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# Safety Margins in the Driver

BY

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## Abstract

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The primary aim of this thesis is to highlight the most important features of driving and to describe the models that have attempted to conceptualise these features. The discussion focuses on the concept of "safety margin." The concept is elaborated upon in an effort to enhance its usefulness as an empirical tool in traffic research. In this study, safety margin is defined as a threshold value that informs the driver when to undertake an action to minimise the risk of a car accident. Three separate studies of various driver behaviours are presented as illustrations of how this view can be applied in a real highway traffic setting. One study (Study I), consisting of three independent but related experiments, examines car following; a second study (Study II) explores gap acceptance at a T-crossing; and a third study (Study III) investigates drivers' braking decisions.

The overall findings of the present studies suggest that it is valid to model driver behaviour as a concern related to the control of safety margins. It was shown that the driver controls time-distance dynamics to leading and following cars when driving in a queue. A bias in the drivers' impressions of distances to leading and following vehicles that has safety promoting implications was also found. There was no evidence for the hypothesised use of the limit for dissolution of time-distance to oncoming vehicles for merging decisions at a T-junction. Drivers' rules for establishing braking decisions were successfully assessed in a field study using linear regression.

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To Martin and Johan

This thesis is based on the following studies, which will be referred to by their Roman numerals:

- I Nilsson, R. (2000). Drivers' impressions of front and rear gaps in queues. *Ergonomics*, 43, 1985-2000.  
In addition, a study previously presented in Swedish, Nilsson (1999), is reported in English in the present thesis.
- II Nilsson, R. (Manuscript). *Drivers' decisions to merge at a T-junction*.
- III Nilsson, R. (Submitted manuscript). *Drivers' decisions to initiate braking*.

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## 1. INTRODUCTION

The driver of a motor vehicle has the task of reaching a destination at the shortest possible time without causing injury or damage to himself or others. Most of those persons who have tried to analyse the driving task agree on this level of analysis. However, in order to move from this trivial level to a fruitful paradigm for studying driver behaviour in such a way that implications for road safety emerge we need to develop theories and methods. In fact, there are still such fundamental discussions as to how research on driver behaviour should be conducted. A multitude of approaches to the problem of risky driver behaviour is perhaps needed but in this thesis one specific line of reasoning is presented, namely, that the driver's task at the automated level is essentially a matter of controlling safety margins.

In this thesis, an effort is made to highlight the most important features of driving and to describe the models that have been presented that attempt to conceptualise these features. This discussion narrows down to the concept "safety margin," which is elaborated upon for making the term useful as a tool in empirical investigations.

Three separate, but related, studies of various driver behaviours are presented as illustrations of how this view could be applied in a research setting: one study, consisting of three independent but related experiments, examines car-following; a second study explores gap acceptance at a T-crossing; and a third study investigates braking decisions.

## 2. MODELLING THE DRIVERS' TASK

### *Control theory.*

In modern human-machine sciences, considerable efforts are expended to model the controlling person's interaction with all relevant aspects of the environment, i.e. the task. This work is done taking into consideration the capacities of the individual. The individual affects the task through his or her actions; the task, in turn, changes and affects the individual who may

thus be motivated to take new actions. This “dynamic” relation between the individual and his or her environment can be modelled using control theory.

For some time, engineers have constructed various apparatuses, that is, servomechanisms to control numerous physical processes and states. Thermostats on radiators and cruise control systems in cars are well-known examples. The typical task of a servomechanism is to maintain some entity at a stable level (e.g., temperature and speed in the above-mentioned examples). The effects of disturbing events, such as a sudden change in weather, are compensated by the servomechanism, so that the temperature is kept constant at the location of the sensor. Concerning cruise control, a good cruise control system accelerates aggressively to the desired speed without overshooting, and then maintains that speed with little deviation no matter how much weight is in the car, or how steep the hill you drive up. The laws for constructing a servomechanism are formulated within control theory.

The idea to model human behaviour with control theory was presented to a wider public of life scientists by Norbert Wiener (1948) in his book, “Cybernetics: Control and Communication in the Animal and the Machine.” However, as Powers (1978) notes, control theory did not make that breakthrough into psychology as was expected at least not during the first 20 years or so after the publication of Wiener’s book. Powers argued that Wiener himself could be partly to blame because his illustration of the basic principles of a control system was not done clearly. This inability, according to Powers (1978), led to misinterpretations. Some of the resistance against the servomechanism as a model of human behaviour was due to the view that control theory involved a machine analogy of man and thus a simplification that leaves out, important emotional aspects of mental life. However, as Powers pointed out, it is more adequate to recognise the servomechanism as a model of a living organism rather than the model of a mechanical device. Living organisms are the only systems in nature that are capable of doing what servomechanisms do, i.e. controlling some state outside the system itself. In fact, servomechanisms were invented to replace humans in tasks that only could be performed by an intelligent controller. Thus, by studying what could be done through

servomechanisms, with support of control theory, there is a possibility that we could also learn something about the principles of human behaviour.

Powers (1973) presented an analysis of human behaviour from the perspective of control theory. The main point is formulated in the title of his book, "Behaviour: The Control of Perception." The behaving individual is not producing behaviours with the purpose of performing an act in and of itself; rather, the individual merely uses behaviour as a means for accomplishing wanted perceptions. This implies that everything that is done by a person is driven by an underlying motive. Furthermore, whether the motives are conscious or subliminal does not matter. Power's studies were followed by the work of Richard Marken, who investigated manual control to demonstrate the principles of analysing control systems (Marken 1980, 1986). Marken (1988) also developed control theory for studying behaviour. In Power's and Marken's view, the prime task of behavioural research is to identify what is controlled, that is, to describe what is kept constant by the individual by seemingly complicated actions. Carver and Scheier (1982) advocated the use of control theory in several areas, including social and clinical psychology. Furthermore, as Powers and Marken, these authors presented similar developments of control theory as a tool for investigating behaviour.

In research on traffic behaviour control theory has been successfully applied to tasks at the automated level. In three Dutch studies on steering behaviour control theory was applied (Blaauw 1984, Godthelp 1984, Riemersma 1987). Lee (1976) discussed control of braking in a theoretical paper and later Newcomb & Spurr (1982) conducted empirical studies on braking. Thus far, no serious attempts have been done to model deliberate driver behaviour, that is, conscious decisions from the perspective of control theory.

#### *The feedback control system.*

Control systems may vary in several ways in their detail but the negative feedback control system can serve as a base for most control systems. In this section the negative feedback control system is delineated with car

driving as a theme. The system is called negative because it tries to eliminate any differences between goal and feedback.

In Figure 1, a negative feedback control system is depicted. The figure has a lower and an upper part separated by a dashed line that represents the interface between the driver and the environment. Elements above the line indicate the regulator, i.e. the driver. Below the line are elements indicating the vehicle and the environment. At the right of the interface, the driver affects the vehicle and at the left information on the effects of the driver's actions reaches the driver via receptors. The arrows represent signals from the components in the system. In the driver these signals are probably best conceived of as information, whereas the signals in the environment reflect causal events.

At the top of the system, there is a reference value, which is a state of conditions that the driver strives to maintain (e.g., the car's speed, the

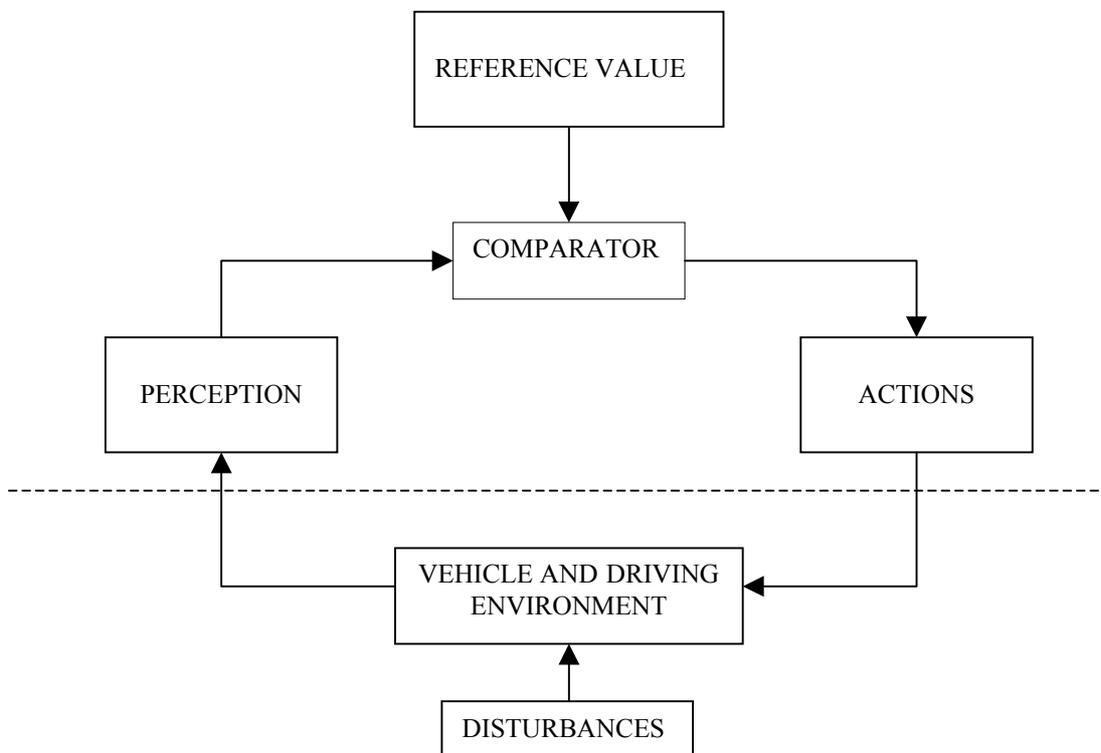


Figure 1. The structure of a negative feedback control system adapted to the driving task.

distance to the car in front or the distance to the roadside). The reference value has several synonyms, including set point, purpose, motive, goal and target. This is the component in the control system that implies that control systems are motivational models. Information on some state, such as distance to the car in front, enters the driver via the perceptual mechanism. The perceived state (i.e. the distance) is compared with the reference value, the distance that the driver wants to maintain at the point referred to as “comparator.” If a difference between the reference value and the perceptual signal occurs, the result will be an error, which the driver attempts to compensate by performing some specific action, such as applying the brakes of the vehicle in order to avoid an accident. The actions of the driver not only affect the vehicle but they also have an impact on the traffic situation. However, expected effects on, for example, distance to the car in front may be compromised by external factors such as a change in speed of the lead vehicle. The joint effects of actions and disturbances are continuously (there may be exceptions) registered by the driver via his or her perceptual system. Thus, information feedback to the driver continuously takes place and the perception of the controlled state (e.g., headway) is repeatedly compared with the reference value. In technical servomechanisms, several other components are needed to tune the system so that it functions in an exact and stable manner. In a driver, there is a great need for supporting components: for tuning, for decision making, for perception, for motor control, etc. The control system’s structure per se does not tell much about how the system accomplishes its task or how the driver acts in various situations. However, it does present a way to map the relation between a driver and the driver’s task, reminding the researcher about the important links in that dynamic process. The control system also sets preconditions as to the motivational reasons for behaviour and points out that more can be learned about a behaving organism by considering what the organism sees rather than what the organism does. Put differently, it is the result of actions, and only those results that are perceivable by the organism, that are of primary concern for the scientist, not the behaviour per se.

If the feedback control system is continuously active, the system is said to have a closed loop. The controller can then uninterruptedly sense input signals and take corrective actions as soon as these are needed. If the

system takes pauses in processing feedback, then the system is alleged to be in an open loop during the time interval in which there is a temporary cessation of input signals. The driver may be performing various overt actions but the consequences are not being processed during the pause.

As suggested by Powers (1973) and Carver and Scheier (1981), the control system may be hierarchical, having several levels. The output (i.e. the actions) on a higher level sets the reference value at the level just below. The output from the lower level, in turn, sets the reference value of the level below that level, and so on. Overt behaviour occurs only as output from the lowest level in the hierarchical system.

Consequently, the structure of control systems may differ in many respects, so it is obvious that just selecting control systems to model driver behaviour will not answer all the questions about how drivers solve their driving-related tasks.

As argued thus far car driving is a dynamic process that can be modelled accurately using control theory but car driving has not been modelled with control theory until the last decades. In traffic psychology, a number of models have been proposed over the years. Because the primary aim of research on traffic behaviour is to bring knowledge that can guide enhancements of traffic safety, most models and theories are developed for the purpose of explaining accidents. Some 40 years ago, the tendency was to identify limits of a driver's capacity (Brehmer, 1993). The driver was largely seen as a victim of an environment that was excessively demanding. For instance, Rumar (1985) modelled the driver with perceptual and cognitive filters that set limits on the driver's cognitive capacity. In line with this framework, studies were designed to examine, for example, the driver's capacity to detect traffic signs and brake reaction time. Such research was consistent with the human factors tradition that started in the USA during the 1930s and was applied in large scale during the second world war in, for example, military aviation (Forbes, 1972).

### *A self-paced task.*

This way of modelling driving failed to recognise the self-paced nature of the driving task (Näätänen and Summala, 1974, 1976). When the task becomes overly demanding, the driver can compensate by performing certain actions, such as decreasing speed, increasing headway, increasing attention on the road or selecting another route in order to remain in control. In this way, the driver is active as opposed to being a passive victim to his or her environment. Looked at from this perspective, accidents are seen as consequences of the driver's failure to adapt to his or her environment.

### *Adaptive control.*

Adaptive control is a special type of control that is maintained in a self-paced task. If the task exerts too much pressure on the driver, the driver can adapt to this circumstance as a means of reducing task demands. Because the driver has access to several means of control, the driver can choose among different actions. Speed can be reduced, headway can be increased or attention to traffic conditions can be enhanced, to mention a few possibilities. Tasks in which several behavioural variables are observed at the same time, have recently been studied (e.g., Van der Hulst, 1999).

Wilde's theory of risk homeostasis (Wilde, 1982) is an excellent example of an adapting system. This is the theory that humans behave in such a way that if a risk is identified in a given system, and is reduced by design, then a compensatory increase in risk-taking will occur somewhere else in the system. However, it is not necessary to adopt Wilde's idea in which perceived risk is the major controlled variable. Wilde suggests that the driver constantly endeavours to maintain a target level of risk. The implication arises when all efforts to promote safety fail because the driver would compensate a reduction of risk in one aspect of the driving situation by increasing the risk in some other aspect. For instance, enhanced safety with the use of seat belts would be followed by a compensatory increase in risk-taking by, for example, driving faster. Wilde's theory has met harsh criticism for its lack of testability. Although his theory has serious deficiencies, it is a motivational model of control that has furnished a better understanding of adaptive control and actuated the problem of behavioural

adaptation (also referred to as compensation) (see Grayson, 1996, for a review on behavioural adaptation). Behavioural adaptation, or risk compensation, is the undesirable response that can occur when some safety promoting measure is imposed on the driver. Adaptive control is the flexible properties of the driver's control system that can cause, among other things, behavioural adaptation. Behavioural adaptation is often in focus in evaluations of new supporting systems in cars (e.g., intelligent cruise controls) (Hoedemaeker and Brookhuis; 1998, Nilsson, 1995). Compensation should be considered when a vehicle is modified to allow for better performance, as when it is equipped with a combined accelerator-brake pedal to reduce drivers' reaction time in braking (Nilsson, in press).

#### *Hierarchical organisation.*

It is plausible to distinguish between rather well-defined levels of driver behaviour. Rasmussen (1987) suggested that behaviour could be divided into skill-, rule- and knowledge-based behaviours. Conscious problem solving is an example of the latter level of driver behaviour, i.e. knowledge-based behaviour. Rule-based behaviour involves activation of rules and plans. Skill-based behaviour is the lowest level, involving automatic procedures and schemata.

Michon (1985) suggested a similar differentiation that includes three levels of driver behaviour: the strategic, the tactical and the operational level. The strategic level, involves such tasks as planning a trip. The tactical level involves features of the task that occur during the driving episode and include speed choice, lane changing, negotiation of curves, etc. At the operational level, the driver steers, accelerates and brakes.

Rasmussen's taxonomy primarily refers to processes that take place within the individual while Michon's taxonomy involves features of the task. However, the two classifications are closely connected in the sense that processes at the operational level govern Rasmussen's skill-based behaviour. Hale et al. (1990) discussed the implications of combining these two categorisations. The taxonomies do not specify processes in any detail and they do not explicitly imply a need for control theory but they do serve as tools for designing levels of a control system for the driver, albeit a

rather course system. These taxonomies are chiefly aimed at organising behaviour to make it easier to investigate driver errors. A recent fruitful effort in that spirit is represented in the work of Rimmö (1999).

An important distinction between the automated and deliberate levels of functioning has been suggested (Schneider and Shiffrin, 1977). To the deliberate level, we assign conscious processes such as problem solving. These processes are slow and demand cognitive effort. At the automated level, which is without volition or conscious control, processing is fast and effortless. Processes are likely to be very dissimilar at the two levels and may therefore require different models (Brehmer, 1993). The automated level of functioning is probably more complex than was believed initially and does not seem to be wholly autonomous (Groeger, 2000). Most of the time, the driver operates at the automated level. The deliberate level is demanded when something new or unexpected happens and the driver lacks experience regarding how to decide and act in such a novel situation.

The deliberate level of functioning may involve intentions that are the causes of behaviour. In the theory of reasoned action (TRA) (Fishbein and Ajzen, 1975) and in its later modified version - theory of planned behaviour (TPB) (Ajzen, 1991) - behaviour is modelled as consequences of intentions to behave. The intentions, in turn, are the consequences of attitudes (a sum of subjective expected utilities) and social norms (also a sum of utilities). The modification in TPB involves the person's perceived behavioural control, that is, the person's feeling of being able to succeed with the intended action. This theoretical framework affords a way of modelling the occurrence of reference values in a control system model of the driver. The reference values, which in some cases can be identified as intentions, are set by a deliberate process at a higher level in the system. The lower levels are executing the control needed for fulfilling the intentions. Both theories, i.e. TRA and TPB have been successfully applied in traffic psychology in explaining drunk driving (TRA) (Åberg, 1993) and several other traffic-related violations (TPB) (Parker et al., 1992).

### *The need for anticipation.*

The driver must negotiate a number of obstacles while driving: curves, plan stops, foresee other driver's actions and avoid collisions to name a few. The physical laws inevitably set limits for how soon a car can be stopped, how fast it can move in a new direction or accelerate to a predetermined speed. This goes for both the driver's vehicle and other vehicles on the road. Delay is also caused by the driver's perceptual, cognitive and motor cortical activity in reaction time.

To compensate for the delay between actions and their effects the driver must constantly anticipate events in the driving environment. Anticipation can come from some inference process within the driver or it can be contained in the information reaching the driver's perceptual system. The latter type of anticipation is intriguing in that it assumes a minimum of processing in the driver. J. J. Gibson, who introduced the ecological approach in perception, showed the richness of the information reaching the eye (Gibson, 1950). The optical flow field, the projection of the outside world on the retina, contains much more than just pictures of the environment. It also contains dynamic properties of the perceived events, properties that may be used as predictors of future events or that at least tell the driver how fast and in what direction events develop. If these properties are possible to perceive, the driver will likely use them.

### 3. SAFETY MARGINS

#### *How to avoid competition on means for control?*

In addition to the ultimate goal of reaching a destination safely, the driver's task might involve a number of sub-goals and extra motives for driving (e.g., the pleasure of speeding along an abandoned road or a way of finding moments of solitude). A system with several goals could naturally be modelled with several parallel reference values. Yet, there are really only two means for control, i.e. affecting speed and/or direction and they must be shared by the different parts of the system. Thus, there may occur conflicts between different parts of the control system. Such conflicts probably could not be tolerated at the automated level of control. At the

deliberate level, however, conflicts are more likely to be solved, which is a prime task for the deliberate level (Schneider and Shiffrin, 1977). Thus, the driver's control system must be either designed to involve a capacity to cope with conflicts or designed so that conflicts are avoided from the beginning.

### *Thresholds and safety margins.*

Is it possible to avoid conflicts among reference values by designing a control system such that the reference values, or rather the errors resulting from comparisons between the feedback and reference values, do not need access to means for control at the same time? This could be the case for a system in which the reference values are thresholds. As long as feedback is below the threshold, the system accepts that things are satisfactory and there is no error signal and no correcting behaviour. Correction is not motivated until the threshold is either reached or exceeded. Thus, at a specific moment in time most, perhaps all, reference values may be resting. Meanwhile, the driver will go along driving as before, without correcting manoeuvres. The driver may be equipped with, for example, thresholds for speed, time distances, forces and metric distances that are set at values that will lead to safe and efficient driving in most situations. Driving would be a comparably easy task with little or no conflicts and very few instances where higher levels in the system must intrude and compromise.

In the features of the driver's control system that are thought to protect the driver from danger, these thresholds would act as margins of safety. Näätänen and Summala (1976) presented a definition of safety margin, a key concept in their zero-risk theory (Näätänen and Summala, 1974). In their definition, a safety margin is "a distance to a threat that the driver does not want to pass by." The zero-risk theory speculates that as long as the driver is further from a threat than the safety margin, the driver will not experience any risk or danger. However, as the safety margin is exceeded, a feeling of danger will immediately arise, causing evasive actions. This notion of safety margin is consistent with the idea of a control system with thresholds.

In Fuller's threat avoidance theory (Fuller, 1984), a behaviourist approach to model driver behaviour, a no risk situation is the preferred state of the driver. Safety margins appear as discriminative stimuli, something in the driving environment that serves as a warning signal for a hazard, and the driver reacts with an anticipatory avoidance response. If drivers miss the discriminative stimuli, they will be confronted with the danger itself. This will cause them to react in a fearful manner, causing a delayed avoidance response. Thus, Fuller's theory is consistent with a threshold model. Moreover, the threat avoidance theory offers a mechanism for learning, which is missing in control theory and motivational models.

#### *Representation of safety margins.*

The engineering definition of safety margin, an extra capacity of a construction to withstand a load, is inadequate for the psychological safety margins discussed here. The psychological safety margin is simply a threshold: there is no assumption of a representation of some other distance or quantity that would define when a catastrophe becomes unavoidable. In some cases, it is possible for the driver to know critical limits, limits that, if they were surpassed, would indicate that an accident must occur. The driver's safety margins must be encompassing to render safe driving. Yet, some safety margins could be closed while others could be far from an objective critical limit. To some extent, the safety margins are independent of the actual driving situation, leading to poor objective safety under certain circumstances and high objective safety under other circumstances. Objective safety would include, for example, passing distances in overtaking or braking reserve when making a stop.

As noted, the foregoing discussion of what constitutes a safety margin is rather abstract. The reason for this is intentional for it is difficult to give concrete and understandable examples of drivers' psychological safety margins. This, in turn, depends on the author's resistance to mislead by using simple examples from physical descriptions of objective safety margins. As long as margins are described by measurable, physical properties of the driving environment, things are rather simple. However, because the psychological safety margin is a representation in the driver that depends on rules for perception of dynamic events, it is not that easy to

give known examples. Gibson and Crooks (1938) suggested a representation that they called “field-of-safe travel.” In this early, but still useful theory, the authors suggested that everything in the driver’s visual field that could be an obstacle or a threat is surrounded by zones, that is, safety margins. In the same representation, the closest distance for stopping the vehicle is merged. The area that is outside the stopping distance and the zones of threat is free for safe driving, that is, a field-of-safe travel. Gibson and Crooks thought of the field-of-safe travel as a kind of safety margin in itself, but they also introduced safety margins as the zones of threat around other vehicles, corners, etc. The zones of threat around other vehicles, corners, etc are comparable to the notion of safety margin in the present study, though they are not distinct thresholds. One objective for control would be to drive so that there is always a field-of-safe travel. In Gibson and Crooks’s theory, the represented entities are rather simple and possible to sketch on a map of the road within the driver’s view. However, in research on representations of safety margins one has to be prepared for the existence of margins that cannot be drawn in a picture. Perhaps the problems with identifying the safety margins and the connected problems with operational definitions of the margins explain the failure of motivational models (e.g., the zero-risk theory) to “generate testable hypotheses necessary for developing a body of empirical findings” (Ranney, 1994, p. 733). It appears that traffic psychology must go deeper into the area of the perception of dynamic events as it is the driver’s possibilities to perceive that provide the framework for the scientist’s search for safety margins.

### *Stereotypic behaviour*

A representation such as field-of-safe travel, in combination with thresholds, has some implications for the character of behaviour. As already noted, the driver has no reason to change speed or direction of the vehicle as long as the safety margins are not in danger of being exceeded, that is, as long as there is a field-of-safe travel, to use Gibson and Crook’s terms. Thus, there will be periods of no apparent control. When a reason for a new action occurs, as when a safety margin is approached, the space between safety margins (i.e., the field-of-safe travel) may allow for a great number of actions (i.e., different speeds and directions). In such a situation

the driver has two options: either to vary behaviour from one occasion to the other, even if the situations are similar because there is room for such variations, or to do the opposite, using a limited number of stereotypic actions or habitual responses in a variety of situations. Stereotypic actions apparently have some benefits in that they are economic and guarantee that the driver is well acquainted with each task, that is, each stereotyped action. Another benefit would be the enhancement of predictability of the driving environment for all traffic participants; however, this presupposes that drivers acquire about the same stereotypic actions. Demonstrations of stereotypic behaviour are rare but Summala (1981) showed that steering response latencies were the same independent of the urgency for the response when a door of a parked car was suddenly opened in front of the driver.

#### *Heuristic rules*

Heuristic rules, sometimes referred to as “rules of thumb,” are rules that can simplify decisions when there is lack of information or when the rule for an optimal decision is complex. Safety margins can function as a kind of heuristic rule. For instance, minimum passing distance when overtaking cannot depend on the perceived movements of the overtaken vehicle to any great extent but is probably a function of experience from previous overtaking manoeuvres. The passing distance could be set by a heuristic rule that is independent of the unique features of the present situation, unless these features are unusual (e.g., the leading driver is reckless). Generally, safety margins function as heuristic rules for when to act while stereotypic actions function as the outcome of heuristic decision rules for what to do when the margin of safety is in jeopardy. Even if there is sufficient information for an optimal decision that only needs a simple decision rule, a heuristic action rule might be used because a representation analogous to field-of-safe travel allows for it.

#### *Feedback via perception.*

As mentioned previously, perception, particularly visual perception, plays an essential function in control. The driver receives feedback via perceptual system and what is possible to control is dependent of what is possible to

perceive. The argument can be turned around because the need for control (i.e. the reference values) puts demands on perception, which may give hints about what we can expect from perception. However, it is probably wise to start where there is a body of knowledge, i.e. by considering what is known about perception. In this theoretical framework of control, in which the control of safety margins is central, the interest will focus on visual variables and thresholds on visual variables.

What in the driver's visual field informs the driver about the development of events in such a way that it guides the driver to act appropriately? Which are the visual variables that can inform the driver about a jeopardised safety margin? Studies on visual perception give some answers to these questions. Gibson has contributed with the field-of-safe travel and analyses of the richness of the visual flow field (Gibson and Crooks, 1938; Gibson, 1950). One finding from theoretical analyses of the visual flow field is the invariant time-to-contact (*TTC*) or  $\tau$  ("tau"). *TTC* is specified at any moment by some quantity (e.g., a distance to an obstacle), divided by the rate of change of the quantity per time unit (e.g., the velocity of the approach against the obstacle). Lee (1976) suggested that the driver could use *TTC* for control of several components of the driving task (e.g., braking and car following). Lee demonstrated that controlling the rate of change per time unit of the time distance to a desired stopping point ( $\dot{\tau}$ ) could control the course of braking. However, there is little empirical support for the hypothesis. Nevertheless, *TTC* and derivatives of it seem to convey the kind of information needed by a controller who must foresee events in a dynamic environment. The inherent meaning of *TTC* is in fact a prediction of a collision. Thus, the perceiver is given ready-made information and does not have to infer beyond that. There is therefore hope for the existence of intelligent perceptions of the difference between feedback and reference values. In other words, perhaps the driver is presented with what the comparator produces, something that would imply that the comparator is a part of the perceptual system. The perceiver only has to preserve reference values that set limits for the development of events (e.g., the time limit for how close to an obstacle the car is allowed to come before a braking manoeuvre is needed). These limits are likely a product of experience.

The visual variables suggested do not solve all parameters that appear important in driving (e.g., perceptions of absolute distance and acceleration). As long as the opposite remains to be proven, it seems safe to assume that the driver must have access to information for control in cases where the absolute level of such entities as distance, inertia and kinetic energy is important. Perhaps these tasks can be solved with vicarious control of perceptual invariants supported by experience of how to use situation-specific cues?

#### 4. SUMMARY OF THEORETICAL STATEMENTS

In the preceding discussion about driving the following points have been described:

1. The task is dynamic.
2. The task and drivers' behaviour should be modelled based on control theory.
3. The task is self-paced.
4. The driver performs adaptive control that sometimes causes compensation.
5. The control system is hierarchical.
6. Anticipation is needed.
7. The system has many goals but few means for control and it must be designed to avoid conflicts between goals.
8. Reference values are thresholds, that is, safety margins.
9. Driving is a matter of controlling safety margins.
10. Behaviour is stereotypic.
11. Drivers use heuristic rules to simplify decision-making.
12. Safety margins are contained in perceptions.

This sequence of arguments leads to a model of behaviour that aims at protecting the driver from hazards. Behaviour of this type seems to be adequately classified as automated (Schneider and Shiffrin, 1977), skill-based (Rasmussen, 1987) and tactical (or operational) (Michon, 1985).

## 5. METHODOLOGICAL IMPLICATIONS.

### *The primary enterprise for behavioural studies.*

The theoretical approach of control implies that the primary task for behavioural science is to identify the reference values, that is, the safety margins. The reference values are concealed within the driver and may not be apparent to either the researcher or the driver. As argued here, because the safety margins are contained in what the driver perceives an analysis of the information that reaches the driver's eye could possibly reveal something about safety margins. Further, because the margin in the driver's perceptions is largely a function of what the driver does with the car, at least as long as the driver is in control, the behaviour of the car would also disclose something about safety margins. In fact, the behaviour of the car would divulge more than the driver's motor behaviour inside the car. Focus should be entirely on the perceptual aspect of the feedback control system to avoid artefacts from falling victim to the "behavioural illusion" (Marken, 1988). The behavioural illusion may appear when, to take a very simple example, the driver attempts to drive in a straight path but the direction of the car is disturbed by varying wind and declination of the road surface. Observations of movements of the steering wheel only could lead to the false conclusion that the driver's intention is to perform complicated manoeuvres. However, observations of movements of the car when the driver is in full control would lead to the correct conclusion, i.e. that the driver's intention is to drive in a straight path.

### *The assumption of constant reference values.*

It is implicit in the descriptions of control systems that the reference values are constant. This is because it would facilitate the search for the reference values if they were constant. In a hierarchical system, however, when the reference values are set by output from higher levels, the reference values are not constant. This could happen if, e.g., the driver adapts to a situation where the only way to cope is to increase cognitive attention. Increased attention would allow for smaller safety margins, i.e. the reference values are changed. To keep the reference values constant in a hierarchical adaptive system it is probably necessary to perform studies with control over most parameters that can influence the way the driver adapts to the

particular driving task. In such studies there would be great risk for drawbacks as poor ecological validity of the task. The effects of variations of task demands, which could influence attention, have been studied by Van der Hulst (1999).

*Constant reference values stabilise the driving environment.*

Even if measurable entities in the driving environment (e.g., headway, lateral force when passing the curve ahead and minimum braking force to avoid a collision) do not have matching reference values within the driver, control by constant reference values will probably result in invariant relations among measurable entities. If the reference value is kept constant, the driving environment will also be stable to some extent. For instance, if the driver wants to keep a constant metric headway, the headway, defined by distance to the leader in metres, will be the same independent of speed. If the driver wants to keep time headway constant, the distance will be the same in seconds but vary in metres. The constant property of the driving environment is often much more complex than these examples but somewhere there will be something invariant: the problem is to find these invariants. When that hidden invariant has been discovered, we then have a clue to a reference value and a visual variable.

*The open loop effect of thresholds.*

According to a threshold model, most of the time the driver is not in contact with safety margins. Corrective actions would be caused by safety margins only from time to time. After the corrective action, the system would be in an open loop state until the next contact with a safety margin. This open loop effect makes it almost impossible for an observer to know when the safety margins are having an influence on behaviour. Data from unobtrusive measurements of, e.g., gap acceptance at crossings are displayed as distributions of accepted gaps as a function of gap size. A large gap will be accepted by a driver with a small safety margin (smallest acceptable gap) and by a driver with a large safety margin; it is not possible to infer individual drivers' safety margins from such single observations. Every driver rejects a very small gap and the same difficulty will occur when inferring the individual's safety margin. Given controlled conditions

and the same safety margin in all drivers, the safety margin should be at a specific value in distance or time or some function of these properties. In this case, all presented gaps larger than the safety margin would be accepted. Studies on gap acceptance never show such results; rather, they only present S-shaped probability distributions of accepted gaps as a function of gap size (e.g., McDowell, Darzentas and Wennell, 1981; Bottom and Ashworth, 1978). This is due to inconsistency in the drivers or to aggregation of observations of several drivers with individual safety margins. The safety margin is thus difficult to infer, but several models can describe the relation between size of presented gaps and probability of acceptance of gap, including logistic regression models. The gap size, in which the probability of acceptance is 0.5, can then be interpreted as the mean safety margin.

*Experimental control of contacts with safety margins.*

In the above discussion, it was concluded that unobtrusive observations of traffic behaviour could not be expected to reveal safety margins very often, according to the way safety margins are defined here. The core problem is to know when the driver controls for a safety margin. To solve this problem some kind of manipulation is needed. An ingenious example of a mild manipulation comes from Summala (1985). He observed passing distances as moving cars passed a bicyclist that was standing still at the roadside. Passing distances were observed at roads with different widths, where the narrower the road became, the closer the distribution of passing distances came the bicyclist. Yet, when the road width reached a critical value, the passing distances no longer decreased, even if the bicyclist was placed at narrower roads. This smallest passing distance indicated a safety margin. Naturally, manipulations of this sort are sensitive from an ethical standpoint. In experiments, the possibilities are much larger to present situations on which the experimenter knows with considerable certainty when the participant controls for a safety margin. For instance, an obstacle on a test track can be placed so that the driver has no other alternative but to stop the car. On the other hand, experiments have their drawbacks in terms of poor ecological validity.

## 6. EMPIRICAL STUDIES

Three studies are described in this thesis. The subject matter of the studies varies but the studies are related in the sense that they share the same theoretical framework. The studies should be regarded as examples of how various aspects of the theoretical framework can be applied in research. The empirical work is not an effort to test the theoretical framework though there are tests of specific hypotheses that are deduced from specific theories and data that belong to the theoretical framework.

*STUDY I. Drivers' impressions of front and rear gaps in queues.* Study I comprises two published experiments and an unpublished follow-up study. The annoyance associated with tailgating was investigated in a field study with an arranged queue. The drivers were asked to indicate their safety margins directly by manoeuvring their car into positions that they felt were "adequate," "critical" and "legal." These margins were indicated for leading and following vehicles. Surprisingly, the drivers accepted shorter distances to followers than to leaders. This effect was further studied in an experiment in which the drivers made judgements of distances to leading and following cars when standing still and when travelling at 80 km/h. A perceptual bias consistent with the finding in the first study was noted. The findings indicated that drivers tended to overestimate distances to followers. The effect, however, was too small to explain the whole effect in the first experiment. In a follow-up study, it was hypothesised that the bias was due to varying degrees of control over front and rear distances. The hypothesis was tested by manipulating the degree of control, which could be achieved by letting the participants indicate safety margins when driving the car and when serving as the passenger. The hypothesis was only weakly supported by the data. The results suggest that the observed bias has safety promoting implications.

*STUDY II. Drivers' decisions to merge at a T-junction.* Unobtrusive observations were made of gap acceptance at a T-junction where drivers waited for an opportunity to merge onto a highway. Data from other studies indicated that time gap, i.e. the time distance to an oncoming vehicle, was

rejected if the gap was less than the limit for dissolution of the visual variable *TTC*. Thus, the drivers apparently followed the simple heuristic rule: do not merge if you feel that a vehicle is approaching - otherwise, merge. The predicted effect that drivers would accept shorter gaps under conditions of poor visibility was not supported by the data.

*STUDY III. Drivers' decisions to initiate braking.* It is unclear as to what information in the visual field the driver is willing to use when deciding to start an effective braking manoeuvre. Drivers' decisions to start braking at varying speeds and in front of different "obstacles" were studied in a field experiment. Data were collected so that the rule used by the individual driver could be assessed by linear regression of time distance to the obstacle on speed at the start of the braking manoeuvre. The method has an advantage over others in that several hypothesised rules could be tested concurrently. These hypothesised rules included constant deceleration, Newcomb & Spurr's constant, constant time-to-collision (*TTC*), constant angular velocity and constant metric distance. Most drivers showed a rule similar to Newcomb and Spurr's finding, both in normal braking and in critical braking. The study is an example of a method to determine what parameters the driver keeps constant.

## 6.1 STUDY I

### DRIVERS' IMPRESSIONS OF FRONT AND REAR GAPS IN QUEUES.

As a consequence of the increasing number of vehicles on the roads, rear-end accidents have become a serious problem as indicated by the 40% increase of such accidents in Sweden during the period 1987-1997 (SCB 1998, 1999). Of more than 6 million crashes that occurred on U.S. highways in 1999, Rear-end collisions accounted for almost one-third of these crashes (1.848 million) and 11.8% of multi-vehicle fatal crashes (1,923). Too small headway is the main cause of these rear-end collisions. Median time headway is in the range 1-2 sec as reported by Hoban (1984). In Sweden, 23.7% of time gaps were less than 1 sec in 1996 (The Swedish

National Road Administration, 1997a, b). Apart from the risk involved in small gaps, it is an exceedingly stressful situation to be followed at a dangerously close distance (Glad et al., 1996)). Although it is illegal to tailgate, Swedish law does not guide the driver by specifying a minimum legal gap.

Among several reasons for tailgating, Rajalin and Hassel (1992) reported that being followed too closely could incite the driver being followed to tailgate in turn. Glad et al. (1996) reported that drivers could accept a very small distance to the car ahead in comparison to a very small distance to a follower. Moreover, close followers could cause the driver being pursued to sustain higher speeds than normal. Perhaps the reason for this is that drivers have control over the distance in front of them but not over the distance to the follower. The reported influence on the driver's selection of headway from the distance to the follower seems important enough to motivate an investigation.

Experimental studies of car following (e.g., Colbourn et al., 1978; Fuller, 1980) have shown that preferred headway varies between 1.5 and 2.0 sec. Some data on drivers' impressions of rear distances come from studies on effects of curvature of rear-view mirrors (see Flannagan and Sivak, 1993 for a review). However, to our knowledge, there are no studies on drivers' impressions regarding front and rear gaps in the same queue-driving situation.

Controlling the front and rear distance to other vehicles is probably a matter of controlling safety margins. Dangerously close distances between cars will generate a feeling of risk. During steady state car following, most drivers will hardly ever reach such a dangerously close distance but instead will maintain at a distance that could be termed "adequate." The adequate margin could be set by factors as, for example, too high mental load in being closer rather than by factors that cause a feeling of danger. The minimum legal distance sets another limit, but it is not likely that drivers will react when they pass that margin in normal driving. In the present paper the safety margins per se were not of primary interest. Rather, it was the comparison of margins in the forward and rearward directions that was of central concern, not so much the specific content of margins or their

absolute levels. The method in the following studies takes advantage of the opportunity to make direct measurements of safety margins by letting the driver manoeuvre to positions where they feel contact with the margins.

### *Experiment 1.*

Three questions were addressed in Experiment 1. First, how wide are the drivers' adequate and critical gaps to leading and following vehicles? Second, do the individual differences cause conflicts? Third, what are the drivers' sentiments on smallest legal gaps?

Ten adults aged 26 – 49 years, five of each gender, participated as drivers in a field experiment. Observations were made during speeds of 40 km/h and 80 km/h. Two cars were used. One car was driven by the participant while the experimenter was sitting in the passenger seat. The second car served as a stimulus car that drove either ahead of or behind the participant's car. Distance between the cars was registered on video from inside the participant's car.

When the driver acted as follower, he or she slowly closed the distance to the lead car. As soon as the participants felt that the distance was uncomfortably small, they were asked to respond with the word "adequate." The drivers, however, continued to close the distance until they no longer wanted to come closer. At that time, the drivers said, "stop." The drivers then started to increase the distance and when they felt comfortable with the distance, the drivers again announced "adequate." The procedure was the same when the participants were driving the leading car but now the participants kept a constant speed and watched the follower via the flat interior rear-view mirror as the follower slowly closed the distance. The participants announced "adequate" when they started to feel uncomfortable about the rear gap and announced, "stop" when the follower was too close. The follower then increased the distance and the participants said "adequate" when the rear gap was again at a comfortable distance. In a final stage, data were collected in a similar way on drivers' impressions of minimum legal front and rear gaps. This procedure presupposes that there are driver thresholds that correspond to the limits for adequate, critical and legal gaps.

The results revealed two distinct phenomena. First, in each direction \* task condition, indicated time gap was constant independent of speed (Figure 2). This implies that metric gap is proportional to speed. Second, in all three tasks the drivers indicated shorter rear gaps than front gaps (Figure 3).

The finding of a constant time gap was expected and has been reported in other experimental studies (e.g., Colbourn et. al., 1978). This finding implies that time is the probable denomination of the safety margins used by drivers in a queue of vehicles.

The general tendency of drivers to indicate shorter rear gaps than front gaps was contrary to expectations. Depending on condition, indicated front gaps were between 0.46 – 0.78 sec longer than the rear gaps. Two explanations to account for this tendency are equally plausible. First, there may occur a bias in perception of distances because of different conditions for viewing through the rear-view mirror in comparison with viewing through the windscreen. The drivers cannot spend as much time when they watch rearwards as they can when they look ahead. In addition, the field of view

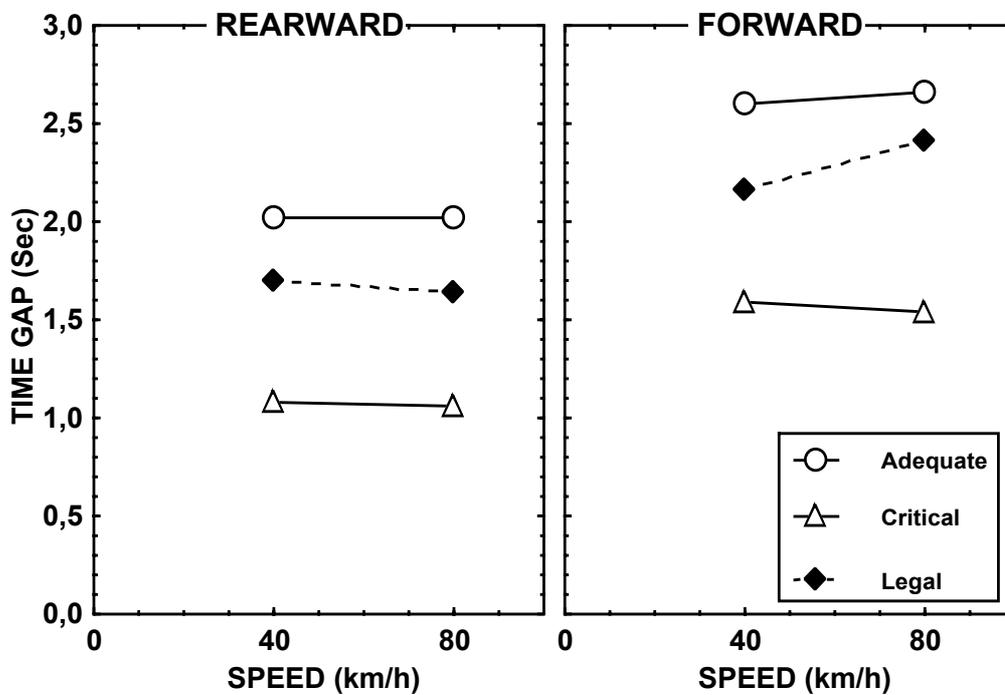


Figure 2. Indicated adequate, critical and legal time gap within the forward and rearward directions at 40 and 80 km/h.

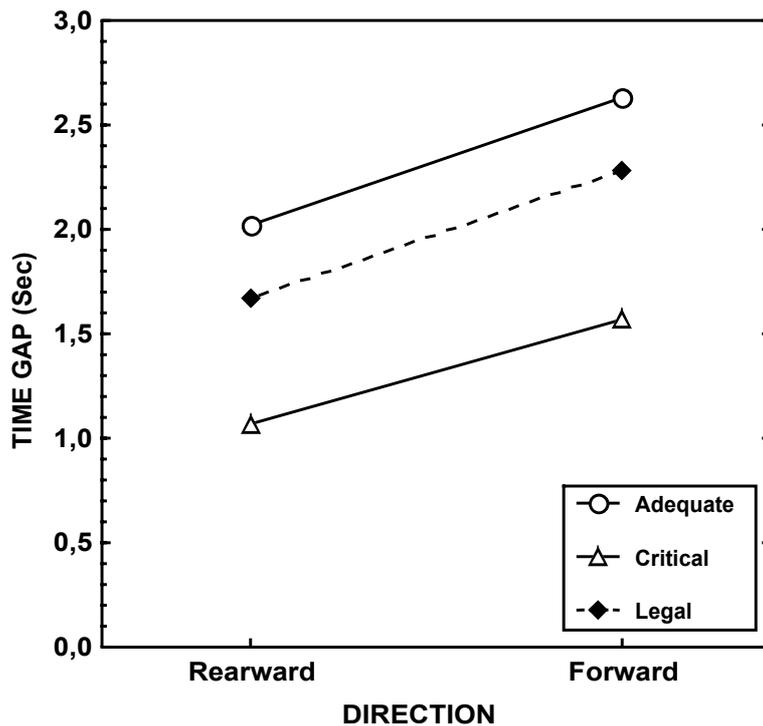


Figure 3. Indicated adequate, critical and legal time gaps in the forward and rearward directions.

is small and the visual field is diminishing when looking backward through the mirror while the field of view is wide and the visual field is expanding when looking forward through the windscreen. Second, there are differential preconditions for control in the two directions as to the consequences of hard braking. Drivers know when they plan to brake but they cannot know when the leading driver is about to brake. Therefore, a rear gap can be allowed to be smaller as compared with a front gap.

#### Experiment 2.

The aim of Experiment 2 was to determine if there was any bias in distance perception in the forward and rearward directions. Five male and five female drivers participated in a field study with an arranged queue length of three cars. The participant drove the car in the middle of the queue. Data were collected under two speed conditions. The vehicles were either standing still or moving at 80 km/h. The driver was given two tasks to perform: judging front and rear gaps in metres and positioning their car in

the middle of the other cars in the queue. The midpoint-adjustment task was used because it does not involve any interpretations of distances in terms of length units or car-lengths but only involves comparison of impressions of front and rear gaps. To our knowledge, this method has not been used before. The judgement task was included to give an opportunity to explain the source of any bias revealed in the midpoint-adjustment task. It was predicted that if the asymmetry in indicated front and rear gaps in Experiment 1 is contingent on a perceptual bias, such a bias would materialise in the drivers' positioning of their car closer to the car at the rear of the queue in the midpoint-adjustment task.

The procedure in Experiment 2 was comparable to the one used in Experiment 1, except that there were no direct measurements of safety margins. A sequence of trials was initiated with large distances between the cars. The participants made judgements of front and rear gaps and then manoeuvred to a position that appeared to be midway in the queue. Next, the car at the rear of the queue moved to a position about halfway to the participant's car. At this time, the participant was asked to make new judgements and again make a midpoint adjustment. The procedure was repeated until the driver (or the experimenter who sat next to the driver) felt uncomfortable about the distances and the car at the rear started to double the distance. As before, the participants made judgements and midpoint adjustments about five times during the distancing phase. The closing and distancing cycle was repeated several times.

The results showed a marked effect of speed. When the queue stood still, the drivers managed to position their car in the middle and judgements were made equally correctly in both directions. The data indicated the typical effect of distance on judgements, with participants reporting increasing underestimation at larger distances. When driving at 80 km/h, however, the participants usually placed their car closer to the car at the rear, if they felt they were in the middle.

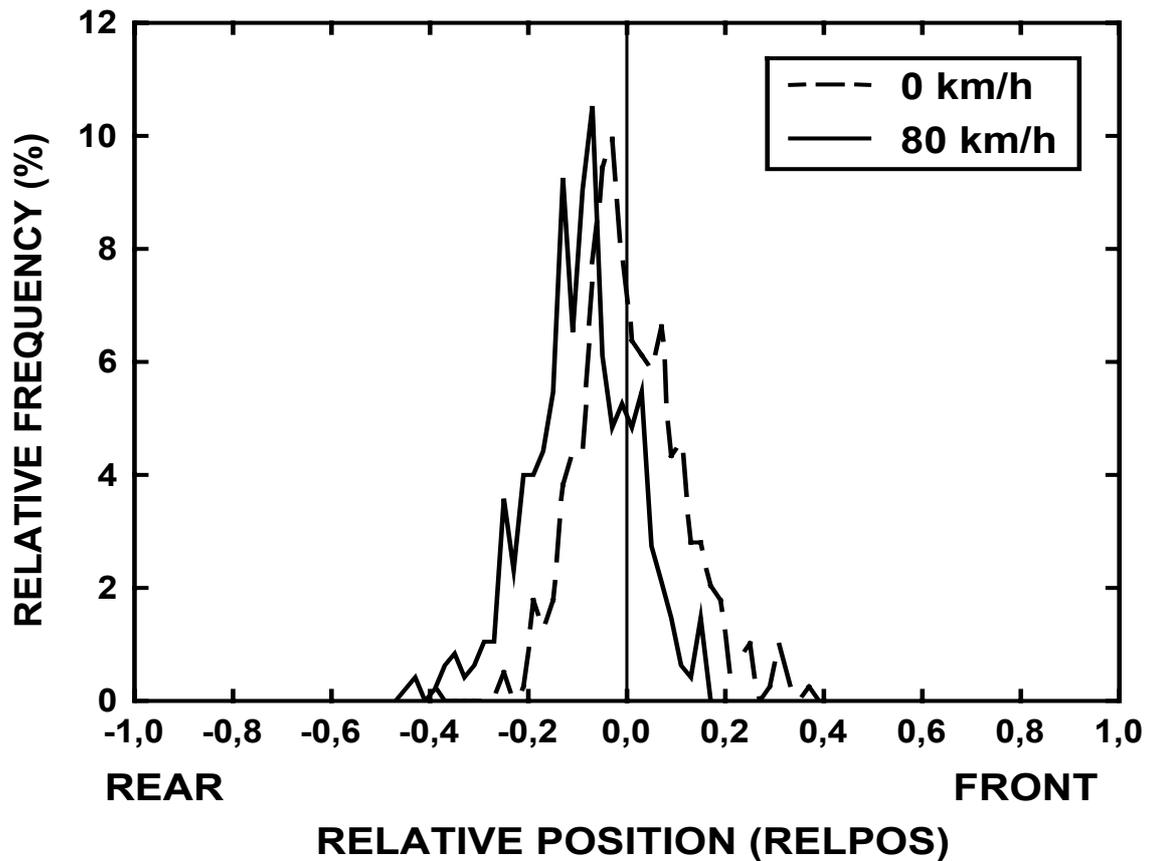


Figure 4. Distribution of relative positions when standing still and when driving at 80 km/h. Positions of the leading and the following cars are indicated by +1 and -1, respectively.

Figure 4 displays the results from the midpoint-adjustment task. Data from midpoint adjustments were aggregated by transformation to a measure of relative position (RELPOS).

$$\text{RELPOS} = (\text{rear distance} - \text{front distance}) / (\text{front distance} + \text{rear distance})$$

(Note that distance refers to the distance between the camera and the car, whereas gap refers to the distance between the bumpers of two cars.)

As can be seen in Figure 4, the distribution of midpoint adjustments was closer to the car at the rear when travelling at 80 km/h. The mean of RELPOS was -0.075, indicating that, on average, the participant's car was 7.5% closer to the car at the rear than the halfway distance between the car

at the rear and the car in front. (The halfway distance is at RELPOS = 0. The deviation from 0 was significant,  $t(9) = -6.66, p < 0.001$ .)

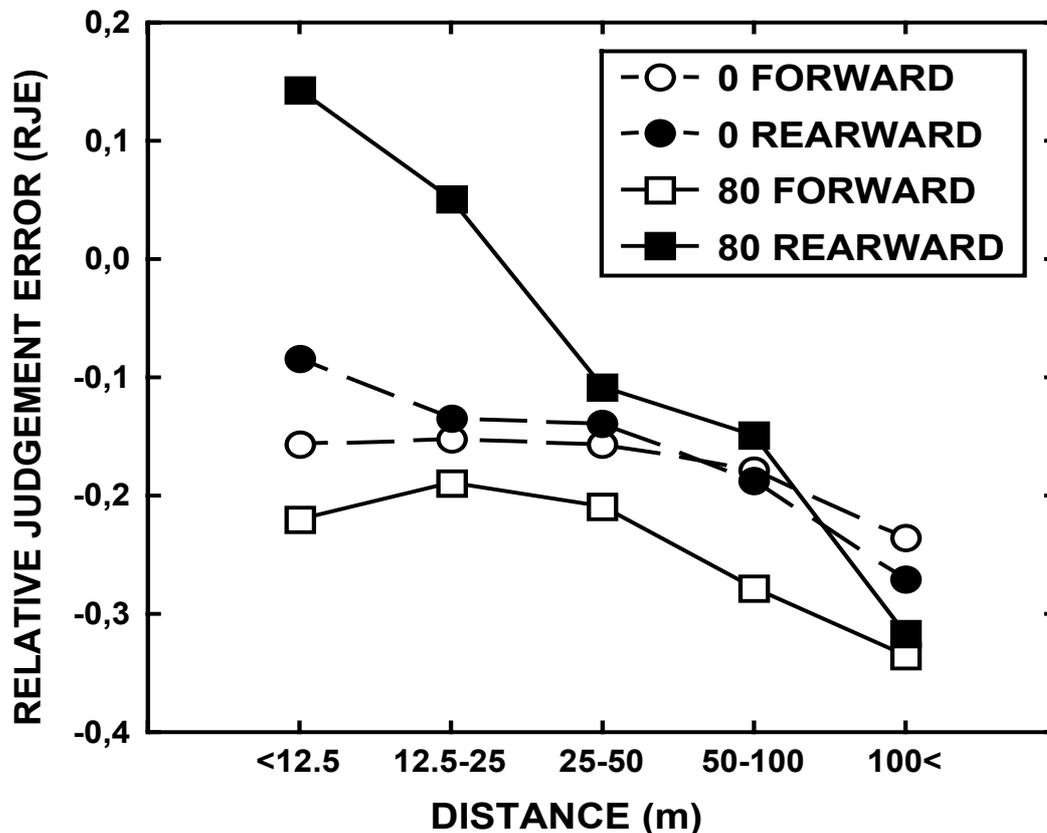


Figure 5. Relative judgement error (RJE) in the forward and rearward directions at speeds of 0 and 80 km/h as a function distance.

A reasonable explanation for this phenomenon is that when travelling at a constant velocity of 80 km/h, rear distances below 25 metres are much less underestimated than distances in all the other conditions (Figure 5). In Figures 5 and 6, data on relative judgement error are portrayed. Relative judgement error (RJE) is a measure of the degree of over or underestimation of gaps.

$$RJE = (\text{judgement of gap} + 2.4 - \text{distance}) / (\text{distance})$$

In the above equation, 2.4 metres were added to judgement of gap in order to obtain an estimate of judgement of distance. This procedure gives a

conservative value of RJE in cases of underestimation of gap. Our experience tells us that drivers are usually underestimating gaps.

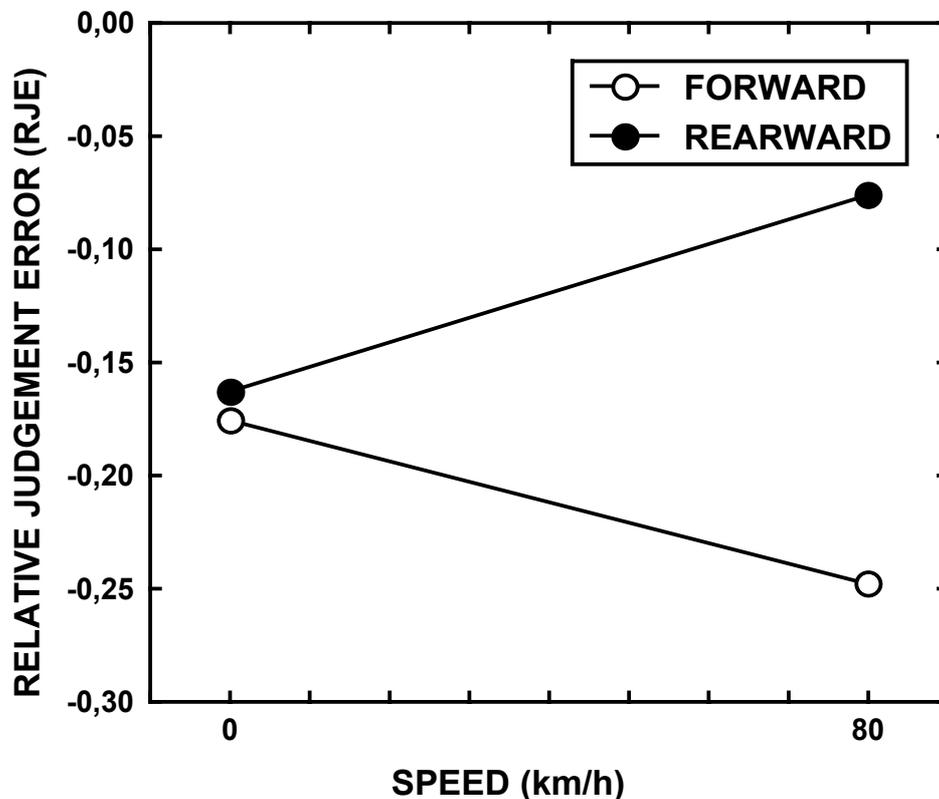


Figure 6. Relative judgement error (RJE) in the forward and rearward directions as a function of speed (0 vs. 80 km/h).

Figure 6 illustrates that gaps are underestimated to the same extent when standing still. However, at 80 km/h, the gaps are underestimated to a lesser extent in the rearward direction than in the forward direction.

The asymmetry between indicated gaps in Experiment 1 could partly be explained by the perceptual bias that was noted in Experiment 2. However, the perceptual bias cannot account for the entire difference found in Experiment 1. RELPOS should have been in the range  $-0.12$  to  $-0.20$  (these values are estimated from the data in the 3 [tasks] \* 2 [speed conditions] of Experiment 1), well below the value of  $-0.075$  that was obtained in Experiment 2. Thus, it is obvious that some factor additional to perceptual bias caused the effects found in Experiment 1. It is suggested

that this factor might have been the differential opportunities to have control over hard braking.

The drivers' selection of comparatively longer front gaps, in combination with their tolerance of shorter rear gaps, which should be rare if the follower also prefers longer front gaps, implies a lower frequency of conflicts with close followers than had the preferences been the same in both directions. This asymmetry promotes safety in that without it gaps would probably be smaller than they already are.

#### TEST OF THE INFLUENCE OF DEGREE OF CONTROL.

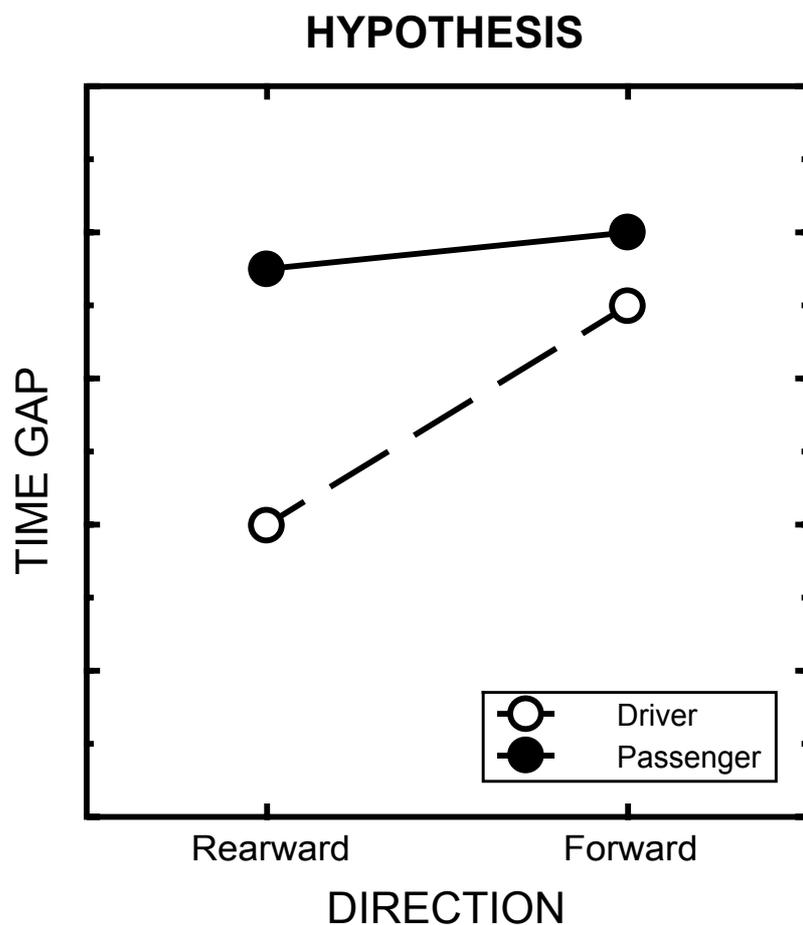
(This next experiment was done after the publication of Paper I and is published in Swedish (Nilsson, 1999)).

##### *Experiment 3.*

Experiment 1 established that there is a bias in the driver that forces the driver to accept shorter rear gaps. In experiment 2, evidence was found that some of the bias could be explained by a perceptual bias in the driver though the perceptual bias could not account for the total effect observed in Experiment 1. The remaining part of the bias obtained in Experiment 1 could be caused by the difference in control of the consequences of hard braking. Experiment 3 was designed to test this hypothesis.

The degree of control was manipulated by letting the participant act as both driver and passenger. It was assumed that when driving, the person has a feeling of being in control; that feeling, however, is weaker when sitting as a passenger. When the participants are passengers, they have no control of either the front or rear gaps. Consequently, the participants will prefer wider gaps in both directions when they are the passengers than when they are the drivers. Because a passenger does not have much less information than a driver on the leading driver's sudden braking manoeuvres, the difference between preferred front gaps when a driver and when a passenger should be minimal. However, the difference between preferred gaps when driving as compared with when sitting as a passenger should be much larger in the rearward direction because, as a passenger, one does not

know much more about when sudden braking will occur in one's own car than in the leading car. The predicted effects are summarised in Figure 7. As can be seen, an interaction between role (driver and passenger) and direction (forward and rearward) is also predicted.



*Figure 7. The hypothesised expected structure of indicated unpleasant time gaps when driving and when sitting as a passenger.*

*Method.*

Six men and six women participated in a field study. Speed was 80 km/h. Two cars were used. The participant was driving or sitting as a passenger in the experimental car while the second car was used as a stimulus vehicle that alternated between leading or following the participant's car. When the participant was acting as passenger, the experimental car was driven by the experimenter, that is, the present author. When looking in the rear, the

participant used the flat interior rear-view mirror, both when acting as driver and as passenger. Inter-vehicle distances were registered on video.

The method for presenting gaps was the same as in the earlier experiments. Briefly, the participants were instructed to indicate when they felt that the gap was unpleasant, which was about the same type of task as to indicate critical gaps in Experiment 1. Forty observations of unpleasant gaps were made for each participant, 20 in the role as driver and 20 in the role as passenger. Within each role, there were 10 observations of unpleasant front gaps and 10 observations of unpleasant rear gaps.

### *Results.*

The effects on time gaps, as estimated from the video recordings, were analysed in a two-way repeated-measures analysis of variance (ANOVA). A significant main effect was found for direction,  $F(1,11) = 8.13, p < 0.05$ . This result was expected in that this effect replicates the bias found in the earlier study. There was no effect of role and no interaction between role and direction. Thus, the hypothesis that there are different preconditions for control in the two directions did not receive support. In Figure 8, the mean time gaps are exhibited for the experimental conditions. The levels of mean gaps are lower in this experiment than in the critical condition in Experiment 1.

Contrary to the hypothesis, the participants accepted shorter front gaps when they were passengers than when they were drivers. A tendency for an interaction between roles and direction in the predicted direction is apparent but not significant. However, our data allowed for individual analysis. This analysis indicated that the four most experienced participants showed patterns of results that were in accordance with the hypothesis.

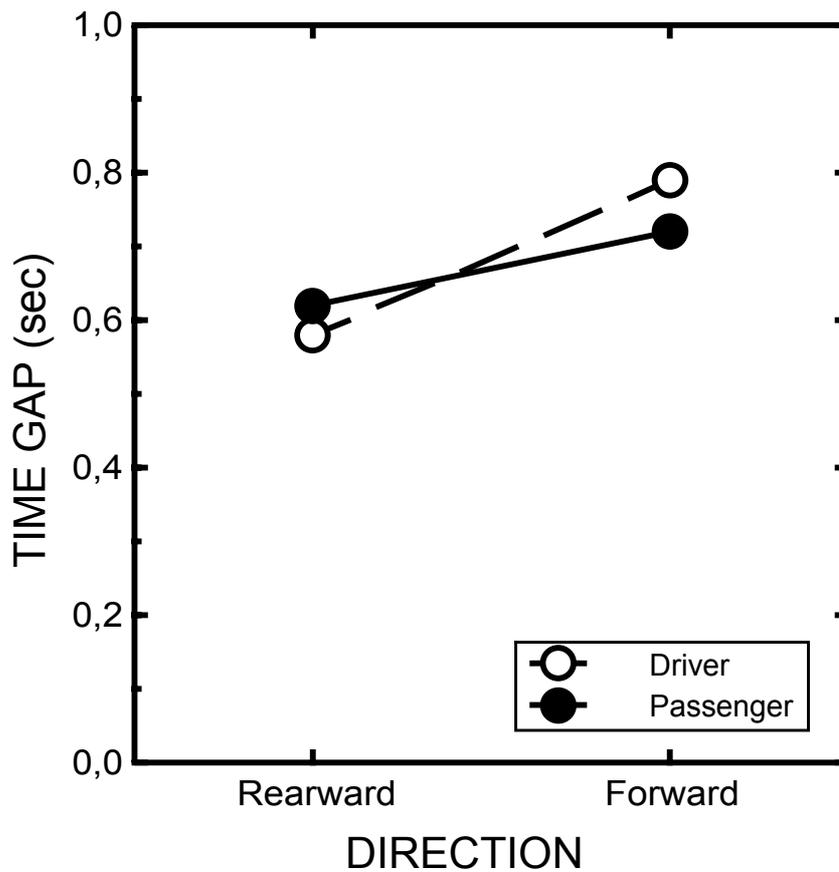


Figure 8. Indicated unpleasant time gaps when driving and when sitting as a passenger.

*Conclusions.*

Either the hypothesis that the bias found would depend on different preconditions for control in the respective directions is false or there was something wrong with the experimental manipulation of control. The experimenter was driving the experimental car when the participant indicated unpleasant gaps as a passenger. It was obvious that the participants had very good faith in the experimenter when the latter was driving. It seems as if the less experienced drivers had more faith in the experimenter than they did in themselves, whereas the experienced drivers were confident with their driving. If the participants had been forced to be passengers when someone less trustful than the experimenter drove, perhaps a larger number of the participants would have responded as did the experienced drivers, i.e. according to the hypothesis. This is, however,

speculation since the experiment was not designed to test the effect of experience.

## 6.2 STUDY II

### DRIVERS' DECISIONS TO MERGE AT A T-JUNCTION.

In order to cross or merge into a traffic stream the driver must decide if the distances to oncoming vehicles on the crossing road are large enough to allow for a safe entry. Merging is particularly demanding because, apart from perceiving distances to oncoming vehicles, the driver must consider the time and distance needed to accelerate up to the speed of the oncoming vehicles after merging in front of them. This situation, to accept or reject distances to oncoming vehicles before merging, should be appropriate to model as a task suited for control by safety margins.

Most research on merging concerns traffic engineering studies. The need for understanding individual behaviour when building models of the traffic process motivated these studies (see McDowell et al., 1981; Darzentas, 1983 for reviews). Several studies have reported a negative correlation between approach speed and minimum accepted time distance (Bottom and Ashworth, 1973, 1978; Cooper et al., 1976, 1977; Darzentas et al., 1980a). The following model was fit to these observations:

$$T = C1/V + C2 \quad (1)$$

Where  $T$  is minimum accepted time distance,  $V$  is approach speed and  $C1$  and  $C2$  are constants.

In a theoretical analysis Lee (1976) showed how the limit for dissolution of the visual variable  $TTC_{(th)}$  depends on speed ( $V$ ) and width ( $W$ ) of the oncoming vehicle and the dissolution of rate of expansion of the projection of the vehicle on the retina ( $\dot{\alpha}_{(th)}$ ) (radians per second). This model can be

expressed as:

$$TTC_{(th)} = \sqrt{W / (V \times \dot{\alpha}_{(th)})} \quad (2)$$

Models (1) and (2) describe about the same relation between speed and minimum time distance. It also happens that observed T and estimated  $TTC_{(th)}$  are about equal under conditions of good visibility. Thus, the observed behaviour of drivers as described in model (1) seems to follow the limit for dissolution of TTC as described in model (2). This suggests that the driver applies the following rule when accepting or rejecting a time gap to an oncoming vehicle: if time distance ( $TTC$ ) is perceived, do not merge (reject the gap); merge (accept the gap) only if there is no perception of time distance. This would qualify as a heuristic rule in that it is not optimal but it simplifies the driver's decisions in traffic and is sufficient in most cases.

If the drivers apply the suggested rule, it follows that they will accept smaller gaps under conditions of poor visibility because, as Lee established, visibility has a strong influence on  $TTC_{(th)}$ . Only one study (Darzentas et al., 1980b) has manipulated visibility by observing vehicles merge into traffic, both at night and during the daytime. Their results were difficult to interpret and visibility at night is not equivalent to poor visibility caused by poor weather conditions in daytime.

We tested our hypothesis by observing drivers, as they were about to merge at a T-junction between a small, rural road and a highway on two occasions. On the first occasion, visibility was good; on the second occasion, visibility was extremely poor (haze and rain). On the day with good visibility, data from 239 merging cars were collected; on the day with poor visibility, data from 116 merging cars were collected. Accepted and rejected time gaps were categorised into time intervals of one second. Probabilities for acceptance (P(A)) were calculated for each gap category for both visibility conditions. These data are given in Figure 9.

Data analyses showed no significant effects of visibility conditions. Figure 9 also indicates that there were no salient differences between conditions. Thus, it appears as though  $TTC_{(th)}$  is not used in decisions on accepting or

rejecting a time gap to oncoming vehicles. Moreover, given that the manipulation of  $TTC_{(th)}$  succeeded,  $TTC$  is not used for merging decisions in poor visibility because, according to Lee's calculations,  $TTC$  cannot be perceived at distances where  $P(A) = 0.5$ , i.e. around 6 sec. However, the manipulation of  $TTC_{(th)}$  is questionable. The mandatory use of headlights during the daytime in Sweden might have counteracted the effect of poor visibility by enhancing the definition of oncoming cars on the hazy and rainy day. A lower average speed (speed was not measured in this study) on the day with poor visibility might also have counteracted the expected effect. Nonetheless, the effect of speed on  $TTC_{(th)}$  is rather small and hence could not have significantly affected the outcome of the study.

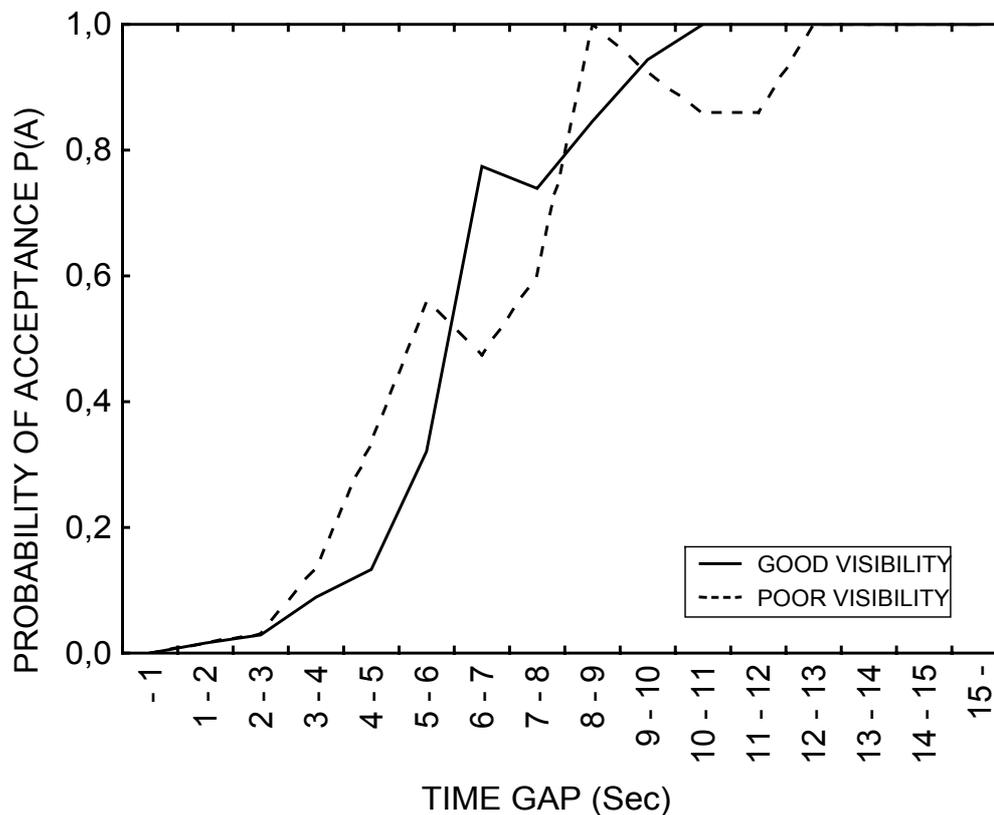


Figure 9. Probability of acceptance ( $P(A)$ ) as a function of time gap to oncoming vehicles.

## 6.3 STUDY III

### DRIVERS' DECISIONS TO INITIATE BRAKING.

Safe driving requires the ability to brake adeptly. Braking involves two stages: first, the driver has to make the decision when to brake and, second, once the brakes are activated the driver must control the course of braking. During the course of braking, the driver can use information about the change in various inputs (e.g., the rate of change of *TTC*). However, before the start of the braking process, i.e. while the driver is still deciding when to begin braking, these sources of information are not yet available. Thus, it seems as if different processes govern the decision to start braking and the control process in ongoing braking.

Lee (1976) showed that some of the braking traces reported by Spurr (1969) are obtained if the driver keeps the time derivative of the visual variable *TTC* (or as it is denoted  $\dot{\tau}$  ["tau-dot"]) constant during the course of braking. Van der Horst (1991) demonstrated with the occlusion technique the necessity of  $\tau$ -information for control of the course of braking as suggested by Lee. The "tau-dot" theory was criticised by Kaiser and Phatak (1993), who showed that most data on braking did not fit a constant  $\dot{\tau}$ -trace. They also discussed a misunderstanding among scientists at that time showing that a braking process, in which  $\dot{\tau} < -0.5$  but  $\dot{\tau} > -1.0$ , does not necessarily lead to collision with the obstacle. A simulator study (Yilmaz and Warren, 1995) supported the theory that  $\tau$ -information is used for control of braking in that the addition of spatial cues did not enhance braking performance. However, the braking trace was seldom characterised by a constant  $\dot{\tau}$  in Yilmaz and Warren (1995) study. Thus, although there are some descriptions of the braking process, it still is unclear how the driver controls braking.

It is still not fully understood how drivers make their decisions about when to initiate braking. As Lee (1976) suggested,  $\tau$ -information might be used even in this case. A simple rule would be to start braking at the same time distance to stopping-points independent of speed. However, as Lee (1976) pointed out, a constant time rule is not optimal because braking force would have to be stronger the faster the car travels. Newcomb and Spurr

(1982) reported that drivers start braking so that a constant ( $K$ ) is returned if the velocity ( $V$ ) at the start of braking is divided by the distance to the obstacle ( $S$ ) raised to  $2/3$ .

$$K = V / S^{2/3} \quad (3)$$

This model (3) can be described as a compromise between a constant deceleration rule and a constant  $\tau$ -rule. It is not clear how a visual variable would be used for control according to the rule expressed by Newcomb and Spurr. Malaterre et al. (1986) found that drivers used two types of rule when making simulated avoidance manoeuvres. The driver indicated either a constant deceleration rule or a constant  $\tau$ -rule.

Control of the course of braking is a task suited for control of a target value (e.g., a level of  $\dot{v}$  rather than control by safety margins). A braking process that is controlled by keeping a level of a quantity constant would probably produce a smoother behaviour than a process controlled by avoiding a threshold, i.e. a safety margin. However, a process that is controlled so that the driver brakes in a gradual manner such that  $\dot{v}$  never falls below  $-0.5$  would guarantee a safe stop provided there is constant friction with the road surface. The decision to initiate braking seems suitable to model as control of a safety margin. To start braking early is clearly not optimal. On the other hand, it could be dangerous to start braking too late. Thus, somewhere ahead of the obstacle a limit should not be passed. Objective safety is simple to define in braking. Braking should never start later than what the friction between tyres and road surface allows and deceleration should be constant during a manoeuvre. Moreover, deceleration should not be larger the higher the speed.

This study aimed at answering the following questions regarding drivers' initiation of braking:

1. What does the driver control? That is, what is the denomination of the safety margin?
2. How large is the safety margin?
3. Do safety margins imply safe driving?

4. How can the perceptual system deliver information about the safety margin?

*Models of braking decisions.*

Five models of braking decisions were tested:

Constant deceleration ( $K_{(Dec.)}$ ). To apply this rule means to start braking at such distances that the deceleration (braking force) during the braking manoeuvre can be the same at all speeds. This rule is optimal with respect to objective safety. According to this rule, no visual variable is known that can inform the driver about the proper moment to start braking.

Newcomb & Spurr's constant ( $K_{(N\&S.)}$ ). This rule was reported by Newcomb and Spurr (1982). Although this model would give reasonable safety, no apparent visual variable can inform the driver about the proper time to begin braking.

Constant TTC ( $K_{(TTC)}$ ). This rule was suggested by Lee (1976) and received some support by Malaterre et al. (1986). The visual variable  $\tau$  can inform the driver when to brake according to this rule. However, braking force would have to be stronger the faster the car travels, which can be critical at high speeds.

Constant angular velocity ( $K_{(Rd/s)}$ ). Angular velocity refers to the rate of expansion of the projection of an object on the retina as the distance to the object decreases (denomination: radians per second, Rd/s). However, there are problems with the application of this rule because angular velocity depends on both object size and approach speed. Concerning safety, the rule is far from optimal for braking force must increase dramatically with increasing speed.

Constant distance ( $K_{(Dist.)}$ ). This rule was included mostly for demonstrating what happens at the extreme of this family of hypothesised rules. This rule suggests that the driver would start braking at the same metric distance to the obstacle independent of speed and the braking force would have to increase by the square of speed.

## MODELS FOR BRAKING DECISIONS

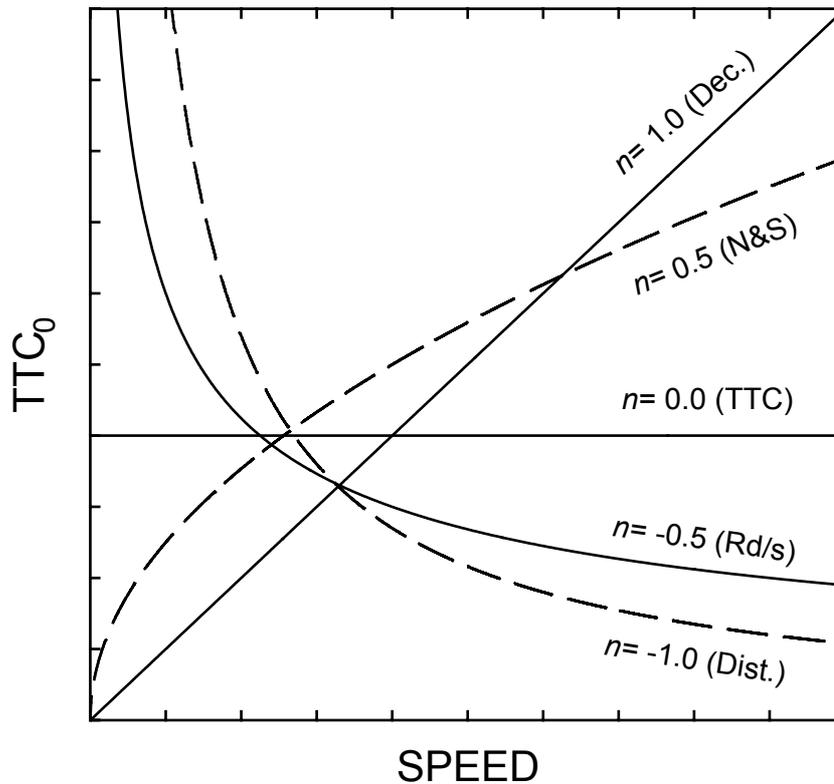


Figure 10. Characteristic shapes of the relations between speed and TTC at the moment of initialisation of braking ( $TTC_0$ ) for the suggested decision rules.

In Figure 10, the suggested rules are sketched by the time distance to the obstacle at the start of braking ( $TTC_0$ ) as a function of speed.

The aforementioned rules can all be described by a power function:

$$K = TTC_0 / V_0^n \quad (4)$$

where:

- $K$  = constant (threshold or safety margin)
- $TTC_0$  = time distance to obstacle when braking starts
- $V_0$  = speed when braking starts
- $n$  = constant exponent

The equality (4) implies:

$$TTC_0 = K * V_0^n \quad (5)$$

The driver's rule was assessed by linear regression of  $TTC_0$  on  $V_0$  after taking the logarithm of equation (5):

$$\log TTC_0 = \log K + n * \log V_0 \quad (6)$$

The value of the parameter  $n$  determines the denomination of  $K$ , i.e. the denomination of the variable on which the safety margin  $K$  has its value. Thus, the value of  $K$  denotes the actual safety margin. This method gave answers to questions 1 (What does the driver control? That is, what is the denomination of the safety margin?) and 2 (How large is the safety margin?) in the same operation. Table 1 shows the connections between suggested rules and values of the exponent  $n$ .

*Table 1. Possible decision rules for initialisation of braking.*

| Exponent ( $n$ ) | Rule                    | Denomination of $K$ | Index                    |
|------------------|-------------------------|---------------------|--------------------------|
| 1.0              | $K = TTC_0 / V_0$       | Deceleration        | $K(Dec.)$                |
| 0.5              | $K = TTC_0 / V_0^{0.5}$ | "Newcomb& Spurr"    | $K(N\&S)$ <sup>(1)</sup> |
| 0.0              | $K = TTC_0$             | Time-to-collision   | $K(TTC)$                 |
| -0.5             | $K = TTC_0 * V_0^{0.5}$ | Angular velocity    | $K(Rd/s)$                |
| -1.0             | $K = TTC_0 * V_0$       | Distance            | $K(Dist.)$               |

<sup>1</sup> Transformation of equation (3) to (4): Substitute  $S$  in (3) for  $TTC_0 * V_0$ . Simplify and raise to  $-1.5 \Rightarrow K^{-1.5} = TTC_0 / V_0^{0.5}$ . Because  $K^{-1.5}$  is a constant, the equation has the form (4).

To assess drivers' decision rules data on decisions to initiate braking were collected. In a field study, 13 participants drove at varying speeds(30, 50,

70 and 90 km/h) under two conditions: normal braking and critical braking. Normal braking involved a planned stop while critical braking was the smallest distance to the obstacle that the driver believed would allow a safe stop. Because of potential training effects, the drivers made simulated decisions and indicated when they wanted to brake by saying, “stop.” Time distance ( $TTC_0$ ) was measured with a stopwatch from the time the driver said, “stop” until the car at constant speed passed the “obstacle.” Various road signs along the road constituted the “obstacles.” In all, 48 recordings of time distance were made for each driver in each condition (normal and critical braking).

*Table 2. Values of  $K$  and  $n$  arrived at through linear regression.*

| Participant | Normal braking |       |       | Critical braking |       |       |
|-------------|----------------|-------|-------|------------------|-------|-------|
|             | $K$            | $n$   | Rule  | $K$              | $n$   | Rule  |
| 1           | 1.34           | 0.48  | N&S   | 1.20             | 0.27  | (N&S) |
| 2           | 2.77           | 0.10  | TTC   | 1.41             | 0.02  | TTC   |
| 3           | 2.48           | 0.13  | (TTC) | 1.87             | -0.10 | TTC   |
| 4           | 1.20           | 0.47  | N&S   | 0.59             | 0.42  | N&S   |
| 5           | 1.31           | 0.59  | (N&S) | 0.45             | 0.83  | (Dec) |
| 6           | 0.52           | 0.85  | (Dec) | 0.27             | 0.87  | (Dec) |
| 7           | 2.17           | 0.43  | N&S   | 0.55             | 0.52  | N&S   |
| 8           | 1.20           | 0.64  | (N&S) | 0.58             | 0.62  | (N&S) |
| 9           | 1.99           | 0.64  | (N&S) | 0.58             | 0.67  | N&S   |
| 10          | 1.54           | 0.32  | (N&S) | 1.67             | -0.03 | TTC   |
| 11          | 2.49           | 0.41  | N&S   | 0.90             | 0.48  | N&S   |
| 12          | 0.63           | 0.68  | (N&S) | 0.36             | 0.60  | N&S   |
| 13          | 1.21           | 0.48  | N&S   | 1.58             | 0.15  | (TTC) |
| Mean        |                | 0.479 |       |                  | 0.408 |       |

Table 2 presents the values of  $K$  and  $n$ . In the column headed “Rule” the classification of the nearest rule model is given. If the nearest model deviated significantly, the model is listed in brackets. Only constant deceleration ( $K_{(Dec.)}$ ), Newcomb & Spurr’s constant ( $K_{(N\&S.)}$ ) and constant TTC ( $K_{(TTC)}$ ) were observed. In normal braking 10 of 13 rules were classified as  $K_{(N\&S.)}$ ; in critical braking 7 rules were classified as  $K_{(N\&S.)}$  and there were more cases of  $K_{(TTC)}$ . The correlation between the obtained values of  $n$  in the normal and critical conditions was  $r = 0.87$ , indicating that the drivers used comparable decision rules in the two braking conditions.

If it is assumed that the braking capacity of the experimental vehicle was 0.8 g (the road surface was dry), the minimum time distance ( $TTC_0$ ) for a safe stop at 90 km/h is 1.59 sec. In the normal condition no driver was even close to that limit but in the critical condition three drivers (drivers 2, 3 and 10 in Table 2) approached that limit. These drivers used the rule constant TTC ( $K_{(TTC)}$ ). Thus, drivers employ considerable physical safety margins when they are planning braking manoeuvres. The results also suggest that drivers are generally not cognisant of the critical limits for initiating braking. When asked about at what speed they started braking at the largest time distance, they were usually uncertain even whether they used very different time distances at varying speeds, that is, a much longer time distance at 90 km/h than at 30 km/h.

The most frequent rule, initiation of braking according to Newcomb and Spurr’s rule ( $K_{(N\&S.)}$ ), is close to optimal though it is unclear how the driver is informed about when it is time to stop. There might exist a visual variable that has still to be discovered. Thus, one line of research would be to specify that variable. The driver may have acquired a judgement capacity where judgements are based on various cues in the driving environment. The large individual differences we observed may indicate this possibility.

It can be shown that there is a relation between  $\dot{v}$ -based control of the course of braking and the decision rules described here in the sense that  $K$  can be kept constant during braking which is controlled by keeping  $\dot{v}$  constant.

$\dot{\tau}$  as a function of  $n$ :

$$\dot{\tau} = -(n/(1+n)) \quad (\text{Undefined for } n=-1.0) \quad (7)$$

Although it would seem convenient for the controller not to have to give up control of one safety margin as the task changes, it is not necessary to maintain control of  $K$  during the course of braking. A study in which braking decisions and the course of braking are examined could determine if the drivers maintain control of  $K$  even during braking. Newcomb (1981), for instance, observed that drivers had difficulties controlling the course of braking if they were forced to start braking at some other distance than the distance they themselves preferred. This observation indicates that there is some connection between initiation of braking and the course of braking.

## 7. GENERAL DISCUSSION

From the present investigations, is it possible to conclude unquestionably that the driver's task is mainly a matter of controlling safety margins? The answer is of course no. The theory on safety margins was not directly put to test. Rather, we inferred that safety margins exist and the empirical studies aimed at shedding some light on these margins. However, some observations support the idea of control of safety margins.

The drivers had no apparent difficulties indicating limits in the experimental studies (Studies I and III), indicating that thresholds are somehow represented in the cognitive system of drivers. This was especially the case in the study on braking decisions (Study III), where the drivers expressed a high degree of certainty regarding the correct moment of starting a braking manoeuvre. Perhaps such distinct feelings of the appropriate time to begin the act of braking (i.e. thinking to brake and actually applying the brakes) can appear even if some other principle governs the decision, but such feelings must exist in case the decision is based on a safety margin. If the drivers had been unsure and inconsistent in their decisions, this would have been a strong argument against thresholds.

In the experiments on queue driving (Study I), the drivers seemed less confident in their impressions of various limits (Experiments 1 and 3). This could partly depend on the instructions, which the drivers seemed to interpret differently. These problems did not impair the findings of the studies on queue driving significantly and the effect of direction was consistently replicated.

We believe that the methodological principle to search for something constant was successfully applied in the braking study. However, it must be emphasised that the method for analysing data guarantees that some value of the constant  $K$  will be found.  $K$  is a constant that will be created by the regression method, whatever the true nature of braking decisions. Thus, the results from the braking study should be interpreted only as suggestions on safety margins, given the assumption that safety margins were in operation. One way of judging the plausibility to interpret  $K$  as a safety margin would be to connect  $K$  to some information that can be detected by the perceptual system. Study III was designed to examine this issue by classifying the constant ( $K$ ) values. This endeavour, however, was not completely successful and in some cases it is not known how perception can deliver the information needed to apply hypothesised rules such as Newcomb & Spurr's rule. This could also be taken as an enterprise for perceptual investigations to reveal where the information is.

Individual differences were rather large in all our studies, a problem that is difficult to handle with the concepts outlined in this thesis. Individual differences are expected only with respect to the level of a threshold. However, if the individuals' thresholds have different denomination, it is difficult to explain why people adopt different rules. It has been an implicit (and optimistic) assumption that the processes involved when controlling safety margins are inborn and similar in all individuals. This assumption is not critical for the theory of control of safety margins because a task can be solved by control of any of several possible margins as shown in Study III. However, the theory has no elements that can predict an individual's decision rule. The methods used in Studies I and III allowed for individual analysis, a prerequisite for revealing rules with high precision, but the individual differences remains to be explained. In Study II, on merging decisions, the method assumed that individual drivers apply the same

heuristic rule: otherwise, no effect could be expected unless at least a majority used the same rule. There is probably not much hope for finding facts regarding specific safety margins with methods where data are aggregated over drivers as in Study II.

The present work could be seen as a response to Ranney's (1993) complaint about the poor outcome of motivational models (i.e. Näätänen & Summala's, 1974 zero-risk theory, Wilde's (1982) theory of risk homeostasis and Fuller's (1984) risk-avoidance model). Ranney called for a more elaborate theory that could generate testable hypotheses at the individual level. However, a theory that automatically implies precisely what and how empirical work should be done is probably unrealistic, especially in an applied area such as traffic research. In this thesis, an effort was made to derive some ideas from existing models and theories of how to search for knowledge about driving: in that process the author found possibilities to study three important driving situations (i. e., queue driving, merging and braking). Perhaps the ideas to perform these studies could have been arrived at via other channels of thinking. Nonetheless, the studies are intended to demonstrate that knowledge can be produced using the motivational models as a theoretical base. However, it seems that, in addition to building fruitful theories, clever methods must also be designed. And there is also that complicated reality...

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