minimum distance to the lead vehicle. Similar effects were found for a larger initial deceleration by the lead vehicle and a larger secondary deceleration by the lead vehicle.

Effects of THW$_{pref}$ group. Table 5 lists the effects of THW$_{pref}$ group and interactions between THW$_{pref}$ group and the independent factors on the dependent variables.

Table 5. Main effects of THW$_{pref}$ and interactions on dependent variables. ** = $p<0.01$; * = $p< 0.05$, dec-1 represents primary deceleration and dec-2 secondary deceleration.

Dependent	Independent	F(21,2)
RT	THW$_{pref}$	0.10
	THW$_{pref}$xTHW	0.08
	THW$_{pref}$xdec-1	0.60
	THW$_{pref}$xdec-2	0.25
BIMT	THW$_{pref}$	0.36
	THW$_{pref}$xTHW	0.09
	THW$_{pref}$xdec-1	0.11
	THW$_{pref}$xdec-2	0.01
BCMT	THW$_{pref}$	2.04
	THW$_{pref}$xTHW	0.13
	THW$_{pref}$xdec-1	0.30
	THW$_{pref}$xdec-2	0.67
MAXBRFO	THW$_{pref}$	0.76
	THW$_{pref}$xTHW	1.15
	THW$_{pref}$xdec-1	0.02
	THW$_{pref}$xdec-2	0.10
NRCOR	THW$_{pref}$	4.47 *
	THW$_{pref}$xTHW	0.45
	THW$_{pref}$xdec-1	8.18 **
	THW$_{pref}$xdec-2	4.03 *

There were no significant main effects of THW$_{pref}$ group on RT, BIMT, BCMT and MAXBRFO. Also none of the interactions of THW$_{pref}$ with the independent factors reached significance on any of these dependent variables. This means that these results do not support the hypotheses mentioned in the introduction. However, NRCOR, the number of movement corrections during the closed-loop phase, was significantly affected by THW$_{pref}$ group and revealed significant interactions of THW$_{pref}$ group with initial and secondary deceleration, see figure 2. The effects on NRCOR were as follows: only for the group of short followers was NRCOR affected by dec-1 ($F(10,1)=20.65$, $p<0.001$) and by dec-2 ($F(10,1)=12.08$, <0.006). For the group of long followers, the effects of both dec-1 and dec-2 on NRCOR were not significant ($F(10,1)=0.05$, $p<0.822$ for dec-1 and $F(10,1)=0.46$, $p<0.512$ for dec-2).

These effects strongly indicate that long followers moved their foot directly to the maximum brake position, irrespective of the development of criticality in time, while short followers were more sensitive to the manipulations of initial and secondary deceleration on this measure.

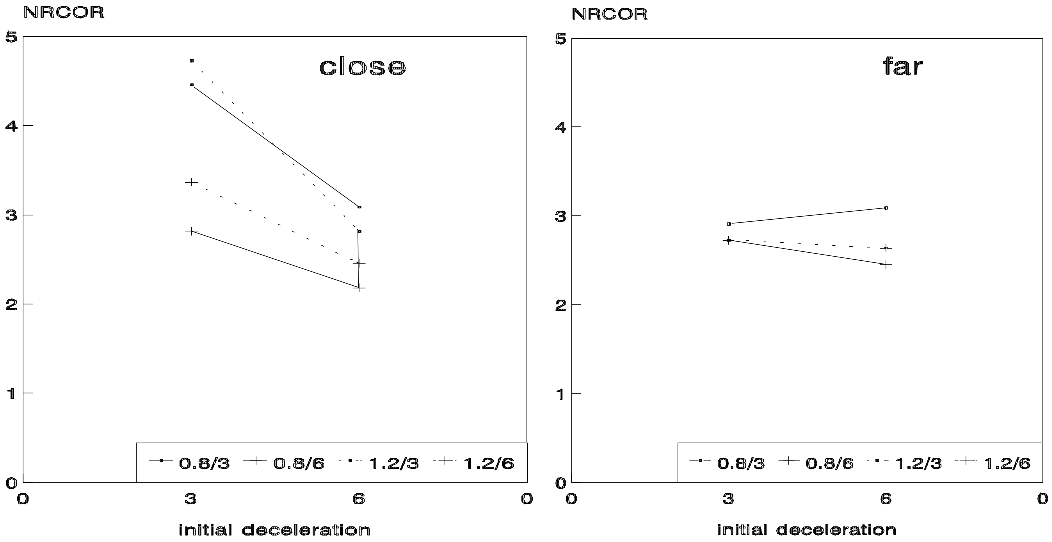

Figure 2. NRCOR as a function of THW$_{pref}$ group, initial deceleration (dec-1) and secondary deceleration (dec-2).

8.4 Discussion and conclusions

Based on a number of previous experiments it was tested whether short followers differ from long followers in both the open-loop and closed-loop phases of the braking process. This was tested by manipulating these phases. The open-loop phase was manipulated with two levels of initial deceleration of the lead vehicle. After the brake was touched by the subject, the deceleration of the lead vehicle changed. This secondary deceleration manipulated the closed-loop phase of the braking response. The hypotheses were:

1) there is an interaction between following group and primary deceleration on the duration of the open-loop phase (BIMT), defined as the interval between the moment the foot is released from the accelerator pedal and the moment the foot touches the brake pedal. This would support the idea that short followers differ from long followers in the open-loop phase.

2) there is an interaction between following group and secondary deceleration on the maximum brake force excerted, the number of movement corrections during the closed-loop phase and the duration of the closed-loop phase (BCMT), defined as the interval between the moment the foot touches the brake pedal and the moment the maximum brake force is excerted. This would support the idea that short followers differ from long followers in the closed-loop phase.

In general, these hypotheses were not supported. There was no significant interaction between following group and any of the independent factors, initial THW, primary and secondary deceleration, on RT, BIMT, BCMT and the maximum brake force. However, the interaction between following group and initial deceleration on the number of movement corrections was significant as was the interaction between following group and secondary deceleration on this variable. The number of movement corrections (NRCOR) during the closed-loop phase were conceived as an expression of uncertainty induced by a change in deceleration after the braking response was initiated. Although NRCOR was affected by secondary deceleration, it was also affected by primary deceleration. The pattern of effects suggests that NRCOR expresses the necessity to move the pedal straight to the maximum without hesitation. The results showed that only the group of short followers was sensitive to the effects of initial and secondary deceleration on NRCOR, while the long followers moved their foot to the maximum with the same number of movement corrections independent of primary and secondary deceleration. In a previous study it was found that NRCOR strongly determines the duration of the closed-loop phase. From this perspective, it would be expected that NRCOR and BCMT are affected by following group and the independent factors in a similar way.

However, as was already apparent, there were no significant effects of following group on BCMT. Closer inspection of the data revealed that only in the trials where the secondary deceleration was high, the correlations between NRCOR and BCMT were significant, see table 6.

Table 6. Correlation between NRCOR and BCMT, depending on THW_{pref} group and secondary deceleration (dec-2).

	dec-2	
	3	6
short	0.30	0.68 **
long	0.30	0.59 **

This suggests that a causal relation between NRCOR and BCMT only exists if criticality is high enough.

The lack of support for the hypotheses may have been caused by specific task related factors. The subjects generally described the task as boring, mainly because of the long task duration and the low event-rate. There were only 8 braking trials over a duration of 45 minutes. This may have resulted in a vigilance task with two separate effects. On the one hand, the braking trials may have generated startle reactions, resulting in fast responses irrespective of the manipulations. On the other hand some responses may have been slow because of state-related factors. This would have resulted in a high variance in the data that was not caused by the manipulations of THW, initial and secondary deceleration. Figure 4 illustrates the distribution of RT as a function of the THW manipulation. It can be seen that the distributions are skewed on the right side, especially for the THW=1.2 condition, suggesting low-vigilance effects, although there are two distinctive peaks in the distributions.

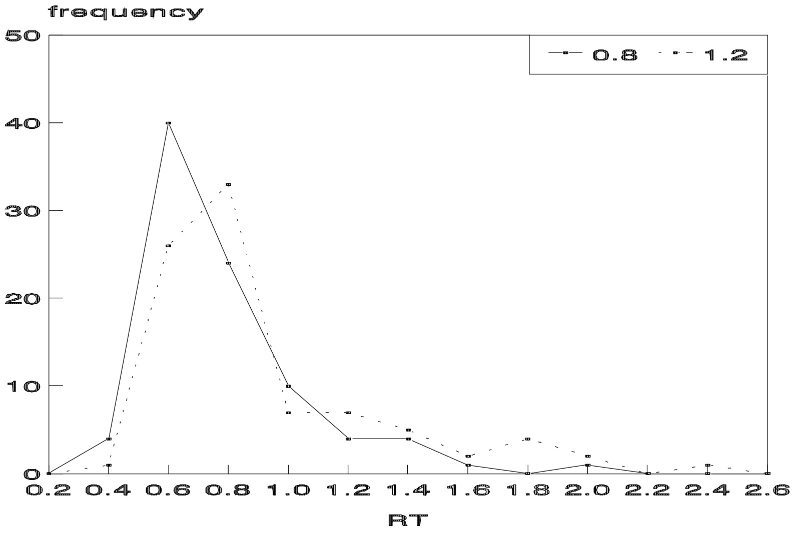

Figure 4. Distributions of RT as a function of the THW manipulation.

Figure 5 and 6 show the distributions of BIMT as a function of initial deceleration for THW=0.8 and THW=1.2 respectively. These figures show that the distributions of BIMT are skewed on the right side and that the effects of initial deceleration are mainly caused by 'outliers' on the right side of the distribution. Especially for the THW=0.8 condition, the primary peak of the low deceleration condition occurs before the primary peak of the high deceleration condition, which obviously is not in the expected direction and opposite to the effects of the analyses of variance, which are based on the means. The distributions of BIMT in the THW=0.8 condition are visualized separately for the short followers and long followers in figure 7.

It can be seen that for the short followers there are two distinctive peaks as a function of initial deceleration in the expected direction, while for the long followers the primary peaks overlap. Moreover, it can be seen, that the primary peak in the BIMT of long followers occurs before the peaks of the short followers. This suggests that BIMT of long followers has suffered more from startle reactions resulting in BIMTs that were fast and not tuned to differences in initial deceleration, while the BIMTs of short followers were more sensitive to initial deceleration.

Thus, the distributions of the data and task-induced startle responses and low-vigilance effects may have given results that failed to support the hypotheses. This will be tested in the next experiment, with multiple measurements per manipulation, a higher event-rate and shorter task duration in order to prevent undesirable state-related effects.

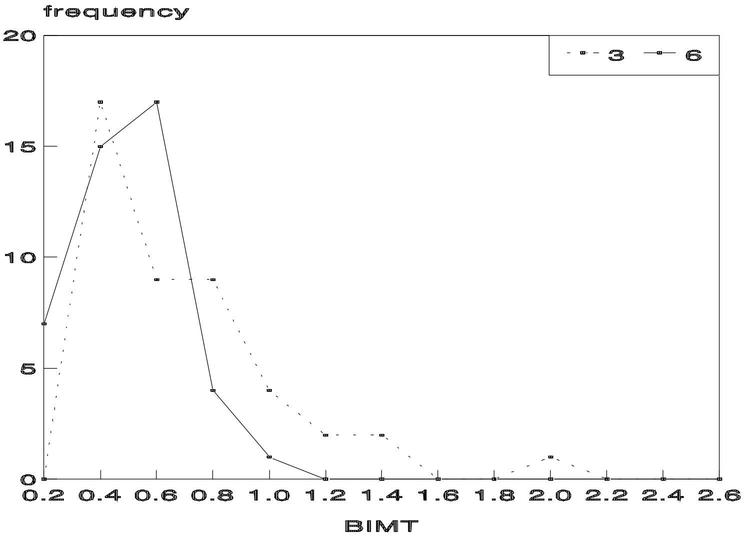

Figure 5. Distribution of BIMT as a function of initial deceleration for the THW=0.8 condition.

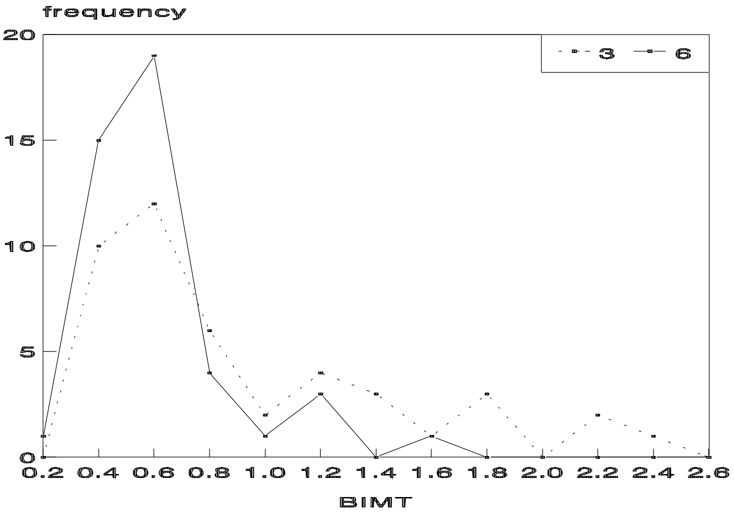

Figure 6. Distribution of BIMT as a function of initial deceleration for the THW=1.2 condition.

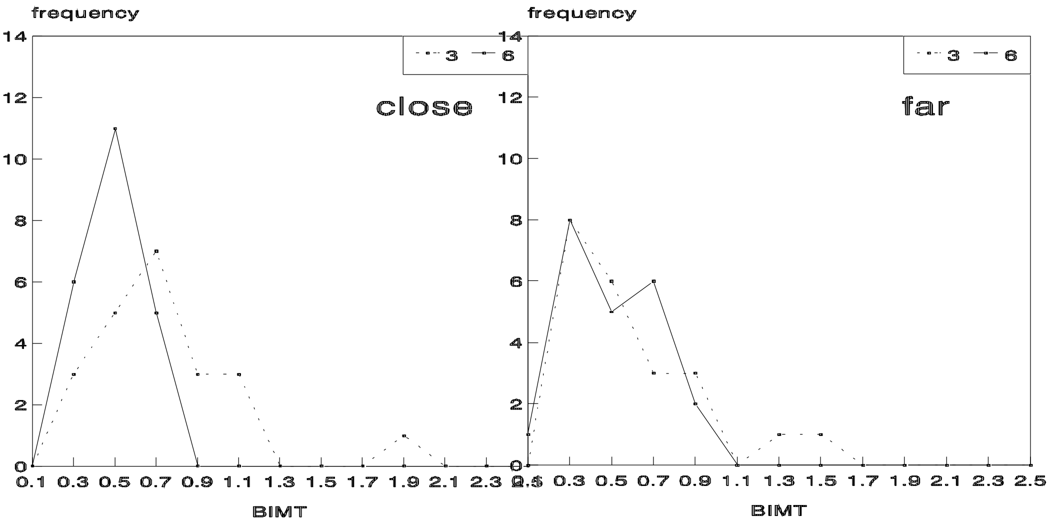

Figure 7. Distribution of BIMT as a function of initial deceleration for the THW=0.8 condition, for short and long followers.

Chapter 9

9. EXPERIMENT 6: Perceptual-motor skills and sensitivity to TTC as a function of preferred time-headway in car-following

Submitted for publication in *Ergonomics*

Based on the results of previous experiments it was tested whether the sensitivity of the braking response to time-to-collision information differs as a function of preferred time-headway in car-following. In an experiment performed in a simulator time-to-collision was manipulated by varying the level of deceleration of the lead vehicle with a pre-selected group of short and long followers. In addition, it was tested whether choice of time-headway is related to more general differences in perceptual-motor skills. It was found that short followers perform better at both lateral- and longitudinal tracking tasks and that the braking response of short followers is more sensitive to differences in time-to-collision. The results support the hypothesis that preferred time-headway is at least to some extent an adaptation to individual differences in operational braking performance and perceptual-motor skills.

9.1 Introduction

The hierarchical control structure of car driving behaviour has been presented as a framework for driver modeling (Michon, 1985; Ranney, 1994) in which driving is regarded as concurrent activity on strategic, tactical and operational levels. The tactical level includes, for example, choice of speed on straight roads and in curves and choice of headway in car-following. Steering and braking are on the operational level. Adaptation may be understood as a compensation of behaviour on the strategic and tactical levels of the driving task for individual differences in skills at the operational level. Thus, the process of adaptation connects the different levels of the driving task. It has been used as an explanation for the relatively safe driving records of functionally impaired drivers (Brouwer et al., 1988).

Adaptive processes involving interaction between different control levels has been demonstrated for the case of transient changes in operational level performance, through environmental manipulations (reducing sight distance) or changes of internal state (marijuana). Tenkink (1988) demonstrated that a reduction of sight distance affects operational performance of the lane-keeping task and results in a speed reduction to compensate for these effects. He found that under self-paced conditions where drivers were free to choose their speed, a reduction of sight distance resulted in the choice of a lower speed while the standard deviation of lateral position was not affected. Under non self-paced conditions, however, reductions of sight distance resulted in a higher standard deviation of lateral position. Also, variations in internal state-related factors have been shown to result in adaptations of behaviour on the tactical level. For instance, in a study of Casswell (1977) drivers under marijuana appeared to compensate for what they perceived as adverse effects on driving ability by driving more slowly. Marijuana affects operational car driving performance while it also results in increased time headway (THW) during car-following and in choosing a lower speed (Smiley et al., 1981; Smiley et al., 1985; Smiley et al., 1986). Time-on-task has been shown to increase time-headway during car-following, accompanied by verbal reports of performance decrements, drowsiness and exhaustion (Fuller, 1981). These findings suggest that the driver compensates for effects of various factors on operational performance by adapting behaviour on the tactical level.

Recently, Van Winsum and colleagues found some evidence that supports the adaptation theory on the individual level. In a study on speed choice in curves as a function of curve radius a clear relation was established between steering competence and speed choice in curves: drivers with larger steering errors during straight road driving, indicating poorer steering competence, choose lower speeds in curves (Van Winsum and Godthelp, 1996). Also, in a number of experiments it was investigated whether drivers who follow at a larger THW can be characterized by poorer braking performance compared to drivers who follow at a smaller THW. In Van Winsum and Heino (1996) and Van Winsum and Brouwer (1996) preferred THW during car-following proved to be consistent within the driver. This means that drivers can be characterized as consistent short or long followers and, thus, that individual differences in choice of THW are consistent. Van Winsum and Heino (1996) found that the initiation and control of braking are both affected by time-to-collision (TTC) at the moment the lead vehicle starts to brake. This strongly suggests that TTC information is used for judging the moment to start braking and during the control of braking. Drivers with a smaller preferred THW were better able to program the intensity of braking to required levels, depending on TTC, and tuned the control of braking better to the development of criticality in time during the braking process. Short followers appeared to be more sensitive to TTC information and may differ from long followers in programming and execution of the braking response as a function of TTC information.

Van Winsum and Brouwer (1996) analyzed the braking response in terms of three sequential phases in the braking process. The first phase covers the interval between the moment the lead vehicle starts to brake and the moment the driver releases the accelerator pedal. This is measured by the reaction time (RT). The second phase consists of the open-loop ballistic motor response and is measured as the interval between the moment the accelerator pedal is released and the moment the brake pedal is touched and referred to as Brake Initiation Movement Time (BIMT). The third phase is a closed-loop motor response during which visual feedback is used to control the braking response. The duration of the open-loop phase was strongly determined by TTC at the moment the accelerator pedal was released. It was found that drivers who prefer a smaller THW during car-following (short followers) exhibited a faster open-loop motor response that was not caused by a smaller TTC at detection time.

The results of both experiments support the hypothesis that the motor response of short followers is more sensitive to TTC information compared to drivers who prefer a larger THW (long followers). This hypothesis is tested explicitly in the present experiment.

The results of Van Winsum and Brouwer (1996) have indicated that the duration of the open-loop phase is strongly affected by the TTC at the moment the driver detects the deceleration of the lead vehicle. Manipulation of this TTC then is expected to affect the duration of the open-loop response, but more so for short followers compared to long followers. TTC at the moment of detection has been operationalized as TTC at the moment the accelerator pedal is released ($t_{acc)}$ by Van Winsum and Brouwer. TTC_{tacc} is affected by the level of deceleration of the lead vehicle. If the lead vehicle decelerates stronger, the TTC at the moment the driver initiates the motor response will be smaller if all drivers are subjected to an equally small initial time-headway to the lead vehicle.

In summary, in the present experiment the level of deceleration of the lead vehicle is manipulated and this manipulation is expected to affect TTC_{tacc}. Since TTC_{tacc} affects the duration of the open-loop phase of the motor response (BIMT), an effect of level of deceleration of the lead vehicle on BIMT is expected. The main hypothesis is that short followers differ from long followers in the sensitivity of the motor response to differences in TTC. From this it is predicted that there is a significant interaction between following group (short vs. long) and level of deceleration of the lead vehicle on BIMT.

In addition to this, the aim of the present study is to acquire more insight in the basic skills underlying these performance differences. Differences in sensitivity of the motor response to visual information may be the result of a more general skill involved in the transformation of dynamic visual information into an appropriate motor response. Tracking tasks require the subject to continuously use visual feedback to control a motor response and as such these tasks differ from braking for a lead vehicle where discrete responses are required. In the present experiment a longitudinal and a lateral tracking task are used to test whether short followers differ from long followers in basic skills related to the transformation of visual input to a motor response. The experiment was performed in the TRC driving simulator.

9.2 Method

Subjects. Eighteen subjects participated in the experiment. The subjects were selected from the TRC database by the following procedure. First a preselection was made on the basis of age and driving experience. Only subjects between 25 and 40 years of age with a minimum driving experience of 10000 km that were known not to be susceptible to simulator sickness were preselected from the database, resulting in 150 cases. These were send a photo-preference test that measures preferred THW. This test consisted of 6 numbered photographs with scenes of a lead vehicle at different distances in front of the car on a highway. The pre-selected subjects were required to choose the number of the photograph that best matched the preferred time-headway while driving with a speed of 110 km/h on a highway. This test procedure has been shown to result in a reliable estimation of preferred time-headway during car-following on the road (Heino et al., 1992). Table 1 shows distance and time-headways, as well as the number of subjects that participated in the experiment for each photo number.

Table 1. Relation between photo number and headway on the photo preference test and number of subjects.

Photo number	DHW	THW	number of subjects
1	6	0.20	0
2	11	0.36	0
3	25	0.81	5
4	33	1.08	5
5	45	1.47	3
6	65	2.13	5

DHW=distance headway in meters, THW=time headway in seconds.

Subjects with a preferred headway of less than or equal to 4 were categorized as short followers (10 subjects) while a score of larger than or equal to 5 resulted in assignment to the group of long followers (8 subjects). These groups are referred to as 'THW_{pref} groups'.

The average age was 31 years. The subjects had held a driving license for 11 years on average and the average annual kilometrage was 26000. Sixteen subjects were male and two were female. Table 2 gives the results of analyses of variance for age and driving experience as a function of THW_{pref} groups. The short followers who participated in this experiment had more driving experience, expressed as annual kilometrage, compared to the long followers.

Table 2. Age and driving experience: effects of THW_{pref} group, df between brackets.

dependent	F (17,1)	short	long
age	1.86	29.50	32.50
years licensed	0.40	10.55	12.06
annual kilometrage	5.48*	38000	11625

*=p<0.05; **=p<0.01.

Apparatus. The experiment was performed in the driving simulator of the Traffic Research Centre (TRC). This fixed-based simulator consists of two integrated subsystems. The first subsystem is a conventional simulator composed of a car (a BMW 518) with a steering wheel, clutch, gear, accelerator, brake and indicators connected to a Silicon Graphics Skywriter 340VGXT computer. A car model converts driver control actions into a displacement in space. On a projection screen, placed in front, to the left and to the right of the subject, an image of the outside world from the perspective of the driver with a horizontal angle of 150 degrees is projected by three graphical videoprojectors, controlled by the graphics software of the simulator. Images are presented with a rate of 15 to 20 frames per second, resulting in a suggestion of smooth movement. The visual objects are buildings, roads, traffic signs, traffic lights and other vehicles. The sound of the engine, wind and tires is presented by means of a digital soundsampler receiving input from the simulator computer.

The second subsystem consists of a dynamic traffic simulation with interacting artificially intelligent cars. For experimental purposes different traffic situations can be simulated. The simulator is described in more detail elsewhere (Van Wolffelaar & Van Winsum, 1992 and Van Winsum & Van Wolffelaar, 1993).

Tasks and procedure. The circuit was made of two-lane roads with a lane-width of 3 m. and alternating left- and right turning curved road sections (radii 1000 m.). All roads had delineation with broken center lines and closed edge lines.

Lateral tracking task. After a practice run in the simulator for about 8 minutes, the subject was instructed to drive with a fixed speed of 100 km/h on a winding road while steering as accurately as possible. Steering performance was measured on 2 left- and 2 right-turning curves. The speed (in km/h) was shown in front of the subject in the same place as during the longitudinal tracking task.

Longitudinal tracking task. During this task a lead vehicle pulled up to 100 km/h. Then it alternated its speed continuously between 100 and 80 km/h, while it decelerated and accelerated smoothly with a frequency of 0.07 Hz. In front of the subject a text with the speed of the simulator car was shown. If the bumper to bumper distance was precisely 5.7 m., the text fell on the line between the rearlights of the lead vehicle. The subject was required to maintain the text precisely on that line by following the speed of the lead vehicle as accurately as possible. In order to do this, the subject was allowed to only use the accelerator pedal and to drive in third gear. After a practice period, behaviour was measured on the same 2 left and 2 right turning curves as during the lateral tracking task. During the longitudinal tracking task steering performance was measured as well since this constitutes a more difficult (double task) lateral tracking task.

Braking task. After this, braking behaviour was measured by the following procedure. The subject was instructed to drive with a constant speed of 100 km/h, to stay in the right lane and to avoid a collision with a lead vehicle in case it braked. While driving, the subject was overtaken by another vehicle every 5 seconds on average. The lead vehicle merged in front of the lead vehicle and started to drive at a fixed THW of 0.8 seconds. After a stable THW was reached it braked from 100 to 60 km/h. After a while the lead vehicle pulled up to 120 km/h, while the subject pulled up to 100 km/h. The another vehicle merged in front of the simulator car and the cycle repeated itself. Braking occurred twice per minute on average. The lead vehicle applied either a deceleration of 3 or 6 m/s^2 in random order. The driver was subjected to a total of 30 braking trials, with 15 trials for each level of deceleration. The task took 15 minutes to complete.

Data collection and analysis. Lateral tracking performance was measured with the steering error, δ_{se} (see Van Winsum and Godthelp, 1996), computed on-line and sampled with a frequency of 10 Hz, together with lateral position. Steering error was computed as the difference between the actual steering-wheel angle and the required steering-wheel angle (δ_s - δ_{sr}), whereas required steering-wheel angle was computed as δ_{sr}=GL(1+Ku^2)/R_r (see Godthelp, 1986). In this R_r represent the road radius in meters, G the steer-to-wheel ratio, L the wheel base, K a vehicle related stability factor and u the longitudinal speed in m/s. From δ_{se} the following measures were derived :

- standard deviation of δ_{se}, $SD_{\delta se}$
- the average of all steering error maxima, $MAX_{\delta se}$

- the average duration of the period where steering error was larger than zero, $T_{\delta se}$

A larger $MAX_{\delta se}$ means a larger steering error, while a smaller $T_{\delta se}$ indicates more frequent steering corrections, see figure 1. In addition to this the standard deviation of the lateral position (SD_{latpos}) was analyzed. Only those samples were analyzed where the subject had traversed more than 100 meters from the start of a curved segment until the subject was 100 meters to the next curved segment. This procedure ensured that only closed-loop steering in the curve was analyzed. Lateral tracking performance was measured during the lateral tracking task and the longitudinal tracking task. This constitutes the within-subjects manipulation TASK. The dependent variables were analyzed with repeated measures analysis of variance with TASK as a within-subjects factor and THW_{pref} group as a between-subjects factor.

During the longitudinal tracking task the speed of the lead vehicle and the simulator car and the bumper to bumper distance between the two vehicles were sampled with a frequency of 10 Hz. The subject was instructed to keep the distance to the lead vehicle constant. The standard deviation of distance headway, SD_{DHW}, then measures the quality of longitudinal tracking performance. In order to keep the distance headway as constant as possible, the subject had to vary the speed in the same manner as the lead vehicle. This was analyzed with a coherence analysis of the two speed signals (see Brookhuis and De Waard, 1994, for an explanation of the method). From this analysis three measures express the quality of tracking performance: coherence, phase shift and modulus. The coherence is a measure of the accuracy of the subject's speed adaptations. The phase shift measures the delay of the subjects' speed variations with respect to the speed variation of the lead vehicle. The delay can be computed from the phase shift via a simple transformation. The modulus is a gain factor that expresses the extent to which the subject overreacts to decelerations and accelerations of the lead vehicle.

During the braking task the following variables were analyzed. At t_0 the lead vehicle started to brake. The moment the accelerator pedal position was less then 4% after t_0 was registered as t_{acc}, and RT was computed as t_{acc}-t_0. The moment after t_{acc} at which the brake pedal force was more than 3 Nm, was registered as t_{br} (the moment the brake pedal was touched). BIMT (Brake Initiation Movement Time, or the open-loop ballistic response) was computed as t_{br}-t_{acc}. The maximum brake force was detected on-line and the moment this was reached was registered as t_{maxbr}. BCMT (Brake Control Movement Time, or the closed-loop braking response) was computed as t_{maxbr}-t_{br}. The maximum brake force excerted, MAXBRFO, was stored as well. During the closed-loop phase a number of decelerations typically occur in the brake pedal signal. These decelerations reflect movement velocity corrections of the right foot. The number of decelerations in the brake pedal signal (NRCOR) was analyzed as well. The time-history of braking can be seen in figure 2.

The dependent variables were analyzed with repeated measures analysis of variance with THW_{pref} group as a between-subjects factor and deceleration of the lead vehicle as a within-subjects factors.

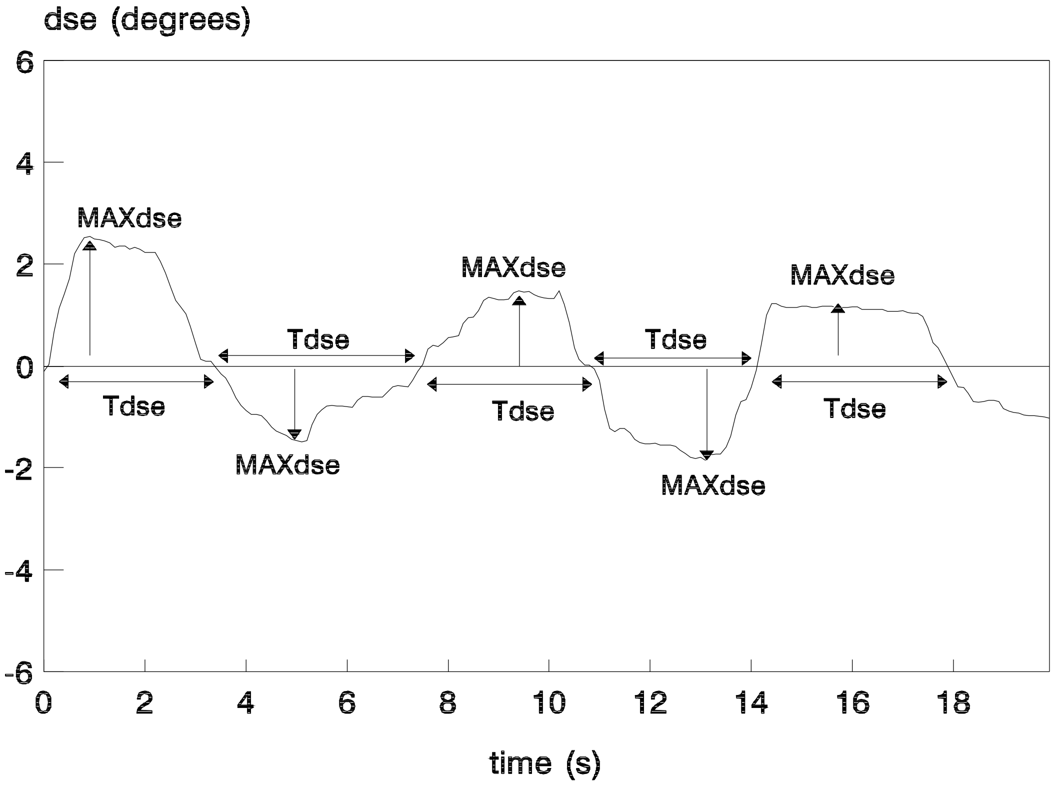

Figure 1. Time history of steering errors during curve negotiation.

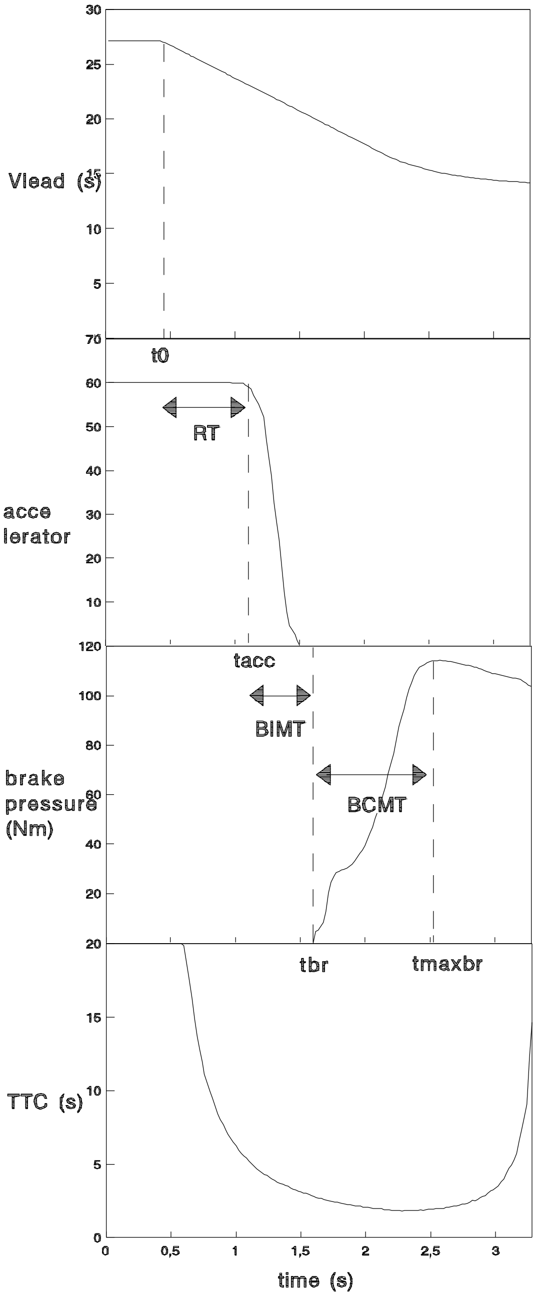

Figure 2. Time history of braking and dependent variables.

9.3 Results

Lateral tracking performance. Table 3 lists the results of analysis of variance and table 4 gives the average values.

Table 3. Lateral tracking performance: effects of TASK and THW_{pref} group, df between brackets.

dependent	effect	F (16,1)
$SD_{\delta se}$	THW_{pref}	6.44*
	TASK	89.22**
	THW_{pref}xTASK	6.66*
SD_{latpos}	THW_{pref}	1.19
	TASK	0.14
	THW_{pref}xTASK	6.61*
$MAX_{\delta se}$	THW_{pref}	6.85*
	TASK	80.01**
	THW_{pref}xTASK	3.84
$T_{\delta se}$	THW_{pref}	2.62
	TASK	167.88**
	THW_{pref}xTASK	0.02

*=p<0.05; **=p<0.01.

Table 4. Averages of lateral tracking performance measures by TASK and THW_{pref} group.

dependent	lateral task		longitudinal task	
	short	long	short	long
$SD_{\delta se}$	1.468	1.986	2.919	4.528
SD_{latpos}	0.157	0.162	0.143	0.172
$MAX_{\delta se}$	1.969	2.848	4.117	6.201
$T_{\delta se}$	2.749	2.437	1.319	0.978

$SD_{\delta se}$ and $MAX_{\delta se}$ in degrees, SD_{latpos} in meters and $T_{\delta se}$ in seconds.

Standard deviation of steering errors was significantly affected by TASK. During the longitudinal tracking task, which is a double task situation, $SD_{\delta se}$ was larger compared to the simple lateral tracking task. This suggests that the double task situation deteriorated lateral tracking performance. The effect of THW_{pref} group on $SD_{\delta se}$ was significant as well. This means that short followers steered more accurately compared to long followers. Performance in the double task situation deteriorated for both groups, but much stronger for the long followers, see figure 3. Lateral tracking performance during the more difficult longitudinal tracking task was characterized by larger steering errors (effect of TASK on $MAX_{\delta se}$) and more frequent steering corrections (effect of TASK on $T_{\delta se}$). Close followers made smaller steering errors compared to long followers, but the interaction between THW_{pref} and TASK was only marginally significant ($p<0.068$). The results indicate that the effects of THW_{pref} group on the standard deviation of the steering errors was mainly caused by the fact that close followers committed smaller steering errors. The effects of TASK on $MAX_{\delta se}$ were counterbalanced by faster steering corrections. This is supported by the large negative correlation between $MAX_{\delta se}$ and $T_{\delta se}$ (R=-0.88, p<0.01, in the longitudinal tracking task). This possibly prevented a significant TASK effect on SD_{latpos}, although the interaction between THW_{pref} group and TASK on SD_{latpos} was significant.

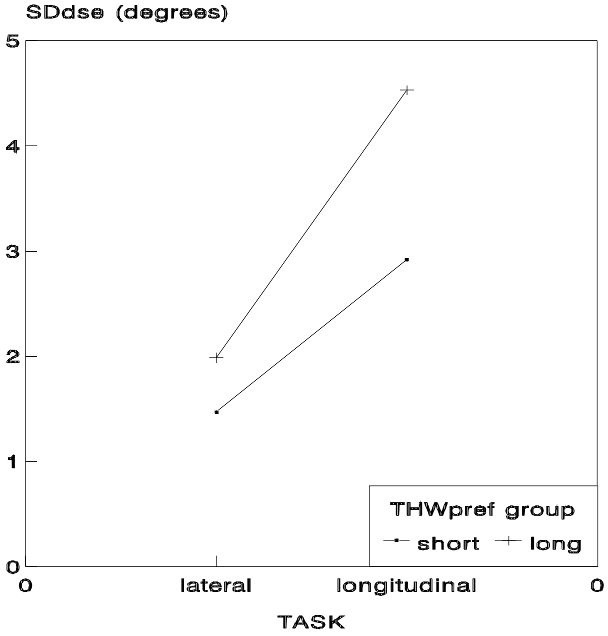

Figure 3. Standard deviation of steering errors as a function of THW_{pref} group and TASK.

The results indicate that long followers steer less accurately. Steering behaviour deteriorates when the task becomes more demanding, but it deteriorates stronger for long followers compared to short followers. Short followers then differ from long followers in lateral tracking performance.

Longitudinal tracking performance. Table 5 gives the results from the analyses of variance on the dependent variables.

Table 5. Longitudinal tracking performance: effects of THW_{pref} group, df between brackets and averages.

dependent	F (16,1)	short	long
SD_{DHW}	9.79**	1.049	1.489
Coherence	5.69*	0.998	0.991
Delay	4.22*	0.458	0.625
Modulus (gain)	5.63*	1.134	1.182

*=p<0.05; **=p<0.01.

Short followers performed significantly better on the longitudinal tracking task on all dependent variables. For both groups the coherence was extremely high, indicating that the task was performed quite well by both groups. Close followers maintained a more constant distance to the lead vehicle (effect on SD_{DHW}), controlled their speed more in accordance with the speed of the lead vehicle (effect on coherence), responded faster to speed variations of the lead vehicle (effect on delay) and overreacted less strongly (effect on modulus) compared to long followers.

Table 6. Correlations between lateral and longitudinal tracking performance measures.

	SD_{DHW}	Coherence	Modulus	Delay
Lateral task:				
SDδse	0.40*	-0.70**	-0.17	0.39*
MAXδse	0.43*	-0.76**	-0.18	0.39*
Tδse	-0.28	0.21	0.10	-0.34
longitudinal task:				
SDδse	0.44*	-0.62**	0.24	0.26
MAXδse	0.38	-0.53*	0.25	0.20
Tδse	-0.44*	0.49*	-0.21	-0.31

*=p<0.05; **=p<0.01.

Table 6 shows the correlations between the performance measures of the lateral and longitudinal tracking tasks. It can be seen that the correlations of SDδse and MAXδse with especially coherence are substantial. This suggests that, to some extent, the quality of performance on both lateral and longitudinal tracking depend on the same basic skills.

Braking performance. As expected, there was a significant main effect of level of deceleration of the lead vehicle (DEC) on TTC_{tacc} (F(16,1)=293.24, p<0.0001). The effect of THW_{pref} group on TTC_{tacc} was not significant (F(16,1)=0.75, p<0.40), and neither was the interaction between THW_{pref} group and DEC on TTC_{tacc} (F(16,1)=0.88, p<0.363). This indicates that the manipulation of the deceleration of the lead vehicle was successful in affecting TTC_{tacc}, and that differences between short and long followers cannot be attributed to differences in TTC_{tacc}.

Table 7 lists the effects of THW_{pref} group and deceleration of the lead vehicle on braking performance measures and table 8 lists the average values.

Table 7. Braking task: effects of THW_{pref} group and deceleration (DEC), df between brackets.

dependent	effect	F (16,1)
RT	THW_{pref}	0.19
	DEC	2.67
	THW_{pref}xDEC	0.66
BIMT	THW_{pref}	7.16*
	DEC	20.58**
	THW_{pref}xDEC	8.33**
BCMT	THW_{pref}	2.12
	DEC	0.23
	THW_{pref}xDEC	0.13
MAXBRFO	THW_{pref}	0.00
	DEC	72.79**
	THW_{pref}xDEC	0.04
NRCOR	THW_{pref}	0.24
	DEC	18.38**
	THW_{pref}xDEC	0.14

*=p<0.05; **=p<0.01.

There were no significant effects of deceleration of the lead vehicle and THW_{pref} group on RT. A larger deceleration of the lead vehicle resulted in a faster open-loop motor response (BIMT), as expected. Also, in support of the hypothesis, the interaction between THW_{pref} group and level of deceleration of the lead vehicle on BIMT was statistically significant, see figure 4. The deceleration of the lead vehicle did not affect the duration of the closed-loop phase (BCMT). A larger deceleration of the lead vehicle resulted in a higher maximum brake pressure and fewer movement corrections during the closed-loop response. There were no statistically significant effects of THW_{pref} group on the closed-loop response related variables.

Table 8. Averages of braking performance measures by deceleration (DEC) and THW_{pref} group.

dependent	DEC = 3 m/s²		DEC = 6 m/s²	
	short	long	short	long
RT	0.600	0.598	0.589	0.546
BIMT	0.981	0.580	0.598	0.495
BCMT	1.276	1.114	1.210	1.104
MAXBRFO	50.185	51.982	156.945	153.677
NRCOR	3.280	3.094	2.443	2.392

RT, BIMT and BCMT in seconds, MAXBRFO in Nm.

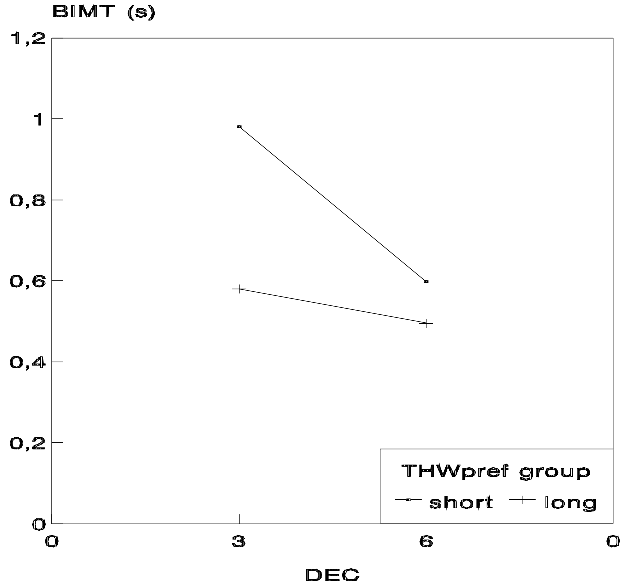

Figure 4. Duration of the open-loop motor response (BIMT) as a function of deceleration of the lead vehicle (DEC) and THW_{pref} group.

9.4 Discussion and conclusions

The theoretical perspective of the present study is that choice of time-headway during car-following is an adaptation to skills involved in operational braking performance. Drivers with poorer operational performance adapt their behaviour on the tactical level accordingly as a form of self-regulation. In the introduction evidence was presented that adaptation of behaviour on the tactical level occurs for transient degradations in operational performance. Here it is suggested that this phenomenon is more general and also occurs on the level of individual differences in tactical behaviour. In Van Winsum and Heino (1996) and Van Winsum and Brouwer (1996) it was demonstrated that there are consistent individual differences in choice of THW during car-following. The main hypothesis of the present study was that drivers who prefer a smaller time-headway during car-following differ from driver who prefer to follow at a larger time-headway in the sensitivity of the motor response of braking to differences in time-to-collision (TTC). This hypothesis was inferred from the results of two previous experiments (Van Winsum and Heino, 1996; Van Winsum and Brouwer, 1996). TTC was manipulated by the level of deceleration of the lead vehicle. The results indicate that the open-loop response of short followers is more sensitive to differences in TTC compared to long followers. Long followers generate a similar motor response irrespective of the task demands or visual input characteristics, while close followers adjust the open-loop motor response to what they perceived visually.

The assumed causal chain in this reasoning is that individual differences in some basic psycho-motor skill affect the quality of the braking response. It is assumed that drivers are aware of this and adapt the choice of time-headway during car-following accordingly. In this way drivers protect themselves against poorer operational performance. However, it may be argued that short followers have had more practice in braking resulting in increased operational performance because of learning effects. To rule out this explanation it was examined whether short followers differ from long followers in psycho-motor performance in tasks unrelated to braking. It is demonstrated that short followers perform better on lateral tracking tasks as well as on a continuous longitudinal tracking task. In addition to this, performance on both types of tracking tasks correlates significantly. The results indicate that:

1) Short followers differ from long followers in perceptual-motor skills related to the transformation of visual information to a motor response,
2) these differences in skill are not acquired as a function of differences in following behaviour,
3) these differences in skill affect the quality of braking performance in the sense that short followers tune the braking response better to the requirements of the situation, giving them a higher sense of control,
4) resulting in the choice of a larger time-headway for drivers with poorer operational performance and a smaller time-headway for drivers with better operational performance.

The short followers in the present experiment were more experienced drivers compared to the long followers in the sense that annual kilometrage was higher. This factor may have contributed to the higher skill level and better operational performance of short followers. Van Winsum and Godthelp (1996) found a relation between annual kilometrage and steering performance. On the other hand, it is somewhat hard to image how the skills involved in the longitudinal tracking task could improve as a function of driving experience.

The results suggest that adaptation of behaviour on the tactical level, such as the choice of speed in curves and straight road sections and choice of headway during car-following, to operational performance may be a general phenomenon that applies to both transient and situational determined changes in operational performance as well as to individual differences in operational performance.

Chapter 10

10. General discussion and conclusions

10.1 Testing the adaptation model for the case of individual differences: discussion of results from the experiments

The adaptation model predicts that factors that affect operational performance will normally result in an adaptation of behaviour on the tactical level, such that constant safety margins are maintained. Individual differences in operational performance are then predicted to be reflected in individual differences in behaviour on the tactical level. The results of the experiments support the adaptation model applied to the relation between individual differences in behaviour on the tactical level and the operational level for both the car-following task and the curve negotiation task. The general results from these experiments and the relevance for the adaptation model are discussed in this chapter.

If individual differences in skills and operational performance result in adaptation of behaviour on the tactical level then this behaviour must be consistent and characterized by individual differences. This implies that, in addition to the transient effects on tactical behaviour discussed in previous paragraphs, some level of consistency and constancy must exist in, for example, speed choice and choice of headway during car-following. If the adaptation model also applies to individual differences then at least some part of the between-subjects variance in behaviour on the tactical level must be explained in terms of the between-subjects variance in operational performance. The tasks of curve negotiation and car-following were selected for closer examination. Speed choice during curve negotiation is considered as an example of the effect of lateral control performance on behaviour on the tactical level. Choice of time-headway in car-following is described as an example of the effect of longitudinal control performance on tactical behaviour.

Experiment 1 deviates from the other five in that it not only examines the effect of individual differences in operational performance but also the effect of a situational factor, i.e. curve radius. Explaining speed choice as a function of curve radius has been a long lasting problem that has been investigated in a large number of studies. The problem is usually described in terms of a relation between lateral acceleration and choice of speed. The underlying process has never become clear. However, the results of experiment 1 clearly suggest that the inverse relation between lateral acceleration and speed, often referred to in the literature, is the result of a process of adaptation of speed choice together with a strategy of maintaining constant safety margins. Speed choice in curves proves to be a consistent measure of tactical behaviour. Also measures of operational performance prove to be stable and consistent within the driver. This indicates that the important prerequisite for the validity of the adaptation model that both operational performance and behaviour on the tactical level are consistent and characterized by clear individual differences is fulfilled for the case of lateral control performance and speed choice in curves. Steering is discussed as the factor that affects choice of speed in curves. A model of steering is presented that suggests that steering errors are affected by individual differences in steering competence and by required steering-wheel angle. A larger required steering-wheel angle then results in larger steering errors. The situational factor road radius, together with speed, affects required steering-wheel angle. A smaller radius increases required steering-wheel angle and thus steering error, which is compensated or adapted for by choosing a lower speed. The same reasoning applies to individual differences in steering performance. This is measured independently during straight road driving. Drivers with poorer steering competence are characterized by larger steering errors which is compensated for by choosing a lower speed in curves according to the adaptation model. Summarizing, in experiment 1 the adaptation model is tested in two different manners for the case of speed choice in curves:

- curve radius affects operational performance which affects speed choice, and
- steering competence affects operational performance which affects speed choice.

These hypotheses are supported by the results of experiment 1. The results indicate that a smaller curve radius and poorer steering competence increase steering errors and result in such speed reductions that TLC is kept on a constant minimum value. These results then strongly support the adaptation model discussed in paragraph 2.5 and the value of the concept of a time-based safety margin that is controlled during driving.

Experiments 2 to 6 consider the task of car-following. During car-following the driver never knows whether the lead vehicle will brake, and if it does, how hard it will brake and for how long. It is then assumed that the driver has learned the quality of his or her braking performance from previous experiences and that this results in the choice of a preferred time-headway (THW). THW is the time available to the driver to reach the same level of deceleration as the lead vehicle in case it brakes, without becoming involved in a collision. Braking performance is assumed to affect the time required to reach the same level of deceleration as the lead vehicle. Adaptation of THW may then be regarded as a compensation strategy for drivers with poorer braking performance.

The detailed examination of the car-following task introduces some specific problems. First of all, it is not immediately clear which aspects of operational performance play a role in choice of time-headway. This is examined in the experiments 2 to 6.

Secondly, the literature on choice of THW during car-following is not very extensive. The literature on braking is limited as well and mainly restricted to emergency braking (braking as fast as possible), see chapter 5. This implies that the theoretical perspective on braking and car-following had to be developed during the course of experimentation and that the number of experiments required to test the theoretical model is larger for the case of car-following than for speed choice in curves.

Thirdly, an important limitation in the study of car-following is that the details of operational braking performance can only be compared between different drivers if they start braking at the same distance- or time-headway. This means that, in studying braking performance, drivers will have to be forced into time-headway conditions they would not choose themselves, which may result in differential effort allocations as a function of the discrepancy between preferred THW and actual THW. This was illustrated by the results of an experiment by Heino et al. (1992). They found that particularly drivers who normally follow at a larger THW increase their mental effort, as measured by heart rate variability, when they are forced to follow at a smaller THW. This means that the methodological prerequisite of measuring braking performance in forced-paced situations may, to some degree, obscure individual differences in braking performance because of between-subjects differences in effort allocation. Nevertheless in the present studies, this method is preferred to the alternative where braking performance is measured while drivers follow at their preferred THW. Drivers who follow at a smaller THW would be forced to brake faster compared to drivers who follow at a larger THW, and this would damage the comparability of braking performance between drivers.

The results of experiments 3 and 4 demonstrate that choice of THW is consistent and constant over different speeds. In experiment 3 preferred THW is measured at speeds of 40, 50, 60 and 70 km/h. Speed has no significant effect on preferred THW and the within-subjects reliability of the THW's is high. This is confirmed by the results of experiment 4. The high consistency in choice of THW has been confirmed in an on-road experiment by Heino et al. (1992). They reported a correlation of 0.85 between time-headways measured on two different stretches of road. Other studies on the consistency of THW are discussed in chapter 6. The results indicate that choice of THW is independent of speed and consistent within the individual driver and that clear and reliable individual differences exist in choice of THW. This is an important prerequisite for the application of the adaptation model to individual differences.

Experiment 2 examines the relation between preferred THW and the ability to brake as fast as possible, the speed of stimulus encoding and response preparation. The additive factor logic (see Sternberg, 1969) is applied to examine the locus of effect of operational performance differences. The search for differences in the ability to brake as fast as possible stems from the tradition in the literature on braking where the quality of braking is generally examined in terms of the ability to brake as fast as possible. Experiment 2 may therefore be regarded as a search for individual differences in the limits of performance. The braking parameter that is studied in detail is reaction time (RT), defined as the interval between the moment the lead vehicle starts to brake and the moment the subject starts to release the foot from the accelerator. Again, this approach stems from the dominant view in the literature on braking, i.e. that differences in braking performance originate from perceptual factors measured by RT. Differences in the speed of stimulus encoding regarding the braking action of the lead vehicle would suggest that drivers with a smaller preferred THW (short followers) perceive the braking of the lead vehicle earlier. Differences in response preparation would suggest that the state of motor readiness is reached earlier by short followers compared to long followers. The results indicate that choice of THW is not related to individual differences in RT for a decelerating lead vehicle, to differences in stimulus encoding or to differences in response preparation. From this it is concluded that differences between short and long followers cannot be explained in terms of "limits of perceptual and motor skills". However, differences in preferred THW appear to be related to braking performance in quite another way. Differences in response execution speed as a function of preferred THW are restricted to braking situations characterized by uncertainties concerning the braking of the lead vehicle, the required deceleration and the duration of braking, as is always the case in real world car-following situations. The results suggest that individual differences in the transformation of visual feedback to the motor response may be related to choice of THW.

Experiment 3 considers these aspects in more detail and examines the use of time-to-collision (TTC) during braking and the way the braking response is executed. The process of braking is connected explicitly to the literature on time-to-collision (TTC). TTC is defined as the time required for two vehicles to collide if they continue at their present speed and on the same path (see for example Van der Horst, 1990). In the literature it is often suggested that the perception of TTC from the optic flow field is an important skill related to the initiation of braking. But curiously, only a few experimental studies have connected the concept of TTC to the braking response. The general conclusion from the literature is that TTC is underestimated and that there are large individual differences in the ability to accurately estimate TTC. In experiment 3 the hypothesis is tested that preferred THW is related to the sensitivity to TTC information. According to this reasoning, drivers who are more sensitive to TTC information are better able to judge the moment to start braking while drivers who are less sensitive to TTC information run the risk of starting to brake too late. This may result in a compensatory larger preferred time-headway for these drivers. The results indicate that both the initiation and the control of braking are strongly determined by TTC on the moment the lead vehicle starts to brake. Short followers differ from long followers in the control of braking: short followers brake harder and more efficiently, and, most importantly, the intensity of braking is more sensitive to TTC differences, compared to long followers. Yet, a confounding factor may have affected the results. Because the absolute levels of TTC differ between short and long followers in this experiment, short followers may have been forced to brake more efficiently.

Experiment 4 explicitly controls this confounding factor. Braking performance is measured with identical initial time-headway for all subjects. The subjects are unaware of the fact that the lead vehicle will brake and of the required deceleration and the duration of braking. A model of braking is discussed in which the process of braking is divided into three separate phases: the RT phase, the open-loop ballistic phase and the closed-loop phase. The RT phase is defined as the interval between the moment the lead vehicle starts to brake and the moment the foot starts to be retracted from the accelerator pedal. The open-loop phase is operationally defined as the period that starts when the subject retracts the foot from the accelerator after the lead vehicle has started to decelerate and ends when the brake pedal is touched. During the closed-loop phase visual feedback is used to control the process of braking. It is defined operationally as the period between the moment the brake pedal is touched by the foot and the moment the maximum brake position is reached. It is hypothesized that the speed of the open-loop ballistic response is determined by TTC on the moment the driver detects the deceleration of the lead vehicle, while the duration of the closed-loop phase is determined by the number of decelerations in the brake pedal signal (movement corrections). The results show that reaction time is not related to preferred time-headway. This confirms the results of the experiment 2. The open-loop phase of the motor response appears to be very sensitive to TTC, and especially to TTC on the moment the foot is retracted from the accelerator pedal. This supports the hypothesis. Also, the results indicate that short followers are characterized by a faster open-loop response that is not caused by a smaller TTC. This suggests that short followers program their movement speed to a higher level compared to long followers. The duration of the closed-loop phase of the motor response is, in accordance with the hypothesis, strongly related to the number of movement corrections. Short followers exhibit a faster closed-loop response with fewer movement corrections. The results also indicate a strong effect of total movement time on preferred THW, strengthening the conclusion that short and long followers differ in both the open- and closed-loop phases of movement. This suggests that short followers are more sensitive to the task requirements in braking situations, confirming the results of experiment 3.

Experiments 5 and 6 test the hypothesis that short followers differ from long followers in the sensitivity of the braking response execution to TTC information. Both experiments apply the model of braking discussed in chapter 7. In experiment 5, the RT phase, the open-loop and the closed-loop phases of the braking process are manipulated independently. If short followers differ from long followers in either of these phases then the factor "preferred THW" should interact with any factor that manipulates these phases. The RT phase is manipulated with the factor initial THW on the moment the lead vehicle starts to brake. The duration of the open-loop phase is manipulated by the factor initial deceleration. The level of deceleration (3 vs. 6 m/s^2) of the lead vehicle is expected to affect the TTC on the moment the subject detects the braking of the lead vehicle and thereby the duration of the open-loop phase. The closed-loop phase is manipulated by the factor secondary deceleration: as soon as the foot touches the brake pedal (this is the moment the closed-loop phase starts) the deceleration of the lead vehicle changes. This requires the use of visual feedback in order to change the programmed motor response. Although the results show that the respective phases of the braking response are affected by the manipulations, the predicted interactions of preferred THW with the factors that manipulate the open- and the closed-loop phases are not statistically significant. The pattern of results suggests that task-specific factors resulted in undesirable startle reactions and vigilance effects.

Because of this the final experiment 6 applies multiple measurements per manipulated factor, a higher frame-rate and shorter task duration, in order to prevent startle reactions and vigilance effects. The main hypothesis is that short followers differ from long followers in the sensitivity of the motor response to TTC. TTC is manipulated with two levels of initial deceleration of the lead vehicle (3 vs. 6 m/s^2), in random order. The results indicate, in support of the main hypothesis, that the open-loop response of short followers is more sensitive to differences in TTC compared to long followers. The assumed causal chain is that individual differences in some basic perceptual-motor skill affect the quality of the braking response. The driver is assumed to adapt the choice of THW during car-following accordingly. In this way drivers protect themselves against poorer operational performance. However, it may be argued that short followers have had more practice in braking resulting in improved operational performance because of learning effects. To rule out this explanation it is examined whether short followers differ from long followers in perceptual-motor performance in tasks unrelated to braking. In order to test whether choice of THW is related to more general perceptual-motor skills that require the transformation of visual information to a motor response, performance on a lateral tracking task and a longitudinal tracking task is tested. The results clearly indicate that short followers perform better on both the lateral tracking tasks and the longitudinal tracking task. In addition to this, performance on both types of tracking tasks is significantly correlated. This strongly suggests that:

1) Short followers differ from long followers in perceptual-motor skills related to the transformation of visual information to a motor response,

2) these differences in skill are not acquired as a function of differences in following behaviour,

3) these differences in skill affect the quality of braking performance in the sense that short followers tune the braking response better to the requirements of the situation, giving them a higher sense of control,

4) resulting in the choice of a larger time-headway for drivers with poorer operational performance and a smaller time-headway for drivers with better operational performance.

10.2 General conclusions and next steps

The impact of vehicle factors and situational factors related to road, weather and temporary state on driver behaviour and the underlying mechanisms of behavioural effects have been addressed in this study. Mechanisms related to individual differences in driver behaviour have been tested from the perspective of the adaptation model. It is clear that the system components vehicle and environment have an important effect on driver behaviour, mediating the effects on accident involvement and traffic safety in general. Adaptation mechanisms are best studied by measuring driver behaviour as a function of vehicle factors, individual differences in skills, situational factors and temporary states instead of accidents, because these factors affect behaviour directly while they affect accident involvement indirectly. One of the reasons for the lack of progress in driver modeling, referred to in chapter 1, is the abundance of determinants and factors that operate simultaneously. This has resulted in several theories that apply only to a limited problem domain. The adaptation model integrates the operational and the tactical level of driver behaviour into one framework. As discussed in chapter 2, driver models and studies in traffic psychology usually examine only one of these levels. It is suggested that these levels should always be studied in their mutual relationship. For example, if the effect of a roadmeasure on speed is examined it should also examine the effects on operational performance at the same time. Of course practical problems may prevent this and this is one of the reasons why simulators may be useful. However, the results suggest that measurement of behaviour on one level may be meaningless when behaviour on another level is excluded from examination. Several other driving tasks such as speed choice on straight roads, gap acceptance at intersections, stopping for traffic lights, overtaking and so on need to be examined within this framework.

According to the adaptation model, drivers with poorer operational performance protect themselves by adapting behaviour on the tactical level, resulting in a lower speed or larger time-headway. The other side of this reasoning is that drivers with better perceptual-motor skills and good operational performance drive at higher speeds or follow at smaller time-headways. However, it is not by any means intended to suggest that drivers with higher speeds are not dangerous because they have a highly developed skill level. Undoubtedly, some drivers who follow other vehicles at a close distance or who drive faster than average are not characterized by better operational performance. The suggested relation is a probabilistic one, and not mechanistic. However, the line of reasoning makes clear that the concept of risk becomes more meaningful if skills and level of performance are added to the equation. This is to say that a certain speed may not be as risky for one person as for the other if they differ in certain required perceptual-motor skills, from the same perspective as the fact that flying an F16 fighter plane is considerably more risky for the author of this thesis than for an experienced pilot.

Also, it is often assumed that higher speeds and shorter following distances are associated with a high accident risk although a number of studies do not confirm this simple relation. The effect of variability within the traffic system on accidents is one of the reasons why Summala (1985) promoted the introduction of speed limits. This has greatly reduced the accident risk in a number of countries. Speed limits reduce the variability of speed in the system and this reduces accident risk. Brehmer (1990) predicted that accident probability is lowest for cars driving with the average speed, but increases for drivers who deviate more from the average speed, either to lower or higher speeds. He referred to a study of Solomon (1964) on the relation between speed and accident rate on US highways, that supported this hypothesis. Munden (1967), referred to in Rooyers et al. (1992), reported a U-shaped relation between speed and accident rate as well. Brehmer also predicted that accident rates are higher in environments where the variance of the speed distribution is highest. A study of Greenberg (1964) was referred to which demonstrated a positive correlation between accident rate and speed distribution for a sample of US roads. Numerous authors have mentioned that it is an established fact that accident risk is related to driver speed, and that speeding therefore can be regarded as a form of driver error, related to poor speed perception skills or poor hazard perception. However, whether a higher speed is riskier compared to a lower speed with identical speed distributions is an unresolved matter. A similar point can be raised with regards to headways during car-following. Shorter time-headways are usually associated with a higher risk of rear-end collisions. In a large-scale study on the relation between time-headway and accident risk in several countries a relation was found between rear-end accident rates per 100 million vehicle kilometers and time-headway (Benjamin, 1980). This relation was however strongly affected by the flow of traffic or traffic density. Traffic volume affected both time-headway and the number of rear-end collisions so that a causal relationship between close following behaviour and rear-end accidents could not be established. It was already demonstrated in the fifties by the studies of Herman (referred to in Forbes, 1972) that, even in car-following situations with conservative headways, normal speeds and short response times of drivers, flow disturbances by the platoon leader (the first car in the chain) may cause a chain reaction that makes it impossible for drivers downstream to avoid a collision. This indicates that the relation between speed choice, choice of time-headway and accident risk is not as straightforward as often suggested.

The general principle of behavioural adaptation demonstrates the inherent flexibility of human behaviour. This flexibility resembles the issue of 'human behaviour feedback', discussed in chapter 1, which has puzzled many traffic safety researchers and triggered fierce discussions about the effects of safety measures. The adaptation model may offer the concepts and methodology to clarify the issue of this 'human behaviour feedback' in more coherent terms. Driver adaptation of tactical behaviour to effects of safety measures on operational performance may be an important determinant for the success or failure of intended safety changes in the road-vehicle-driver system.

Although the process of adaptation appears to be 'normal behaviour', it also seems clear that certain factors prevent adaptation resulting in increased accident involvement. Examples of this are the consumption of alcohol and the case of the young male driver. Citing from paragraph 2.3.4: "The interaction of BAC level and age on accident involvement suggests that both factors share a common locus of effect, in the sense that the factor that causes the higher accident rate of young drivers is aggravated by alcohol. In the discussion of the effects of alcohol it was suggested that the lack of compensation for impaired performance may be the cause for the large role of alcohol in accident causation. Evidence was presented that drivers are unaware of performance decrements under alcohol which is possibly the cause for the absence of compensatory speed changes and effort. From the same perspective it may be suggested that young and inexperienced drivers have not yet learned to recognize the effects of situational factors on their performance and thus fail to compensate for these effects resulting in speeds that are too high for the circumstances". Clearly this is an issue that needs to be investigated further. There are some indications that alcohol inhibits the perception of feedback from the driving task. The assumed lack of adaptation in young (male) drivers also needs to be explored further. The theory presented in this study offers a framework to examine these issues.

An important next step is the further validation and testing of the adaptation model. In the present study only a limited part of the model was tested. For example, the principle of effort allocation under forced paced conditions and the effects of this on operational performance need to be tested in further studies. The six experiments described in this study are only a first step in the direction of testing the limits and scope of the model of adaptation.

References

Summary

From adaptive control to adaptive driver behaviour

Progress in the field of driver behaviour modeling has been limited during the last ten years. One of the main problems arises from the emphasis on traffic accidents and accident causation instead of everyday driving. Also, the partiality of the various approaches involved in driver modeling has impeded progress. Existing models are exclusively directed at either the operational level or the tactical level of the driving task. Moreover, existing models focus either on individual differences or on situational factors. In contrast, the approach advocated in this thesis emphasizes the integration of behaviour on the operational and the tactical level together with a relation between individual differences, vehicular and situational factors on the one hand, and operational performance on the other hand in a systems approach that stresses the interaction between man, machine and environment. Starting from a discussion of a number of important models and approaches in traffic psychology, the adaptation model is developed in chapter 2. In this model, several factors are assumed to affect performance on the operational level. For example, drugs and alcohol affect skills involved in vehicle handling. These skills are affected by the process of aging as well. Yet, there is little evidence for a relation between skill level and traffic safety. It is suggested that this is caused by a compensation or adaptation of behaviour on the tactical level for deteriorations of skill level and operational performance. This means, for example, that when steering performance is negatively affected by whatever reason, drivers take account of this by lowering their speed. Operational performance is not only affected by skills. Vehicular factors and situational factors related to the road, sight distance and weather affect operational performance as well. In chapter 2 a number of experimental results are discussed that suggest the existence of a process of adaptation of behaviour on the tactical level under these circumstances. Behavioural adaptation then appears to be a general phenomenon that normally occurs when operational performance is affected and when this is perceived by the driver. However, this process of adaptation appears to be prevented in some conditions, for example after alcohol ingestion or in the case of young male drivers. This results in a dramatic increase of accident risk. Motivational models play an important role in contemporary traffic psychology. Some elements of the ‘Zero Risk Theory’ and the ‘Threat Avoidance Model’ are integrated with the adaptation model.

An important starting point of the adaptation model is that car driving is essentially a self-paced task. The driver determines how to drive and makes decisions on the tactical level of driving behaviour. When the driver has little choice, the task is forced paced. Deteriorations of operational performance have to be handled differently in that case, as discussed in chapter 2.

Paragraph 2.5 discusses time-related safety margins such as the time-to-collision (TTC) and time-to-line-crossing (TLC) as control mechanisms for the extent to which behaviour on the tactical level is adapted to operational performance.

In paragraph 2.6. the research questions are discussed for six experiments that examine an important aspect of the adaptation model: the extent to which individual differences in operational performance result in individual differences in behaviour on the tactical level. The two different driver tasks of curve negotiation and car-following are examined in detail. Curve negotiation was selected because the lateral control task, and especially the quality of steering performance, affects the choice of speed in curves. Car-following was selected because it was expected that the longitudinal control task, and more specifically braking performance, determines choice of time-headway. This research then tries to answer the questions why some negotiate curves at higher speeds than others, and why some drivers follow at a small time-headway while others follow at larger headways.

The experiments discussed in this thesis were performed in the TRC driving simulator. The author has, together with a collegue, developed the software for this research instrument. Because the design and implementation of

components of the simulator constitutes an important element in the preparation of this thesis, the functionality of the simulator is discussed in some detail in chapter 3.

Chapter 4 discusses an experiment in which the relation between speed choice in curves on the one hand and steering competence and road radius on the other hand is examined. Road radius affects required steering angle and, thus, required performance. The magnitude of the steering error is determined by both required steering wheel angle and steering competence. It was found that both factors determined both operational performance and speed choice in curves such that the minimum TLC to the inner lane boundary is constant. This confirms the hypothesis that several factors affect operational performance and that behaviour on the tactical level is adapted to this. It also confirms that, in lateral control tasks, adaptation is controlled by safety margins.

In the chapters 5 to 9 five experiments are discussed that examine the relation between choice of time-headway (THW) during car-following and operational performance in braking. Chapter 5 studies the relation between choice of THW and the ability to brae as fast as possible. No differences are found between short and long followers in this ability, in the speed at which they perceive the lead vehicle brakes, or in the speed of response preparation. However, there appear to be differences in the response execution of braking. These differences are restricted to situations where the driver does not know in advance that the lead vehcle will brake or how hard it will brake.

Chapter 6 examines the relation between the use of time-to-collision (TTC) information during braking and choice of THW. Both the initiation and the control of braking appear to be determined by the TTC at the moment the lead vehicle starts to brake. It was found that the intensity of braking is more sensitive to TTC information for short followers compared to long followers. This suggests differences between short and long followers in perceptual-motor skills involved in the response execution of braking. However, a confounding factor may have affected the results: absolute differences in TTC may have forced the short followers to brake more efficiently.

In the experiment discussed in chapter 7, this confounding factor was controlled for. Three sequential phases of braking are distinguished: the reaction time (RT) phase, the open-loop ballistic phase and the closed loop phase. It appears that the duration of the open-loop phase is strongly determined by the TTC at the moment the driver detects the deceleration of the lead vehicle. The duration of the closed-loop phase is related to the number of movement corrections during the process of braking. Short followers exhibit a faster open-loop and a faster closed-loop response compared to long followers. The results suggest that drivers with a smaller preferred THW are more sensitive to task requirements than drivers who prefer to follow at a larger THW.

In the chapters 8 and 9, two experiments are discussed in which the hypothesis is tested that short followers differ in the sensitivity of the braking response to TTC. In the experiment in chapter 8 the RT, open-loop and closed-loop phases are manipulated separately. Although the different manipulations specifically affect the different phases of the braking response, the predicted interactions between following group (short vs long followers) and the manipulations of the open- and closed-loop phases are not statistically significant. The results suggested that task-specific factors evoked undesirable startle and vigilance effects that preclude confirmation of the hypotheses. Therefore, the final experiment, discussed in chapter 9, was designed such that these task-specific effects were prevented. The open-loop phase was manipulated by the level of deceleration of the lead vehicle. A larger deceleration of the lead vehicle results in a smaller TTC at the moment the driver detects the deceleration. This effect speeds up the open-loop phase. If response execution of short followers is more sensitive to TTC information compared to long followers, a statistical interaction is expected between following group and level of deceleration of the lead vehicle on the duration of the open-loop phase. The results confirmed this hypothesis. It was also investigated whether short followers differ from long followers in other tasks requiring a dynamic perceptual-response coupling by measuring performance on a lateral tracking task and a longitudinal tracking task. It was found that performance on both tasks was significantly correlated and short followers perform better on both tasks compared to long followers. These results support the hypothesis that long followers choose a larger THW during car-following because they are less skilled in dynamic tasks requiring a perception-response coupling.

Chapter 10 discusses the extent to which the results of the experiments support the adaptation model together with a number of general conclusions.