Driver-Vehicle Interaction
Identification, Characterization and Modelling of Path Tracking Skill

Andreas Erséus

Doctoral Thesis in Vehicle Engineering

TRITA-AVE 2010:29
ISSN 1651-7660
Abstract

Since the dawn of the automobile, driver behaviour has been an issue. Driving can result in accidents that may harm not only the driver but also passengers and the surroundings. This calls for measures that restrict the usage of vehicles and to assist the individual driver to conduct the driving in a safe, yet practically efficient manner. The vehicles should therefore be both safe and intuitive, and preferably answer to the different needs of all kinds of drivers.

Driving skill can be defined in many ways, depending on the objective of the driving task, but answer in some way to the question of how well the driver can conduct the driving task. To assist low skill drivers without compromising the driving demand for high skill drivers, it is of highest importance that vehicles are tested and designed to meet those needs. This includes both the testing activities in the vehicle design phase in general but also the configuration for active systems and preventive safety, preferable with settings that adapts to the skill of the individual driver.

The work here comprises the definition of skill and of driver recruitment procedures, scenario design, the development of an analysis method for objective measures, and the gathering of metrics to characterize the driver skill. Moreover, a driver model has been developed that makes use of driver skill characteristics. To gather the information needed, extensive multidisciplinary literature studies were conducted, as well as using field tests and test using an advanced moving base driving simulator. Here the focus is on path tracking skill, which is the main control aspect of driving, although the developed driving scenarios allow a varying degree of path planning, which is more related to regulation. The first simulator test was done with a very simple criterion for driver selection, but the results gave a good insight into the variation between drivers in general. For the following tests the recruitment procedure was refined to find drivers with high or low vehicle control and regulation skill, a recruitment that also was verified to really represent two different populations.

A method was defined that successfully identified sets of skill-related measures, with some variation in composition depending on the path tracking demand on the driver. In the curving road scenario, for example, the highest number of skill-related measures is identified in the curves, which is reasonable since the straight segments do not require the same amount of active control from the drivers.

The driver model developed uses a quasi-static analytical description of the driver knowledge of the vehicle dynamics, but possesses the capability of nonlinear descriptions. The parameters in this model are mainly physical properties that easily can be related to the driving process. Metrics gathered are used for identification of the driver model setup for a double lane change scenario using an optimization routine, with adjusted parameter settings for different velocities.

With a subjective comparison of the recorded driving simulator data, the method is verified to enable driver skill settings for driver models. In addition, the method allows metrics to be gathered for driver skill identification routines, meeting the defined objectives of the project.
Preface

Can one vehicle be designed to meet every possible demand? Well, that might be difficult to achieve, but a regular car should at least be driveable by a wide range of different people with driving licences issued under different conditions. Understanding the behaviour of these people might be one of the biggest challenges in vehicle design today. The latest advancements in preventive safety tools for focused driver support could be a great aid, especially for less skilled drivers, but this also introduces a risk of interfering with the drivers’ intentions. What really inspired me to take on the challenge of doing this thesis work were the possibilities of active vehicle adjustments to best suit the current driver and state that could emerge if the specific driver’s needs is known. This leads us to the intriguing question that appeared in the beginning of this work: Is it really feasible to measure and model driving skill using in-vehicle sensors?

Acknowledgements

This research project has been performed at KTH Vehicle Dynamics, in collaboration with General Motors North America, Saab Automobile and VTI (the Swedish National Road and Transport Research Institute). The financial support by VINNOVA (The Swedish Agency for Innovation Systems) is also gratefully acknowledged.

I would like to express my gratitude to my academic supervisor, Professor Annika Stensson Trigell, for the support provided during the project, with her unceasing positive spirit and encouragement. Thanks are also extended to Lars Drugge, who has been a co-advisor for me during the later part of the project, with fruitful discussions and straightforward feedback. Special thanks are given to Staffan Nordmark, also a co-advisor, who put me on the right track after some setbacks and devoted many hours to provide valuable input in the development of the driver model. Thanks are also due to Gunnar Olsson for his feedback and hearty interest in the project, inspiring us with his long experience of vehicle design and testing, to Arne Nåbo for providing much appreciated expertise in human factors and Steve Chin for encouraging us to strive for more knowledge. I am also grateful for the fantastic support given by Håkan Sehammar, Göran Palmkvist and Mats Lidström at VTI. Present and past colleagues, first and foremost Markus Agebro, Johan Andreasson and Jonas Jarlmark that were at KTH when I started, it has been a real privilege to work with you during these years.

My wonderful newly wedded wife Emmeli, you have been unbelievably supporting despite the long hours which I had to devote to this work. My parents, relatives and friends, thank you all for encouraging me and for being there for me when I needed. Even though some of you are not with us any more, I know you never doubted me to complete this work. You have been the best sources of inspiration and still are.

Andreas Erséus
Stockholm, Sweden, May 2010
Appended papers

Paper A


Contributions of authors: Erséus (formerly Nilsson) and Agebro designed the scenario, recruited the drivers and supervised the test. Agebro implemented the vehicle model’s steering servo. Erséus did the analysis and wrote the paper. Stensson Trigell and Drugge provided useful ideas, valuable comments and proofread the paper. Erséus also presented the paper at FISITA’06 World Automotive Congress, Yokohama, Japan, October 22-27, 2006.

Paper B

Erséus, A., Stensson Trigell, A. and Drugge, L. Methodology for finding parameters related to path tracking skill applied on a DLC-test in a moving base driving simulator, submitted for publication (this is an extended version of Nilsson, A., Stensson Trigell, A. and Drugge, L. Methodology to find parameters characteristic to path tracking skill – DLC-test in a moving base simulator, Proceedings of the 21st International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD’09), Stockholm, Sweden, 2009).

Contributions of authors: Erséus (formerly Nilsson) developed the recruitment criteria and recruited the drivers (with assistance from Markus Agebro). Erséus developed the analysis method, did the analysis and wrote the paper. Stensson Trigell and Drugge provided useful ideas, valuable comments and proofread the paper. Erséus also presented the original paper at IAVSD’09.

Paper C


Contributions of authors: Erséus (formerly Nilsson) designed the scenario, did the analysis and wrote the paper. Stensson Trigell and Drugge provided useful ideas, valuable comments and proofread the paper. Erséus also presented the paper at AVEC’08.
Paper D

Erséus, A. Drugge, L. and Stensson Trigell, A. A path tracking driver model with representation of driving skill, submitted for publication.

Contributions of authors: Erséus (formerly Nilsson) designed the model (with assistance from Staffan Nordmark), did the analysis and wrote the paper. Stensson Trigell and Drugge provided useful ideas, valuable comments and proofread the paper.

Paper E

Erséus, A. Stensson Trigell, A. and Drugge, L. Characteristics of path tracking skill on a curving road, submitted for publication.

Contributions of authors: Erséus (formerly Nilsson) designed the scenario, did the analysis and wrote the paper. Stensson Trigell and Drugge provided useful ideas, valuable comments and proofread the paper.
# Contents

1 Introduction  
1.1 History of driving and introduction to driving skill ................. 1  
1.2 Preventive safety and driver adaptation .................................. 2  
1.3 Path planning and tracking .................................................... 3  
1.4 Driver models ....................................................................... 4  
1.5 Objectives ............................................................................ 5  
1.6 Outline of thesis ................................................................. 5  

2 Method  
2.1 Work process ........................................................................ 7  
2.2 Limitations ........................................................................... 9  

3 The human vehicle operator  
3.1 General driver characteristics ............................................... 11  
3.2 The driving process ................................................................. 13  
3.2.1 Driving functions and tasks ............................................ 13  
3.2.2 Specification of driving activities .................................... 19  
3.3 Individual experience-based differences ............................... 19  
3.3.1 Behaviour development .................................................. 19  
3.3.2 Driving skill and driver performance ............................... 23  
3.3.3 Driving style ................................................................. 25  
3.3.4 Specification of ordinary driving and path tracking skill .......... 28  

4 Measurement of driver characteristics  
4.1 Introduction to driver analysis ................................................ 29  
4.2 Examples of measurements .................................................... 30  
4.3 Driving simulator tests .......................................................... 33  
4.3.1 Test platform ................................................................. 34  
4.3.2 Curved cone track scenario ............................................ 35  
4.3.3 Avoidance manoeuvre scenario .................................... 36  
4.3.4 Driver response scenario ............................................. 36  
4.3.5 Curving road scenario .................................................. 37  
4.4 Proposed driving skill characterization methodology .............. 38  
4.5 Results from driving characterization ..................................... 38  

5 Modelling of vehicles  
5.1 MBS-model description ......................................................... 45  
5.2 Validation of MBS-model ....................................................... 46  
5.3 Driver’s internal vehicle model .............................................. 47
6 Modelling of drivers .................................................................................................................. 51
  6.1 Compensation tracking models ...................................................................................... 51
  6.2 Preview tracking models ............................................................................................... 52
  6.3 Fuzzy set theory models ............................................................................................... 56
  6.4 The KTH Vehicle Dynamics driver model ..................................................................... 59

7 Scientific contributions ............................................................................................................. 61

8 Discussion and conclusions .................................................................................................. 63

9 Recommendations for future work ....................................................................................... 67

References .................................................................................................................................. 69

Nomenclature .............................................................................................................................. 73
Chapter 1

Introduction

This thesis begins with a background of the problem and relevance for regular drivers. Additionally, the opportunities for the future, safety concerns and the potential to enhance the driving experience for all drivers are presented, followed by the defined objectives and outline of thesis.

1.1 History of driving and introduction to driving skill

Since the day when the first man-operated motorized road vehicle appeared, driver behaviour and driving skill have been an issue. In Britain, with the Locomotive Act of 1861, the speed of all horseless vehicles was limited to 10 mph outside towns and 4 mph within, which was mainly due to the steam alarming horses and the vehicles harming the roadways. In the Locomotive Act of 1865, not only was the speed limit lowered to only 4 mph and 2 mph for driving outside and inside towns respectively, but also it was required that a man with a red flag or a lantern should walk 60 yards ahead of each vehicle in towns to enforce a walking pace and to warn about this self-propelled machine [1,2]. Speed regulation is one severe way of limiting the potential danger for the driver and the surroundings used for most roads today, since both the risk of an accident and the result of such an event can be affected by the vehicle speed. Controlled driver support systems are also becoming increasingly important in their role of helping drivers to perform safe driving. However, these and other safety measures, both regulatory and technical, often rely on an average of driver performance and rarely take individual drivers into consideration. This may place unnecessarily hard and sometimes counterproductive restrictions on high skill drivers, while low skill drivers could benefit from more severe interference. Moreover, even when they are not specifically interfering, different setups may prove to be best in supporting different driver types.

Skill is a very broad term that can include many different components, but it usually is a measure on how effective a pre-defined task is completed. The task can be defined at different levels, which for driving can be complex tasks as for example winning races or to go from point A to B without any incidents. It can also be as small as shifting the gear at an appropriate time or spotting wild life at the side of the road. For all these
tasks a person evolves a process of executing the task in a more coordinated or automated way with less mental workload involved and/or less error, which can be considered as becoming more skilled. Specific limited tasks, such as grasping and turning knobs, have been thoroughly investigated in many papers, e.g. in [3], where strategy in knob turning was studied (e.g. arm motion and applied torque), and in [4], where human properties for grasping a knob were identified. For very simple tasks the individual human physical properties can have a large effect, and the amount of training can be of minor importance. These and other aspects of human limitations and learned behaviour will be further explored later in this thesis, see Chapter 3.

1.2 Preventive safety and driver adaptation

Driving consists of highly complex tasks and it would seem preferable if the driver were to use his full potential on the aspects of driving that require decision-making and intelligent thinking. To make that possible, system can be introduced that reduce information uncertainty, correct errors and adapt the vehicle to the individual driver and the situation. Countermeasures that could enhance information acquisition and responses are listed in [5], with special emphasis on operational systems which guide response and direct attention and could support elderly drivers, as well as systems which act on a strategic or tactical level and could be of great benefit to young people, compensating for their inexperience (using a general average of age-typical problems). Piechulla et al present in [6] a situation-adaptive man-machine interface for the optimum allocation of drivers’ attention resources, where they use a demonstrator vehicle with a developed version of a “state-of-the-art” (as it was at that time) adaptive cruise control system (ACC) based on radar sensors and an experimental heading control system (HC) based on computer vision. The HC in this system searches for lane markings and employs small forces on the steering wheel which serve as indicators of how to steer in order to stay in the lane. There is a range of sensors available for probing the environment around the vehicle, and these sensors can be used both as a source of information to the driver and as input to vehicle systems (Figure 1); but the sensors can also be used for determining both the vehicle’s and the driver’s internal status (directly or indirectly from the coupled system).

Figure 1: Range of some available sensors for analyzing vehicle surroundings [7].
Brännström highlights the importance of a good balance between not disturbing the driver in real driving conditions, and supporting the driver in critical situations [8]. With more knowledge of the expected behaviour of drivers, which can vary greatly between individuals, a more elaborate decision-making is possible for the engagement of a preventive safety system in the vehicle. Stability systems that make use of the adjustability of the controlled system, e.g. the adjustability of the steering wheel rate and effort, or the suspension characteristics, might also benefit from knowledge of the effect of different settings on different driver types. The driving workload and distraction aspects could also possibly be improved, e.g. by only showing relevant information when a driver is driving close to the maximum of his or her ability.

### 1.3 Path planning and tracking

Driving requires many different processes to be performed, and path planning and path tracking are terms that are used for two of the elements.

*Path planning* is here referred to as the driver’s mental process of determining the path along which he or she wants the vehicle to go (i.e. a typical duration of less than 1 minute, as part of the regulating loop [9]). This path can be more or less given by the road boundaries, but usually there is enough space to allow some variation in the driver’s choice of the path to track. Moreover, when there is a possibility of selecting action or timing, for example passing a vehicle or performing a lane change, the driver needs to plan the procedure. Since the vehicle performance and driver capabilities can differ, good planning requires some knowledge of what can be accomplished (with the system capabilities) without causing an accident.

*Path tracking* is a term used for the process of the driver following the chosen path (i.e. a typical duration of not more than 1 s, as part of the tracking loop [9]). This can be carried out with greater or lesser accuracy. Both the vehicle and the driver impose delay in the system when a difference between the preferred path and the vehicle’s path is detected. Basic physical effects that slow down the system response are for the vehicle the inertia and tyre force build-up, for example, and for the driver the cognitive process and muscle actuation, for example. This means that good path tracking requires a feed-forward process that compensates for the delays. To enable prediction of the required action, the drivers need to have some level of knowledge of how the vehicle will react on input. Krendel and McRuer divided the tracking characteristics into three basic levels in 1960: the *compensatory* level, i.e. compensation for observed errors; the *pursuit* level, which takes experience and prediction into account, although operating in a closed loop with visual feedback, for example; and the *precognitive* level, which is essentially open loop control based on knowledge of the system and the required future inputs [10]. The third level is not directly considered to be tracking since it is open loop, but it is indirectly influencing the tracking since it is conducted to minimize future path errors.
1.4 Driver models

In many situations it can be beneficial to do analysis of the driver and vehicle with one or the other, or both, replaced by a virtual representation. For real vehicle tests you can replace the driver with a steering robot, being superior to the human in precision and repeatability for pre-defined control of the vehicle. If you instead want to do tests without a physical vehicle but a real driver you can use a driving simulator with a model of the vehicle implemented. This provides a controlled and safe environment, and allows you to do tests with high measurement accuracy that could be dangerous or even impossible to do in reality. Many different vehicle configurations and environments can be tested in a single driving session, which can reduce the number of vehicle prototypes that actually has to be built. If both the vehicle and the driver are replaced with computer models, this allows you to do large batches of tests in desktop computer simulation programs. For the driver input to the vehicle model you can use either open loop pre-defined steering (similar to the steering robot input) or driver models, which more accurately should represent the human driver with his or her limitations.

One of the first recognised model based driver descriptions, prior to any desktop computer system, is to be found in [11] from 1938 by Gibson and Crooks. It treats the vehicle and obstacles as repelling forces that become stronger when the risk of an accident is higher, shaping a “field of safe travel” (Figure 2). A rise in the number of papers on driver models began in the late fifties and the production of papers continued at a high level into the eighties. McRuer is one author who has had great influence on control-theory-based pilot models and driver model development, e.g. in [12,13,14], and with Wier as one co-author in many papers with more emphasis on drivers, e.g. [15,16,17,18,19,20]. Other authors who have pioneered the development of driver models are, to name a few, Fiala (e.g. [21]), Mitschke (e.g. [22]), Allen (e.g. [19,23]), and Donges [24]. In the early eighties, MacAdam presented his work on optimal control [25,26], which provided a much appreciated method for predicting vehicle movement which allowed good path following. In [27] this is put in a larger context with driver limitations included. Sharp has among other things contributed with mathematical model [28] and optimal control model [29] development. Another driver modelling approach was given by Cole, who has studied neuro-muscular activities in the driver’s steer control and implemented this research in driver models, e.g. in [30] by Pick and Cole.

Figure 2: Example showing the field of safe travel in an intersection [10].
Section 1.5 Objectives

Driver models are used not only for simulation of the individual driver, which is the main usage of the driver models referred to here, but also to account for interaction between drivers. These models can be simplified for low-level control, but have to be more elaborate for other levels. In the thesis on driver modelling for transport systems by Ma [31], the driver tasks are divided into three levels, namely the strategic, tactical and operational levels, which have corresponding level descriptions within the field of driver modelling on the individual level, e.g. navigation, guidance and control. The difference is that the focus of driver modelling for traffic simulation is mainly directed on the second level, the tactical [31], while the main focus for individual driver modelling is directed on the operational level. In recent years, however, pattern-recognition, using neural networks, for example, has gained increased attention in studies of the tactical behaviour of individual drivers, e.g. the study by Raksincharoensak in [32,33].

1.5 Objectives

As Fuller says in [34], driving has, compared to most other things we do, a high potential for adverse consequences. With an increasing amount of preventive safety systems and dynamic adjustability of vehicles, knowledge of driver-specific differences in preferences and performance can be of great use. If objective parameters correlated to driving skill could be made available, this might be used for driver type identification and this should enhance the benefit of adaptive configuration of adjustable systems. Such parameters can also be used for metrics to model drivers of different levels of skill for use in a desktop simulation environment, thus improving the validity of simulations that depend on realistic driver models. Miller et al point out in [35] that intelligent driver support systems with the human in control is a promising application area for artificial intelligence research, with autonomous vehicles as a goal when such systems have become a practical solution.

The presented research work is based on the assumption of a human remaining in control most of the time, but with support from active, preventive and personalized systems to improve performance. From the background described here, the objectives of this research are summarized as: to define driving skill (and limitations to apply here) as well as the recruitment process for finding test subjects from populations with different driving skill; develop methods for characterization of the specified driving skill; find objective measures for the specified driving skill; gather driver metrics, and; develop a driver model that can represent different driving skill. The result is intended to be a basis for future development of active safety system solutions that consider different levels of path tracking driving skill.

1.6 Outline of thesis

This thesis comprises an introduction to the research topic, an overview of the performed research, and five appended papers, Papers A – E. These papers include a
number of driving simulator tests designed and used for the study of driving behaviour. Moreover, a test subject recruitment process has been designed to find drivers with specific skills. The results from the simulator tests with these drivers are tested with a method designed for identifying typical characteristics for different driving skill levels. Driver model development has been carried out with specific focus on using a small number of adjustable parameters that can be set for different path tracking skill levels. The results from the driving simulator tests have been used for specification and validation of the driver model.

Chapter 2 presents the method in more detail with the work process of the project, including the limitations imposed. Chapter 3 gives an overview of the vehicle operator, including descriptions of general human behaviour, the driving process and how behaviour is shaped through experience. The purpose of this overview is to put the work in the appended papers in a broader perspective and to describe the background to and motivation for this research work. A brief introduction to measurements and analysis of driver behaviour is given in Chapter 4. Chapter 5 describes the controlled vehicle, both as a model interacting with the driver or the driver model, and as a model that describes the driver’s interpretation of the controlled vehicle (i.e. vehicle model), also used in the driver model presented in Paper D. Chapter 6 gives an overview of different basic driver model types used for modelling individual drivers, as well as a brief description of the developed model presented in Paper D. The main scientific contributions are summarized in Chapter 7, the discussion and conclusions in Chapter 8, and the recommendations for future work in Chapter 9.
Chapter 2

Method

This chapter gives an overview of the work process of this research, with specification of limitations and methods used, and provide information regarding the execution of the experiments.

2.1 Work process

The first part of this work of finding objective parameter measures to characterize driving skill, and to model drivers, was to find the right approach to the problem through extensive multidisciplinary literature studies. These were conducted in a variety of areas such as human cognition, psychology, driving behaviour, man-machine interfaces, vehicle dynamics, driving tests, driving simulators, control theory, optimization, pattern recognition and driver-vehicle modelling. Also, as part of the background, field studies were done for vehicle handling skill and different vehicle designs, including driving with different human vehicle interfaces (such as joystick steering, variable steering wheel gear ratio and 4-wheel steering).

The first driving simulator experiment was scheduled quite early in the project with the main objective of gaining experience, but also to test some initial hypotheses. The experiment was executed in collaboration with a partner project, using the same recruited test subjects for two different tests. The first test, done exclusively for the other project, concerned passing of a truck with meeting traffic in other lane, while the second part, done primarily for this project was designed as a curving road manoeuvre at relatively low speed (using cones marking the way similar to some roadwork situations). More information regarding the driving scenarios can be found in Section 4.3. Test subjects were recruited as being high mileage drivers (driving more than 25 000 km/year) or low mileage drivers (driving less than 5 000 km/year). Some of the high mileage drivers were especially selected professional drivers, while the other test subjects were recruited either from KTH or VTI. After testing and verifying the simulator and scenario setup, a pilot test was performed using both low mileage and high mileage drivers. This verified that the setup was right, allowing the full scale test with 9 low mileage and 9 high mileage drivers being done (during 3 days, i.e. with 6
drivers each day). Each driver was tested in the two scenarios which took approximately half an hour each to complete (the driver was allowed to re-run tests which resulted in some variation in time). Both scenarios included an initial period of test driving, and a break of half an hour was scheduled between the scenarios, in which the drivers had to do some paperwork. The results from the first experiment resulted both in Paper A and valuable input to the rest of the work in the project. Figure 3 presents an overview of the research work in this thesis.

The second simulator test was designed exclusively for this work, studying different approaches to find differences between low skill and high skill drivers. Definitions of driving skill was formed based on expertise experience and state of the art descriptions of driving, where path tracking skill was decided to be the main focus. These results were used as basis for both the scenario descriptions and the recruitment criteria for the test subjects. Drivers were recruited from populations described as low skill and high skill drivers, with a selection of 15 drivers from each category. The selection of test subjects was aiming to end up with a mix of both young and old, and men and women,
but with the main objective to find representative drivers for the two categories. The preparation of the second simulator test was done in a similar way as the first, with initial testing and a pilot test with representative drivers. Four scenarios were used, divided into two sessions of approximately 25 and 19 minutes respectively. The first two scenarios, a double lane change and a line tracking scenario, included a short period of test driving. Between the two sessions was a break during which the test subject answered questions about the tests. The first scenario served as verification of the recruitment, testing the highest speed the driver could drive the manoeuvre, as well as being a part of the regular measurement and analysis done on all scenarios. The session after the break consisted of two scenarios based on driving on curving road. This aimed to test the drivers in normal driving, with the third scenario using two levels of road friction and fourth one using fog to test the effect of limited sight distance. Three of the (low skill) drivers felt tendencies to motions sickness in the last scenario, but these test subjects were removed from the analysis of that particular test. Thus the analysis was based only on the remaining 27 drivers, instead of 30 for this scenario. See Paper B, C and E for more details regarding the analysis of the scenarios in the second diving simulator test.

The driver model was developed as the last part of the research work, based on the results from the literature study together with the results from the driving simulator tests and open loop simulations. The model was specified and tested with the double lane change scenario measurement results from the driving simulator tests, with both a high skill and a low skill setting specified based on the earlier results. See Paper D for more details.

2.2 Limitations

In this work, methods have been derived to specify, identify, analyze and use information regarding driving skill. The scope here has been limited to path tracking driving skill of drivers holding a Swedish driving license, studying characteristic behaviour of the group, i.e. not the individual driver. Only a few scenarios have been used, which limit the direct applicability on identification of individual drivers in real driving cases. However, the scenarios have been chosen in order to test behaviour that has been considered most important for this work, representing an avoidance manoeuvre, vehicle control, and driving on a curving road in some different conditions. The study has also been limited to the driving simulator environment, and although the experience is very similar to driving with a real vehicle, it does not completely replace the need for such studies. Objective measures taken here are used for both characterization and modelling typical behaviour of the two groups of drivers. However, large experiments, at least partly done with real vehicles, should be conducted before application in vehicle design or serial production of cars, or in-vehicle identification of drivers, is feasible. Other types of skill could be possible identify, and other scenarios could also be studied as well as the effects of other driving conditions. Also, larger groups of test subjects could help in identifying other sub-groups of drivers with statistical significance. It is also likely that the driving behaviour is different in different parts of the world, which calls for studies using drivers from the target markets.
Chapter 3

The human vehicle operator

This chapter gives an introduction to general human characteristics and more specific driving-related processes, and provides a description of how experience can affect performance and shape the behaviour of drivers. These individual differences in driver characteristics are important for both the identification and the modelling of drivers.

3.1 General driver characteristics

This section includes an introduction to the purpose of actions, the basic properties of humans, and the perception of information that is used when driving. Groeger stated in [36] that actions are not simply responses or movements that have been initiated, but also attempts to interact with objects in our world. Our movements are constrained by the limitations of our limbs and the brain that controls them, but actions are also constrained by the objects with which we interact. The process of a driver perceiving a situation and responding with an action is very complex and involves many different parts of the brain, from the recognition of the situation (e.g. through visual or tactile stimuli) and taking a decision on which strategy to use for the task, to the very coordination and movement of the limbs.

When trying to understand and model the human driver, a good starting point is to study the general characteristics of the driver from a controller’s point of view. Kinecke and Nielsen summarize the general characteristics of human controllers in [37] as including:

- Operating states (error correction mode, error ignoring mode)
- Nonlinearity (e.g. accelerator pedal)
- Adaptation (requires precise feedback)
- Anticipation (learned behaviour, skill)
- Time variance (time-dependent output)
A more thorough description of the physical limitations and attributes can be found in [27], where MacAdam considers physical limitations such as human time delays and threshold limitations. He also describes physical attributes such as preview utilization, adaptive control behaviour, and the driver’s understanding of the dynamics of the vehicle. Groeger has provided a source of information regarding driver characteristics and aspects of human cognition in [36], and McRuer (e.g. [20]) is one of the most important contributors to describing the human with a control-theory-based approach.

With regard to information acquisition, i.e. perception, MacAdam ranks the primary sensory channels used in driving in the following order, with the first as the most important: vision; the vestibular (inner ear) and kinesthetic (body-distributed) channels; the tactile channel and; the auditory channel. Most information from cues with lower priority also provides redundant/reinforcing cue information that can help the driver to confirm decisions quicker and make better estimations based on information obtained from the channels with higher priority [27].

Humans cannot process all the information available with the same level of detail. In human information acquisition, the intake and processing abilities are limited and queuing theory is one way to present a reproduction of the human system of handling information. Queuing policy is a means of determining which information (clients) is to be processed first and which has to wait or be dismissed. Normally the principle of first come first served is used, but there is a range of other possibilities of handling information [37]:

- **Priority Queuing**

  Clients with the highest priority are served first, independent of the arrival order in the queue.

- **Limited Capacity Queuing**

  This involves a queue that can only hold a limited number of clients prior to processing. No new clients are taken into the queue if it is full, and the clients that have been in the queue too long will be removed without processing.

- **Pre-emptive / Non-pre-emptive**

  Clients appearing in the queue that has the higher priority than the one currently being processed can result in two scenarios. The pre-emptive system processes the higher priority client immediately and the client currently being processed has to wait for service until the prioritized client has been served. A non-pre-emptive system does not process the higher priority client until the currently processed client has been served.

It is quite straightforward to apply these processes on automobile driving, which requires adequate vehicle control combined with the performance of many other tasks more or less loosely related to driving.
3.2 The driving process

Here descriptions of driving goals and how driving tasks are organised in the process of driving are presented. For the purpose of determining what the driver actually is doing, one approach is to study the choices of action which a driver has and what the driver’s goals might be. Rumar has specified what he considers the driver’s high-level goals to be in [38], maintaining that the primary goal for a driver is to reach his or her destination. (Note that for some drivers the driving itself is the goal.) However, Rumar points out that the driver will not accept that goal without reservations. The driver requires a certain time expenditure, safety, economy, and comfort, and this is what Rumar refers to as the driver’s secondary goals. He also stresses the necessity to transform these general goals into operational goals. It is also important to note that the driver behaviour cannot be isolated from the controlled system, since the driver can compensate for relatively large differences in vehicle characteristics to achieve the preferred system characteristics.

3.2.1 Driving functions and tasks

When studying operational goals, terms such as functions and tasks are introduced. Functions can be seen as available functionalities in the joint driver-vehicle system that enable the fulfilment of goals; and tasks can be regarded as actions that can be performed with the help of those functions. In [36] Groeger exemplifies functions with steering, speed control, gear changing, interpreting the road ahead, navigation etc. Therefore, the driver task workload can be reduced by the automation of driving functions. Since driving is a complex task, it requires a large set of activities to be performed by the driver in a safe manner, but many types of activities can be described as distractions from the main task (although sometimes these activities may increase the driver’s general attention). Driver distraction is not in focus in the work conducted here, and instead distractions are kept to a minimum to focus on the driving task. However, it is necessary to have some insight into the topic and a great deal of information about driver distraction can be found in [39]. A popular way of ordering driving tasks that has been used with some differences in the choice of words, but with the same basic categories, is to divide the tasks into a hierarchy of three performance levels, according to the timescale and the level of cognitive activity involved (e.g. [40]):

- Navigation (macro-performance)
- Guidance (situational-performance)
- Control (micro-performance)

Note that the levels in the model above concern tasks during the actual driving and not tasks performed before or after driving, but strategic planning can be considered as macro-performance as well.
Kiencke has made a task description of driving that is divided into more detailed levels [37]:

- Strategic tasks (choice of route, time of departure)
- Navigational tasks (adherence to the chosen route during travel)
- Traffic-related tasks (interacting with other road users in such a way that the traffic is not obstructed and collisions with other road users are avoided)
- Adherence to rules (traffic signs, signals etc.)
- Tasks related to the road (chosen position within traffic, course)
- Speed control (choice of speed according to the situation)

These levels are related to the previously described model, as the first two are components of navigation, the third and fourth are components of guidance, and the last two are components of control.

A complete driver model should, in addition to addressing activities on all of the levels within the scope of the model, also describe the flow within the system. Figure 4 shows the model by Repa, illustrating driver-vehicle interactions using the level description above, with the addition of the communication, comfort, & entertainment level and the pre-/post-driving level of accommodation [41].

![Multi-level structure of driver-vehicle interactions](image)

Figure 4: Multi-level structure of driver-vehicle interactions [41].

Wheeler et al have made a very thorough description of driving that divides driving into private vehicle operations and commercial vehicle operations [42]. The private vehicle
operations are listed below, with the pre-drive and drive tasks organized into separate groups:

**Pre-drive tasks**
- Inspection
- Start-up
- Auxiliary systems
- Planning

**Drive tasks**
- Navigation & routing
- Guidance & manoeuvres
- Control
- Vehicle systems operation & monitoring
- Reacting to emergencies

The pre-drive tasks are more or less covered by the accommodation level in the model by Repa above, as well as by the initial strategic setup level of communication, comfort, & entertainment and the navigation (i.e. planning) level. The drive tasks are here extended with the vehicle systems operation & monitoring level (partly related to communication, comfort & entertainment) and the reacting to emergencies level. This allows a better overview of how the human-machine-interface (HMI) design affects the driver, and provides the possibility of treating extraordinary events separately. In the present work, the focus is on the behaviour of the driver when he or she is driving, i.e. the drive tasks. Below the different sub-tasks of driving from [42] are described in more detail, with the actual goals of the tasks within parentheses:

**Navigation & routing**
- Way finding (going where one intends to go)
- Route modification (changing the route based on the conditions)

**Guidance & manoeuvres**
- Traffic coordination (keeping the vehicle at a safe distance from other vehicles)
- Rule compliance (keeping the vehicle within the regulated safety limits)
- Manoeuvring (causing the vehicle to go where it is intended to go)
- Hazard observation (avoiding hazardous situations)
Control

- Speed control (matching the vehicle speed with the driving requirements)
- Position control (matching the vehicle direction with the driving requirements)

Vehicle system operation & monitoring:

- Monitoring engine operation (ensuring that the engine is operating normally)
- Monitoring control systems and vehicle structure (ensuring that the tyres, brakes, steering, and vehicle structure are functioning normally)
- Adjusting climate control (maintaining a comfortable interior and clear windscreen)
- Initiating turn signals (warning other drivers of one’s turning intentions)
- Operating communications systems (obtaining information from others and giving information to others)
- Using advanced traveller information systems (obtaining and using traveller information)
- Operating cruise control (reducing fatigue by automatic maintenance of speed)
- Operating lighting systems (illuminating the highway and improving the visibility of the vehicle to others)
- Operating windshield washers/wipers (keeping the windshield clean)
- Adjusting rear view mirror (providing a view of the traffic behind without inducing glare)

Since reacting to emergencies is more of a sub-task itself (although not part of non-obstructed driving), no sub-tasks have been described for this level. However, as is the case for all the other sub-tasks, there are even more detailed sub-levels described in [42]. For reacting to emergencies, for example, these detailed sub-levels consist of the following sub-sub-tasks:

- Detecting emergency condition (detecting an emergency in time to take corrective actions)
- Diagnosing the situation (understanding what is happening)
- Determining the action required (planning actions to mitigate the emergency)
- Taking the appropriate action (mitigating the emergency)

For further understanding of why the tasks are grouped as they are, it can be mentioned that many of the sub-tasks in vehicle system operation & monitoring are operations performed on the same system functions as those affected by the sub-tasks of pre-drive: auxiliary systems, i.e. functions not directly related to the level of control, but performed in order to be able to operate the vehicle successfully in the desired way.

A slightly different approach to the components of driving is the functional model called Driver in Control (DiC) presented by Hollnagel et al in [9]. It describes driving...
as cycles that link intentions/objectives, actions, and outcomes together between different levels. The vehicle systems are here considered in the same framework as the driver, and treated as an integrated system. Every level contains a cycle, but with different characteristics in terms of the type of control (feedback or feed-forward), for example. The different loops in the model are referred to as the tracking, regulating, monitoring, and targeting loops. Figure 5 shows the communication downstream between the loops, and also what is related to closed loop compensatory control and open loop anticipatory control.

The different loops are presented below in more detail, beginning with the lowest level (tracking loop) since these activities are the basic ones required for short-term controllability.

- **Tracking loop**

  The tracking level describes the low-level activities required to keep the vehicle inside a region of time-space continuum, i.e. to maintain the speed, the distance from the car in front (and behind), the relative or absolute lateral position etc. These activities are described as mainly closed loop control, which skilled drivers can accomplish with little effort and without paying much attention to them. If the conditions change, however, the actions may require more attention and thereby become more like those at the regulating level. The typical duration of activities in this loop is less than one second.

- **Regulating loop**

  The regulating level provides the input (goals and criteria) for the tracking level. The activities at this level concern mostly closed loop control, although some anticipatory control may occur. They include activities such as regulating the target speed, the specific position and the movement relative to
other traffic elements, as well as the state of the joint driver-vehicle system relative to the driving environment (traffic flow, hazards). These activities refer to specific plans and objectives coming from the monitoring level. One activity at this level is to generate plans and objectives for the tracking level, and a number of tracking sub-loops may be involved. This requires a higher level of attention than the tracking level. The typical duration of activities in this loop is between one second and one minute.

- **Monitoring loop**

  This level concerns the monitoring of the joint driver-vehicle system, e.g. the vehicle status, location, available resources, etc. Monitoring also concerns keeping track of traffic signs and signals such as indications of directions, warnings (e.g. road conditions or curves), and restrictions (e.g. speed limits). Monitoring is therefore a mixture of open loop and closed loop control. Modern vehicles have systems that only warn in cases of severe malfunction and systems that help to clarify ambiguities. The typical duration of activities in this loop is from 10 minutes to the duration of the journey.

- **Targeting loop**

  Targeting is distinctly an open loop activity, implemented by a non-trivial set of actions, often covering an extended period of time. The activities at this level are mainly carried out prior to the journey, but events during driving may trigger an activity, e.g. changing the route, driving faster, etc. Targeting activities. The trigger can be a landmark, traffic information etc. Assessing the change relative to the goal is not based on simple feedback, but rather a loose assessment of the situation, e.g. the estimated distance to the goal. When these activities are performed regularly, they may be considered a part of monitoring. The typical duration of activities in this loop is up to a few minutes.

It is essential that the joint driver-vehicle system (JDVS) should be in control at all the levels all the time for the system to have an effective control. Ineffective control means that control has been lost in one or more of the loops, thereby risking unwanted effects on the joint driver-vehicle system. One advantage mentioned for the DiC model is that it explicitly describes how disturbances can propagate between control levels to several levels, and not just how an activity at one level can affect activities at another level. For example, if the required time of arrival at the destination is changed in the targeting loop, this will propagate to the monitoring loop, where the monitoring priority may change. Moreover, the new plans may result in more risky manoeuvres being chosen in the regulating loop, and this may result in active safety systems kicking in and thus affecting the driver-vehicle control in the tracking loop. The driver and vehicle are in most cases treated as a combined system, referred to as the driver-vehicle system [14], which in many instances cannot be separated into mechanical and purely human components due to the highly coupled interaction [27].
3.2.2 Specification of driving activities

Based on the descriptions above, it is defined here how the activities are grouped for the present research work. They are divided into three main categories depending on their relation to the driving referred to as path tracking, i.e. following a chosen driving path:

- **Primary driving functions/tasks**
  
  Activities at the level of guidance and control, i.e. the activities required by the driver (and/or driver support systems) to keep the vehicle on the road and keep the distance to other objects.

- **Complementary driving functions/tasks**
  
  Activities related to navigation as well as activities performed to maintain/improve driving conditions (keeping the windshield clean, etc).

- **Non-driving functions/tasks**
  
  Activities not intended to improve driving (talking on the phone, yelling at the children, adjusting the radio, etc).

Since the research work presented here is focused on path tracking activities, this limits the scope to the first category of the three. This does not mean that the other functions do not influence the driving, but the aim of the experiment setup is to reduce the need for such activities to a minimum. It is also the undisturbed actions of the driver that are the main concern, and therefore the primary driving tasks of the driver are kept free from interference from preventive safety systems within the primary driving functions.

3.3 Individual experience-based differences

Here theories are presented on how experience shapes human behaviour and how it may improve the performance in certain situations. There are hypotheses concerning how human cognition works which are difficult to combine, but which are allowed to co-exist since the different cognitive processes are difficult to verify or reject. Theories live and prosper in parallel, with the domination of some of them. Therefore, it is difficult to obtain a complete overview of the state-of-art within the area, but here is an attempt to provide an objective introduction to the topic.

3.3.1 Behaviour development

There appears to be general agreement concerning the postulate that most human behaviour is goal-oriented, at least when we make conscious decisions. Rasmussen [43] is of the opinion that human activity in a familiar environment will not be goal-oriented, but rather controlled by a set of rules that has been proven successful previously. When performing a task like driving, we have several sub-tasks that we have to do which are more or less an act of routine, and require less conscious thought
than other sub-tasks. Without an explicit or implicit plan, however, no goal is achieved. Actions are controlled by intentions, but all intentions are not carried out. Some are abandoned and some are revised to fit changing circumstances [44]. It is also important to realize that it is not the physical reality that decides behaviour, but the perceived information. Every road user selects his or her own information [38].

Many scientists base their work on Rasmussen’s three-level behaviour model with its mapping of driving tasks to human cognitive levels [43]. The three levels are:

- Skill-based behaviour
- Rule-based behaviour
- Knowledge-based behaviour

An illustration of the model can be seen in Figure 6.

Figure 6: Simplified illustration of the three levels of performance of skilled human operators. Note that the levels are not alternatives, but interact in a way only rudimentarily represented in the diagram [43].

- **Skill-based behaviour**

  By skill-based behaviour, Rasmussen refers to sensory-motor performance during acts or activities which, following a statement of an intention, take place without conscious control. He describes them as smooth, automated, and highly integrated patterns of behaviour. Performance is rarely based on simple feedback control where motor output is a response to the observation of an error signal representing the difference between the actual state and the intended state in a time-space environment. Skilled behaviour comes from the ability to compose sets of automated behaviour from previous experience for use in a specific situation.


- **Rule-based behaviour**

  At the next level, rule-based behaviour, the composition of a sequence of subroutines in a familiar work situation is typically controlled by a stored rule or procedure which may have been derived empirically on previous occasions, communicated from other persons’ know-how as an instruction, or prepared on the current occasion through conscious problem solving and planning.

- **Knowledge-based behaviour**

  Knowledge-based behaviour is what we are forced to use in unfamiliar situations, faced with an environment for which no know-how or rules for control are available from previous encounters. At this level, performance is goal-oriented and based on knowledge.

According to Goodrich et al, in driving, human cognition can be described using multiple mental models (agents) which can be organized into a society of interacting agents whose structure determines both which agents contribute to driver behaviour and which agents can employ attention resources [45]. As can be seen in Figure 7, Rasmussen’s behaviour model [43] is used as a starting point for further exploration of the concept of mental models. The three levels are skill-based (SB), rule-based (RB), and knowledge-based (KB) behaviour. The figure uses the notation SP for sensor perception, MM for mental model, and BA for behaviour actuation.

![Figure 7: Communication and control within a society of mental model agents [45].](image)

An important distinction in Goodrich research work is a coordination that describes when a driver switches between different skill-based (SB) agents and how attention is shared between agents (Figure 8). Each mental model is assumed to be either enabled or disabled, and engaged or disengaged. With an enabled mental model there is active influence on human behaviour generation and with a disabled mental model there is no such active perception occurring. When a mental model is engaged, attention is being maintained, whereby environmental information is actively being perceived and interpreted, and when the model is disengaged, attention is released and no such active perception occurs.
Chapter 3  The human vehicle operator

22

KB BEHAVIOR

SUPERVISORY
AGENT

CARPHONE

LATERAL
VEHICLE
CONTROL

LONGITUDINAL
VEHICLE
CONTROL

sr 
tr 
ba

Figure 8: Hierarchical structure of agents in a mental society. SB behaviour is exemplified by speed regulation (sr), time headway regulation (tr), and braking to avoid collision (ba) [45].

It is assumed in the theory by Goodrich et al that attention cannot be divided, but must be switched between rule-based (RB) behaviours in such a way that knowledge-based (KB) agents plan and coordinate RB agents. The RB agents determine which SB agent to enable, when to switch from one SB agent to another, and which sensors should be consulted to reduce uncertainty and ensure satisfactory performance. To disable one agent and enable another, the RB agent must identify when currently enabled SB agents cannot accomplish the assigned RB task.

SB controllers execute the task specified by the RB agent, e.g. speed regulation (sr), time headway regulation (tr), and braking to avoid collision (ba). High workload and high perceptual bandwidth tasks must be allocated high attention, and therefore such criteria are communicated within the structure. In these situations the previously described queuing policy by Kinecke and Nielsen [37] plays an important part.

The task demand is defined by Fuller as the objective complexity of the task and arises out of a combination of features of the environment, the behaviour of other road users, the control and performance characteristics of the vehicle, its speed, road position and trajectory, and driver communication, see Figure 9 [46].

Figure 9: Task demand, by Fuller [46].
3.3.2 Driving skill and driver performance

How should one relate the general term *driving skill* to the driver and his or her behaviour? It may be intuitive for some to relate this skill to the actual control of the vehicle, i.e. the precise positioning of the vehicle on the road. Others may primarily relate issues regarding how accurate a person is in predicting and avoiding hazardous situations to driving skill, and some may consider driving skill primarily to be a measure of how accurate the driver is in driving by the traffic regulations. One could say that a skilled driver would achieve a specific goal in a better way than an unskilled driver in all these examples, but the question arises as to whether the definition of the goal is detailed enough for both the observer and the driver to have the same preferences when interpreting what ‘better’ means. Jarlmark deals with the problem of specifying which control behaviour is preferable in a situation, which he asserts is exemplified by the fact that a quicker and more accurate response might actually put the vehicle closer to the limit of the vehicle manoeuvring [47]. In [37] Kiencke refers to a definition of a good, safe driver as follows:

- Has complete command over the vehicle equipment
- Keeps fairly well to the rules
- Takes no unnecessary risks
- Has good ability to anticipate the traffic situation in the immediate future
- Shows consideration for other drivers when they make mistakes
- Keeps his temper under control

Another aspect of skill which is shown by Mitschke [48] and which involves a controller’s viewpoint rather is the ability of the driver to adapt or tune himself to the driven vehicle, which mathematically expressed means that the parameter values in the driver equation are dependent on the parameters in the vehicle equations. This again shows the need for treating the driver and the vehicle as an integrated system. In the research work presented in Paper A, the drivers were tested for their ability to adapt to changed steering characteristics, which some drivers managed to do almost instantaneously. Elander et al [49] refer to skill as the ability of drivers to maintain control over the vehicle and respond adaptively to complex driving situations, or what they express in other words as driver performance; and they state that driving skill is expected to improve with practice or training.

Regarding potential skill, Groeger in [36] suggests that performance, as the driver gradually gains more practice, does not reflect the improvement of single components, but rather the grouping (or “chunking”) of performance components, and consequently skilled behaviour is based on a larger organization of components than unskilled behaviour. He also argues that people develop a measure of proficiency at a number of skills, rather than one single skill, “driving”, and continues by stating that there also exists a transfer of what is learned in one situation to another situation, to a certain degree. It is possible, according to Groeger, that such transfer occurs through declarative similarity rather than functional similarity; i.e. the transfer of skill from one driving task to another is quite limited between different tasks, e.g. turning right
compared to driving straight ahead in a specific junction, while the rate of learning a specific task in different situations, e.g. turning right at different types of junctions, is quite high. Thus driving requires not only multiple functions (e.g. steering, speed control, gear changing, interpreting the road ahead, navigation etc.) to be taken into account, but also the performance of a continuous stream of tasks that are quite different from one situation to another.

Another distinction to be elucidated is the difference between potential and effective skills in driving. Fuller uses the term capability to refer to the momentary ability of the driver to deliver his or her level of competence, i.e. what the driver actually is able to do at any moment, as seen in Figure 10 [46]. By competence he refers to the driver’s attainment in the range of skills, referred to as roadcraft in his paper. Roadcraft is described as a concept which includes control skills, the ability to “read the road” (hazard detection and recognition), and anticipatory and defensive driving skills. This way of viewing capability and competence can be of use when considering the issue of potential and actual performance, which are terms that are very relevant to this study, especially when designing the driving experiments.

![Diagram of determinants of capability](image)

**Figure 10:** Determinants of capability, by Fuller [46].

There are some different opinions about what actually happens when humans perform a familiar task/observation, i.e. when we practise what one could call an acquired skill. Some researchers support a theory of automatic behaviour in combination with the concept of a central bottle neck, maintaining that a certain level of practice can result in an automated behaviour that will release attention resources for other tasks [50]. Others, like Neisser [51], argue in favour of the theory that we create schemata for different tasks, with practice refining the schemata to cope with new situations, which at first require more attention, during training, but then less attention when the schemata are learned well. Neisser argues that, even if we are unaware of ourselves performing actions, this does not mean that we are automatically controlled by simple stimuli. Neisser questions whether any responses but primitive pre-cognitive actions can ever be really automated in the sense that they can be performed no matter what the situation is and without the influence of the person’s own plans and intentions. Groeger also argues that there are reasons to think that activities like braking, car following, and curve
driving require more selective and deliberate action than is possible without attention [36], i.e. in the ‘automated’ way. However, the difference between the two theories is not critical for the work in this thesis. The main observation is that, with either of the two theories (automatic behaviour or schemata), more resources can be allocated to secondary tasks if the driver is familiar with the situation of the primary task.

Wilde presents in [52] a behaviour theory covering issues regarding the risk-taking behaviour of drivers, the theory of risk homeostasis. The theory is well known and the object of debate, and can be summarized as stating that we prefer to adjust our behaviour so that the perceived risk will match the level of target risk, and thereby eliminate the benefit of introduced risk countermeasures. Michon is somewhat critical of the theory of risk homeostasis and maintains: “Only on the extreme implausibility and much too strong assumption that the same homeostat is operating in all individuals (rather than weakly, but more plausibly assuming that any human behaviour is adaptive in some generic sense) is Wilde’s model theoretically correct” [53]. Regardless of the correctness of the theory, Wilde in [52] also includes a useful definition of three types of skills that exert an effect upon driver behaviour:

- Perceptual skills (the extent to which the subjective risk corresponds to the objective risk)
- Decisional skills (the ability of the driver to decide what should be done to obtain the level of risk that the driver prefers)
- Vehicle handling skills (how effectively the driver can carry out his decisions)

All the three types of skills presented above may be improved by enhancing driver education, licensing standards, and the ergonomic environment (e.g. the road geometry, signals, and the controls and displays in vehicle design), according to Wilde. With this definition of skill, all the activities, or performance levels, related to the actual driving are included and therefore not only the low-level control; i.e. vehicle handling skills are considered to be only one of three types of skill. All these levels of skill are treated in the driver model in Paper D, although the perception of both high and low skill drivers is assumed to be very good in the specific test used. The first type of skills, perceptual skills, is in this thesis expanded with anticipatory and interpretational skills to emphasise the driver experience-based ability to predict future states. This is similar to the definition used in [5] for situational awareness, describing it as consisting of three parts. The first part concerns perception of elements in the environment (e.g. the road, traffic and vehicle condition), the second is understanding the current situation (e.g. that a red light on the car in front is an indication of braking), and the third one concerns foreseeing the near future, achieved through understanding the state and dynamics of the elements around us (e.g. understanding that the distance to the vehicle in front will be reduced if that vehicle is braking).

### 3.3.3 Driving style

It is not obvious how to draw a clear line between skill and style for a specific type of behaviour, but with the previously described importance of a well-defined goal for skill in mind, it can be concluded that, at a high level, style should be defined without any
relation to a specific goal. In Elander et al [49], style is referred to as the way in which drivers choose to drive or habitually drive, including the choice of driving speed and headway, and the habitual level of general attentiveness and assertiveness. Driving style is expected to be influenced by attitudes and beliefs regarding driving, as well as more general needs and values. In the previous chapter, Neisser’s theory of schemata [51] was mentioned. If that theory is used, it could be suggested that a person’s own style of driving influences every aspect of driving, even the lowest level of tracking/control.

If we study different classifications of drivers, Taubman-Ben-Ari et al subdivide the driving styles found in literature into four broad domains [54]:

- Reckless and careless (deliberate violations of safe driving norms, and the seeking of sensations and thrills in driving)
- Anxious (driver stress-related, and reflecting feelings of alertness and tension, as well as ineffective engagement in relaxing activities during driving)
- Angry and hostile (expressions of irritation, rage, and hostile attitudes and acts while driving, reflecting a tendency to act aggressively on the road)
- Patient and careful (planning ahead, attention, patience, politeness, and calmness while driving, and keeping the traffic rules)

Continuing with Taubman-Ben-Ari et al, factor analysis is used for the specification of a more detailed description with eight main factors representing specific driving styles:

- Dissociative (e.g. making misjudgements, performing wrong actions, forgetting)
- Anxious (nervousness about driving, frustration, worrying, driving slow)
- Risky (e.g. taking risks, driving at the limit, performing non-driving tasks such as fixing one’s hair/makeup)
- Angry (e.g. shouting, using the horn, flashing lights, manoeuvring to obstruct others)
- High-velocity (e.g. being impatient, tailgating, driving against a red light)
- Distress reduction (performing relaxation activities / muscle relaxation, meditation)
- Patient (e.g. letting others go first, planning in advance)
- Careful (e.g. driving cautiously, readiness for unexpected manoeuvres by others)

The driving style factors are in the paper coupled to driving styles and personality traits like self-esteem, need for control, sensation seeking, and extroversion.

Many studies have been conducted focusing on driver behaviour when using adaptive cruise control (ACC), and the classification of drivers in these studies can be in terms of willingness to pass, distance to the vehicle in front, or similar traits (e.g. [55]).
A commonly used classification of driving styles, exemplified by Tricot et al, is based on the following general classes [56]:

- Economical style
- Normal style
- Sporty style

These are distinguished by the variables accelerator and brake pedal position, steering wheel angle, engine speed, vehicle speed and acceleration in the paper by Tricot et al. A similar categorization was used for the subjective description of a system by Barthenheier et al in [57], where it was applied for the evaluation of parameters for a steer-by-wire system:

- Comfortable
- Sporty / encouraging active driving
- Safe (subjective measure)
- Generally appreciated

A system with specific characteristics can affect the driver behaviour, since driver-vehicle interaction works both ways; for example a sporty feeling is connected to the encouragement of active driving.

Tricot et al also refer to studies where driving styles are differentiated according to the time interval used: a short or a long time interval. The influence of the environment has been taken into account by a few studies, e.g. the road types (urban roads, A-roads / B-roads, and motorways) and the traffic density (dense and light traffic) [56]. In addition to the driving style classification above, the economical, normal and sporty styles, Tricot et al choose to include the environmental variables dense and light traffic in their study. Instructions were given to the drivers, instructing them as to which of the three styles to use; e.g. for the sporty driving condition, drivers were instructed to "drive rather fast but keeping good safety margins", an instruction that could be interpreted differently by different drivers. The study succeeded in making a fairly good distinction between the styles. However, a couple of drivers were clearly classified into the wrong group of style. This was considered to be partly a consequence of the individual differences in their judgment of what was sporty, normal or economical driving. It is important to describe such subjective terms such in more detail, preferably with examples, since they otherwise are very likely to be interpreted differently for different groups of people. Unfortunately the study also used only 13 subjects and a fixed based driving simulator (with a real car cabin).

In the thesis by Jarlmark [47], a categorization of drivers was made according to their compensation velocity, compensation precision, and driving strategy when compensating for a crosswind gust. The drivers were divided into the following categories: quickly and slowly compensating (QC and SC), over-, under- and mixed-compensating (OC, UC, and MC), and continuously oscillating and "correct and hold" (CO and CH) drivers. All of these characteristics seemed to be independent and thus resulted in twelve identified combinations that could be used for further study.
As a last remark about style, we can state once again what was mentioned earlier about human behaviour: intentions can only be expected to predict a person’s attempt to perform, not necessarily his or her actual performance, since external or psychological factors may prevent the actions from taking place [36].

3.3.4 Specification of ordinary driving and path tracking skill

This thesis work concerns ordinary driving, which is defined here as driving whose aim is to achieve safety, compromising performance and comfort. Given this condition, path tracking driving skills are defined here as comprising:

a. The ability to drive with lower friction and at higher speed (handle the vehicle at the limit)
b. The ability to recognize where the limit is
c. The ability to drive with the lowest lateral accelerations and/or sideslip angle (path-dependent)
d. The ability to drive with low deviation from a driver-preferred track (driver strategy)
e. The ability to adapt to new vehicles/situations (always keeping a relevant internal model)
f. The ability to correct for unexpected disturbances

These different aspects of driving skill are in most respects covered in the different papers presented here. Both a) and b) relate to at-the-limit handling, which is not the specific focus of the present research work, but the double lane change manoeuvre in Paper B includes driving that approaches the limit for higher speed. This manoeuvre also benefits from skill related to c) and d). Paper A includes analysis of c), d) and e) for drivers in general. Unexpected disturbances, f), are covered in Paper C, which investigates the driver reaction to a sudden preview path movement. The effect of external forces, such as side wind or tyre failures, may require additional driving competence, and is not covered here (but studies are made in other projects in the research group, see e.g. [47,93]). The driver model in Paper D concerns tracking a path, which relates mostly to d), although it also covers the same aspect as that dealt with in Paper B. The curving road driving in Paper E relates to c) and d) in general, but for very short sight distances the sudden appearance of left and right curves introduces an unexpected disturbance that requires some skill according to f).
Chapter 4
Measurement of driver characteristics

This chapter presents methods for measurement and analysis of driver characteristics, followed by a description of the driving simulator used for the testing and short descriptions of the different simulator tests performed.

4.1 Introduction to driver analysis

There are two main purposes for measuring driver characteristics: to identify the driver or driver type, and to model the driver or driver type. There are significant challenges in modelling driver behaviour since much remains to be learnt about the structure, order, or granularity of an individual’s control system. Human control strategy is both dynamic and stochastic in nature, and the complex mapping between sensory inputs and control action can be highly nonlinear [59].

Diagnosis methods for systems are commonly divided into two families [56]:

- **Internal diagnosis methods**
  Comparison between system model outputs and actual system outputs. A sufficiently complete and precise model of the driver is required in order to describe causality relationships between the information collected by the driver and the reason for his actions.

- **External diagnosis methods**
  Methods based on observation of the inputs and outputs of the process, using statistical analysis methods. These methods do not need any explicit model of the actual system.

For the research presented in [56], Tricot et al could not find any driver model which could deal with internal processes, which could run on a computer, and which was
Chapter 4  Measurement of driver characteristics

sufficiently accurate to be used in a model-based diagnosis application. Based on the assumption that such a model did not exist, the second approach, an external diagnosis method with factor analysis and pattern recognition, was used in their paper. Nechyba et al [59] also argue in favour of the benefits of using an external diagnosis method, since no explicit physical model is required, but they assert at the same time that the lack of scientific justification of such learned models detracts from the confidence that we can show in them. For a dynamic process, model errors can feed back to themselves to produce trajectories which are not characteristic of the source process and may even be unstable. For a stochastic process, a static error criterion based on the difference between the training data and the predicted model outputs may be inadequate and inappropriate for gauging the fidelity of a learned model to the source process. Nechyba et al state that most learning approaches utilize some static error measure as a test of convergence for the learning algorithm, but offer few, if any, guarantees concerning the dynamic behaviour of the resulting learned model. Statistical error measurement methods, such as the root-mean-square (RMS) method, do not provide sufficiently satisfactory model validation for a dynamic process according to the authors, and therefore the Hidden Markov Model (HMM) was used instead in [59] as a validation method for the trained models.

For driver modelling with different levels of detail however, it should be noted that external diagnosis methods used carefully can provide a powerful tool for analysing at least higher-level tactical driver behaviour, since the complex decision-making of humans does not have to be explicitly described, while detailed descriptions using internal diagnosis can give the needed insight into low-level operational driving behaviour.

4.2 Examples of measurements

According to MacAdam [55], it is good to have a thorough understanding of the range of driving styles, including factors such as:

- Acceleration / deceleration comfort levels
- The headway gap sizes employed during following
- The overall level of aggressiveness related to passing and overtaking activities

Savkoor et al perform driver strategy classification according to acceleration in [60], which is illustrated in Figure 11.
Figure 11: Examples of some elementary braking strategies while approaching and negotiating a curved road segment, specifically in relation to the curve beginning (CB). a),b),c) Braking on a straight road segment to the desired speed before the curve begins (pure longitudinal slip followed by pure lateral slip). d),e),f) Braking on a straight road segment and in the curve to the desired speed (pure longitudinal slip followed by combined longitudinal and lateral slip) [60].

In [61] Kuge et al describe a method for driver behaviour recognition that is based “entirely” on HMM, with continuous recognition of driver behaviour. Multiple correspondence analysis (M.C.A.) was used by Tricot et al in [56] to identify the best set of variables to characterize the studied drivers’ behaviour. Discriminant analysis (D.A.) was used afterwards for automatic classification of new observations. In [32, 33], Raksincharoensak et al evaluate the prediction of pattern recognition methods in longer periods of normal driving.

How we perceive information through vision when we are driving is an important parameter when classifying different drivers, since vision is by far the most important sensory queue in driving, although the level of importance depends on the scenario and the situation [27]. Inter-event arrival and service times are described in [37] by Kiencke and Nielsen. The overall viewing frequency is divided between various viewpoints on the road:

- Visual focus (the point which is approximately a 3 second drive away)
- Lead point (furthest point of the driver’s view)
- Road edge
- Road centre (i.e. central reservation)

Service time is the amount of time which the driver spends looking at a particular point, which is given as between 0.25 s and 1.8 s for road viewpoints [37]. MacAdam lists vehicle response signals presumed to be sensed by the driver model for steering and speed control purposes [62].
Chapter 4   Measurement of driver characteristics

- Lateral acceleration
- Lateral vehicle position
- Longitudinal vehicle position
- Vehicle heading angle
- Vehicle forward speed
- Vehicle lateral speed (sideslip velocity)
- Vehicle yaw rate
- Vehicle roll angle
- Vehicle roll rate

These parameters are therefore to varying degrees a part of the driver’s perception of the state of the vehicle in the model by MacAdam. From simulator runs described in the same paper, and further analyzed in [27], one of the conclusions is that novice drivers were more likely to drive slowly and sacrifice path accuracy to retain directional stability near the handling limit, in comparison with expert drivers. The latter were more successful in performing the required manoeuvres at higher speeds, but they were also more likely to exhibit directional instability.

Underwood et al studied eye movement patterns in [63] and noticed a distinction between drivers with various experience. They also referred to studies that showed novice drivers to be focusing longer on hazardous objects and to detect fewer peripheral events than experienced drivers. Piechulla et al [6] used a secondary task consisting of reading a scrolling text in a pilot study to access the driver’s workload, which is possible since the visual workload is considered a crucial component of the total workload. The driver was instructed to consider safe driving as the primary task, and that the driving performance should not suffer from the secondary task. In the study, the number of glances per second was measured, since the glance frequency was described as a sensitive measure of the driver’s visual workload.

Weir and Allen used an electrocardiogram (ECG) and derived the heart rate for measuring the driver stress level in a variety of driving tasks, and concluded that this method provides a comprehensive measure. The stress level is considered to be an important measure of the driver’s state of alertness and level of skill in a given situation. The heart rate is inversely related to the task stress, due to sinus arrhythmia (the influence of breathing on the heart rate) [64].

In the research work here, the focus has been on parameters that are measured in the standard vehicle hardware, i.e. not on parameters obtained by measurements performed directly on the driver. In Paper A, the data was analysed for differences in driver behaviour using only the driven path and the lateral acceleration levels in a repeated guided manoeuvre. The path was analysed in three ways: using the average over a large number of paths to study the difference between the drivers that could be related to cornering strategy; comparing the individual drivers’ deviation from the mean path, i.e. ascertaining the driver repeatability; and investigating the change in deviation from the mean path using modified steering characteristics, i.e. the driver robustness for system
Section 4.3 Driving simulator tests

...changes. In the following research work, Paper B to Paper E, a large number of measures were taken from available vehicle parameters, including parameters with reference to the road curvature as well as the steering wheel movements. Table 1 shows the full set of parameters used in this work. This includes most of the response signals listed by MacAdam in [62], with the addition of angular and torque information for the steering wheel.

Table 1: Evaluated parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>1:st derivative</th>
<th>2:nd derivative</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_{road}$</td>
<td>Lateral position, road reference</td>
<td>$dy_{road}/dt$</td>
<td>$d^2y_{road}/dt^2$</td>
</tr>
<tr>
<td>$\psi_{road}$</td>
<td>Yaw angle, road reference</td>
<td>$d\psi_{road}/dt$</td>
<td>$d^2\psi_{road}/dt^2$</td>
</tr>
<tr>
<td>$\alpha_y$</td>
<td>Lateral acceleration</td>
<td>$da_y/dt$</td>
<td>$d^2a_y/dt^2$</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Yaw angle</td>
<td>$d\psi/dt$</td>
<td>$d^2\psi/dt^2$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Body slip angle</td>
<td>$d\beta/dt$</td>
<td>$d^2\beta/dt^2$</td>
</tr>
<tr>
<td>$\delta_{SW}$</td>
<td>Steering wheel angle</td>
<td>$d\delta_{SW}/dt$</td>
<td>$d^2\delta_{SW}/dt^2$</td>
</tr>
<tr>
<td>$M_{SW}$</td>
<td>Steering wheel torque</td>
<td>$dM_{SW}/dt$</td>
<td>$d^2M_{SW}/dt^2$</td>
</tr>
</tbody>
</table>

The parameters has been analysed with relation to the test subjects’ driving skill, using a number of measures taken in selected parts of the scenarios. More information on this procedure is found in Paper B, where the method for evaluating the measures is also described. This method is also used for the evaluation of measures in the different manoeuvres and driving conditions described in Paper C and Paper E.

4.3 Driving simulator tests

For analysis of the driver behaviour, it does not suffice to analyse the driver isolated, since the driver and vehicle form a coupled system where only the driver behaviour is affected by the driven vehicle. For example, the driver will adapt to changes in the steering wheel gear ratio (Paper A). Since experiments using real vehicles are very sensitive to changes in the driving conditions and may be dangerous for the driver, it is often preferred to use driving simulators instead. Besides that, simulator tests are more time-efficient and can in many cases be more cost-efficient as well, especially if different or complex vehicle and scenario setups are used. Human limitations in remembering and comparing experiences can also be addressed with the instantaneous system or scenario changes that are possible in the simulator.

Simulators have been used for both open loop and closed loop simulations. The closed loop simulations need a strategy for the feedback control, which can be provided either by a driver model or a living operator, i.e. a human driver. The human operator requires an accurate feedback of the system behaviour to achieve realistic control. Fixed base simulators are the most common type for human feedback control, and can be made quite advanced, even with regular personal computer systems and other off-the-shelf products. These simulators can provide visual, auditory and tactile feedback for the driver, but are not equipped to excite forces to represent the movement of the vehicle. This limits the possibility of achieving a realistic response from the driver, especially in situations that normally would generate high vehicle accelerations. For that purpose moving base simulators can offer a better platform for tests.
Moving base simulators provide a realistic complement to real vehicle tests. The repeatability and possibilities of dynamic changes can provide high quality data with little noise. However, the quality depends on the realism of the driving experience and how well different setups are represented by the simulator. A simulator test is only a representation of a real test and the experience can not yet be made into an identical substitute in all respects. Therefore, it is important that thorough real vehicle tests should be performed before the introduction of innovations in production vehicles. However, the results from driving simulator tests can significantly reduce the number of tests to only the most promising configurations.

4.3.1 Test platform

The driving simulator experiments in the present research work were performed using VTI Simulator III [65,66,67] (Figure 12), which has been built around a real vehicle cab and utilises a sophisticated motion system which enables fast acceleration. This simulator can be connected to a vehicle model in an MBS program such as CarSim, which was used in this work. The CarSim model is further described in Section 4.1 and in [68,69].

![Figure 12: The moving base simulator at VTI. The projectors can be seen above the bodywork, projecting a 120° visual field in front of the driver. The major components of the movement system can be seen: the lateral sled, the pitch cradle and the roll axle below the projectors. [Photo: Staffan Gustavsson (Redakta). Illustration: ARIOM.]

The surroundings are simulated and displayed to the driver via three main screens and three rear view mirrors. Under the cab is a vibration table simulating contact with the road surface, providing a realistic driving experience. This is also enhanced by realistic environmental sound and light. In the 3-DOF moving base, the linear lateral movement is large enough to allow realistic acceleration levels on a straight road; a total lateral movement of 7 m is possible. It also includes roll and pitch movement that is used not only for vehicle movement, but also for longer cornering situations and longitudinal accelerations respectively. The vibration platform has possible motions in the vertical, longitudinal, pitch and roll directions to simulate road irregularities (for a technical specification see Table 2).
Table 2: Technical specification of VTI Simulator III [66].

<table>
<thead>
<tr>
<th>Motion system</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch angle</td>
<td>-9° to +14°</td>
</tr>
<tr>
<td>Roll angle</td>
<td>±23°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>External linear motion</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum amplitude</td>
<td>±3.75 m</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>±4.0 m/s</td>
</tr>
<tr>
<td>Maximum acceleration</td>
<td>±0.8 g</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vibration table</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical movement</td>
<td>±6.0 cm</td>
</tr>
<tr>
<td>Longitudinal movement</td>
<td>±6.0 cm</td>
</tr>
<tr>
<td>Roll angle</td>
<td>±6°</td>
</tr>
<tr>
<td>Pitch angle</td>
<td>±3°</td>
</tr>
</tbody>
</table>

The visual system is optimized for short delay times to be acceptable for research use; a maximum transport delay of 50 ms is specified. The visual system includes three video channels projected at an angle of 30° by a 120° continuous screen ahead of the bodywork. The resolution of the system is 1024 by 3840 pixels (i.e. 1024 by 1280 per channel). The steering system has steering wheel torque feedback via an electric motor controlled by a system with an update frequency of 200 Hz.

### 4.3.2 Curved cone track scenario

The aim of the curved cone track scenario, presented in Paper A, was to investigate driver behaviour with a focus on the variation of different drivers’ ability to steer the vehicle, i.e. path tracking skill. The moving base driving simulator was used to study the drivers’ performance and behaviour when following a cone track scenario (see Table 3 and Figure 13), primarily investigating the driven paths and lateral acceleration levels. Relatively low speed was used, 55 km/h, creating a situation similar to some road work conditions. The narrow cone track requires large lateral displacements and relatively high attention being devoted to controlling the vehicle, but allows a limited amount of variance in the chosen path. To investigate if there are differences between drivers with a varying experience of driving, the recruitment base was chosen to be low and high mileage drivers. All the drivers drove the simulator with the validated vehicle model with both the standard setting as a reference and eight other combinations of steering wheel gear ratio and steering wheel effort for comparison.

Table 3: Cone coordinates for the curved cone track scenario.

<table>
<thead>
<tr>
<th>Left [m]</th>
<th>x</th>
<th>y</th>
<th>75</th>
<th>107</th>
<th>139.1</th>
<th>151.25</th>
<th>184</th>
<th>216</th>
<th>248.75</th>
<th>280.9</th>
<th>313</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-2.5</td>
<td>-2.5</td>
<td>-1.5</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>6</td>
<td>-1.5</td>
<td>-2.5</td>
<td></td>
</tr>
<tr>
<td>Right [m]</td>
<td>x</td>
<td>y</td>
<td>75</td>
<td>107</td>
<td>139.75</td>
<td>151.9</td>
<td>184</td>
<td>216</td>
<td>248.1</td>
<td>280.15</td>
<td>313</td>
</tr>
<tr>
<td></td>
<td>-6</td>
<td>-6</td>
<td>5</td>
<td>1.5</td>
<td>2.5</td>
<td>2.5</td>
<td>1.5</td>
<td>-5</td>
<td>-6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.3.3 Avoidance manoeuvre scenario

The objective of the avoidance manoeuvre scenario, presented in Paper B, was to evaluate the relation between the driver skill and a large number of objective vehicle parameters, all measured in the moving base simulator used. The recruitment of test subjects was carried out based on a developed self-evaluation made by the drivers with reference to descriptions of high skill and low skill drivers. A double lane change (DLC) scenario specified according to ISO 3888-1:1999 was used both for recruitment verification and the measurement of objective parameters. In Paper B, a suggested method used for comparison of parameters under equal conditions is described. This method was also used in Paper C and Paper E, and the results from Paper B are also used in the development of the driver model in Paper D.

4.3.4 Driver response scenario

The line jump scenario, presented in Paper C, was designed and evaluated for the investigation of driver-vehicle characteristics when following a movable reference line, as seen in the illustration in Figure 14. The objective of this research work was to investigate driver steering response during sudden unexpected reference path movement, i.e. doing path tracking without preview, and this is possible with the line jump scenario. The scenario design allows path tracking to be evaluated without the uncertainty of a reference path coupled to a driver-preferred lane position or distance to objects. With this scenario, the results instead show the effect of test subjects who can choose how to perform the manoeuvre when guided precisely concerning time and lateral distance, but not forced longitudinally by boundaries of a path, in a way very similar to a regular step response.
4.3.5 Curving road scenario

The objective of the curving road scenario, presented in Paper E, was to evaluate objective parameters for characterization of driver skill when a driver is driving a vehicle on a regular curving road (illustration shown in Figure 15). The reason for performing this experiment is that the identification of driving skill in normal driving conditions can be of great use for the setup of adjustable vehicle systems. A curving road scenario was designed using both clear sight combined with high and medium friction, and high friction combined with a limited sight distance. Fog was used to investigate the effect of forced limitation of the driver preview distance. The method developed compares parameters under equal conditions, identifying the ones with best separation between the two recruited driver types.
4.4 Proposed driving skill characterization methodology

The proposed methodology, presented in Paper B, was used for comparison of measures under equal conditions to identify parameters that are specifically useful for characterizing the drivers’ path tracking skill. The parameters can be used for driver metrics, representing typical driver characteristics in a driver model such as the one presented in Paper D, for example. A method for pre-estimation of driver guidance and control skill, also presented in Paper B, was developed to ensure that two representative sets of drivers were recruited. These two sets are not homogeneous since different driver behaviour to a large extent is shaped through individual experience. The analysis was therefore performed using the two-thirds of the drivers (in the normal case) which were the most separated for each specific parameter measure, calculating a normalized value, the grade, which is used for comparison of the parameters:

\[
Grade = \begin{cases}
1 - \frac{C - \text{abs}(HVS - LVS)}{2 \cdot SS}, & \text{if } HVS > \frac{SS}{2} \text{ and } LVS < \frac{SS}{2} \\
0.5, & \text{or } HVS < \frac{SS}{2} \text{ and } LVS > \frac{SS}{2} \\
\text{else}
\end{cases}
\]  (7)

*SS* = Size of sections used in analysis

*HVS* = Number of high (or low) skill test subjects in the high value section

*LVS* = Number of high (or low) skill test subjects in the low value section

The recorded data from these sections were used to derive driver metrics intervals, with the higher graded characterizing the high skill and low skill differently.

4.5 Results from driving characterization

In the first driving simulator experiment, presented in Sub-section 4.2.3 and Paper A, the drivers were only recruited with a rough definition of driver skill. However, the results revealed some of the complexities in characterising and modelling drivers by showing that the driver-preferred path strategy can differ a great deal between drivers even for a relatively narrow track. Even though the vehicle steering wheel ratio and effort were changed radically (but within realistic values), the driven path remained relatively constant for the individual driver. Several drivers were easily separated from each other in all of the approximately 30 to 50 runs. Some strategies resulted in twice the lateral acceleration for some drivers compared to others, which also means a smaller buffer to the limit set by road friction. This is important to take into consideration when analyzing path tracking skill on a road or through a cone track, since the actual path which the driver is trying to follow may differ in many ways from the optimal path, and thus the drivers may be striving to fulfil different goals. However, as long as the main goal is fulfilled, and no other measurable objectives have been given to the driver (such as keeping a low lateral acceleration), it is not recommendable to make an evaluation
based on these aspects alone. Some experienced drivers tend to prefer to keep the vehicle closer to the limit to be able to feel the transition towards tyre saturation better, while others use their experience to drive with as large a buffer as possible. Examples of the mean path over all the driver runs are shown in Figure 16, showing both test subjects with very different paths (Figure 16a) and drivers with similar paths (Figure 16b).

The cornering strategy is found to be one good measure for analysing the drivers’ decision making, while the magnitude of the standard deviation from the average path is useful for analysing the repeatability of the drivers, and thereby provides an indication of the precision with which the driver controls the vehicle. The ability to handle system changes reflects how well the driver adapts to a new system.

The second driving simulator experiment included several different scenarios, presented in Sub-sections 4.2.4-4.2.6, and in Papers B, C and E. This allowed the same drivers to be used for all the scenarios (15 high skill drivers and 15 low skill drivers), increasing the reliability of comparisons between the scenarios. In Paper B the avoidance manoeuvre scenario is presented. This scenario was used both for validation of the developed recruitment method based on self evaluation and to determine skill-dependent metrics. The questionnaire-based recruitment process successfully provided two distributions of drivers in the DLC-test, with only a very small overlapping of the distributions of drivers with pre-estimated high and low skill for guidance and control, as seen in Figure 17. The two driver populations are also shown to be significantly different ($p=0.000005$).

Figure 16: Mean paths for test subjects with: a) large driving path difference and; b) small driving path difference.
The position in the lane, $y$, has proved to be a parameter which re-occurs as high graded for all the cases tested for this in the DLC simulation, i.e. 50, 60 and 70 km/h (all tests subjects did not manage to drive at higher speed). The maximum value for this parameter is constantly high graded, which indicates that the path strategy shows similarities within the two groups of drivers. For the second half of the DLC-scenario in this test, at the highest speed (70 km/h), several other high grade parameters are also identified, including parameters related to both vehicle movement and steering wheel movement. Since it is mainly the higher derivatives that qualify in this particular scenario, this can be a problem for in-vehicle measurement due to the sensitivity to noise. The standard deviation, however, which is calculated using all the data points within the selected section, is relatively robust as a measure and is effective as a sorting criterion for a number of parameters. For example, good performance can be possible with reliable steering wheel angle measurement, since the standard deviation of both the steering wheel angular rate and the steering wheel angular acceleration is shown to exhibit relatively high grades.

In Paper C the line jump scenario, i.e. path tracking without preview, is presented with results for all the drivers. It is shown that the overshoot amplitude increases for all the cases when the velocity is increased, in most cases considerably. Another observation is that, even though the overshoot increases with larger jumps in most cases, the increment is far from proportional to the increment in the size of the jump. A short rise time is shown to be representative of the high skill drivers in general, while a longer rise time is shown to be representative of the low skill drivers, but, perhaps even more importantly, this is also valid in combination with overshoot. The main reason for this is likely to be that the high skill drivers have better knowledge of the vehicle response, which is crucial for quick and accurate manoeuvres. Several objective vehicle measures are shown to be important in characterizing the difference between high skill and low skill drivers in straight line path tracking. The standard deviation of the lateral velocity and yaw angle show particularly good separation of the two driver categories. These measures relate to the stability of the vehicle after the manoeuvre. Values close to zero are characteristic of the high skill drivers, with the standard deviation of the yaw angle being lower than 0.15 degrees for all the tested jumps.
The results are useful in driver model development and driver skill identification algorithms. Examples of other suitable usage of the simple principle of precision line tracking are investigations of driver response to other forms of disturbances, e.g. side wind or tyre punctures. Driving along a curved line in combination with response to a variation of road friction is also a potential application.

**Paper E** presents a curving road scenario with the results of the driver characterization method applied. The first two scenario sub-parts, called A-1 and A-2, are used with clear sight with high road friction and medium road friction respectively. The remaining five, called B-1 to B-5, are used with a decreasing sight distance (255, 135, 75, 45 and 30 m). Figure 18 shows all the scenario results for the smallest curve radius. Only the centre parts of the curves are used, so that some of the effects occurring when going from straight segments to curves are removed. Because of that, the shortest curve lengths (see Figure 18b) have a sample length part of only ~40 m remaining for analysis, making the analysis of these curves less reliable than that of the longer curves. Driving in these shorter curves is also less similar to steady-state driving, since corner cutting by the drivers is more likely to occur.

![Figure 18: Lateral acceleration levels (minimum to maximum), with green for the low skill section, red for the high skill section and black for all the drivers, in curves with a radius of 150 m. The grade is printed close to each bar. The dashed line shows the ideal lateral acceleration \( a_y \) according to the approximation \( a_y = \frac{v^2}{R} \). a) Left and right turn for a road turning angle of \( \pi/3 \) rad. b) Left and right turn for a road turning angle of \( \pi/5 \) rad.](image)

For the fog-induced preview limitation, shown Figure 19, the number of measures with high grades is starting to increase when the sight distance is shortened. This seems reasonable, since drivers with low skill are expected to be more disturbed by this than the skilled that should have more experience of difficult conditions. For extremely short preview however, which is very difficult for all types of drivers, the number of high grades decreases abruptly.
Figure 19: Number of high grade parameter measures in scenario B, divided into measures also high graded in scenario A-1 and additional measures.

A comparison of the identified measures for the curving road with and without fog-induced preview limitation is presented in Paper E, but it is also interesting to compare these results to those for other scenarios. It is relevant to compare the line jump scenario in Paper C with the curves in Paper D, since driving in both the line jump scenario and the curving road scenario represents a quasi-steady-state behaviour in a relatively active driving situation. The comparison shows good results for finding common parameter measures that are graded high for both scenarios. Therefore, the results for these two scenarios are presented in Table 4 with numbers indicating whether the measure is high graded for both scenarios (blue highlighting), one scenario (grey for the curving road scenario A-1 and hashed red for the line jump scenario), or none of the scenarios (no highlighting). The yaw angle is not the same for the global reference and the road reference, since scenario A-1 uses a curving road and the line jump scenario uses a straight road (thus the hashed red for this parameter means that it is actually identical to the road-referenced parameter, i.e. not new), but many other parameter measures are found to be common for both the scenarios. The grade limit is set a little bit differently in the two scenarios to create a balanced set with the fidelity possible.
### Table 4: Number of occurrences of selected measures for scenario A-1 (grade equal or higher than 0.78) in the in blue and grey and additional measures from the line jump scenario (grade equal or higher than 0.75) hashed in red.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measure</th>
<th>MAX</th>
<th>L</th>
<th>MIN</th>
<th>R</th>
<th>MAX</th>
<th>R</th>
<th>ABS</th>
<th>MEAN</th>
<th>STD</th>
<th>BW</th>
<th>POS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y_road</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Y_road/dt</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Y_road/dt²</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Y_road/dt³</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Ψ_road</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Ψ_road/dt</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Ψ_road/dt²</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>δ_road</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>δ_road/dt</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>δ_road/dt²</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>δ_road/dt³</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>M_road</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>M_road/dt</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>M_road/dt²</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>M_road/dt³</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Since the parameters measures highlighted in blue in Table 4 have high grades both for the driver response in the line jump scenario and the regular driving in the curving road scenario, these show good potential for general usage. Without knowledge of the curvature of the road, the standard deviation of both the steering wheel angle and the lateral acceleration qualify for this. These can also be relatively easy to measure and are not as sensitive as peak values for noise. If road curvature is known, the standard deviation of both the lateral velocity and acceleration relative to the road and yaw angle relative to the road could be used, given that the noise is low enough. With knowledge of the actual levels of the parameter measures for the driver categories in the specific driving case, there are several more parameters that could be interesting, e.g. the yaw angle relative to the road, which is directly related to path planning and tracking.
This chapter gives a brief description of the two different vehicle models used: the complex MBS-model in CarSim that is used as the controlled vehicle; and the simple vehicle model that is used in the driver model as the description of the driver understanding of the controlled system.

5.1 MBS-model description

The vehicle model used in the moving base simulator is a four-wheeled, 42-degree of freedom (DOF) CarSim model, see Table 5 [68,69]. The sprung mass of the vehicle is represented by a rigid body with six DOF. The front suspension and rear suspensions are independent suspensions which have compliance in the lateral and longitudinal directions. The longitudinal and lateral movements are constrained as functions of vertical movement described by nonlinear tables, the camber and toe angles related to the vertical position by nonlinear tables, and the suspension springs include hysteresis due to friction. The dampers produce forces as nonlinear functions of the stroke rate. The suspension roll moments include a nonlinear auxiliary roll moment to account for roll stiffness beyond the effects predicted by the spring properties and geometry. Each wheel has compliance that affects the toe and camber in response to the tyres’ shear forces and moments. The roll and jacking forces are calculated as the natural results of full 3D kinematical curves and compliance effects. Each wheel has one spin DOF and each tyre has two dynamic DOF: one for lagged lateral slip, the other for lagged longitudinal slip. The main model uses nonlinear tables to represent the lateral force, longitudinal force, aligning moment, and overturning moment as functions of slip, load, and camber. The lateral and longitudinal forces and moments are combined using combined slip theory as described by Pacejka and Sharp [70].
Table 5: Degrees of freedom in the CarSim vehicle model [68,69].

<table>
<thead>
<tr>
<th>DOF Description</th>
<th>DOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprung mass</td>
<td>6</td>
</tr>
<tr>
<td>Vertical movement of front suspension</td>
<td>2</td>
</tr>
<tr>
<td>Vertical movement of rear suspension</td>
<td>2</td>
</tr>
<tr>
<td>Front suspension compliance</td>
<td>6</td>
</tr>
<tr>
<td>Rear suspension compliance</td>
<td>6</td>
</tr>
<tr>
<td>Wheel spin</td>
<td>4</td>
</tr>
<tr>
<td>Lagged lateral slip</td>
<td>4</td>
</tr>
<tr>
<td>Lagged longitudinal slip</td>
<td>4</td>
</tr>
<tr>
<td>Friction in suspensions</td>
<td>4</td>
</tr>
<tr>
<td>Friction in tyres</td>
<td>4</td>
</tr>
</tbody>
</table>

The equations of motion are derived from the first principles for fully nonlinear 3D motions of connected rigid bodies. The equations of motion are ordinary differential equations (ODEs) and can be solved with most numerical integration methods. The ODEs are solved using a second-order Runge-Kutta algorithm [69]. The vehicle model used represents a medium-sized car. An external servo is added to the vehicle model for better representation of the steering system in the calculation of the torque at the steering wheel.

5.2 Validation of MBS-model

When a moving base vehicle simulator is used for behavioural research, it is of the utmost importance that the movement felt by the drivers is realistic. This does not necessarily mean that the model has to resemble an existing vehicle, but it should behave as a vehicle could be expected to behave in order to be predictable by the driver. It is of course important that the vehicle model should be validated against real vehicle dynamics if the results are to be applicable for the specific vehicle, but this is not as important here as the requirement that driving the vehicle model should feel the same as driving the vehicle modelled. This feeling is dependent on both the vehicle model and the simulator. The CarSim vehicle model used in the simulator tests performed here has been validated by Saab Automobile within the project. Examples of validation results are shown in Figure 20.
The vehicle model has also been verified in the simulator to be acceptable by several drivers, of which one is a test driver who is familiar with the specific modelled vehicle. The overall behaviour is considered very realistic for lateral movement, but in some special situations with very high lateral acceleration, and in some situation with transition from a straight road to long curves, there are some unresolved discrepancies in movement that can be noticeable (at least by a trained driver). With the limited possibility of generating force for longitudinal dynamics in the setup used for the simulator, i.e. only by tilting the cabin, it is not possible to make this movement with enough realism here, and therefore the acceleration and deceleration phases are kept to a minimum and are not used for analysis.

5.3 Driver’s internal vehicle model

This section describes the fundamental lateral vehicle dynamics that, with appropriate parameter values, can be used for representation of the driver’s knowledge of the controlled vehicle. Where parameter and variable descriptions are left out, these are found described in the Nomenclature. Knowledge of the driven vehicle is a part of driver modelling that can include a dynamic model or more static information. The driver model presented in Paper D is based on the fundamental dynamics presented here, using a quasi-static approximation instead of the full dynamics.

The vehicle equilibrium equations in Equation 1 describe the movement of a front-steered vehicle approximated with two wheels, no height, and no influence of external forces. They are also the basic equations for the simplified vehicle model often referred to as the bicycle model or one-track model. This is a basic vehicle description that is used as a basis for many driver models, and it is employed here as well, since it offers a good approximation of the controlled system. If a more complex description using, for example, four-wheel steering is sought, this can be found in [71] by Abe, for example.
For a more commonly used form of the bicycle model, the last two rows in Equation 1 are rewritten to the matrix form in Equation 2. In this form the tyre forces are approximated with a linear relation to the slip angle of the wheels, and also small angle approximations are used for the tyre slip angles and the steering angle at the wheel. Since both the slip angles and the steering angles are rarely much larger than 5°, the error will be kept relatively small (in the order of magnitude of 1%) for the driver scenarios in this research work.

\[
\begin{bmatrix}
    m(\dot{v}_x - \psi \dot{v}_y) = -F_{12}\sin \delta \\
    m(\dot{v}_y + \psi \dot{v}_x) = F_{34} + F_{12}\cos \delta \\
    J_\psi = f F_{12}\cos \delta - b F_{34}
\end{bmatrix}
\]

Equation 1

\[
\begin{bmatrix}
    mD + C_{12} + C_{34} \\
    f C_{12} - b C_{34}
\end{bmatrix}
\begin{bmatrix}
    \frac{mv_x + f C_{12} - b C_{34}}{v_x} \\
    \frac{f C_{12} - b C_{34}}{v_x}
\end{bmatrix}
\begin{bmatrix}
    \dot{v}_x \\
    \dot{v}_y
\end{bmatrix}
= \begin{bmatrix}
    C_{12} \\
    f C_{12}
\end{bmatrix}
\]

Equation 2

The equations presented in Equation 2 can in the steady state, i.e. \( \dot{v}_x = \psi = 0 \), be expressed as:

\[
\begin{align*}
\delta &= \psi - \frac{L^2 C_{12} C_{34} + m v_y (b C_{34} - f C_{12})}{v_x L C_{12} C_{34}} \\
&= \frac{L}{v_x} - \frac{m (b C_{34} - f C_{12})}{L C_{12} C_{34}} v_y = L \frac{v_y}{v_x} + K_{us} v_y
\end{align*}
\]

Equation 3

where the vehicle understeer characteristics are described by \( K_{us} \), which is constant if the axle characteristics are approximated to be constant:

\[
K_{us} = \frac{m (b C_{34} - f C_{12})}{L C_{12} C_{34}}
\]

Equation 4

With zero body slip angle, the velocity body fixed coordinates \((v_x, v_y)\) will be equal to the velocity in the rotating reference frame \((v_T, v_R)\), with one tangential component and one radial component, directly related to the circle defined by the turning radius. With a body slip angle different from zero, however, there will be a difference in velocity between these systems. This difference can be calculated with:
\[
\beta = \arctan\left(\frac{v_x}{v_y}\right) \Rightarrow v_x = v_y \tan \beta
\]
\[
v_r^2 = v_x^2 + v_y^2
\]
\[
\Rightarrow v_x = v_r \frac{1}{\sqrt{1 + \tan^2 \beta}}
\]
\[
(5)
\]

With values inserted this shows, for example, that a slip angle of 8° would result in less than 1% error for the approximation \(\sqrt{1 + \tan^2 \beta} \approx 1\), i.e. \(v_x = v_r\). This is small enough to allow the small angle approximation here as well, and Equation 3 can be rewritten according to:

\[
\delta = L \frac{v_x \psi + K_v v_r \psi}{v_r} = L \frac{v_x \psi + K_v v_r \psi}{v_r} + K_v a_r = L + K_v a_r
\]
\[
(6)
\]

The term \(L/R\) can be referred back to a case with lateral acceleration close to zero, meaning that the forces generated by the tyres are small. In such a case the geometric steering has much higher relevance than the tyre characteristics or other dynamic properties of the vehicle. This baseline geometric steering wheel angle needed for the specific turn radius is often referred to as the Ackermann angle [72,73], which for the bicycle model is simply \(\delta = L/R\), as presented in Figure 21. Geometrically the angle would be \(\delta = \arctan(L/R)\) according to the figure, but, as for the other small angle approximations used, for \(L\) much smaller than \(R\) the simplified (and commonly used) description will differ very little from the more complex one.

Figure 21: Illustration of the Ackermann angle (\(\delta_A\)) for a bicycle model.

The term \(K_v\) in Equation 6 is a linear approximation that assumes linear dependence of the slip angle and the lateral force at the wheels, which usually is an acceptable simplification for small slip angles, but which does not hold true for large angles, where
the lateral force is saturated. The lateral acceleration $a_y$ can also be used instead of the radial centripetal acceleration $a_R$ with the small angle acceleration, since the difference will be only cosine ($\beta$), which for a reasonably large slip angle of $8^\circ$ is less than $1\%$ as well.
Chapter 6

Modelling of drivers

This chapter gives a brief overview of different driver model types: the compensation tracking type, which does not include any future path information; the preview tracking type, which does take the basic human ability to utilize preview into account; and the fuzzy type, using a blend of simultaneous feedback processes.

6.1 Compensation tracking models

A basic block diagram illustrating the compensation tracking models is shown in Figure 22, where $G(s)$ represents the transfer function of the vehicle system and $H(s)$ represents the transfer function of the driver compensation [74]. Where parameter and variable descriptions are left out, these are found described in the Nomenclature.

\[
H(s) = \frac{K_p s^2 + K_v s + K_i}{s}
\]  

(8)

Figure 22: Basic structure of compensation tracking models [72].

The model presented by Iguchi in 1959 used Equation 8 as a model for the driver block (Figure 22) [75,76,74].
The model is simple, but the coefficients $K_d$, $K_p$, and $K_i$ are difficult to determine and therefore the model has not been used extensively [74].

Ashkens and McRuer presented the model in Equation 9 for the driver block in 1959, introducing the vehicle-independent driver brain response delay, $t_d$, and the driver action delay, $t_a$. Lead, $T_L$, lag, $T_H$, and gain, $K$, however, are dependent on the driver experience and the vehicle driven [77, 74].

$$H(s) = \frac{Ke^{-\omega_c t_d}(1+T_Ls)}{(1+t_a s)(1+T_H s)}$$

In 1967, McRuer presented a method for determining $T_L$, $T_H$, and $K$ by fitting Equation 10, where $\omega_c$ is the cross-over frequency of the open-loop function, $H(s)G(s)$, often referred to as the cross-over model [13,16].

$$H(s)G(s) = \frac{\omega_c e^{-\omega_c t_d}}{s}$$

These models can be useful for corrections of identified errors in specified conditions, but are not fully satisfying for more complex situations due to the simple feedback and lack of effective preview usage.

### 6.2 Preview tracking models

In the preview tracking models, a preview strategy element and feedback function are included. A basic block diagram illustrating the preview tracking models is shown in Figure 23, where $P(s)$ represents the preview strategy, $H(s)$ the control characteristics function, and $B(S)$ the driver’s feedback (or prediction) function of vehicle motion giving the driver estimation of future lateral position after driver compensation, $y_p$, aimed at matching the output from the preview strategy, $f_0$ [74]. Where parameter and variable descriptions are left out, these are found described in the Nomenclature.

![Figure 23: Basic structure of preview tracking models [74].](image-url)
The first preview tracking model, the linear prediction model, shown simplified in Equations 11 to 13, was presented by Kondo in 1968 [78,74]. This model did not take the response delay of the driver into account, but introduced the predicted lateral position, \( y_p \), at time \( t + T_p \) based on the lateral position, \( y \), and heading angle, \( \psi \), at time \( t \), together with the vehicle speed, \( V \) [74].

\[
\begin{align*}
P(s) &= e^{T_p s} \\
H(s) &= K \\
B(s) &= (1 - T_p V) \\
\end{align*}
\]

(11)

\[
\bar{y}(t) = [y(t), \psi(t)]^T \\
y_p(t + T_p) = y(t) + T_p \psi(t) \\
\]

(12)

(13)

By replacing \( V \psi(t) \) with \( \dot{y}(t) \) in the equation above for small \( \psi(t) \) and low frequencies, a single variable feedback can be formed, \( B(s) = 1 + T_p s \) [79,80,81,82].

In 1968, Yoshimoto presented the second order prediction model, where both a second order prediction feedback and a driver response delay are included, as well as an integration block with an empirically determined \( K \) to represent the correction ability of drivers [83,84,85,74].

\[
\begin{align*}
P(s) &= e^{T_p s} \\
H(s) &= \frac{K}{s} e^{-T_p s} \\
B(s) &= 1 + T_p s + \frac{T_p^2}{2} s^2 \\
\end{align*}
\]

(14)

In 1966, Sheridan was the first to present the optimal control concept, in which he considered the driver/vehicle tracking problem using a local optimal preview model where the driver aims at minimizing the tracking error looking over a finite interval of the future path [86,74]. MacAdam, however, developed the concept further in 1980, and with his work the optimal preview control model was taken from theory to engineering application [25,26,74,82].

An extension of the optimal preview control model is presented by MacAdam in [62], using a nonlinear vehicle description. The driver model was developed as a GM project to cover “near/at-limit vehicle handling”, with “substantial utilization of available tyre/road friction”. A key factor in the new model was the inclusion of driver characteristics, e.g. look-ahead/preview sight information; the ability to adapt vehicle dynamic properties at varying adaptation rates; compensatory abilities to alter preview utilization; and anticipatory abilities based on upcoming road geometry or path requirements; as well as the inclusion of limitations, e.g. reaction time delays; neuromuscular dynamic lag; and corresponding frequency response characteristics. In [27],
which focuses on the control aspect of human driving with an internal model in a way similar to that in [62], MacAdam lists what he considers to be a minimal representation of the human driver:

- Transport time delay
- Preview for upcoming lateral and longitudinal requirements
- Driver adaptation provision
- *Cross-over model* behaviour near the cross-over frequency
- Internal vehicle model for prediction

He also lists additional and desirable features:

- Neural delays, thresholds, rate-limiting, and dynamic properties of individual sensory channels
- Neuromuscular filtering
- Previewed path adjustment capabilities and strategies to adjust for e.g. skill and style
- Speed adjustment based on upcoming lateral path requirements
- Surprise or situational awareness features

The situational awareness feature is modelled in the GM-UMTRI model [62] as a cognitive/recognition delay to simulate the “casual” driver control behaviour. What this does is to delay the desired path information until a certain lateral acceleration limit is exceeded, i.e. a conflict or sudden manoeuvring condition is occurring. This function is then deactivated for the remaining part of the simulation run. An illustration of the GM-UMTRI model can be seen in Figure 24, followed by a short description of the ten elements.
Figure 24: GM-UMTRI driver model with reference numbers for each element [62].

The components of the driver model are listed below according to the reference numbers in Figure 24:

1. Previewed scene (desired path or road input description)
2. Sensory limitations and noise (pertaining to incoming vehicle response signals)
3. Internal vehicle dynamics (4 degrees of freedom)
4. Prediction capability
5. Steering control calculation
6. Driver physiological and ergonomic constraints (associated with driver steering and control responses)
7. Path planning options (centre-line smoothing, or minimum curvature path)
8. Fixed or variable driver preview capability (based on upcoming vehicle-boundary constraints and projected interferences)
9. Driver speed control (for accommodating upcoming lateral path requirements and estimated lateral demands)
10. Situational awareness parameter (a simple delay that only affects the path input channel and only during the initial portion of a manoeuvre)
MacAdam does not claim to cover more than the control activities of driving in the described model, even though some activities may go beyond low-level controlling (e.g. driver preview used for adjustment of the speed and track). The model also treats longitudinal and lateral control behaviour separately in the current form, but the combined form of control behaviour that more naturally represents the behaviour of human drivers is described as appealing for future modelling efforts. MacAdam also recognizes driver skill-related issues and techniques for recognizing and representing driver skill as an area that requires more research work. Moreover, the areas of “smart vehicles” potential interaction with human drivers, better understanding and categorization of less skilled drivers, improvements in the understanding of how drivers internalize their view of the external world/controlled vehicle, and the modelling of this, are to be considered for further work, according to MacAdam [62,27].

6.3 Fuzzy set theory models

When mathematical models are unavailable or too complex for the required accuracy and speed of response, fuzzy set theory may be helpful. This allows objects to have partial membership of a set, which is not the case for conventional (crisp) set theory. Human perceptions are more naturally defined by fuzzy sets than by crisp ones, and fuzzy mathematics combined with knowledge-based (expert) logic is what gives the fuzzy logic system the ability to “reason” like humans. Fuzzy logic is, however, not as easy to validate as conventional control theory and empirical methods may be the only way to accomplish this. Fuzzy logic is considered best when a process can be defined with IF-THEN rules, while neural networks are useful when only input-output signals are known [87]. What neural networks really do is to classify data by matching signals to learned patterns, i.e. they provide a pattern recognition method. Neural networks have different properties, depending on how they learn and train. Some networks train only on input data and are particularly good at spotting similarities. The dynamics of these networks are sensitive to repetition, which allows them to evolve transfer functions influenced by natural clustering in the data. Besides being adaptive, neural networks are also robust, since they can give quite good answers even when the input data are noisy or incomplete. Neural networks learn by reading known input/output samples and adapting themselves to map them together, which means that they do not need explicit equations to correlate this relation. This is described by MacAdam in [27] not only as a benefit, since the lack of parameters directly linked to physical characteristics of the driver often makes the results difficult to interpret. Berardinis asserts in [87] that, even if the right network is used for a particular system, this is still not a guarantee of success. If the training data is bad, the result will be bad. It is also important to know that a network performs badly both with too little and with too much training. Trivial relations in the training set which are of no interest for classification may also be a cause of error. As stated by Neusser in [88], one of the major benefits of neural networks is that they are capable of learning complex, highly non-linear relations between input and output, even if these relations are not explicitly known; i.e. the network will learn to extract the essential sensor information, and an actual neural hardware realization will be fast, as neural networks are naturally suitable for a massively parallel execution.
Neural networks are used by MacAdam in [55] for identifying and classifying the on-highway longitudinal control behaviour of drivers based on different levels of displayed aggressiveness, and also for representing or modelling instances of longitudinal control behaviour (Figure 25).

Figure 25: Neural net pattern recognition for classifying driving behaviour [55].

The tests were conducted under normal highway conditions in the USA with measurements of the range and range-rate (with an infrared sensor), driver steering, throttle control, yaw rate and lateral acceleration, for example. Driver style classification was carried out based on the displayed level of aggressiveness in terms of willingness to pass, follow, or be passed by other vehicles. The study shows that a neural net representation derived from prior training data does not necessarily predict future driver control behaviour under similar operating conditions accurately, which can be seen in Figure 26, where the driver behaviour changes several times during driving.

Figure 26: Distribution of driving behaviour identified for an “average” driver over a one-hour period with 135 events [55].
MacAdam suggests that this can be explained partly by the fact that the longitudinal control task in the study was affected by components of the driving environments, such as the road grade, nearby vehicles, visual distractions, and other influences that are not reflected directly within the limited sensor information provided only by the range and range-rate measurements in the study. He also suggests that casual control activity perhaps does not demand the same level and continuity of attention as is required for path following. It was concluded that drivers are probably affected by other influences beyond just the range and range-rate, which implies that a dynamic classification of a driver is preferable.

In [89] Ohno uses a three-layer feed-forward neural network model with a sigmoid-type activation function for the units in the hidden and output layers. This model performs both control and learning at the same time. The study is focused on the use of adaptive cruise control (ACC) and an important lesson is that some drivers tend to over-trust the technology and put the driver-vehicle system in a situation where an accident cannot be avoided.

Although neural networks and other similar pattern recognition methods that use automatic training are very powerful for recognition of complex patterns, they are sensitive to the training procedure, and since a mix of parameters are used, it is often difficult to make any detailed conclusions of the reasons behind the results and the internal process. With sufficient knowledge of the internal structure of the modelled system, and a careful selection and usage of parameters, these methods can be very useful for identification of system state and to model complex decision-making. For lower level control and regulation tasks however, there are more benefits of using a model which is more explicitly defined, and with an isomorphic model in which the internal structure of the system is also described, it is possible to set parameters that are relevant for the internal process.
6.4 The KTH Vehicle Dynamics driver model

The objective of the KTH Vehicle Dynamics driver model is to create a model that can be configured to represent a typical high skill and a typical low skill driver in a path tracking scenario with constant driving speed. The model described in Paper D is a preview tracking model with feedback of the lateral position of the vehicle’s centre of gravity (CG) relative to the preview path and yaw angle with a curvature reference to the path.

A driver model is proposed that is based on a relatively simple internal vehicle model. The driver model is flexible and intuitive for the setting of physically relevant parameters and the current design shows that both simulation of general driver characteristics and differentiation between high and low skill driver behaviour can be accomplished. By using the moving base driving simulator, VTI Simulator III [65,66,67], integrated with the desktop vehicle simulation program CarSim [68], it is possible to use the same validated vehicle model in both the driver model and the simulator and only replace the source of input. The model separates three levels of driving skill: perceptual, anticipatory & interpretational; decisional and; execution skills, into different blocks.

The validation of the model is performed using the results from driving simulator tests with the ISO 3888-1:1999 double lane change scenario. The parameter sets used for the model configuration are selected based on physical relevance to the model, and optimization is carried out with a Nelder-Mead implementation [90], which is based on the Simplex method [91]. The driver model that is presented here has been shown to be able to resemble the characteristics of different driver types in a path tracking scenario for 70 km/h (examples are shown in Figure 27), and with reasonable modifications the driver model can represent drivers at other speeds. Since the settings are composed of driver type specifications for each measure for the groups of drivers, individual drivers fulfil most of the metrics in the same run but not necessarily all of them, which is also shown in Paper B.
Figure 27: Measured driving simulator data for steering wheel angle using sample drivers for three consecutive runs (from the test in Paper B), and the driven path of the driver model using the two skill settings derived from optimization at 70 km/h. The cones are marked with red and green circles, the extrapolated width of the vehicle is presented in black (not yaw-compensated), and the distance is measured in metres. Dotted vertical lines indicate estimated time stamps in seconds. a) Actual runs from one high skill driver. b) Driver model results for the high skill setting. c) Actual runs from one low skill driver. d) Driver model results for the low skill setting.
Chapter 7

Scientific contributions

This chapter lists the main scientific contributions of the thesis and appended papers:

1. The identification of very different driver-selected paths in a narrow cone scenario in Paper A. In addition, the identification of driver differences in adaptation to different steering settings by comparing changes in the standard deviation from the mean path.

2. The recruitment process described in Paper B, enabling a good selection of drivers with high and low path tracking skill prior to any actual driving tests.

3. The design of the simulator tests presented in Paper C and Paper E, providing a valuable base for analysis of the path tracking behaviour:
   a. The line jump scenario in Paper C, which removes the uncertainty of driver path selection by using a single line to track, and the preview strategy by instantaneous movement of the line.
   b. The curving road scenario in Paper E, which allows regular countryside driving to be analysed for different curve types and straight segments individually, which also allows straightforward comparison of different situations, e.g. the varied preview limit used in the paper.

4. The method for evaluating the different objective parameter measures, the grade-calculation presented in Paper B, which simplifies creating the metrics with intervals that can represent drivers with typical path tracking characteristics.

5. The parameters identified as skill-related for the different scenarios, with emphasis on the potential benefit of the curving road scenario if used in identification of driver skill in real vehicles.

6. The driver model in Paper D, using physical parameters and a simple internal vehicle model to enable the setup of models describing different types of driver skill, with validation against metrics gathered in a driving simulator test using the same scenario.
Chapter 8

Discussion and conclusions

The aim of this work was to determine the driving skill definition to use, define the recruitment process, and develop a method to characterize the driving skill. Also, a driver model was to be developed using metrics from objective measures related to the driving skill.

In the first study, presented in Paper A, it is observed that different strategies can be found for drivers in a relatively narrow cone track, which indicates that it should be possible to observe some differences besides those concerning the actual hitting of cones. However, with a small number of test subjects and a relatively rough definition of driver categories, it is not obvious how to relate these differences to driver experience or driving skill. In the following simulator tests a thorough investigation of objective parameter measures was conducted using test subjects recruited as being representative of high skill and low skill drivers. A recruitment procedure was proposed and evaluated on 30 test subjects, and the verification of the recruited set of drivers in a double lane change scenario shows a wide variation in the actual performance, but only a small overlap between the recruited groups, thus verifying a successful recruitment of test subjects for this test. Since the term skill is quite complex, it is also often difficult to find a consensus as to what the term comprises and what should be measured. However, this study is focused on finding metrics that can be used successfully for describing the skill level of the group of drivers in some very different situations, not to describe the behaviour of a specific driver in every situation. Below are some comments about the use of the scenarios in this work:

- For the double lane change scenario (Paper B), objective parameter measures sampled in the second half of the double lane change manoeuvre for the higher velocity are found to be most useful for categorization of drivers (with good correlation to drivers recruited as low skill and high skill drivers), which can be derived from the fact that inadequate driving skill becomes more evident in the second part of the scenario. The standard deviation of the steering wheel rate and the standard deviation of the angular acceleration are both measurements that were found useful.

- For driver skill characterization, the line jump scenario (Paper C) has been analyzed not only with measures describing the response of the drivers
primarily by their behaviour during the first few seconds after the line jump, but also with the objective parameters used in the other scenarios, calculated from data at the time from 4 to 8 s after the jumps. The last four seconds are used for emphasis on the straight line path tracking skill after the large movement from the previous position of the line (centre of the road). Relatively good categorisation performance is found for some measures, both for the first and last part. A short rise time, by itself and also in combination with a small overshoot, is shown to be an important characteristic of the high skill drivers. Several of the objective vehicle parameters also demonstrate a difference between the groups of high skill and low skill drivers, with low standard deviation of the lateral velocity and the yaw angle as examples that can be interpreted as typical high skill driver characteristics.

• For the curving road scenario (Paper E), the curves are found to be more reliable for identifying driver skill than the straight road segments, and a number of measures show good performance in characterizing driving skill under the tested conditions, both for clear sight and with the preview limited down to 30 m. The standard deviation proves to be very useful as a measure, and qualifies for successful driver skill categorization for commonly sampled data such as the lateral acceleration, yaw rate and steering wheel angle. However, since these measurements are taken exclusively during curve negotiation, these situations need to be identified during driving. Moreover, even though the parameters that are readily measurable can be sufficient, a significant improvement of the number of useful measurements can also be achieved if accurate information about the road curvature is available. This should be possible to solve using state-of-the-art GPS-systems. When the preview shortens, new measures appear that also separate the driver groups, but for an extremely short preview the number of separating parameter measures is reduced rapidly, which can be an effect of both the high skill and low skill drivers performing at an equally low level. These results should be a good starting point for online classification of driving skill that can be used for adaptation of adjustable vehicle systems to aid and support the driver with the driver ability taken into consideration.

Since the parameter measures which can be used with most success for the characterisation of driver path tracking skill are different for different scenarios and scenario sections, and since drivers may be skilled at different tasks, the best results are found when knowledge is possessed of such things as the curvature of the road (or at least whether or not the road has a curvature at the present location of the vehicle) or the type and part of the current manoeuvre. However, good correlation between results and driving skill is found for several cases using common parameter measures, and the case studied here involving normal driving conditions (a curving road) seems to be excellent for categorizing drivers based on the skill level. The double lane change manoeuvre and the line jump scenario have proven to be very interesting as well, since they show relatively high driver classification validity for a number of parameter measures. However, the double lane change scenario measures are not directly comparable with the measures of the other scenarios, since the double lane change is analyzed without a relevant path reference (due to the more apparent possibility of selecting different path strategies within the cone track).
Parameters measures with high grades both for the driver response in the line jump scenario and the regular driving in the curving road scenario on the other hand show good potential for general usage. Without knowledge of the curvature of the road, the standard deviations of the steering wheel angle and of the lateral acceleration are such measures. If the road curvature is known, the standard deviations of the lateral velocity and of the acceleration relative to the road, and the standard deviation of the yaw angle relative to the road, should be of interest as well.

The developed driver model presented in Paper D includes a quasi-static vehicle description and is quite a simplified representation of a driver. On the other hand, it enables straightforward modifications of physical parameters that affect the model behaviour to represent both typical high skill and typical low skill drivers, and this can be much more complicated in a dynamic model since it involves more parameters being set. A complex model may also be too advanced to be a realistic representation of the driver anticipation of the vehicle motion, while the vehicle understeer behaviour used is quite an intuitive representation of the vehicle characteristics. Nonlinearities in a more advanced model may also be difficult to use inverted, and therefore one may have to rely instead on interpolation between the results of several tested steering angles as in [62]. The vehicle model is a validated standard configuration of a medium-sized passenger vehicle, and changing this model to another may require some adjustments of the driver model settings. Although it was concluded in Paper A that drivers tend to choose the same path to track, even when the steering characteristics of the vehicle are changed, the vehicle characteristics may still affect the driver action as described in this thesis. The ISO 3888-1:1999 double lane change scenario was chosen for the initial setup of the driver model, since this manoeuvre is quite demanding and thus also demanding for the driver model. Using the driver model in another scenario, e.g. for the curving road in Paper E, requires that the parameters are identified for the driver behaviour in this situation, since the requirements on the drivers are different, and this can be accomplished with the same method as that presented in Paper D for the double lane change.

To conclude, the developed methodology for finding objective parameters that are typical of driving skill has proven successful. The results from the simulator experiments show that several parameters have measures that can be used to describe driver skill, and several have measures that are very useful for driver modelling. A model has also been presented that can be set for the driver skill. If driver skill characterization is used in the driven vehicle, this also gives a potential benefit for automated adjustments of vehicle systems.
Chapter 9

Recommendations for future work

The driver skill characteristics identified here can be used both for the design of a driver model and the classification of drivers, but only the driver model application has been explored here. The measures with a high grade could be combined to provide a higher possibility of correct classification. A good preview path is also an important building block of a driver model, and although the paths used here are based on the results of real drivers, a good method for creating artificial paths is to be preferred to improve the flexibility of the model. The path used here shows remnants of the individual drivers, and although a filtering process would smooth the path out, there could still be low frequency parts that are unwanted. It is also seen in the results that the frequency of the steering signal from the driver model in some cases features more periodic high frequency contents than would be expected from a real driver, which may be avoided by the addition of metrics directly linked to the behaviour in the frequency domain. Moreover, a more advanced optimization routine that succeeds better in finding the global optimum may also result in sets of parameter values that are even better at representing the two driver categories. The identification of driver types in running vehicles on any road should be explored further, since this unfortunately did not fit into the project timeframe. Pattern recognition routines could be trained with data found relevant to driving skill in given situations, for which the baseline is given here.

Even though it was concluded in Paper A that drivers tend to choose the same path to track even when the steering characteristics of the vehicle are changed, depending on which parameters are used, greater or smaller adjustments have to be made to reflect the driver behaviour in a vehicle with new characteristics. It is obvious that the vehicle representation in the driver model must be changed according to the new vehicle, but changed vehicle characteristics may also affect the metrics used for the driver categories, due to driver shortcomings in adapting to the new vehicle (resulting in degradation in performance), due to the enabling of a higher (or lower) driver-vehicle performance, or due to other vehicle response changes which the driver voluntarily or involuntarily is not cancelling out through changes in his or her behaviour. Another aspect is, of course, the use of different scenarios and velocities for which validation
should be performed as well if the model is to be used for such cases. The curving road scenario does feature a variation in curve types, but this variation does not cover more than two radii. Even though a general driver model or identification algorithm could be configured to interpolate and extrapolate from the results, it is obvious that more tests could be necessary, especially with driving on real roads. These roads are also more irregular in shape than the currently tested artificial roads. The road used in the driving simulator is flat and the constant radius curves are placed directly after the straight segments, and this is not the most common configuration found on roads built today. To make curves easier for the driver to negotiate, the Swedish design rules suggest that sharp curves should begin with either a transition curve with half the curve radius or with a clothoid [92]. Moreover, banking of curves is a measure that is often used, and this can be accomplished with different centres of rotation [93]. Therefore, it is suggested that real roads or simulated roads with more realistic features should be examined to gain further knowledge of the effect of these variations.
References

41. From Brian Repa, presented by Steve Chin, GM North America, 2004
78. Kondo, M. and Ajimine, A. Driver’s sight point and dynamics of the driver/vehicle system related to it, SAE paper No. 680104, 1968.
Nomenclature

Notation

\( a_y \)  
Lateral acceleration \([\text{m/s}^2]\)

\( a_r \)  
Radial (centripetal) acceleration \([\text{m/s}^2]\)

\( b \)  
Distance from the vehicle’s centre of gravity to the rear axle \([\text{m}]\)

\( B(s) \)  
Driver feedback (i.e. prediction) function

\( C \)  
Set of ordered consequences

\( C_B \)  
Curve beginning

\( C_{12}, C_{34} \)  
Cornering stiffness coefficient, front and rear axle \([\text{N/rad}]\)

\( D \)  
Derivative operator

\( f \)  
Distance from the vehicle’s centre of gravity to the front axle \([\text{m}]\)

\( F_{12}, F_{34} \)  
Lateral force, front and rear wheels respectively \([\text{N}]\)

\( G(s) \)  
Transfer function for the vehicle system

\( H(s) \)  
Transfer function for the driver compensation

\( HVS \)  
Number of high (or low) skill test subjects in high value section

\( J_z \)  
Inertia \([\text{Nm}\cdot\text{s}^2]\)

\( K \)  
Gain \([1]\)

\( K_{us} \)  
Understeer gradient \([\text{rad}\cdot\text{s}^2/\text{m}]\)

\( K_d, K_p, K_i \)  
Driver model coefficients (derivative, proportional, and integration)

\( L \)  
Wheel base \([\text{m}]\)

\( LVS \)  
Number of high (or low) skill test subjects in low value section

\( m \)  
Mass \([\text{kg}]\)

\( M_{3w} \)  
Steering wheel torque \([\text{Nm}]\)

\( P(s) \)  
Driver preview strategy

\( R \)  
Curve radius \([\text{m}]\)
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{min}}$</td>
<td>Smallest curve radius [m]</td>
</tr>
<tr>
<td>$s$</td>
<td>Laplace derivative operator</td>
</tr>
<tr>
<td>$SS$</td>
<td>Size of sections in grade calculation</td>
</tr>
<tr>
<td>$t$</td>
<td>Time [s]</td>
</tr>
<tr>
<td>$t_d$</td>
<td>Brain response delay [s]</td>
</tr>
<tr>
<td>$t_h$</td>
<td>Driver action delay [s]</td>
</tr>
<tr>
<td>$T_L$</td>
<td>Lead [s]</td>
</tr>
<tr>
<td>$T_f$</td>
<td>Lag [s]</td>
</tr>
<tr>
<td>$T_p$</td>
<td>Preview time [s]</td>
</tr>
<tr>
<td>$U$</td>
<td>Set of decisions or actions</td>
</tr>
<tr>
<td>$V$</td>
<td>Velocity [m/s]</td>
</tr>
<tr>
<td>$v_x, v_y$</td>
<td>Longitudinal and lateral velocity [m/s]</td>
</tr>
<tr>
<td>$\dot{v}_x, \dot{v}_y$</td>
<td>Time derivative of longitudinal and lateral velocity [m/s$^2$]</td>
</tr>
<tr>
<td>$v_T, v_R$</td>
<td>Tangential and radial velocity [m/s]</td>
</tr>
<tr>
<td>$y_{\text{road}}$</td>
<td>Lateral position, road reference [m]</td>
</tr>
<tr>
<td>$y_p$</td>
<td>Predicted lateral position [m]</td>
</tr>
<tr>
<td>$\bar{y}(t)$</td>
<td>Feedback vector</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Body slip angle [rad]</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Steering angle [rad]</td>
</tr>
<tr>
<td>$\delta_A$</td>
<td>Ackermann steering angle [rad]</td>
</tr>
<tr>
<td>$\delta_{sw}$</td>
<td>Steering angle [rad]</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Perceived state of the environment</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Friction coefficient [1]</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Yaw (heading) angle [rad]</td>
</tr>
<tr>
<td>$\dot{\psi}$</td>
<td>Yaw rate [rad/s]</td>
</tr>
<tr>
<td>$\ddot{\psi}$</td>
<td>Yaw acceleration [rad/s$^2$]</td>
</tr>
<tr>
<td>$\psi_{\text{road}}$</td>
<td>Yaw angle, road reference [rad]</td>
</tr>
</tbody>
</table>
Nomenclature

\( \omega_c \)  Cross-over frequency [Hz]

### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D</td>
<td>3-dimensional</td>
</tr>
<tr>
<td>ACC</td>
<td>Adaptive cruise control</td>
</tr>
<tr>
<td>BA</td>
<td>Behaviour actuation</td>
</tr>
<tr>
<td>ba</td>
<td>Braking to avoid collision</td>
</tr>
<tr>
<td>CG</td>
<td>Centre of gravity</td>
</tr>
<tr>
<td>CH</td>
<td>Correct and hold</td>
</tr>
<tr>
<td>CO</td>
<td>Continuously oscillating</td>
</tr>
<tr>
<td>DA</td>
<td>Discriminant analysis</td>
</tr>
<tr>
<td>DiC</td>
<td>Driver in control</td>
</tr>
<tr>
<td>DLC</td>
<td>Double lane change</td>
</tr>
<tr>
<td>DOF</td>
<td>Degrees of freedom</td>
</tr>
<tr>
<td>ECG</td>
<td>Electrocardiogram</td>
</tr>
<tr>
<td>GM</td>
<td>General Motors</td>
</tr>
<tr>
<td>HC</td>
<td>Heading control system</td>
</tr>
<tr>
<td>HMM</td>
<td>Hidden Markow model</td>
</tr>
<tr>
<td>ISO</td>
<td>The International Organization for Standardization</td>
</tr>
<tr>
<td>JDVS</td>
<td>Joint driver-vehicle system</td>
</tr>
<tr>
<td>KB</td>
<td>Knowledge-based</td>
</tr>
<tr>
<td>KTH</td>
<td>The Royal Institute of Technology</td>
</tr>
<tr>
<td>MBS</td>
<td>Multi-body system</td>
</tr>
<tr>
<td>MC</td>
<td>Mixed compensating</td>
</tr>
<tr>
<td>M.C.A</td>
<td>Multiple correspondence analysis</td>
</tr>
<tr>
<td>MM</td>
<td>Mental model</td>
</tr>
<tr>
<td>OC</td>
<td>Over-compensating</td>
</tr>
<tr>
<td>ODE</td>
<td>Ordinary differential equations</td>
</tr>
<tr>
<td>QC</td>
<td>Quickly compensating</td>
</tr>
<tr>
<td>RB</td>
<td>Rule-based</td>
</tr>
<tr>
<td>RMS</td>
<td>Root-mean-square</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>SB</td>
<td>Skill-based</td>
</tr>
<tr>
<td>SC</td>
<td>Slowly compensating</td>
</tr>
<tr>
<td>SP</td>
<td>Sensor perception</td>
</tr>
<tr>
<td>sr</td>
<td>Speed regulation</td>
</tr>
<tr>
<td>tr</td>
<td>Time headway regulation</td>
</tr>
<tr>
<td>UC</td>
<td>Under-compensating</td>
</tr>
<tr>
<td>UMTRI</td>
<td>The University of Michigan Transport Research Institute</td>
</tr>
<tr>
<td>VINNOVA</td>
<td>The Swedish Agency for Innovation Systems</td>
</tr>
<tr>
<td>VTI</td>
<td>The Swedish National Road and Transport Research Institute</td>
</tr>
</tbody>
</table>