Adaptive behaviour in traffic: An individual road user perspective

Sara Nygårdhs

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ABSTRACT

Road-user adaptation is a prerequisite for traffic to run smoothly. By adaptation, the road user aims to ensure a feeling of comfort according to his or her present state and capability. In this thesis, adaptive behaviour of car drivers and cyclists in response to different factors is explored, using the individual perspective of the road user. The research focuses on investigating how adaptation in the road traffic environment can be described, and what adaptations road users make in traffic in response to static and dynamic infrastructure, additional tasks and other road users.

One simulator study and three field studies in real traffic were carried out. The study results implied that the current road-user role and the preconditions for that role, in terms of vehicle and infrastructure, affect adaptive behaviour. The results also showed that in non-complex situations, there is a certain level of visual guidance above which more detailed information does not have any effect on speed adaptation. Detailed information that allows road users to improve their predictions to take action to ensure a feeling of comfort, is however preferred. Under increased situational demands, vehicle speed can be reduced to maintain the safety margins. It was found that there are individual strategies concerning what degree of complexity for interaction with an additional task is acceptable.

A conceptual model of adaptation in relation to the environment and subjective perceptions of safety and a feeling of comfort is proposed and applied to different traffic situations. For future transport system designs it is advised that adaptive behaviours of road users are supported.

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LIST OF ABBREVIATIONS

ADAS – Advanced Driver Assistance Systems

ANOVA – Analysis of Variance

CDT – Countdown Timer

COCOM – Contextual Control Model

DiC – Driver in Control

ECOM – Extended Control Model

ETTO – Efficiency-Thoroughness Trade-Off

FOT – Field Operational Test

JCS – Joint Cognitive System

MiRA – Minimum Required Attention

NASA-TLX – National Aeronautics and Space Administration – Task Load Index

NASA-RTLX – National Aeronautics and Space Administration – Raw Task Load Index

OECD – the Organisation for Economic Co-operation and Development

RSME – Rating Scale Mental Effort

SMS – Short Message Service

SWAT – Subjective Workload Assessment Technique

TPB – Theory of Planned Behaviour

TOTE – Test-Operate-Test-Exit

VRU – Vulnerable Road User

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1. INTRODUCTION

Essentially everyone is a road user on an everyday basis. To go to school, kindergarten or work, to run errands, to visit friends and family, for exercise and for recreational purposes people become part of the traffic system in diverse ways. Whether it is by walking, riding a bike, going by bus, driving a car or some other means of transportation, they are still part of the same traffic system and try to make sure that the goal of their journey is achieved. What they are experiencing, both in terms of internal factors such as drowsiness, time pressure, anger etc., and external factors such as stressful traffic, text messages, road equipment, unexpected traffic manoeuvres from other road users etc., will affect their behaviour in different ways and also differently for different persons. Miscellaneous strategies are adopted to handle these internal and external factors in connection to transportation, with a constant trade-off between safety, the influencing factors and the other goals of the journey, striving for a general feeling of comfort. In this thesis, adaptation in the road traffic environment will be viewed as the road user setting the safety margins of the comfort zone according to his or her present state and capability. The comfort zone is where the road user experiences a feeling of comfort, with large enough subjective safety margins. These concepts will be further discussed within the text. The overall strategies and momentary adaptations are manifested by the behaviour of the road user. Identifying what kind of adaptations are made in certain situations, and why, contributes to understand road-user adaptations. This understanding forms a basis for a deeper knowledge of human behaviour in traffic. If the adaptations made are not adequate for the prevailing situation, the consequences can be severe, and knowledge about human behaviour in the traffic environment can potentially be used to take both proactive and reactive measures, mitigating the effects of inappropriate adaptation or preventing it. During the last couple of decades, the perspective on road safety has developed from focusing on the road user to the transport system overall, where all parts of the system should be considered to increase safety. For instance, in the Swedish Vision Zero the shared responsibility for traffic safety between those designing and those using the transport system is acknowledged (Swedish Transport Administration, n.d.). Since it is unfeasible to change the way that humans function, the system needs to be adapted to the humans for which it is made.

The goal of this thesis is to increase and accumulate knowledge about road-user adaptation in the traffic environment. This knowledge should aid in designing the traffic system in support of road users trying to achieve their goals.

For private individuals who are in control of their own locomotion, driving a car, riding a bicycle and walking are common means of transportation. The Swedish national travel survey of 2015-2016 showed that of all main trips (basically trips starting and ending at a person's home or workplace) undertaken, 27% were performed by bicycle or walking with an average travel distance of 3.2 km, and 54% by car with an average distance of 36 km (Trafikanalys, 2017). In this doctoral thesis, the focus is on driving and cycling, because of their prevalence and the speed associated with the vehicle, which reduces the time available for adapting to new situations compared to walking. Driving a car and cycling include many different, but also similar aspects. Similarities include that it is possible to decide at will (within constraints) when to travel and to choose your own way to get to your destination. In both driving and cycling you will have to attend to varying objects depending on the current traffic situation. The most salient feature distinguishing car drivers from cyclists is the degree of vulnerability.

While a car driver is protected by the hard shell of the car, the seatbelt, air bag and other safety equipment in the car, a cyclist may wear a helmet but is otherwise unprotected in traffic. The room for manoeuvre is restricted for cars, because drivers are only allowed to drive within their own lane and it is not acceptable to stop the car unless there is a special place to do so. Although a bicycle also has a limited path on which to travel, a cyclist can slow down substantially or pull over at his or her own convenience, without disturbing other traffic in the same cycle path. The infrastructure is also different for cars on roads where rules and regulations apply that a driver must learn before applying for a driving licence. The infrastructure for bicycles is often more limited and cycle paths may not always lead the whole way to the destination. Although it is allowed to cycle along a rural road, it can be associated with danger for cyclists to do so, because the lateral clearance between a cyclist and an overtaking vehicle has been found to be less than 1.5 m in many cases (Dozza, Schindler, Bianchi-Piccinini, & Karlsson, 2016). The room for mistakes or deviations is hence narrow for both road-user roles but the cyclist is more vulnerable if an accident occurs. Demography is another difference concerning who can use a certain means of transportation. While children can learn to ride a bicycle at an early age, guided by adults in their presence, there is an age requirement as well as practical and theoretical tests to pass before receiving a driving licence for a private car. Physical abilities limiting car driving include eyesight restrictions, while cycling on the other hand demands a certain degree of physical health. Social factors such as economic capacity also influence who can afford to apply for a driving licence and to buy a car.

Research has, over the years, developed a number of behavioural models that can be used to investigate road-user behaviour from different perspectives. Several of them have in common that the road user will try to keep his or her effort, or workload, at a comfortable level. Some of the models concern the individual road-user behaviour while other models are extended to include the vehicle as well. The behavioural models in turn illuminate different aspects of adaptive behaviour. In this thesis some of the most important models will be described and evaluated regarding their usefulness for understanding adaptive behaviour in traffic. The extended control model (Hollnagel & Woods, 2005), ECOM, is chosen as an analytical framework. What makes ECOM appropriate is discussed later.

Behavioural models are however not enough for understanding adaptive behaviour in traffic, since adaptations are influenced by a number of important factors in the environment. **Static infrastructure** denotes components of the infrastructure perceived as constant by the road user from the moment they are detected until they are no longer perceivable. Examples include road delineators, static road signs etc. **Dynamic infrastructure** refers to infrastructure components that can change from the perspective of a single road user moving in traffic. Variable message signs, traffic signals and dynamic speed bumps are examples of these. Aspects of both static and dynamic infrastructure will be addressed in this thesis.

It is also important to realise that most people are not only focused on the traffic when driving, cycling etc. The term **additional task** is here used for a task that is not directly connected to the driving or cycling task. However, this does not mean that the task is not considered as important to the road user as moving in traffic. Some examples are changing radio channel and using a mobile phone. (The often-used term *secondary task* is not used because of its implication that one task is more relevant than another.)

The term **other road users** refers to the presence and behaviour of other relevant road users as perceived or predicted by a specific road user. An example is when a cyclist going straight predicts that there might be a car coming from an obscured road to the right.

Research issues concerning road user adaptation in response to the factors stated above have been narrowed down to research questions. The investigation of the research questions has been operationalised by studies with participant drivers or cyclists or both and consists of one simulator study and three field studies. The research questions are as follows.

On a general level:

1. How can an adaptation in the road traffic environment be described in terms of comfort zone and safety margins?

In relation to static infrastructure:

2. How do drivers adapt their speed in response to different road delineator configurations?
3. How do drivers and cyclists adapt their behaviour in intersections?

In relation to dynamic infrastructure:

4. How do cyclists adapt their behaviour to a countdown timer to green traffic light for cyclists?

In relation to additional tasks:

5. How do cyclists adapt towards text messages received on their mobile phone?
6. How do drivers adapt their speed in connection to an additional task inside the car?

In relation to other road users:

7. How do drivers and cyclists adapt to other traffic in a mixed traffic intersection with stop rule and in a signalised intersection?

Research questions 2 and 6 are addressed in Study I, research question 5 is examined in Study II, research questions 3 and 7 are studied in Study III and research question 4 is investigated in Study IV. Research question 1 is mainly addressed by theoretical considerations and supported by the empirical studies.

Taken together, the research questions all have the same overall aim, i.e. to describe and understand adaptations in the road traffic environment from the perspective of individual road users. The intention is that the transport authorities can use this knowledge and be aided in planning and decision-making to facilitate for road users, especially in complex situations that are difficult to understand.

1.1. Delimitations

The means of transportation in focus for this thesis are driving a private car and cycling. Emphasis is placed on the human behaviour of the person driving or cycling, not on the specific vehicle. Professional drivers in general have more driving experience than the average driver which may lead to other ways of handling traffic situations. To minimize the heterogeneity and the number of aspects to consider, only non-professional drivers and adult cyclists are included. The non-professional drivers constitute the majority of people driving in

traffic. The same reasoning can be applied for autonomous/self-driving cars, which are also excluded. Interaction between several road users is not examined here, other than from the individual perspective of a single road user, where other road users are perceived as factors affecting adaptation. Hence, the title of the dissertation. Additionally, environmental factors such as weather conditions are not specifically included in the thesis but are factors occurring naturally in field studies. Moreover, this thesis is not intended to evaluate the effects of different road safety measures, but instead to address how humans adapt their behaviour in traffic, to cope with a variety of challenges in traffic situations.

According to the definition by the Organisation for Economic Co-operation and Development (OECD) “behavioural adaptations are those behaviours which may occur following the introduction of changes to the road-vehicle-user system and which were not intended by the initiators of the change” and “behavioural adaptations occur as road users respond to changes in the road transport system” (OECD, 1990, p.23). Throughout this thesis, some characteristics differ from this definition, and need to be clarified: Here a micro perspective is used, and the timeframe is short. Additionally, the road *traffic* system, which includes pedestrians and vehicles on roads, is handled, in contrast to the road *transport* system which involves the act of transporting.

1.2. Contributions to society

While the focus in this dissertation is primarily on the scientific aspects of adaptive behaviour in traffic, the topics of the studies in this thesis have not only been chosen for their scientific relevance, but also because they address issues that can have direct or indirect consequences for society. All studies contribute by providing a knowledge base that can be used for designing road infrastructure to how road users behave; Study I contributes by increased knowledge about how people adapt in terms of speed to different road delineator configurations (one part leading to road authorities changing their regulations), Study II contributes to the knowledge about various ways for cyclists to adapt to incoming text messages, Study III provides increased knowledge about the interaction between car drivers and cyclists and what factors affect adaptation at intersections, whereas Study IV provides increased knowledge about what information cyclists use and how they adapt their behaviour to the information of a countdown sign.

2. INCLUDED PAPERS

Paper I

Nygårdhs, S., Lundkvist, S.-O., Andersson, J., & Dahlbäck, N. (2014). The effect of different delineator post configurations on driver speed in night-time traffic: A driving simulator study. *Accident Analysis & Prevention*, 72, 341-350.:

- My contribution to paper: Participated in the planning of the study, data collection, analyses, authoring the paper.
- Co-authors' contributions: S.-O. Lundkvist led the planning of the study, Jan Andersson supervised the analyses and the writing of the paper and Nils Dahlbäck supervised the writing of the paper.

Paper II

Nygårdhs, S., Ahlström, C., Ihlström, J., & Kircher, K. (2018). Bicyclists' adaptation strategies when interacting with text messages in urban environments. *Cognition, Technology & Work*, 20(3), 377-388.:

- My contribution to paper: Involved in planning, data collection, planning analyses together with colleagues, analysing (part of) data, main author of the paper.
- Co-authors' contributions: Christer Ahlström wrote the introduction and analysed part of data, Katja Kircher supervised the writing of the paper, Christer Ahlström, Jonas Ihlström and Katja Kircher were all involved in planning the study and collecting data.

Paper III

Nygårdhs, S., Kircher, K., & Johansson, B.J.E. (2020). Trade-offs in traffic: does being mainly a car driver or a cyclist affect adaptive behaviour while driving and cycling? *European Transport Research Review*. Advance online publication. doi:10.1186/s12544-020-0396-y:

- My contribution to paper: Involved in planning and data collection, analysing and interpreting the data, authoring the paper.
- Co-authors' contributions: Katja Kircher took part in the data collection and data reduction process and added part of the discussion section, Björn J E Johansson supported the writing of the parts concerning the extended control model.

Paper IV

Nygårdhs, S. (submitted). Cyclists' adaptation to a countdown timer to green traffic light.:

- My contribution to paper: Involved in planning, all parts of data collection, analysing and interpreting the data, authoring the paper.

3. THEORETICAL BACKGROUND

Adaptation has been described in many ways and differently in different disciplines. The term *adaptive behaviour* stems from biology and refers to behaviour that contributes to an individual's survival or reproductive success, i.e. natural selection. *Behavioural adaptation* denotes adapting to changing situations and changing environments (Carsten, 2013) and in the traffic area it has often been used for traffic behaviour in general regarding introduction of new road safety measures (Rudin-Brown & Jamson, 2013).

Considering adaptation in the road traffic setting, terms such as compensatory behaviour, adaptive behaviour, behavioural adaptation and self-regulation have been used. The term *compensatory behaviour* has been used for self-selected added workload, e.g. in naturalistic driving to describe how drivers conversing on a hand-held mobile phone changed lanes less frequently and looked forward more (Fitch, Grove, Hanowski, & Perez, 2014). In simulated driving, compensatory behaviour has been used for describing how drivers minimized cognitive workload from driving by reducing their speed to focus on an additional task (Son, Lee, & Kim, 2011), and in cycling for terming behaviours such as speed reduction and choosing an appropriate location for performing additional tasks (Adell, Nilsson, & Kircher, 2014). The term *adaptive behaviour* has been used for tactical compensation in traffic, such as speed adaptation and keeping distance from the car in front but also for anticipation to avoid accidents when cognitive or neuropsychological functions or both have declined (de Raedt & Ponjaert-Kristoffersen, 2000). Adaptive behaviour has further been referred to in connection with for example road-crossing behaviour in a simulation study where pedestrian crossing time was adjusted to the time-to-arrival of a bike (te Velde, van der Kamp, Barela, & Savelsbergh, 2005). The term *behavioural adaptation* has often been used in connection with safety measures, where introduction of a safety measure has other than the intended effects (Rudin-Brown & Jamson, 2013), for example better visual guidance may lead to increased driving speeds (e.g. Kallberg, 1993). *Self-regulation* is a term typically used in connection with older drivers, where self-regulatory behaviours such as avoiding driving at night and in busy traffic are reported (Blanchard & Myers, 2010; Charlton et al., 2006).

To summarize, compensatory behaviour and adaptive behaviour are terms that have been used more or less interchangeably concerning individual road-user behaviour in specific situations, although compensatory behaviour often includes the accommodation of an additional task and adaptive behaviour is more linked to situational changes. Furthermore, behavioural adaptation has been more connected to a population of road users reacting on road safety measures, whereas self-regulation has been used for road users reasoning about their own capabilities on a strategic level.

In this thesis the term adaptation is used to address the adjustments individual road users make to handle the demands of the current and in the near future expected road traffic situation, with respect to possible additional tasks. By *individual* I mean to investigate the individual perspective of a road user, with the aim to understand more global issues. The *demands* include static and dynamic infrastructure as well as other road users. *Current* refers to momentary, reactive, adaptations, while *in the near future expected* refers to proactive adaptations that are carried out in a time interval of a few seconds for urban areas but can be somewhat longer for rural areas. This is visualized in Figure 1.

Figure 1. Adaptation from the individual perspective of a road user in this thesis.

One way of sorting adaptive behaviours is to discern between proactive and reactive adaptations. Proactive adaptations are made in relation to anticipated upcoming situational demands and are based on one's own prerequisites such as being in a hurry, more steady environmental features such as weather conditions, and self-paced activities such as initiating a phone call. Reactive adaptations are made as a reaction to the current traffic situation, including other road users and additional tasks that call for immediate attention, such as answering a phone call.

For an adaptation to take place, there must be something to adapt to, either at present or expected. For simplicity's sake this will hereafter be called an *adaptation object*, although it does not have to be a physical object but could also be more abstract things such as rules, goals and emotions. Knowing that there is a support system may initiate adaptation to it, for instance by not manually correcting for swerving inside the lane with a lane departure warning system. No adaptation can take place without attending to the adaptation object, whether consciously or not. The following section addresses attention in traffic.

3.1. Attention

Attention is understood on an intuitive level as the often-cited quote by William James (1890) states: "Every one [sic] knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains . . . of thought." A definition of attention has, however, not been agreed upon, although attempts have been made. Here the stance is taken on attention as a cognitive process that can use sensory input to confirm the current situation and to predict how the situation will emerge. Attention is used for selecting what input should be processed when the prediction is uncertain to increase knowledge of the situation. With such knowledge decisions can be made concerning whether an adaptation is necessary and if so, what kind of adaptation.

In traffic, as in many other aspects of life, knowledge, expectations and goals guide our information intake to relevant parts of a scene (Corbetta & Shulman, 2002; Land, 2006; Neisser, 1976; Yarbus, 1967). This top-down processing of the brain can however be interrupted by bottom-up information if new, unexpected, salient and possibly hazardous stimuli are detected (Corbetta & Shulman, 2002; Itti & Koch, 2001), such as other road users suddenly crossing the road ahead without previous notice. These stimuli can lead to reactive adaptive behaviours by avoidance manoeuvres. Attentional selectivity helps governing what people become aware of, and through attention a person selects subsets of the information he or she receives for further processing, while information that does not receive such further processing often fails to reach awareness (Hyman Jr, Sarb, & Wise-Swanson, 2014; Most, Scholl, Clifford, & Simons, 2005).

It is important to acknowledge that the mind does not consciously attend to (i.e. is subjectively aware of) everything that is presented to it, neither visually, auditorily nor through any of the other senses. On the other hand, as phrased by Koch: “When attending to something, the rest of the world doesn’t disappear” (Koch, 2004, p. 171) and sensory input is continuously collected. Visualising attention by terms such as “a spotlight” (see for instance Findlay & Gilchrist, 2003) could therefore be misleading. While haptic input can give sensory information about the state of the road surface, smell can give information about where (not) to go to avoid fumes, sound and vision can give information about the emerging situation. By hearing, information of approaching vehicles from behind can for instance lead cyclists to adapt to the situation by adjusting their speed before an intersection. However, the main information source used by attention in the traffic context is often vision.

Charlton and Starkey (2013) argue that for skilled performance, such as experienced driving, there are two processes involved. In the “operating process” attention to the task is conscious and intentional, whereas in the “monitoring process” nonconscious surveillance is performed where incoming stimuli are compared to earlier instances of driving. Conscious attention to the driving task is needed when the monitoring process detects an unfamiliar situation or stimuli related to loss of control or potential threats.

Previous experiences are indeed necessary for predicting the future, which is of high relevance in the traffic environment because it will guide our expectations. Neurological evidence states that when a person is not attending to a particular task, i.e. when no goal-directed attention is used, some parts of the brain, called the default mode network, increase their activity (Raichle, 2010) compared to when attention is needed for performance. The default mode network is important for the episodic memory (Snyder & Raichle, 2012) in which personal experiences are stored and is hence input for the monitoring process described by Charlton and Starkey (2013). Outcomes of different alternatives in the past, including emotional responses (see the somatic marker hypothesis in Damasio, 1996), will guide decision-making in a certain situation and hence play a role in determining which adaptive behaviour should be performed when faced with an adaptation object.

Drivers have been observed to focus the fovea on places from which they need to obtain information (Land, 2006) and allocating attention to an object has processing advantages such as level of detail (Findlay & Gilchrist, 2003). Visual sampling has been further explored by Kircher and Ahlstrom in studies with occlusion glasses (Kircher & Ahlstrom, 2017a), eventually resulting in the theory of Minimum Required Attention (MiRA; Kircher &

Ahlstrom, 2017b). The MiRA theory states that as long as a driver samples sufficient information from relevant parts of the traffic environment at relevant points in time and with a sufficient enough frequency, he or she should not be perceived as inattentive, regardless of whether the driver is executing other tasks or not. Eye tracking is one way of assessing this information intake for visual sampling, which can be both foveal and peripheral.

Because of the vast amount of information in a visual scene, most visual sampling occurs without fixating individual objects (Wolfe, Dobres, Rosenholtz, & Reimer, 2017). The point of fixation is not the only part of the visual field that is attended to, or that can be attended to, and peripheral vision plays a very important part here (Wolfe et al., 2017). Due to the fast information processing from peripheral vision to higher order understanding, it is enough with just a glance of the traffic scene to achieve a basic understanding of it (Wolfe et al., 2017). Whether an adaptation is needed and what type of adaptation will be carried out is based on the expectations that are associated with the traffic scene, in combination with other input. Apart from retaining information in driving, peripheral vision is also useful for guiding eye movements to interesting areas where more information needs to be sampled, and to facilitate perception of the world in absence of eye movements (Wolfe et al., 2017). It makes it possible to navigate the world safely without running into obstacles when conscious attention is directed elsewhere. This nonconscious adaptive behaviour of smooth navigation has been observed for people interacting with their mobile phone while avoiding to walk into branches of a tree with money attached to them, without observing the money (Hyman Jr et al., 2014).

Change blindness and inattentional blindness are phenomena that can clarify why adaptation to relevant information does not always occur, although the information seems to be acquired. Change blindness can be defined as the failure to attentionally experience changes to a scene, and inattentional blindness as the failure to attentionally experience the appearance of an object or an event (Rensink, 2009). These phenomena can explain why brake lights and traffic light changes are unnoticed, and why people fail to notice an object appearing right in front of their eyes when occupied with an attentionally demanding task (Most et al., 2005).

3.2. Behavioural models

Over the years, a number of behavioural models have been developed focusing on understanding, describing or predicting some aspect or aspects of human behaviour. By modelling, an aspect of behaviour is organised into its core parts, enhancing understanding and prediction of behaviour. Some examples of generic models for understanding human behaviour are the simple *test-operate-test-exit unit* (TOTE) which implicates a coordinated sequence of tests and actions until the preferred result is achieved (Miller, Galanter, & Pribram, 1960), the *perceptual cycle* in which the perceiver constantly anticipates specific types of information and explores the world to achieve this information, directed by anticipatory schemata, which are in turn modified by the available information (Neisser, 1976), the *theory of planned behaviour* (TPB), which highlights the role of attitudes, subjective norms and perceived behavioural control in predicting behavioural intentions (Ajzen, 1985), the *skill-, rule- and knowledge-based performance model* (SRK) with three levels of performance (Rasmussen, 1983) and the *contextual control model* (COCOM), which is a cyclical model of human action, that describes action and control and where events modify the current understanding, leading to further actions which in turn influence events and feedback and so on (Hollnagel, 2003; Hollnagel, 2016a; Hollnagel & Woods, 2005). Several theories and models have been used for understanding human behaviour in general

and road-user behaviour in particular. In this section more road-user centred models are presented in chronological order, together with their implications for adaptation.

3.2.1. The field of safe travel

The field of safe travel suggested by Gibson and Crooks (1938) has had a large impact on visual perception theory. In their hypothesis the field of safe travel “consists, at any given moment, of the *field of possible paths which the car may take unimpeded*” (Gibson & Crooks, 1938) (italics in original). The field is spatial and moves along with the vehicle. Lee (1980) acknowledged that the perceptual systems, especially vision, play a crucial role when moving through and interacting with the environment. He used the term optic flow field to recognise that visual stimuli change with time and space. That the optic flow affects speed perception has for instance been shown by Prokop, Schubert, and Berger (1997), where participants walking on a self-driven treadmill adjusted their speed to the optic flow although they were instructed to keep their walking speed constant. When presented with constant motion the visual system will, however, adapt to it and the impression of speed will eventually attenuate (Jagacinski & Flach, 2003). This can have severe consequences in traffic, for instance when exiting a motorway at too high speed.

Figure 2. The field of safe travel of a driver in traffic. Reproduced from Gibson and Crooks (1938).

In models focused on the visual field, experienced speed affects adaptation. In the field of safe travel, adaptive behaviour can be seen in the adjustments made to stay within the unimpeded zone, where steering, accelerating and decelerating are the most obvious ones.

3.2.2. Zero-risk theory

The zero-risk theory, which was first proposed by Nääätänen and Summala (1976) and further described by Summala (1988), entails that drivers are not adjusting risk but when they become more experienced they adapt to risk. Risk is controlled by maintaining safety margins, i.e. so that loss of control does not occur. According to this theory drivers are typically motivated to increase their speeds and if the traffic system offers opportunities to satisfy these motives, drivers tend to use them. Summala advocates speed limits as necessary for restricting drivers from adapting to greater risks in the traffic system.

With zero-risk theory as a behavioural model, adaptation can be defined as the adjustments made to maintain safety margins. The zero-risk theory maintains that drivers use speed as an adaptation measure to handle the traffic system.

3.2.3. A two-level model of driver steering behaviour

Donges (1978) investigated driver behaviour in terms of steering and suggested a two-level model of driver steering behaviour, in which duality of information to the driver is a basis. This means that the visual field presented to the driver is one source of information, showing the current and future road ahead, for the driver to extrapolate for anticipation. The other source of information in the visual field contains static as well as dynamic cues, concerning deviation information between the path the vehicle is taking and the desired path. Donges's model contains an anticipatory open-loop control and a compensatory closed-loop control, both affecting the steering wheel angle. The steering behaviour, i.e. the adaptation in this model, is mainly affected by vehicle speed and road curvature.

Figure 3. Block diagram of the two-level model of driver steering behaviour. Adapted from Donges (1978).

3.2.4. Task hierarchical model

Michon (1979; 1985) proposed three levels of skills and control in traffic. These are the strategic (planning), tactical (manoeuvring), and operational (control) levels. The strategic level concerns the planning of the trip, e.g. the goal of the trip, what means of transportation and what time of day should be chosen. At the tactical level decisions such as making a lane change to overtake a vehicle in front or slowing down is made, while the actual steering and speed adjustments are handled at the operational level.

Figure 4. The hierarchical structure of the road-user task. Adapted from Michon (1985).

Taking this view, adaptation is carried out at the tactical level, where the decisions of carrying out adjustments are made, while the adaptations are operationalized at the operational level.

3.2.5. Risk homeostasis theory

In the risk homeostasis theory by Wilde (1982; 2001), the target level of accident risk is determined by the expected benefits and costs associated with risky as well as with safe behaviour alternatives. The target level of traffic accident risk is the level of subjective accident risk at which the subjective difference between benefits and costs is maximized.

Figure 5. Homeostatic model relating accident rate to driver behaviour. Adapted from Wilde (1982).

Adaptation in the risk homeostasis theory is carried out considering benefits and costs in the future.

3.2.6. Task-capability interface model and task difficulty homeostasis theory

The task-capability interface model of driving (Fuller, 2000) includes the notion that task demands, such as environment, other road users, vehicle and speed were contrasted with the driver capability to achieve a safe outcome from competence and human factors at any given moment. The model was among other things based on the fact that drivers try to avoid collision. Later, Fuller carried out trials showing no correlation between subjective ratings of perceived risk and ratings of statistical risk (Fuller, 2005). This finding instead lead to the theory of task difficulty homeostasis which Fuller considers to be one of the sub-goals in driving and the main tool to manage task difficulty is that of speed choice (Fuller, 2005).

Feelings of risk were proposed to motivate avoidance of too high a level of task difficulty (Fuller, McHugh, & Pender, 2008). Ratings of risk were highly correlated with ratings of task difficulty in Fuller's trials (Fuller et al., 2008) but the data were all subjective ratings, which one should in general be careful to interpret.

Figure 6. The task-capability interface model. Adapted from Fuller (2000).

In the task difficulty homeostasis theory, adaptation by choice of speed is used for handling the demands of the driving task.

3.2.7. Driver-in-control and the extended control model

Along the same line of models with different levels as Donges (1978), Michon (1979) and Rasmussen (1983), the researchers Hollnagel, Nbo, and Lau (2003) propose a driver-in-control model (DiC) with four levels. In the DiC model, the tracking level is considered to involve compensatory (feedback) control and being highly automated, e.g. maintaining speed, while the regulating level includes movement relative to other vehicles and anticipatory control (feedback and feedforward) and demands high attention at uncommon manoeuvres. Condition monitoring (feedback and feedforward) is involved at the monitoring level, e.g. traffic flow, whereas goal setting (feedforward) is at the targeting level with high demands to attention, mostly before the journey is started, e.g. choice of destination. Hence, all levels continuously communicate with each other and effective control is at hand if the joint driver-vehicle system is in control at all levels simultaneously.

The driver-in-control model was developed into the more comprehensive extended control model (ECOM), which can be used for describing how the performance of a joint cognitive system, such as a driver and a vehicle, takes place on several layers of control at the same time; tracking, regulating, monitoring and targeting (Hollnagel, 2016b; Hollnagel et al., 2003; Hollnagel & Woods, 2005), see Figure 7. At the tracking control layer, activities crucial for staying within a desired region of the time-space continuum are described. When applied to driving, such activities can be keeping an intended speed, lateral position on the road and distance from the car in front. In the regulating layer, goals and criteria for the tracking control layer are defined, involving positioning the vehicle in relation to other elements in traffic, e.g. avoiding obstacles and overtaking. Monitoring is concerned with the state of the joint driver-vehicle system relative to the driving environment and includes keeping track of

traffic signs and signals. Targeting involves goal setting, typically in terms of destination, but also driving performance criteria, such as increasing speed if the driver thinks she or he will arrive late otherwise, or driving with extra caution if there is a person in the vehicle who needs to be handled with extra care.

Figure 7. The extended control model. Retrieved from <http://erikholtnagel.com/ideas/ecom.html> Copyright 2016 by Erik Holtnagel. Reproduced with permission.

Adaptation in ECOM is most evident in the regulating layer but it is affected by information of the monitoring layer and operationalised in the tracking layer. Strategic adaptations such as selecting time of day and route to avoid challenging travel conditions and situations can be made in the targeting layer.

3.2.8. Predictive processing framework

Although ECOM can be used for describing road-user behaviour in traffic, it does not explicitly treat predictions made by road-users. Theory on prediction is however accounted for in the predictive processing framework (Clark, 2016; Lupyan & Clark, 2015). According to the predictive processing framework, the brain constantly predicts the world and seeks information to confirm the prediction. If there are prediction errors, a new prediction will be made based on this information. Hence, the flow of processing in the brain is a mixture of top-down expectation and bottom-up error correction (see Figure 8). This suggests that prior beliefs, i.e. predictions or expectations, guide information intake, and that the difference between the prediction and the information intake leads to new, updated predictions, and so on. Actions taken to sample relevant information also alter the situation, and new predictions are made. Having an active top-down model will cause a person to discard some information and amplify other. The prior knowledge about the world hence greatly influences how the world is perceived, how signal is extracted from noise.

Figure 8. A schematised view of the predictive processing account of information transfer in the brain. Adapted from Lupyan and Clark (2015).

In the predictive processing framework, adaptation occurs when the prediction errors lead to new predictions.

3.2.9. Comfort zone

Since the introduction of the concept field of safe travel by Gibson and Crooks (1938), other fields and zones in traffic have been added. Often used in recent studies is the idea of a comfort zone, within which the road user experiences a subjective feeling of control (Bärgman, Smith, & Werneke, 2015; Engstrom & Ljung Aust, 2011; Ljung Aust & Engström, 2011; Panero, 2018). The multiple comfort zone model was first proposed by Summala (2005) and further elaborated in (Summala, 2007). According to this model, several functional control variables must all be within an acceptable range, or above a certain threshold, for a driver to experience a general feeling of comfort and hence be in his or her comfort zone. If the acceptable range is exceeded (or the threshold not achieved) by some variable, there is a feeling of discomfort. The functional control variables include sufficient time and space margins to avoid a crash, to provide a smooth and comfortable travel, to avoid sanctions and to have an expected travel progress. When humans are presented with multiple goals like this, the choice mechanism *satisficing* (Simon, 1956) is often applied, by which goals are not individually optimised but rather all fulfilled to a satisfactory level. Summala (2007) means that at routine driving without arousal, tension or activation, the driver aims to keep within comfortable limits, where no feelings of risk, anxiety or discomfort are present. As long as the comfort zone boundary is not exceeded, the driver experiences a feeling of control and performance is experienced as good enough (i.e. satisficing is applied), and there is no need for corrective actions. If safety margins are breached, a subjective risk monitor is activated, and the driver senses a feeling of risk. Normally, this subjective risk feeling is reduced by driver behaviour such as making corrections of speed and steering. However, motives and goals, rules, social norms, vehicle characteristics and the road system are factors which can push drivers towards shorter safety margins (Summala, 2007).

3.3. Discussion of the theory chapter

Among the theories and behavioural models for understanding road-user behaviour some are stimulus-driven, e.g. the field of safe travel, while others are goal-directed, e.g. zero-risk theory and risk homeostasis theory. At present it seems that the extended control model of ECOM is one of few that acknowledge that both bottom-up and top-down processing can occur simultaneously. Another is the predictive processing framework, which states that humans are in fact constantly predicting the world, i.e. top-down processing occurs, and that the prediction is also constantly modified by bottom-up processing. There is however no complete model for studying individual road user adaptation in traffic. Neither ECOM nor the predictive processing framework explicitly state internal factors such as emotions, feelings or capability. Considering that ECOM is a model with different performance layers interacting with and influencing each other all the time, i.e. bottom-up and top-down adaptations occur concurrently, ECOM is here chosen to be the basis for analyses.

With the discussion about comfort zone in mind while attempting to discern between adaptation and adaptive behaviour, adaptation can be viewed as setting the margins of the comfort zone according to the present individual state and capability. The individual state can affect performance but it does not have to do so, depending on whether the task difficulty has been adapted through adaptive behaviour, such as reducing speed while driving (de Waard, 1996). The adaptive behaviour is the instrument used for meeting the margins of the comfort zone.

In the behavioural models previously described, adaptation is handled in various ways. In some models, the adaptive behaviour is very specific, such as steering or altering speed, while other models perceive adaptation as the modifications made to maintain safety margins. The goal of maintaining safety margins is to stay within the comfort zone, where the demands of the task can be handled with subjectively experienced control.

Adaptation can hence be described as setting the safety margins of the comfort zone, whereas **adaptive behaviour** is shown in the adjustments made to stay within acceptable safety margins.

Adaptation in traffic implies two things – first that there is an adaptation object (e.g. a traffic sign, rule or an action by another road user), whether present or predicted, and second that the road user attends to the adaptation object, consciously or not. Therefore, the importance of expectations as well as of peripheral vision for directing attention in traffic should be acknowledged. Adaptation can be made both as top-down, with the road user skill and goals of the travel, and as bottom-up, where the specific situation, i.e. an external adaptation object, influences the adaptation. Bottom-up input however influences top-down processes in which the input is interpreted.

Even if there is an adaptation object at hand, and the road user attends to and adapts to it, there might be other relevant adaptation objects around that are not attended to. Sometimes the adaptation made by the road user to the attended adaptation object will aid in handling the other adaptation objects too, for instance increasing the comfort margins by reducing speed will give more time to detect and further act on other objects. If all relevant objects in a certain traffic situation are attended sufficiently to predict what will happen in the near future and choose an appropriate action, the road user can be considered attentive.

When no adaptive behaviour can be noted, although there is an obvious adaptation object, the concept of inattention blindness, where the mind is occupied elsewhere, could be useful. Together with change blindness this explains that adaptation does not always occur, although objectively, all the cues are there to make an adaptation. Other explanations for not adapting are that the individual does not interpret the adaptation object properly, for instance the intention of other road users, or that it is a calculated risk, where the individual deliberately wants to provoke something, and decreases his or her safety margins.

Table 1 shows a list of adaptive behaviours as mentioned above, together with the type of adaptation and in which situation the adaptation is carried out (present or prior to the journey). As can be seen, speed reduction and distance keeping from a vehicle in front can be both proactive and reactive adaptations. While an anticipating driver may reduce speed by letting go of the gas pedal in advance to keep the safety margins at a comfortable level, another driver may be surprised by traffic events and reduce speed by applying the brakes hard. While a proactive driver may keep the distance from a car in front anticipating irregular speed behaviour, another driver may experience that he or she must keep the distance to a car in front when performing an additional task.

Table 1. Type of adaptation, adaptation situation and examples of adaptive behaviour.

Proactive/reactive	Type of adaptation		Adaptation situation	Example of adaptive behaviour
	Control layer (ECOM)	Task hierarchical model		
Reactive	Regulating	Tactical	Present	Reducing lane change frequency
Reactive	Tracking	Tactical	Present	Looking forward more
Proactive/reactive	Regulating	Tactical	Present	Reducing speed
Proactive/reactive	Regulating	Tactical	Present	Keeping distance from vehicle in front
Proactive	Regulating	Tactical	Present	Choosing appropriate location for executing additional task
Proactive	Regulating	Tactical	Present	Anticipation to avoid accidents
Proactive	Targeting	Strategical	Prior	Avoiding challenging driving conditions and situations

While the behavioural models and theories contribute to ways of looking at road-user behaviour, the attention features are useful in understanding what the road user can adapt to. Recognising that adaptation can involve both top-down and bottom-up processes is crucial for understanding road-user adaptation.

In this thesis, individual road user behaviour in response to different adaptation objects in road traffic, namely static and dynamic infrastructure, additional tasks and other road users, is studied. The study results are used for theory development in the area of adaptation in the traffic environment from the perspective of individual road users. ECOM accounts for internal input in terms of strategies and goals but does not explicitly include emotions and feelings

that may affect the comfort zone. Because of the relative comprehensiveness of ECOM, it is used for setting up testable hypotheses of observable adaptive behaviour in traffic.

4. METHOD

Adaptation in traffic is a large and complex area to describe and analyse, which requires several methods to capture relevant data. Controlled studies can be appropriate for studying isolated phenomena while conducting semi-controlled studies is a way to come closer to the naturalistic setting that is present in real life of real road users accomplishing real tasks. Obviously, different data acquisition methods are needed depending on what kind of phenomenon is to be investigated. An overview of the studies included in this thesis together with the most important characteristics is given in Table 2.

Table 2. Overview of studies.

	Study I	Study II	Study III	Study IV
Sample size	14	41	23	26
Gender (women/men)	5/9	19/22	12/11	11/15
Mean age$\pm$SD (ys)	42 $\pm$ 15	37 $\pm$ 11	39 $\pm$ 14	35 $\pm$ 15 ¹
Design	2 $\times$ 7 (within-group)	2 $\times$ 3 $\times$ 2 (within-group)	2 $\times$ 2 (mixed)	before-after (within-group)
Independent factors	<ul style="list-style-type: none"> • Distraction task (2) • Delineator post configuration (7) 	<ul style="list-style-type: none"> • Music (2) • Segment (3) • Text message (2) 	<ul style="list-style-type: none"> • Character role (2) • Condition (2) 	<ul style="list-style-type: none"> • CDT sign (BL/TM)
Setting	Moving-base simulator	Field study	Field study	Field study
Scenario	Driving on night-time rural road	Cycling in daytime urban real traffic	Driving and cycling in daytime urban real traffic	Cycling in daytime urban real traffic
Measurements	Driving speed	SMS interactions MiRA fulfilment NASA-RTLX Glance behaviour Complexity level	Behaviour at intersections Glance behaviour Complexity level Pedalling behaviour	Behaviour at intersection MiRA fulfilment Glance behaviour Pedalling behaviour System acceptance scale Subjective opinion of system

¹ Age at treatment

In the studies included, both the field in terms of the real world and a moving base passenger car simulator have been used as study settings. For data collection different methods and technical systems have been used, including eye tracking, NASA-TLX and complexity classification. Accumulating data from different sources, using different methods, allows for complementary angles in trying to understand the intricate area of adaptation in traffic. While an observer perspective makes it possible to look at more objective measures of action, subjective measures can be used to understand why certain actions occur. The studies were

carried out in different ways and with different participants, from a controlled simulator study with car drivers to semi-controlled field studies with cyclists and car drivers. In this chapter, the methods used in the studies are summarized.

4.1. Study settings

There are several ways to investigate research questions but for understanding individual road-user behaviour, simulator studies and field studies are suitable, because of the opportunity to observe behaviour in action. A controlled simulator study as well as semi-controlled and quasi-experimental field studies have been carried out.

4.1.1. Simulator study

Study I was performed using a moving base passenger car simulator. Advantages of using a simulator for carrying out studies include the possibility to present all participants with the same traffic conditions and environments. There will be no differences in weather conditions, or the type of vehicle used. Randomizing condition order between participants is also easily done. Testing of behaviour in extreme or rare conditions such as high speed of own vehicle or odd or risky behaviour of other road users (e.g. a parked car suddenly driving out in the lane, a person running out in the street from behind a bus, or a vehicle break-down in front of one's own vehicle) can be accelerated. Obviously, a simulator can be used for simulating risky situations and for studying risky driving behaviour (e.g. Horberry, Anderson, Regan, Triggs, & Brown, 2006; Åkerstedt, Peters, Anund, & Kecklund, 2005). Adaptation towards certain adaptation objects in a simulator could therefore be studied without restricting driver behaviour to any greater extent.

Disadvantages include the fact that the participants know that they are safe and that if they behave inappropriately, they will not be harmed. This knowledge can lead to behaviour that is not in accordance with their normal behaviour, for instance in terms of speeding, lane keeping and overtaking. Another disadvantage is the occurrence of motion sickness (see e.g. Johnson, 2005; Kolasinski, 1995; McCauley, 1984; Stanney & Kennedy, 2010). This can lead to situations where people who suffer from motion sickness adapt their behaviour to this by altering their normal driving behaviour (e.g. Helland et al., 2016; McCauley, 1984). People with known problems of motion sickness are frequently excluded from simulator studies, which leads to a biased population. Even people who normally do not experience problems with motion sickness, may do so in a simulator, e.g. in studies including sharp curves or hard braking or both. At present, all conditions in natural driving cannot be simulated. Especially lighting conditions such as glare from on-coming vehicles are hard to simulate.

4.1.2. Field study

Field studies have been used to a large extent for increasing external validity. Some example topics of field studies in the traffic environment are investigating driver behaviour in relation to additional tasks (e.g. Anttila & Luoma, 2005), braking performance of experienced and novice motorcyclists (e.g. Vavryn & Winkelbauer, 2004), the effect of variable message signs on driver behaviour (e.g. Erke, Sagberg, & Hagman, 2007), pedestrians' behaviour at pedestrian crossings (e.g. Avineri, Shinar, & Susilo, 2012) and driver aggression (e.g. Hennessy & Wiesensthal, 1999). In addition, field operational tests, FOTs, have been conducted when performing long-term field tests, for instance to explore the effects of

different advanced driver assistance systems (ADAS) (Benmimoun, Pütz, Zlocki, & Eckstein, 2013).

Advantages with on-road field studies with car drivers and cyclists are that they include real conditions in terms of vehicle, infrastructure and potentially even other road users that must be taken into account as with normal driving or cycling, when not being part of a study. Hence, there is no margin for extra risky behaviour as in a simulator. The participants' ability to deal with external and internal demands, and consequently adaptation related to these, are better studied out in the field, where they naturally exist.

Disadvantages include that weather conditions and traffic conditions such as interactions with other road users are not the same between participants. This can make it hard to isolate the effect of a specific variable.

4.1.3. Semi-controlled study

In general, we know that what experimenters do and say affects the participants. When participants know that they are being observed, there is always risk of the *observer effect*, i.e. that they alter their behaviour because they know that they are monitored (e.g. McCambridge, Witton, & Elbourne, 2014). Compliance due to being part of a study is a problem when aiming to explore natural behaviour, because the participant wants to do correct things.

While controlled studies in laboratory settings have been carried out due to their virtue of testing isolated phenomena, naturalistic studies have been used to study subjects' natural behaviour while affecting the subject to a minimum. Although naturalistic studies are seemingly preferable in theory, in practice this is proven difficult. Filming drivers inside a car in a field study or making cyclists in traffic wear eye tracking equipment without noticing and approving is not possible. Furthermore, to be able to study a certain phenomenon, naturalistic studies can often be time-consuming and it can be hard to make any causal inferences.

In the field studies reported in Paper II and Paper III within this thesis, a semi-controlled study approach (Kircher, Eriksson, Forsman, Vadeby, & Ahlstrom, 2017) has been applied. A semi-controlled study is a combination of a controlled and a naturalistic study, where the researcher can decide which participants should be selected, which route should be driven or ridden, and what task should be carried out. (The task could be the act of driving or cycling as well as an additional task.) The participants are however given more freedom to decide if, when, where and how to perform the task. An advantage of using a semi-controlled method is that the adaptive behaviour when executing a task can be examined in a more naturalistic setting compared to in a controlled study. Disadvantages include reduced control and more complicated analyses.

4.1.4. Before-after study

A before-after study encompasses a quasi-experimental design, where the participants are not randomly assigned to an intervention. In this kind of study design, there are certain threats to internal validity that could provide alternative explanations for observed evaluation results. Common threats, or biases, in before-after studies such as the one described in Paper IV are (e.g. Ho et al., 2018):

- The *history threat*, which means that there might be other changes than the treatment in between the periods of measurement that could affect the results.

- *Regression-to-the-mean*, which occurs when participants are chosen based on their extreme values and compared after an intervention when their values may have decreased or increased to the mean value quite naturally.
- *Test performance bias*, which involves that the first test could have an effect on the outcome of the second test, irrespective of intervention.
- The *maturation effect*, which occurs when psychological or physiological features change with age or experience or both.
- *Dropout effects*, which occur when the participants in the before study are not present for the after study for some reason or another.

In the before-after study conducted in Study IV, the history threat was noted since there were some changes in the infrastructure between the periods of measurement. These changes were not considered to influence the parameters examined in the study though. The effect of regression-to-the-mean was handled by not choosing participants based on any extreme criteria, such as red-light-violators or fast cyclists. The test performance bias was hard to assess in the study. There is a possibility that having performed the test in baseline might affect performance in treatment. However, because of the long period, 12 months, between the two tests, it seems unlikely that baseline participation would have affected adaptive behaviours in the treatment phase. The maturation effect was handled in Study IV by using adult participants only, who all had experience of both living in the city and cycling in the studied intersection. The dropout effect is a real problem in studies where participants should return several times for participation. In Study IV, this was handled by recruiting and using a number of participants in baseline that allowed for some dropouts.

4.2. Data acquisition methods

The selection of data capturing methods and the quality of the data achieved will affect what can be inferred and the certainty thereof. Objective measures include behaviour that can be observed, i.e. actions performed by the road user. It is however up to the observer to determine what behaviours are to be reported and to interpret these. To understand the underlying factors of the behaviour carried out, subjective measures such as interviews, rating scales or think-aloud protocols can be used. While interviews and rating scales concerning past behaviour are retrospective in nature, think-aloud protocols are intrusive and may affect behaviour (Hertzum, Hansen, & Andersen, 2009). In this section, data acquisition methods for exploring road-user adaptive behaviour are discussed.

4.2.1. Eye tracking

In Study II, III and IV, eye tracking was used. Vision has an important role for input to attention in traffic, and hence for the discovery of possible adaptation objects and predictions of how the situation will evolve. Eye tracking is a method intended to capture visual aspects of attention.

Advantages with eye tracking include that it is possible to track where people direct their foveal vision. Hence, visual information intake can be traced, which indicates what the road user finds relevant.

Disadvantages are that the peripheral vision is not accounted for, and that it is not possible to discern between conscious and nonconscious attention. It is not certain that where a person looks is where conscious attention is paid and likewise, not fixating an object does not mean

that conscious attention cannot be set to it. There are also technical limitations with the eye tracking system that was used in the studies, as there were some eyesight restrictions (vision could be corrected within the interval of ± 4 diopters in steps of 0.5 dioptres, but no other correction could be made), that the view was somewhat impaired due to the frames of the eye tracking glasses, that calibration was needed for every participant, that the data analyses were time-consuming and that the tracking quality was sensitive to weather, mascara etc. However, use of eye tracking is one possible way to assess and evaluate if targets in traffic are attended to or neglected.

4.2.2. Workload

One of the aspects affecting the current situation and hence that sets the prerequisites for and needs of adaptive behaviour is workload. This aspect was assessed in Study II. Workload has been defined by de Waard and Lewis-Evans (2014) as the interaction between the task demands and the capacity, i.e. the capability of the operator to perform the task. Therefore, it is of interest to know if the traffic environment affects the perceived workload of the road user when performing an additional task.

There are many workload measures available, including physiological indices such as heart rate variability and electrical potential in the brain in response to events, but also subjective ratings such as the Bedford scale (Roscoe, 1984), the Rating Scale Mental Effort (RSME) (Zijlstra & van Doorn, 1985), the Subjective Workload Assessment Technique (SWAT) (Reid & Nygren, 1988) and the NASA Task Load Index (NASA-TLX) (Hart & Staveland, 1988). Carsten (2014) states that although workload can be measured by operationalised subjective means, caution should be used when the values are used, since there is no absolute value. It can however be used for comparison between different conditions in within-subjects designs.

The NASA-Task Load Index (NASA-TLX) scale is a multidimensional rating scale of subjective workload-related factors that was developed by Hart and Staveland (1988). The scale consists of six factors with the endpoints low vs. high for the factors mental demand, physical demand, temporal demand, effort and frustration level, whereas the endpoints for the factor performance is good vs. poor. In its original form, the subjective importance of each factor for the specific task should be used as a weight for that factor. In Study II, where text message interaction while cycling was investigated, the NASA-TLX was adapted to cycling. The scale was used mainly because of its non-intrusiveness and multidimensionality, which led to information about mental as well as physical demand, experienced time pressure, self-rated performance, effort and frustration. Compared to SWAT, it is also more sensitive for low workload conditions (Nygren, 1991). Since equal weights of the scale were used, the scale in the study is the NASA-Raw Task Load Index (NASA-RTLX) (Hart, 2006). The disadvantage of not measuring workload momentarily must be balanced against the intrusiveness of doing so and the easy implementation of the NASA-RTLX scale. In addition, the filling out of the scale was carried out quickly by simply placing a mark on a continuous line for each of the six factors concerning the last segment cycled. The adapted NASA-RTLX was primarily used for investigating if there was any experienced difference between segments cycled in the study.

An obvious problem with the NASA-TLX or NASA-RTLX is that the scale is used for a segment of a road, but given after the segment was cycled, not continuously. In addition, the scale is subjective and there will be different outcomes for different persons. However, since

the purpose of using the NASA-RTLX in Study II was to indicate whether there was any difference between cycling on a particular segment while e.g. receiving a text message or not in a within-subjects design, this was not considered crucial.

4.2.3. Complexity classification

In an everchanging traffic environment, it is apparent that the complexity of the current traffic environment affects the road user. Equating the same intersection and the same driver at separate occasions, once without traffic and once with a lot of traffic, is not correct. Several attempts have been made to rate complexity of a traffic scene in different ways and examples of these are presented in this section.

In a framework for task analysis by Fastenmeier and Gstalter (2007) a step-by-step procedure is performed that is derived from classifications of road traffic situations and a model of the drivers' information processing. The classification of road traffic situations includes road design (e.g. a two-lane rural road), road layout (e.g. a straight signalised junction with traffic lights) and traffic flow (e.g. bottlenecks and left turn). The driving task is divided into subtasks and behavioural requirements are organized into perception, expectations, judgement, memory, decision, driver action and errors. This is eventually used for calculating ratings of complexity. A high complexity task can consist of many requirements that have to be fulfilled under time pressure with high accuracy.

Another way of dealing with complexity is to provide anchor examples. Building upon the work by Fastenmeier and Gstalter (2007), Paxion, Galy, and Berthelon (2014) stated that low density traffic flow on a straight motorway should count as a simple situation, while a moderate density traffic flow on a rural road with a few curves would be a moderately complex situation and a busy city road with many curves would be a very complex situation. For other combinations of these features, for instance high density traffic flow on a motorway, it is not specifically stated which category of situation complexity would be appropriate. Other attempts to classify route complexity have been made through high or low demands on information processing and vehicle handling, respectively (Patten, Kircher, Östlund, Nilsson, & Svenson, 2006), for instance high/high (demands on information processing/demands on vehicle handling) complexity when driving within city centre environments, high/low or low/high complexity at intersections regulated by road signs or at signalised intersections, and low/low complexity driving unhindered in urban and rural areas and on motorways.

Anchor examples can also be shown to the participants in the form of video clips, as reported in a workload study by Schweitzer and Green (2007). In their study two video clips of forward road scenes, with the set anchor workload rating of 2 and 6, i.e. light and heavy traffic, respectively, were shown to the participants. After practicing, the participants were asked to rate other video clips of forward road scenes within the interval of 1 to 10, in relation to the anchors.

Some simulator studies varied traffic flow and presence of lane change (Teh, Jamson, Carsten, & Jamson, 2014) or buildings, oncoming vehicles etc. (Horberry et al., 2006) to create situations of more or less complexity. In other simulator studies, speed has counted as a factor contributing to the complexity of the situation. Examples are the three situations of driving on straight roads with essentially unvaried speed, approaching intersections where a stop should be made, and overtaking a slower vehicle, studied by Cantin, Lavallière, Simoneau, and Teasdale (2009).

Nunes and Recarte (2004), on the other hand, used a three-point scale for rating traffic complexity from video recordings of car driving. The scale was defined as 0, meaning that there are no vehicles or one vehicle visible, but very far away; 1 meaning that there is one vehicle visible ahead but that there is no significant action involved such as overtaking or being overtaken and there is no lane change; and 2 meaning that at least two vehicles are visible or that the driver is changing lanes or performing other more complex manoeuvres.

Another way of recognising complexity is to ask the participants, i.e. to employ road-user subjective rating. That speed is related to complexity was acknowledged by de Craen, Twisk, Hagenzieker, Elffers, and Brookhuis (2008), who presented photographed traffic scenes to participants and asked them to state their preferred driving speed for each scene. For each photo there was another, almost identical one, differing in one detail, increasing the complexity of the traffic scene. The participants could only look at one photo at a time and were not given the opportunity to go back. The paper does not explicitly state which details are considered to increase the complexity. However, from the cases revealed, a pedestrian walking close by the road on a traffic island, and a cyclist in the same lane looking over his or her shoulder are some examples.

Efforts have been made to rate complexity more implicitly while driving, exemplified by Hulse, Dingus, Fischer, and Wierwille (1989) who used a nine-point subjective rating scale for visual attentional demand rating when driving on a road. The rating should be given at the beginning of each roadway segment and was triggered by an experiment leader in the vehicle. The scale was linked to the drivers' ability to look away from the roadway, where 1 represented the lowest level of attentional demand and was defined as "Can look away from roadway for long periods, possibly 4 secs. or more. (Frequent and long duration looks away are possible.)", whereas 5 was defined as "Can look away from roadway for intervals of 1 to 1.5 secs., but no longer. (Looks away must be followed by quick return to roadway.)" and 9 represented the highest level of attentional demand and was defined as "Cannot look away from roadway for even a brief glance. (Total visual attention required by roadway.)" Besides the ability to look away from the roadway, the participants were also instructed to consider the type of roadway, the possibility of unanticipated traffic and the effects of intersections and interactions with other vehicles in their subjective rating.

Summary and development of complexity classification

Although classification of road traffic situations can be done according to Fastenmeier and Gstalter (2007), it is difficult to include all possible road designs and layouts and traffic flow constellations. The interaction between the components of this type of rating is on an aggregate level and not easily apparent. Use of anchor examples allow for more dynamic situations but are still limited to situations similar to the examples used and are therefore not applicable in all contexts. Rating the traffic complexity only does not acknowledge the margins that the road user has for adaptation and can be used in more static surroundings such as simulator settings. All these ways to classify complexity are in various degrees limited to a certain pre-defined setting.

The subjective rating scale by Hulse et al. (1989) was used directly on road users in traffic and was based on attentional demands, which is important for adaptation. In the attempts to code complexity in this thesis, a scale similar to Hulse et al. (1989) has been used, but for video analysis (Nygårdhs, Ahlström, Ihlström, & Kircher, 2018). This means that the

participants do not rate the complexity in any way, but that this is done subsequently from the video data, by the experimenters. While looking at the video, driver speed is a factor that contributes to the rating. Whereas the nine-point scale used by Hulse et al. (1989) contained three pre-defined benchmarks, at the lowest and the highest score, and the one in the middle, the aim here was to specify complexity for all points of the scale to reduce uncertainty. Additionally, to facilitate similar classification between experimenters, too many steps should not be included. This resulted in four complexity levels categorized in Table 3 and used in Paper II and III. The advantages are that speed is a factor integrated within the rating, that the complexity level is not subjectively rated by the participant and that the rating scale is easy to understand and apply. The complexity level is also independent of subjective workload.

Table 3. Complexity levels used by expert rater to classify traffic situations from video.

Complexity level	Time possible to close eyes or look away from road
0	> 3 s
1	1-3 s
2	< 1 s
3	Not possible

4.2.4. System acceptance scale

The system acceptance scale (van der Laan, Heino, & de Waard, 1997) was developed for measuring driver acceptance of new technology and was used in Study IV to assess how cyclists experienced a countdown to green system (see Figure 9). The nine items of the scale load onto two subscales, the usefulness scale and the satisfying scale, both ranging from -2 (totally negative) to +2 (totally positive). The scale is simple and quick to use and is well established as a standard for measuring user acceptance of systems in traffic.

I find the traffic light system I have experienced (please tick a box on every line)

1

Useful

Useless

2

Pleasant

Unpleasant

3

Bad

Good

4

Nice

Annoying

5

Effective

Superfluous

6

Irritating

Likeable

7

Assisting

Worthless

8

Undesirable

Desirable

9

Raising Alertness

Sleep-inducing

Figure 9. The system acceptance scale used in Paper IV. Adapted from van der Laan et al. (1997).

4.3. Discussion of methods

As pointed out above, different research settings as well as methods were applied in the studies included in this thesis. Study I was conducted in a simulator while the other three studies were conducted in real traffic. The difference between Study I and the subsequent studies is primarily a result of the fact that fast manipulation of static infrastructure is expensive and potentially dangerous to carry out in real traffic, and the fact that the situation of interest in Study I, driving a car at night on rural roads, can be simulated with a sufficient degree of realism. However, investigating people's behaviour in their everyday life in simulators or laboratory settings is in general inappropriate because it is impossible to evoke all aspects of adaptive behaviour in such settings. Therefore, it is crucial to have a realistic setting when studying these phenomena and semi-controlled studies offer a plausible way forward. Study II had the aim of investigating road-user strategies and was hence conducted as a semi-controlled field study in real traffic, as was Study III, which examined how road-user roles affected adaptation in a natural setting.

In traffic, visual sampling is one of the main sources available for information intake. Although eye tracking as a method has its limitations both in terms of technical issues and of what conclusions can be drawn about attention, it is the best measure accessible. It is impossible to know what the participants are thinking without asking them, but if they are asked, their natural behaviour is disturbed and the result will not be accurate. In studies II, III, and IV, data from eye tracking were used for analysing visual sampling, and for studies II and IV it was possible to examine if requirements based on the MiRA theory were fulfilled.

Acknowledging the fact that the traffic situation is an important determinant for human performance, and hence adaptation, there is a need to describe complexity in traffic in a comparable manner. Different approaches have formerly been used for complexity classification. While some of them aim to classify complexity from road and traffic features taking the researcher's point of view, others provide anchor examples from which other situations should be classified by participants. Anchor examples are still limited because there are uncertainties in how to interpret other situations. Asking the participants to make a road-user subjective rating of complexity while driving is another approach. However, an objective comparison between different participants in different situations cannot be made. Hence, complexity classification according to Table 3 was made from videos for investigating the possible influence of complexity on glance behaviour in studies II and III. Although the classification was new and untested, it was considered necessary to try an approach allowing for all kinds of environments and situations that can happen in real traffic, considering the real traffic setting used in the studies. The simplicity of the complexity classification with only four categories allowed for a rather time-effective rating over interesting situations.

For Study II, the NASA-RTLX scale was adapted for the specific road-user category (cyclists) and used for apprehending the subjective experience of different parts of the route. Although the scale uses a retrospective approach, it was here considered acceptable because of the need for a measure of workload that did not interfere with the cyclists' natural behaviour but could still be compared between participants. It was further used as a complement to observational measures, which were the main measures in this study.

Introduction of a new roadside piece of equipment in traffic in Study IV prompted subjective system evaluation in addition to the observational measures. The system acceptance scale was

chosen to have a simple and easy measure giving an overall opinion of how the cyclists as a whole perceived the new system. A disadvantage is that the subjective opinion is given in retrospect and may be influenced by the fact that the participant knows that the study is about this specific equipment and may e.g. be overly positive in the presence of the experimenter. To avoid this, the experimenter stated specifically that he or she was not involved with the roadside piece of equipment construction or installation and that the interest was to know what the participants really thought about the system. In addition, the system acceptance scale was preceded by other, open, questions concerning the participants' opinion of the system.

Summing up, different study settings as well as data capturing methods have their benefits and drawbacks. To illuminate the complex subject of road-user adaptation in the traffic environment, a battery of methods is necessary. The methods that exist today will be refined and new methods are constantly being developed, in the search for better understanding of human behaviour. In the next chapter studies utilizing the methods mentioned here are presented.

5. EMPIRICAL STUDIES

The studies included in this thesis examine adaptive behaviour in traffic from various perspectives and they each contribute to the understanding of road user adaptation. In Figure 10 an overview of the included papers (each corresponding to a study) and their focus is presented.

Figure 10. Rough overview of papers, how they are related, and which road-user types are studied in each paper.

Additional tasks are hence studied in Paper I and Paper II, while other road users are studied in Paper III, static infrastructure in Paper I and Paper III, and dynamic infrastructure in Paper IV. Paper I uses car driver participants, while Paper II and Paper IV uses cyclists, and both car drivers and cyclists participate in the study reported in Paper III.

- Study I was conducted as a controlled study in a moving-base car simulator, and was financed by a co-operation between the national road keepers of the Nordic countries, called NMF. The main aim was to investigate how different delineator post configurations affected driver speed. Paper I is based on this study and was published in *Accident Analysis and Prevention*, 2014.
- Study II was a semi-controlled field study with cyclist participants, carried out within the research programme “A strong research environment in the field of non-motorised vulnerable road users”, financed by the research fund of the insurance company Länsförsäkringar. The main aim of the study was to explore cyclists’ adaptation strategies when interacting with text messages in real traffic. Paper II reports this study and was published in *Cognition, Technology & Work*, 2018.
- Study III was a semi-controlled field study with cyclists and drivers, financed by the partnership programme FFI (Strategic vehicle research and innovation). The main aim was to investigate what trade-offs can be observed when driving and cycling in the same traffic environment and if the road-user role that a person is most familiar with

influences adaptation. Paper III is based on this study and was published in *European Transport Research Review*, 2020.

- Study IV was a before-after field study with cyclist participants, carried out within the EU project Xcycle (H2020 – 635975). The main aim was to examine cyclists' adaptive behaviour towards a countdown timer to green traffic light. The results of the study are reported in Paper IV, which has been submitted to an international journal.

Each study above is presented below including aim, method and main results. In addition, the contribution of each paper is stated.

5.1. Paper I. The effect of different delineator post configurations on driver speed in night-time traffic: A driving simulator study

The aim of the study was to investigate how different delineator post configurations affect driver speed in night-time traffic. The potential speed effect of introducing an additional task was also investigated.

The following predictions were made:

- Presence of delineator posts lead to increased driver speed compared to absence of delineator posts on the whole road stretch and in curves.
- Given that there are delineator posts present continuously on the road, driver speed is dependent on the spacing between them.
- Drivers reduce their speed in connection to an additional task.
- There is an interaction between presence of an additional task and presence of delineator posts, in terms of driver speed.

To investigate the predictions, a controlled car simulator study presenting the task of night-time driving on a rural road was conducted. The only visual cues were road markings and road delineators, see Figure 11.

Figure 11. An example view from the driver's position in the simulator study. Source: VTI/Björn Blissing.

Seven road delineator configurations were tested, where each differed from the others in the distance between the road delineators in at least one of the following road segments: on straight road stretches, before/after a curve, in curves with large radius, or in curves with small radius.

An additional visual distraction task, previously developed within the EU project HASTE (Jamson & Merat, 2005), was used and shown on a touch screen inside the simulator car, see Figure 12. The task was to look at the screen for any arrow pointing upwards and if so, push the button YES, and else push NO.

Figure 12. Two examples of the principle of the additional task used in the simulator study. To the left, the correct answer is NO, since no arrow is pointing upwards. To the right, the correct answer is YES, since there is an arrow pointing upwards.

A road stretch of 6 km including six curves was driven for each road delineator configuration, first without any additional task and then with the additional task appearing four times for each configuration. The configurations were counterbalanced to the extent possible given the limited number of participants. Data from fourteen drivers were analysed.

The results from Paper I show that absence of delineator posts lead to reduced speed. However, if there are delineator posts continuously present along the road, driver speed is essentially the same, regardless of the distance between the delineator posts. The results also imply that using more compact spacing of posts in curves with small radius as compared to in curves with a larger radius, could potentially reduce driver speed in curves with small radius. The speed reducing effect of an additional task only existed where the task was initiated, i.e. before a curve but not in or after the curve.

The outcome of the study was that:

- Presence of delineator posts did lead to increased driver speed compared to absence of delineator posts seen over the whole road stretch as well as in curves with a large radius. However, the same was not true in curves with a small radius.
- Given that there are delineator posts present continuously along the road, driver speed did depend on the spacing between them before and in curves but not after curves.
- Drivers did reduce their speed in connection to an additional task where it was initiated, i.e. before curves, but not in or after the curves.
- There was no interaction between presence of an additional task and presence of delineator posts, in terms of driver speed either before, in or after curves.

5.1.1. Contribution of Paper I

Paper I contributes by examining the effect of static infrastructure in road users' speed adaptation. It gives empirical examples of how road users adapt to visual guidance, suggesting that above a certain level of visual guidance, more detailed information does not have any effect on driver speed adaptation in non-complex situations. Situations that are more demanding (infrastructural or cognitive demands) seem to entail maintained safety margins by decreased driver speed. In more demanding situations, there are implications that more detailed information about the increased complexity leads to proactive adaptations according to the visual information.

Paper I also contributes by showing that a visual system-paced (initiated by someone else) additional task introduced before an upcoming complex situation, led to (reactive) speed adaptation in connection with the task, but that there was no added contribution of the additional task in the subsequent complex situation.

5.2. Paper II. Bicyclists' adaptation strategies when interacting with text messages in urban environments

The aims of the study were to investigate how cyclists adapt their traffic behaviour when texting and listening to music in a complex urban environment, and if they compensate enough to maintain safe traffic behaviour.

Forty-one cyclists participated in a semi-controlled study, using their own bicycle and smartphone in real traffic. A head-mounted eye tracker was used throughout the study, where each cyclist travelled two laps completing a total of 6 km divided into six road segments. For one of the laps, the cyclist was asked to listen to some audio of their choice via ear buds connected to his or her mobile phone. On three of the segments, a text message containing a question was sent to the cyclist. The cyclist was supposed to handle these messages as he or she normally would have done, if not being part of a study. The influence on attention was examined using measures based on static minimum attention requirements, while the complexity of the situations was accounted for by complexity classification according to Table 3, and workload was approached by requesting the cyclist to fill out a NASA-RTLX scale after each segment.

The results from Paper II show that listening to self-chosen audio through ear-buds while cycling did not affect workload, speed, SMS interaction or attention significantly. Seven different adaptive behaviours were identified when cycling and receiving a text message: The text messages were either ignored, handled when the destination was reached, handled by the cyclist making a specific stop to deal with the message, handled at a red light, read but not answered while cycling, read with a delayed answer while cycling, or read and answered in direct sequence while cycling. Figure 13 illustrates these behaviours and the outcomes of each behaviour.

Figure 13. SMS interactions. Total number of outcomes in parenthesis.

Individual cyclists applied different personal strategies for dealing with incoming text messages. Half of the cyclists sometimes read or replied to a message while cycling. One fourth of the cyclists never interacted with their phones before reaching their destination. The remaining quarter of the cyclists sometimes stopped before reaching their destination to interact with their phones, either by making a dedicated SMS stop or by taking the opportunity to deal with the text message while waiting for green at a traffic light, but they never interacted with their phone while cycling. There were no differences in the duration of glances towards the phone between the different complexity levels when interacting with the phone. Generally, the cyclists managed to integrate SMS interactions with their cycling behaviour. Nevertheless, there were two occasions when necessary attention criteria were violated in connection with texting.

5.2.1. Contribution of Paper II

Paper II contributes by giving empirical examples of adaptive behaviours in connection to additional tasks in an authentic road traffic setting. The tasks included both a system-paced (initiated by someone else) and a self-paced (initiated by the road user) component. How additional tasks are executed in a real-world setting was exemplified and discussed.

The paper suggested that road users have a personal strategy with respect to the maximum complexity of interaction they accept, and that the interaction can be modified according to the current circumstances. Almost half of the road users sometimes performed the system-paced component of the additional task while cycling and many of those (39%) performed the self-paced component while cycling too.

Paper II contributes to methodology in adaptation research by showing how eye tracking and the MiRA theory can be used for examining the effects that text messages have on attention in a complex real traffic setting. It further contributes to theory by exemplifying that the comfort zone is subjective while the safety zone is objective and that the comfort zone is not always

smaller but may in fact be larger than the safety zone. (In this case, the adaptation object was probably misinterpreted.)

5.3. Paper III. Trade-offs in traffic: does being mainly a car driver or a cyclist affect adaptive behaviour while driving and cycling?

The aim of the study was to investigate observable trade-offs when adapting to other road users and the infrastructure as a cyclist and as a car driver in the same traffic environment. The influence of the road-user role that the person was most familiar with (cyclist or car driver) was also examined.

Twenty-three participants, whereof twelve regular cyclists who seldom drove a car (character cyclists) and eleven regular drivers who seldom cycled (character drivers), participated in a semi-controlled study in real traffic. All participants were equipped with a head-mounted eye tracker and travelled a specified route in an urban environment twice, once while cycling using their own bicycle and once while driving a car. The car route was equal to the cycling route but extended in the end. The participants were instructed to behave as they normally would have, if not being part of a study. The influence of main road-user role and current road-user role on observable adaptive behaviour was studied in intersections of different types (mixed traffic/separate paths, signalised/unsignalised) using measures based on glance behaviour and video data, while complexity was classified according to Table 3. The extended control model was used as a framework for predicting adaptation.

Figure 14. Actions when cycling in mixed traffic at the intersection with stop rule. Result in total (number of outcomes for character cyclists + number of outcomes for character drivers).

The study revealed trade-offs in relation to rule-following, safety, efficiency and physical comfort. The results from Paper III show that adaptive behaviour is not governed by whether the road user is a regular cyclist or a regular car driver, but of the current road-user role and the demands for that role in the current situation. Cycling in a mixed traffic intersection with stop rule, different actions are performed by different persons, according to the traffic

situation (see Figure 14): If there was no traffic, about equally many stopped as did not stop formally, while if there was traffic, the majority made a formal stop, irrespective of whether there was a potential conflict or not.

Driving a car at the same intersection the participants stopped to a larger degree, irrespective of current situation in terms of potential conflicts in the intersection (see Figure 15).

Figure 15. Stopping behaviour when driving in mixed traffic at the intersection with stop rule. Result in total (number of outcomes for character cyclists + number of outcomes for character drivers).

Cycling in a signalised intersection, over 80 % looked over their shoulder before passing the intersection at green signal, for their own safety. Driving in the same intersection and turning right, all but one driver looked for vulnerable road users (VRUs) from behind before turning, and all drivers with an approaching VRU yielded to the VRU.

In an intersection where the cycle path was separated and situated on the right hand side of the car path, the side road to the right was checked significantly more in the current role as cyclist than as car driver. When cycling, there was no difference regarding looking into a side-road to the right between a mixed traffic intersection and an intersection where there were separated paths for cyclists and car drivers. However, significantly fewer drivers looked into a side-road to the right when approaching the intersection with separated paths, compared to in the mixed traffic intersection.

The highest complexity levels involved the highest gaze change frequency and the lowest number of glances to non-relevant objects. Whether the participants were in their most familiar role or not did not influence the results.

5.3.1. Contribution of Paper III

Paper III contributes to methodology in adaptation research by using the same participants in both familiar and more unfamiliar road-user roles in real traffic and gives empirical examples of adaptive behaviour with respect to other road users, both potential and present, from observations of two road-user roles.

Paper III further contributes by showing that the effect of main road-user role was overruled by the effect of the current road-user role and the demands and opportunities for that role. The study generated hypotheses suggesting that current prerequisites, in terms of environment, complexity and vehicle, determine the capacity for action related to adaptive behaviour.

The importance of the situational demands for comfort has been discussed and exemplified. The paper showed that the propensity to stop at an intersection where the stop rule applies, was primarily affected by the stop sign when driving a car but that while cycling, the tendency to stop appeared to be more associated with presence of other road users in the intersection. This has implications for the comfort zone, because breaking the cyclist's flow is more discomfoting compared to that of a car driver.

5.4. Paper IV. Cyclists' adaptation to a countdown timer to green traffic light: a before-after field study

This paper aimed to examine cyclists' adaptation to a countdown timer (CDT) to green traffic light, and if the adaptation had any detrimental effects on crucial information intake. ECOM was used as a structure for setting up hypotheses on observable cyclist behaviour and the MiRA theory was used for defining attention targets.

Twenty-six cyclists participated in a before-after study with a within-group design. In baseline, each participant was equipped with a head-mounted eye tracker and cycled with his or her own bicycle, also equipped with cameras, four times towards the same signalised intersection in real traffic with the traffic light to the left of the cycle path. There was also an experiment leader cycling behind the participant, filming the traffic environment. After baseline, a countdown timer to green traffic light was installed at the intersection on the right-hand side of the cycle path. The treatment study was conducted a year after baseline, using the same procedure.

The results of the study indicate that cyclists look for and use the information presented to them on a CDT showing the remaining time left to green traffic light. In general, the information was more used for their own efficiency and comfort than for safety, at least in the rule-based sense. The start-up delay times were reduced with the CDT, but the number of red-light violations seemed to increase. Overall attention to necessary targets was similar in baseline and treatment. Cyclists adapted their speed to the information of the CDT to try to avoid coming to a complete stop. Pedalling behaviour indicated that without the CDT, cyclists prepared to stop more than with the CDT. One participant stated that the CDT was beneficial for keeping the flow because of other road users' adaptation to it. The cyclists in general found the CDT quite useful but thought it could be improved, with the most common improvement suggestion to place the CDT and the traffic light on the same side of the cycle path.

Figure 16 shows the distribution of glances in relation to the distance from the intersection in baseline and treatment, respectively. It can be observed that the glances to the CDT are taken from glances towards the traffic light. The same pattern is noted during the last two seconds before setting off after a stop, see Figure 17.

Figure 16. Glance distribution in relation to distance from intersection. Glances when standing still excluded.

Figure 17. Glance distribution during the last 2 s before starting to cycle after having stopped at red light.

During the last two seconds before moving after a stop, neither the traffic light nor the CDT was monitored in about half of the cases both in baseline and in treatment. For the cases in treatment where glances to either the traffic light or the CDT were observed, the largest share was to the CDT only.

5.4.1. Contribution of Paper IV

Paper IV contributes by assessing adaptive behaviours related to a dynamic infrastructure system. The added detailed information given by the system was appreciated by the road users and used in addition to the standard information system.

The findings of Paper IV suggest that road users strive to stay within the comfort zone using the available means of detailed predictive information. Examining adaptive behaviour towards a CDT for cyclists in addition contributes to the applied field since studies in this area have been very few.

5.5. Methodological considerations

In this thesis, the primary unit of analysis is individual road users, not overall behavioural adaptation of road users as a collective. The advantage is that the same road user can be examined in different situations, and individual adaptive behaviours can be studied in response to changes in visual guidance, vehicle, with or without an additional task, with or without a support system.

None of the studies performed within this work incorporated all interesting aspects to consider. Instead, they complement each other in digging into the subject of road user adaptation. While the controlled study has its advantages of varying an interesting factor while keeping other aspects constant, the ecological validity is higher in the semi-controlled studies. On the other hand, all kinds of circumstances can influence behaviour and since it is important to compare relevant things, the analysis becomes more complicated. Then again, the ecological validity is larger when behaviours are performed “in the wild” which goes for all field studies in this thesis: In a natural setting it should be kept in mind that taking chances in the study equals taking chances in real traffic and this may cause fines and, even worse, injuries or death.

There are numerous ways of designing additional tasks that are intended to correspond to real tasks in traffic that are not immediately related to operating the vehicle. In this thesis two extremes were given; one was totally made up and would never happen in a natural setting, and the other was a commonly occurring task in real traffic. The advantage of using the invented task was that it was equally unknown to all participants, so that there were no biased interactions. This task was a system-paced task which was given to all participants at the same position for causing a distraction from the driving task that needed both perceptual and motoric attention. The other, more natural, additional task was probably more familiar in traffic to some participants and less to some. The basis for using this task was to detect naturally occurring adaptive behaviours in relation to an ecologically valid task.

In Study IV a full year passed between baseline and treatment. During this time span, outside of the study, the approach to the studied intersection was renewed. The most apparent changes were the colour of the cycle path (changing from red to dark grey) and that there was lane separation for cyclists’ turning right in baseline but not in treatment. Although it cannot be ruled out that these changes have had an effect, for instance in where cyclists turning right position themselves to the right of the cycle path, the probability of behaviour change in relation to the introduction of the CDT is estimated as low.

Some additional issues with real-world resemblance in the studies are given here:

- In the simulator study, the exact level of the speed is not to be considered as on the road, but speed differences between delineator configurations should be correct. A validation study on a real road (Rajamäki, Luoma, & Rämä, 2013) was carried out after the simulator study with four of the seven road delineator configurations. This study could not verify the results from the simulator, which might be explained by varying weather and road surface conditions during the two months that the study was conducted.
- Conducting a simulator study, motion sickness is an issue affecting who will participate, both when recruiting people and when the study is conducted. Although this is a restriction on whose data is collected, this was not perceived as a major

problem of the study here where different visual guidance features should be compared by means of driver speed.

- Participants in all the three field studies carried eye tracking glasses. Due to the large sidepieces, it is possible that the gaze behaviour was supplemented with more head movements than if the participants would not have worn them. However, all participants were affected equally in all conditions and the information gathered by visual sampling is considered unlikely to change by the restrictions of the eye tracking equipment.
- The field study with mainly car drivers vs. mainly cyclists whose task was to cycle and drive a car along a predefined route is considered quite ecologically valid, since what differed from normal riding and driving was the presence of an observer and wearing eye tracking glasses. In the driving condition, however, the car was unfamiliar to the participants.
- The field study with cyclists riding through the same intersection four times per participation occasion, with one year in between, cannot simply be assumed to be free of familiarity issues. The participants were chosen based on their recurring cycling in the area and therefore familiarity with the intersection was high. Familiarity with the CDT in the treatment phase varied though. However, when comparing the first lap with the other laps, no differences in either the time on approach or stopping duration were noted. Therefore, different experiences with the CDT were neglected in the analyses.

6. THEORETICAL AND EMPIRICAL IMPLICATIONS

From theory on adaptation, attention and behavioural models, adaptation in the road traffic environment can be viewed as the road user setting the safety margins of the comfort zone according to his or her present state and capability. Adaptation can however only be measured in terms of perceivable adaptive behaviour, which is reported in the papers of this thesis and further discussed below. Adaptive behaviour is shown in the adjustments made to have large enough subjective safety margins, i.e. as perceived by the road user. Proactive adaptive behaviours are applied if the road user predicts that the margins will be too short otherwise, while reactive adaptive behaviours are employed when the subjective safety margins are already too short.

Behavioural models depict adaptations in different ways. In common for several of the models is that adaptive behaviour can be viewed as the adjustments made to maintain safety margins of the comfort zone. Here, the comfort zone is defined by its subjective safety margins when they are sufficiently large for a feeling of comfort. The margins differ depending on how close to the subjective safety zone boundary it is comfortable to be for different functional control variables, in line with the perspective of Summala (2007) described in 3.2.9. The safety margins and the comfort zone depend on what state the road user is currently in. Road user state depends on the internal and external factors that may influence adaptation, where being in a hurry and driving through a non-complex road environment can allow for decreased safety margins, whereas being well-rested, driving on icy roads and carrying a load that needs to be handled with extra care may lead to increased safety margins. Note that in both cases, the road user operates within the comfort zone, as long as he or she feels comfortable.

Not only driver state but also the capability of the driver matters for setting the safety margins. A person experiencing low capability can set the margins larger than a person experiencing high capability of conducting the task. For instance, inexperience with a certain vehicle, route or system can increase the safety margins. It is important to acknowledge that these are *subjective*, and not *actual* safety margins. Even though a driver thinks that he or she has set the safety margins so that there is extra space for taking decisions on a non-familiar route, these may still not suffice for the driver to handle a demanding situation without loss of control.

Figure 18 shows a conceptual model of how comfort zone, discomfort zone, adaptive behaviour and subjective safety margin are linked together for a road user within his or her comfort zone. While the objective safety margin (or rather margins, in different directions) always follows the road user, the subjective safety margin(s) is not considered by the road user as more than sufficiently large, as long as he or she is within the comfort zone.

Figure 18. Conceptual model showing relations between comfort zone, discomfort zone, subjective and objective safety margins and adaptive behaviour for a road user (depicted by a yellow circle) within the comfort zone.

The boundaries of the comfort zone and of the subjective safety zone continuously change in time and space, according to external and internal factors. External factors are attributed to the context and present situation, whereas internal factors include the capability, internal state, emotions and feelings, personal strategy and goals that the road user has. If ECOM is applied to this, the setting of safety margins for the comfort zone is seen as a combination of more steady conscious strategies decided upon in the higher layers of ECOM, and more instantaneous decisions that may be either conscious or nonconscious and carried out in the lower layers of ECOM, related to the present context, but also to internal factors that are not a part of ECOM. When the road user is outside the comfort zone the subjective safety margins are shorter. This can be acceptable under certain conditions, i.e. with extra motives (Bärgman et al., 2015; Näätänen & Summala, 1976). Näätänen and Summala (1976) proposed six categories of extra motives: Goals set for the trip or during it, emotions (in a traffic situation or external to traffic), behavioural models (e.g. norms among the road user's social group), showing off and the need to prove oneself, hedonistic objectives (pleasure of driving) and, finally, risk for risk's sake. Although there might be such extra motives, there is also a personal limit concerning how small the road user is willing to let the subjective safety margin be. This is here called the non-acceptable part of the discomfort zone and it is an area which the road user would never enter deliberately. The predictive processing framework (Lupyan & Clark, 2015) is useful for understanding the constant interactions between predictions made both in higher and lower layers of ECOM and the corresponding prediction errors. As illustrated in the figure, there can be a discrepancy between the subjective and objective safety zones. This is not apparent to the road user until predictions are evidently incorrect. If outside of the objective safety zone boundary, control is lost and an unplanned outcome will occur, which can range from a skid to a fatal crash, depending on the vehicle, other traffic and surrounding infrastructure.

Figure 19. A-F illustrate different traffic situations. A: Small objective safety margin. B: Large objective safety margin. C: The subjective safety margin exceeds the objective safety margin. D: Proactive behaviour is performed to stay within the comfort zone. E: Road user in the acceptable part of the discomfort zone. F: Road user in the non-acceptable part of the discomfort zone.

Figure 19 exemplifies how the conceptual model is affected by different traffic situations. In A, the road user utilises the capacity of the traffic system as the comfort zone boundary is close to the subjective as well as objective safety zone boundary. In B, on the other hand, the subjective safety zone is much smaller than the objective safety zone, e.g. when a driver thinks that the road surface is slippery and drives with extreme caution when in fact it is not. In C, a situation is illustrated that is more hazardous than the road user thinks, e.g. due to a combination of icy roads and bad tyres. D illustrates proactive adaptations made by the road user to an anticipated situation to stay within the comfort zone, such as a cyclist stopping before initiating a call. As soon as a functional control variable is not within its acceptable range, the feeling of comfort is lost, and the comfort zone boundary is exceeded as illustrated in E and F. In E, the road user is within the acceptable part of the discomfort zone and may choose to stay there under certain conditions, or to perform adaptive behaviour to return to the comfort zone. The road user can also act proactively, to avoid the non-acceptable part of the discomfort zone. The road user in F has entered the non-acceptable part of the safety zone, for instance as a result of experiencing visual impairment from glare, and adaptive behaviour is performed to increase the safety margin.

6.1. Road-user adaptation in response to static infrastructure

The results in Paper I show that presence or absence of road delineators affects adaptation in terms of speed behaviour more than the exact distance between the delineators. When the visual guidance is adequate, more detailed information does not affect the subjective safety margins because the road user is already within the comfort zone and the overall feeling of comfort remains. The substantial speed reduction related to absence of road delineators can be interpreted as the visual information being insufficient for accurate prediction of the future path given the current speed. Adaptive behaviour is then adopted to return to the comfort zone where the driver feels in control of the situation and the safety margins are satisfactory. The study by Kallberg (1993), where driver speeds increased on roads with low but not with high geometric standard when road delineators were introduced, also supports this: When predictions of the future path are experienced as hard but turn out easier, drivers may have extended their comfort zone in relation to the current infrastructure. On roads with a higher geometrical standard, more detailed visual guidance does not influence the predictions to any larger extent, and they are already good enough for the driver to perform within the comfort zone.

There are implications that drivers make proactive adaptations to upcoming curves by reducing their speed more to curves ahead with a small radius compared to curves with a large radius, given that the distance between the road delineators is smaller in the curves with small radius than in those with large radius. This implies that a way to make it easier for drivers to perceive that there is a sharp curve ahead, and hence to adapt their speed appropriately, is to place road delineators more densely together in those curves than in milder ones. This probably triggers bottom-up attention which makes them more aware of the objective safety margins by way of road boundaries, which in turn makes them adjust their subjective safety margins to stay within the comfort zone. The speeds in curves with smaller radii were always lower than in curves with larger radii, which means that reactive speed adaptations when the driver has already entered the curve also occur, when the boundaries of the comfort zone are exceeded.

Findings from Paper II and Paper IV revealed that not all the necessary attention requirements in intersections were attended to. One reason for this could be that the zones for attention requirements are wrong. Another could be that the eye tracking measure is not adequate. As previously stated, eye tracking is not an exhaustive measure for attention, not even for visual input, and leaves non-visual cues, such as audio, neglected. When cycling in open air, both visual and audible information is mostly present. However, audible information can guide visual sampling and hence, if hearing a threat (i.e. a prediction error, according to the predictive processing theory) the focus of the eyes can move towards the source to sample more information. If no threat is heard, however, the foveal attention of the eyes may not change, so that the person is not considered attentive from an observer perspective. In the case that the attention requirements were implemented properly, and the eye tracking was adequate, then the observed inattention can have consequences for traffic safety. If a road user is inattentive to the necessary attention requirements, this can be due to a mismatch between the subjective and objective safety margins and can have severe consequences for his or her own safety and that of others. In a situation studied in Paper II a participant seemed to have mistaken the green traffic light for cars as the one for cyclists and went on to cross the intersection, negotiating with a car turning right as a result. In the conceptual model in

Figure 18 this is a case of lost control where the cyclist was saved by others and had to make new predictions from bottom-up stimuli due to the right-turning car, leading to adjusted subjective safety margins.

Other adaptations in relation to the static infrastructure include riding on the pavement along a mixed traffic road in Study III. Although it is prohibited to ride a bicycle on the pavement, some people still did so rather than using the road. At least three possible alternatives for this behaviour can be discerned: 1) The cyclist does not know that he or she is supposed to use the road. 2) The cyclist trades rule-following for perceived safety. 3) The cyclist trades rule-following for efficiency. For the first alternative, information and clarity of the infrastructure should help to diminish confusion. For the last two alternatives, which may in fact apply simultaneously, the cyclist knows that it is not legal, but experiences that the (safety) loss of riding in mixed traffic or (efficiency) gain of using the pavement surpasses the lawful behaviour. This is in accordance with the efficiency-thoroughness trade-off (ETTO) principle, in which a continuous trade-off between efficiency and thoroughness are made depending on the main concerns for the moment (Hollnagel, 2012). The cyclist may feel that his or her safety margins cannot be made satisfactorily large on the road, hence being pushed into the discomfort zone. Due to different perceptions and motives for different persons, some people act within the acceptable part of the discomfort zone and stay on the road, while others ride on the pavement to increase the subjective safety margins. Changes in the infrastructure can affect the comfort zone. Going from a cycle path to a mixed traffic road might either decrease the comfort zone, increase it or leave it unaffected, depending on the individual and other situational demands. For some persons, the increased space given by a road in relation to a cycle path increases the comfort zone and the road may be preferable and perceived as more efficient. Some road users may be indifferent to the variation in infrastructure and stay in their comfort zone, while others feel that they are being pushed out of it. This is supported by (Ihlström, Henriksson, & Kircher, submitted) in their finding that cyclists who feel uncomfortable sharing the road with motorized traffic either choose to ride on the pavement or continue to ride on the mixed traffic road, e.g. because they do not want to behave illegally. In this thesis this is interpreted as extra motives in line with Näätänen and Summala (1976).

In Study III, it was also found that the setting and context, i.e. the situational demands, affect adaptation. That the specific situational demands affect coping behaviour in traffic has previously been recognized by e.g. Hennessy and Wiesensthal (1997). Situational demands include those represented by both infrastructure and traffic. While the infrastructure sets the arena in which behaviour can be performed, it also gives the road user expectations of the future path and traffic. These expectations, which are also influenced by current regulations, affect how the road user prepares for an upcoming situation. If the road user feels discomfort due to the predictions being uncertain, he or she can adapt, for instance by slowing down, increasing the time available for acquiring information to improve the prediction and hence return to the comfort zone. If the road user is within the comfort zone but has wrong expectations, adaptive behaviour towards an upcoming situation may be inappropriate. This has e.g. been shown in a simulator study by Martens and Fox (2007), where repeated exposure to an intersection lead to certain expectations, leaving a change in the priority situation unnoticed by the participants.

6.2. Road-user adaptation in response to dynamic infrastructure

Paper IV revealed several adaptive behaviours in relation to the traffic light and the CDT. In general, cyclists used the dynamic infrastructure to be effective and to avoid discomfort proactively. With the traffic light only, at red they stopped pedalling early to avoid the effort of coming to a complete stop and continued to roll and pedal when the traffic light was green. The physical effort of stopping and starting over also breaks the riding flow, which is often not preferred (Broach, Dill, & Gliebe, 2012). It seems that the more detailed information given by the CDT led to better predictions and allowed for the cyclists to continue pedalling to a larger extent, while still being within the comfort zone in anticipation of the green traffic light without having to stop. Cyclists adapted to the CDT by searching for and taking in information from it and using it for improved predictions in their speed adjustment. If a stop was inevitable, then the CDT was used for predictions and hence efficiency in terms of reducing start-up delays but there were also cases of red-light violations. These effects have also been shown in relation to CDTs showing the remaining time left to green for car drivers (Chiou & Chang, 2010; Islam, Hurwitz, & Macuga, 2016; Liu & Kircher, 2018; Wenbo, Zhaocheng, Xi, & Feifei, 2013; Yuan, Zhang, & Lei, 2009). This can be interpreted as the subjective safety margins being large enough for the road user to move while expecting green signal, in relation to the discomfort of frustration with unnecessary waiting time or, at least for cyclists, of having to travel within a crowd, which could be the result of waiting a bit longer. These perceptions are individual but also context-related since they can vary depending on traffic and familiarity with the intersection and traffic light. For the kind of dynamic infrastructure examined here, i.e. two information sources concerning the same circumstance, but on different levels of detail, the cyclists applied visual time-sharing. Using this strategy, the more detailed information of the CDT contributes to the prediction of the traffic light, which formally decides when to go and hence needs to be checked. By prediction, the road user controls that the safety margins are large enough for comfort.

6.3. Road-user adaptation in response to additional tasks

Results from Paper I show that when drivers received an additional task before a curve ahead, they slowed down before the curve, but there was no speed reduction due to the additional task in or after the curve. This implies that the drivers were proactive in the sense that they tried to deal with the additional task before the curve and reduced their speed then, so that they didn't have to deal with the demands of the curve at the same time as the additional task. This can be a strategy to keep within the comfort zone, or at least within the acceptable part of the discomfort zone, in more complex situations. Other simulator studies (Oviedo-Trespalacios, Haque, King, & Washington, 2017) support this, showing that drivers who had to engage continuously in an additional task (a mobile phone conversation) when driving chose a lower speed driving along a curved road compared to when they did not have any additional task.

In Paper II, listening to a self-chosen audio with ear-buds while cycling did neither affect the cyclists' experienced workload, which varied on low levels, nor their speed. The possibility that listening while cycling could have had an impact on speed if experienced workload had involved larger variations cannot be excluded since this could have affected the comfort zone. Furthermore, with experimental control of the volume level and content of the audio, listening has been reported to impair cyclists' response to other auditory signals (see de Waard, Edlinger, & Brookhuis, 2011). Hence, the results in Paper II indicate that if cyclists can

decide for themselves, they choose a level of volume and a content that they are able to listen to without exceeding the boundaries of their comfort zone.

The empirical material supports the claim that comfort zones differ between individuals, because the cyclists in Paper II applied different strategies for dealing with incoming text messages on an individual level. The maximum complexity of interaction can be consciously decided upon as a personal strategy, while the interaction in a given situation is highly context specific. When the additional task is announced, the road user may not feel that attending to the task is as important as efficiency of the trip and as a result keeps on cycling without attending to it. If the cyclist is forced to stop and wait, for instance at a traffic light, the efficiency cannot be influenced by the cyclist without violating the rules, and other goals or tasks can emerge as important, such as attending to the text message. Given that the cyclist feels comfortable with this, this is carried out within the comfort zone. If the context changes, e.g. by the traffic lights turning green, and this is noted, the efficiency goal can rise again, and the road user may feel that he or she is pushed into the discomfort zone unless continuing cycling. Either the cyclist finalises the interaction while in the acceptable part of the discomfort zone or decides to abandon the task in favour of the efficiency goal.

For cyclists who do not feel that the cycling efficiency goal is dominant, additional tasks can have higher priority and a location can be chosen where the comfort zone is intact, by making a dedicated stop. Alternatively, the individual can incorporate the task within the personal comfort zone while cycling by controlling factors such as speed and choosing an appropriate context for interaction. This way, the additional task is integrated within the cycling task and the subjective safety margins can be maintained. The adaptive behaviour of reading a text message with a delayed answer while cycling implies that the cyclist could read the message in a certain environment or situation but waited for a better opportunity before replying, which requires both perceptual and motoric skills. If the cyclist is within the comfort zone in a given context, the decision to check the text message could be taken. While cycling and reading the message, the cyclist may feel that he or she is pushed into the discomfort zone, either because of the added demands of the reading task or of changing context, or both, possibly making predictions of the future path insufficiently precise for comfort. Then the answering of the text message is postponed to when the cyclist has returned to the comfort zone, where the subjective safety margins are sufficient, i.e. when the cyclist estimates that the current situation allows for interacting with the additional task within the comfort zone or at least within the part of the discomfort zone that is acceptable under certain conditions.

6.4. Road-user adaptation in response to other road users

The results from Paper III demonstrated that cyclists showed different adaptive behaviours in relation to presence of other traffic in a mixed traffic intersection with stop rule. The major part of the cyclists stopped formally if there was traffic in the intersection, irrespective of whether there was a potential conflict or not. This was not the case if they did not encounter any traffic, where about half of the cyclists did not make a formal stop. Presence of other road users, i.e. basically the relevance of the stop rule, appears to be an important determining factor of rule compliance for cyclists. The behaviour was related to the road-user role, because traffic in the intersection did not lead to that much different adaptive behaviours when driving a car, since most made a formal stop, irrespective of traffic situation. This difference between driving a car and riding a bicycle can have various reasons. One could be the more formal rules that are associated with driving a car and reflected in that the fines are

higher for neglecting the stop sign with a motorised vehicle than with a bicycle (at least in Sweden, where the study was conducted). Another could be the different physical setting that is related to the different types of vehicles: at the stop line a cyclist is situated closer to the intersection and has a more unobstructed view from higher up compared to a car driver. In addition, the physical effort of stopping and starting over is higher when cycling than when driving and is more important to avoid for a cyclist than for a driver.

As previously noted (in Section 6.1), some cyclists rode on the pavement on the mixed traffic section and one possible explanation of this behaviour might be that avoiding motorised traffic is perceived as safer than sharing the road. Pavement cycling is further investigated in (Ihlström et al., submitted) where the phenomenon is considered as rational in mixed traffic when infrastructure is unclear. Since the safety margins need to be large enough for the road user to be within the boundaries of the comfort zone, in this case the comfort of the cyclist is clearly affected by the infrastructural setting and the eventuality of motorised traffic in the same lane. For the majority of cyclists who used the mixed traffic road for cycling, it is not clear whether this was within their comfort zone or not. If it was not, then there might be extra motives to have a feeling of discomfort, in accordance with the term of Näätänen and Summala (1976). The most reasonable ones here are goals set for the trip (“obey the rules”), emotions (fear of reprisals) and norms (“we do not use the pavement for cycling”).

Paper III also revealed that cyclists going straight and car drivers turning right in a signalised intersection adapted to each other. From an individual perspective, the situational demands, in terms of presence, intention and relative speed of the other, expected time until red and the restriction of the regulations seemed to determine who went first. All these aspects are inferred by the individual, and the future course of events predicted. Although the regulations state that drivers should yield to cyclists in this situation, most of the cyclists checked that they were given right of way before passing the intersection. This behaviour can be interpreted as a way to check and maintain the safety margins of the comfort zone, i.e. to perform proactive adaptive behaviour according to the description in the beginning of this chapter. In addition, an individual road user can affect the objective safety margins of other road users. If the light is green for right-turning vehicles and for cyclists going straight ahead, a car driver can slow down or stop well before the intersection, increasing the objective safety zone for a crossing cyclist. On the other hand, the objective and subjective safety margins can both be decreased by a car driver driving close to a crossing cyclist. Conversely, a crossing cyclist can affect the (objective and subjective) safety margins of a car driver. Renner and Johansson (2006) emphasise that the capacity for coordination, i.e. adaptation between road users, in traffic should be enhanced. This would mean that it should be easier for road users to maintain each other's safety margins. The most obvious example of adaptation between road users was found at an intersection in Study II, where a cyclist was saved by a car driver when the cyclist's prediction in retrospect was wrong and the subjective safety zone exceeded the limits of the objective safety zone.

7. GENERAL DISCUSSION AND CONCLUSION

The theoretical frameworks that are included in this thesis are synthesized by defining adaptation in the road traffic setting in relation to the road user's subjective safety margins and comfort zone. In addition, adaptive behaviour is perceived as how the adaptation is operationalised, and hence is observable from an outside perspective. All studies examine factors affecting adaptive behaviour in the road traffic environment. The major theoretical contribution of this thesis is the development of the conceptual model of comfort zone in Chapter 6 that describes when and why adaptive behaviour in traffic occurs. In this view, proactive adaptive behaviours are employed in the light of predictions made by the road user of upcoming situations that would otherwise result in too small safety margins. Reactive adaptive behaviours are, on the other hand, performed when the current traffic situation already provides too small safety margins. Adaptations can occur proactively in the comfort zone, proactively or reactively in the acceptable part of the discomfort zone, and reactively in the non-acceptable part of the discomfort zone.

Examples of adaptive behaviours of road users in response to static and dynamic infrastructure, additional tasks and other road users, have been demonstrated. In general, these correspond well with the concept of the comfort zone where the road users have a feeling of comfort as long as their subjective safety margins are sufficiently large, but that adaptations are carried out when these margins are exceeded or are predicted to be exceeded. The results illustrate that the subjective safety margins can extend beyond the objective safety zone. It is indeed possible that the subjective safety zone can be smaller than the objective safety zone, e.g. depending on experienced capability, but this was not shown in this work.

According to the often-used definition of the comfort zone (Engstrom & Ljung Aust, 2011; Ljung Aust & Engström, 2011; Panero, 2018), a feeling of discomfort leads to adaptive behaviours. Unless this feeling does not have to reach consciousness, I tend to disagree. There are adjustments carried out within the tracking layer of ECOM all the time, such as small corrections of steering and speed, which are not necessarily deliberated but performed automatically.

The subjective safety margins of the comfort zone are set in accordance with both the road user's capabilities and his or her personal strategies. The strategies involve trade-offs between goals, which are evident in ECOM where one goal can be suspended for a while, to the advantage of another. Support for this perspective was given by the resulting interactions connected to the ecologically valid additional task. The invented additional task vividly called for attention and needed to be handled within a certain time limit regardless of the road user's current driving task. The ecologically valid additional task did not call for attention acutely, and the road user could decide to neglect it or choose an appropriate location for handling the task. Considering that executing the natural additional task while moving did not cause any delay, the locations were probably chosen deliberately and not at random.

Another examined phenomenon was how the invented additional task, which can be seen as an externally paced adaptation object, led to reactive adaptive behaviour in terms of speed reduction, that was only present in connection to the task initiation. The effect of the adaptive behaviour was not prolonged further, i.e. the speed reduction caused by the additional task did not affect the total speed reduction in connection to the complexity of the static infrastructure ahead. Hence, people tend to get rid of the task and shift focus to the next task, and static

infrastructure affects behaviour more than an additional task. The infrastructure will affect comfort, and possibly safety margins, in a more tangible way because the physical environment is changed, as opposed to the additional task which affects cognitive comfort.

Information level of detail for static and dynamic infrastructure was investigated in the thesis in Paper I and Paper IV. It appears that if the (top-down) predictions are correct, the road user is within the comfort zone, and more detailed information about visual guidance does not alter the behaviour. However, if the future path is more uncertain and adaptive behaviour is needed to maintain safety margins, then people use more detailed information available, consciously or non-consciously, to carry out proactive adaptations.

Complexity affects the capacity for action related to adaptive behaviour. When the situational demands (complexity levels) are highest, predictions need to be verified more thoroughly (comfort zone margins need to be maintained) and road users focus more on taking in relevant information by changing their gaze more frequently and neglecting non-relevant objects (Paper III). Furthermore, people have different personal strategies with respect to the maximum complexity of interaction with an additional task that they accept (Paper II). If the situational demands are too high, focus is not shifted to an additional task until demands are lower. Only a few interactions were conducted at the highest complexity level in Study II and for the other complexity levels, there was no difference in glance duration towards the adaptation object. A hypothesis is that additional tasks are handled when the road user thinks that his or her capacity to handle the task is sufficient considering the current complexity, whilst fitting with the personal strategy (see also de Waard, 1996).

The external demands make up the structure for how the individual can and will act to keep the safety margins sufficiently large. This work has contributed by acknowledging that external demands in traffic are imposed by the current road-user role, which contains a certain type of vehicle and infrastructure setting. In addition, these factors determine the available options for adaptive behaviour. This is in line with situated cognition which emphasises the importance of the context in which actions are carried out (Lave & Wenger, 1991; Suchman, 1993; Suchman, 1987). From the perspective taken here, the actual behaviour performed is a matter of predictions made by the road user, personal strategy and capability, i.e. also of the internal processes. The capability depends on the means available and it should be acknowledged that when cycling or driving, the individual does not act alone, but all the time together with (and restricted to) the vehicle. Using the description by Hollnagel and Woods (2005), the two components of person and vehicle form one of the smallest aggregations of a joint cognitive system, a JCS. Another smallest aggregation of a JCS is that of two persons working together, which could be interpreted in traffic as two road users adapting to each other, since adaptive behaviour towards other road users is not an isolated issue, but an interaction that depends on the adaptive behaviour of the other part or parts. Coordination between road users is indeed crucial, but is an aspect that is often neglected in road-user models (Renner & Johansson, 2006). Nonetheless, the emphasis of this dissertation is on the single road user, and how he or she adapts in relation to various factors affecting adaptation, here called adaptation objects. Hence, although it is an important area to investigate in traffic research, road-user coordination as such is outside of the scope of this work. Adaptations in traffic are not perceived as going on inside the individual only and detached from the rest of the world. Instead, the adaptation is performed within a certain context, with external and internal demands and prerequisites attached to it. In this thesis, the unit of analysis is the

individual while the vehicle, infrastructure, other road users and additional tasks are viewed as contextual factors.

The same person can have different comfort zones depending on the current road-user role, not only depending on the overall strategy of the individual, but also on the trade-offs that are made in connection to the available means of transportation and the corresponding effort. This can clarify why more formal rules are broken when cycling than when driving. The rules are not broken without distinction, rather the functional rules, with the overarching goal of no accidents, are followed. There are numerous ways of explaining why drivers do not break the rules to the same extent. One reason might be that regulations are often formed from a driver perspective. Another could be that the fines are higher for driver violations, and a third might be physical restrictions with no option to go to the side if something happens. The vehicle and the infrastructure hence form the options. The bicycle offers another physical setting for the cyclist and at the stop position at an intersection, the cyclist is closer to the intersection and the eyes are positioned higher up from the ground, allowing for a better overview of the situation. If the situational demands are such that they allow for a better prediction of relevant future events, such as traffic and traffic signals, the road user will use this information to achieve his or her goals. If the context, such as current infrastructure and signage, presents an uncertainty in relation to the existence of and/or what could be expected from other traffic, the road user strives to minimize this uncertainty, either by changing the situational demands (e.g. pavement riding) or by increasing the information intake. For adaptation objects in general, the current and predicted situational demands together with the internal state, strategy and capability, determine what adaptation is carried out.

Although external factors are included in ECOM, by situation assessment in the monitoring and tracking layers (Hollnagel, 2016b), ECOM does not explicitly state the role of internal factors. The internal factors are described by goals, targets, plans, objectives and current understanding, but the prerequisites for determining the goals, such as emotions and feelings, are not visible in the model. Instead, these are accounted for in the conceptual model in Chapter 6, based on the multiple comfort zone model. The conceptual model acknowledges that there can be a part of the zone outside of the comfort zone that the road user can be willing to accept under certain conditions but that there is also a certain boundary which will never be exceeded voluntarily. Adaptive behaviours can be performed proactively, as a result of predictions, and reactively, when the subjective safety margins are not large enough for experienced comfort.

In the view of theory and the results of the studies reported within this thesis, the surface of what adaptation and adaptive behaviours in traffic are, has begun to be scratched. The results reported call for other studies to be carried out to develop the understanding further. In this sense, the number of participants, means of transportation, participant cohort and methods used could be increased or developed. There are also other possible aspects that could influence road-user behaviour apart from static and dynamic infrastructure, other road users and additional tasks, such as one's own vehicle, internal factors, policies and legislation. Future work could include how adaptive behaviour is influenced by internal factors such as being in a hurry, habit, waiting for an important telephone call or emotions such as anger. To impose those internal factors naturally is however difficult and more knowledge is needed. Every factor examined in this thesis could also be examined in other ways, for example the number of additional tasks used in the studies here was limited, and there could be numerous

more, possibly affecting adaptive behaviours in other ways. The same reasoning goes for both static and dynamic infrastructure, which could have very different visualisations. “Other road users” is a factor that varied naturally in the studies, but that could be varied systematically in future studies, e.g. encountering pedestrians, buses, motorcycles etc. In addition, other road-user roles than passenger car drivers and cyclists, such as pedestrians, could be studied to investigate adaptive behaviours and to see if the results in other roles would differ. Pedestrians have even more degrees of freedom than cyclists but is a very heterogeneous group, including all ages and all physical abilities and disabilities.

From this thesis as a starting point, revealing adaptive behaviour in different applications and settings from the individual perspective of a road user, supplementary studies can be made for scrutinising adaptation in traffic further. One interesting area of research would be the coordination of road users, when they perceive and adapt to each other. What determines the interactions? How can this be studied in real traffic circumstances? Improved traffic infrastructure and perhaps special regulations for cyclists could be developed and evaluated to facilitate road-user effectiveness and comfort while mitigating violations.

Neither ECOM nor the predictive processing framework seems to be perfectly aimed for examining adaptive behaviour, because of their lack of internal factors such as emotions etc., but ECOM was found useful for setting up hypotheses on adaptive behaviour covering various aspects, and for understanding adaptation in relation to behavioural models. The results of this work could be used for developing road user models that incorporate the comfort zone of the road user, as affected by the internal state, along with top-down and bottom-up processes.

To conclude, road-user behaviour should not be dismissed as typical of the individual and his or her character but rather be understood in relation to the prerequisites of the current road-user role, i.e. the vehicle and infrastructure available. When designing and planning for infrastructure, the needs of all road-user roles should be regarded. Improved traffic infrastructure and perhaps differentiated regulations for different road-user roles should be developed and evaluated to support road-user effectiveness and comfort while mitigating violations. To facilitate for road users to stay within their comfort zone, it should be easy to make correct predictions while striving for personal goals of the trip. When the road user is within the comfort zone, the subjective safety margins are sufficient for comfort and there is an extra capacity for unexpected events. Hence, infrastructure design should be adapted to the road user, to facilitate adaptive behaviours.

8. REFERENCES

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