THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN MACHINE AND VEHICLE SYSTEMS

Modelling driver steering and neuromuscular behaviour

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ABSTRACT

This thesis challenges the traditional view of treating steering behaviour as a *tracking* task, instead treating it as a *reaching* task. Here, reaching refers to a fundamental human behaviour with the the intriguing characteristic of having a linear relationship between maximum speed and distance, effectively making the movement time constant. Historically, by contrast, human steering behaviour has been modelled as tracking, since it was assumed that drivers follow the road by applying continuous error-minimising control. Early on, it was found that linear control could to some extent represent human steering behaviour, but with a consistent non-linear error referred to as the *remnant*. Using instead the framework of reaching, as in this thesis, one can better explain even the non-linear parts of steering behaviour.

In the analysis of data collected within the work presented here, it was found that up to 70 % of all steering behaviour can be modelled as individual reaching movements or, in the case of driving, steering corrections. It was furthermore shown that, by allowing the superposition of two such corrections, nearly *all* steering behaviour can be modelled. In addition, apart from control aspects, the heuristics used by the driver have also been studied. By modelling driver behaviour in various traffic situations, it was found that the angle to an *aim point* was the best stimulus for a steering action. Based on reaching theory and the aim point heuristic, a new driver model was developed and tested in three different situations: A double lane change, a head-on collision scenario, and a lead vehicle braking scenario. In open-loop simulations, the model showed good results when compared with observed behaviour, for all three scenarios.

Furthermore, special care was taken to avoid *parameter redundancy.* The model could, in fact, be defined by using only *one* tunable parameter, representing the stress level of the driver. From the simulations, it was found that larger values of the parameter were required in critical situations compared the values used in normal driving. The neuromuscular aspects of the driver were also studied. The new driver model mentioned above was refined to include such aspects, using the fact that a reaching movement can be explained by *antagonistic muscle pairs.* However, since driving also involves limb stabilisation, muscle co-contraction is also relevant. In a separate experiment, involving both adults and children, the reaction to a sudden and unexpected torque disturbance was studied. The observed behaviour could be attributed to both the *stretch reflex* and an automatic subconscious cognitive action. The thesis also discusses some applications where driver models of realistic steering behaviour can be useful, focusing on *active safety* systems and *autonomous vehicles.*

Keywords: Driver behaviours, driver models, lateral control, reaching, neuromuscular behaviours, active safety, autonomous vehicles

Tillägnat Olle, Annie, Ingvar, Linnea. Ni är jag.

Preface

The work presented in this thesis was carried out at Chalmers University of Technology, at the Department of Applied Mechanics, in the Division of Vehicle Engineering and Autonomous Systems (VEAS), and in the group Adaptive Systems. The supervisor was Prof. Mattias Wahde, and the co-supervisor was Dr. Krister Wolff. The work was funded, under the project name QUADRA, by a grant from the VINNOVA Swedish Governmental Agency for Innovation Systems (2009-02766), and initiated by AB Volvo.

Acknowledgements

To write a thesis is like creating a cake, first one needs the ingredients, then one bakes the layers, and in the end one puts it all together and makes it look nice. For my metaphorical cake that is my thesis, the taste, freshness of ingredients, and polish have all been of equal importance and I'm very proud to now serve it. I hope that you eat it all, and also save some for the future.

First of all I thank my wife Lisa, for keeping me healthy and in love during this important part of my life. Then I thank, with the utmost gratitude, Prof. Mattias Wahde for taking me in, believing in me, and forming my academic mind. I also thank Krister Wolff for his friendship and support throughout the years. I look forward to our future work with the tiny cars and emotional trucks. Furthermore, a very special thanks goes to Gustav Markkula for dragging me along, and teaching me the practical things.

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Thesis

This thesis consists of an extended summary and the following appended papers:

Paper A	G. Markkula, O. Benderius, K. Wolff, and M. Wahde. A review of near-collision driver behavior models. *Human Factors: The Journal of the Human Factors and Ergonomics Society* **54**.6 (2012), 1117–1143
Paper B	O. Benderius, G. Markkula, K. Wolff, and M. Wahde. Driver behaviour in unexpected critical events and in repeated exposures – a comparison. *European Transport Research Review* **6**.1 (2014), 51–60
Paper C	G. Markkula, O. Benderius, K. Wolff, and M. Wahde. Effects of experience and electronic stability control on low friction collision avoidance in a truck driving simulator. *Accident Analysis & Prevention* **50** (2013), 1266–1277
Paper D	G. Markkula, O. Benderius, and M. Wahde. Comparing and validating models of driver steering behaviour in collision avoidance and vehicle stabilisation. *Vehicle System Dynamics* (in press)
Paper E	O. Benderius and G. Markkula. Evidence for a fundamental property of steering. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting.* Vol. 58. 1. SAGE Publications. 2014, pp. 884–888
Paper F	P. Nilsson, L. Laine, O. Benderius, and B. Jacobson. A Driver Model Using Optic Information for Longitudinal and Lateral Control of a Long Vehicle Combination. *Proceedings of the 17th International Conference on Intelligent Transportation Systems (ITSC).* IEEE. 2014, pp. 1456–1461
Paper G	K. Wolff, O. Benderius, and M. Wahde. Scaled test track: A novel approach for active safety system development, testing, and validation. *Proceedings of the 14th Mechatronics Forum International Conference.* 2014, pp. 458–465

TECHNICAL TERMS

CONTENTS

Chapter 1

Introduction and motivation

A large portion of the world population knows how to drive a car. In fact, to most drivers, driving feels as natural as walking or running, even in very complex traffic environments. Strangely so, since driving is a very different task from the natural task of walking, for example. On the one hand, one may argue that walking is a simpler task, since it is a very natural human behaviour, but on the other hand, when considering pure body control, one might instead argue that driving is the simpler task, since it requires relatively little effort from the driver. Furthermore, from a philosophical perspective, it is interesting to reflect on how driving is *subjectively experienced* by the driver. Is it possible that the neural expression of any form of personal navigation, independent of its means and control, is cognitively the same? If so, what are the underlying cognitive mechanisms?

A clue to the answer can be drawn from an experimental study that was conducted, as a part of this thesis, in which children were asked to drive in a driving simulator, on a winding rural road, without any other traffic. Surprisingly, it was found that the children, obviously driving a car for the first time, could navigate the car in each bend without problem, and in addition stay in their own lane, during the whole drive. From the experiment, it may be concluded that (i) no practice, or very little, is needed to navigate a car, even in a relatively complex environment, and (ii) navigation is generally a very natural behaviour, without any strong connections to *how* it is performed. However, it must also be said that navigation is not *necessarily* natural as, for example, when the result of the navigation is projected on an external medium, such as when controlling a pointer on a computer screen. From a cognitive point of view, such navigation is probably harder, compared to steering a car. Arguably, the naturalness of navigation is coupled with (i) how intuitive the control action is, meaning that an action should have a direct impact on the used heuristic, or stimulus, and (ii) how natural the actual control action is. When driving a car, even when completely disregarding the vehicle dynamics, the control action is very intuitive, since a turn on the steering wheel directly makes the world turn around the driver. When, for example, reversing the car, the same kind of direct heuristic–control relation does not hold, and it is therefore expected to be harder, much similar to the case of moving a pointer on a computer screen. Furthermore, when driving, the applied control action is also very natural, since the turning of the steering wheel very much resembles the bodily action of *leaning* to the left, or to the right. To conclude this discussion one can claim that driving is not about moving an object through the perceived world, but rather to move the perceived world to where one wants it to be.

In this thesis, realistic[1] steering behaviour is considered, especially mathematical models of such behaviour. A distinction is also made between *heuristics*, motivating the behaviour, and *control*, which creates it. In much of the previous work, this distinction is not entirely clear. As regards heuristics, in this thesis it has been found that models developed from the theory of visual perception showed the most realistic steering behaviour. Moreover, it is noted that a majority of driver models were developed by means of control theory, effectively treating human steering as an engineering problem. However, in the models developed in that framework, it appears that different kinds of simplifications are common, such as the linearisation of heuristics and control, as well as the assumption that the driver perceives the world in a metric coordinate system rather than a radial one. Furthermore, the control applied by a typical control system is based on the minimisation of some error signal that, as discussed much in this thesis, is not necessarily a natural human behaviour. Therefore, in the writing of this thesis, no *a priori* assumptions have been made regarding which theoretical framework should be used in the driver modelling.

The first model of human control behaviour was developed by Tustin in 1947 [111]. He observed that the behaviour could be approximated by a linear controller, a discovery which became the basis for much of the continued control-theoretical work in the 1950s and 1960s. Furthermore, Tustin specifically referred to the non-linear parts of the observed control behaviour as the **remnant**. Since then, the remnant has generally been considered as an error, or an artefact, originating from the driver. However, one of the main contributions of this thesis is to offer an alternative way to treat human steering behaviour, which suggests an explanation to Tustin's remnant. The solution presented here is to view steering as the basic human behaviour of **reaching**[2], rather than *tracking*. In practice such a distinction means that, instead of continuously tracking the road, the driver maintains the course by applying individual course corrections whenever they are needed.

1.1 Scope and contributions

The aim of this thesis is to deepen the knowledge on driver behaviour in which the driver interacts with a steering wheel. The thesis especially treats *realistic* steering behaviour carried out by a human driver. Chapter 2 gives a review of the most important milestones in the study and modelling of driver steering behaviour, both concerning conventional and neuromuscular models. Then, in Chapter 3, a discussion is given regarding the nature of realistic steering in terms of heuristics and control. Furthermore, based on the discussion and experimental findings, a novel model of driver steering is defined and tested with promising results, in three different traffic scenarios. In Chapter 4, the neuromuscular aspects relevant to steering are reviewed from a physiological perspective and, based on

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[1] Here, realistic steering behaviour refers to the behaviour exhibited by drivers in normal traffic.

[2] Reaching, or *rapid aimed movements*, is a basic human behaviour, which is considered a separate field of study [86, 34, 43, 41].

such theories, the model presented in Chapter 3 is extended also to treat neuromuscular behaviour. Then, the behavioural relevance of muscle **co-contraction** is demonstrated and explained from an experiment. In Chapter 5, applications of driver models are briefly discussed, with special emphasis on realistic behaviour in connection with active safety systems and autonomous vehicles. Finally, in Chapter 6, some conclusions are given, as well as some notes on future work.

Apart from the introductory discussions, the thesis consists of seven peer-reviewed papers. The author was the main contributor of Papers B and E, one of two main contributors of Papers A, F, and G, and had a more limited role in the writing of Papers C and D. Additionally, the author wrote [12, 10], and is a co-author of [97].

As a foundation for the work carried out for this thesis, several driving experiments were conducted. In 2010, a small truck driving experiment was carried out on the Arjeplog test track where a truck driver performed repeated double lane changes, with and without an **electronic stability control** (ESC) system. Furthermore, in 2011, a large driving simulator study was conducted in the VTI driving simulator *Sim II* in Linköping. In the experiment, also involving an ESC system, 48 truck drivers were each subjected to one unexpected lead vehicle braking scenario on a slippery road, and then to 12 repetitions of the same event. The author was one of two main contributors in the planning and execution of the experiment. The results formed the basis for Papers B, C, and D.

Then, in late 2011, another large experiment was conducted in the VTI driving simulator *Sim IV* in Göteborg. With the purpose of conducting initial tests of driver behaviour related to automated steering wheel torque interventions, 40 passenger car drivers were subjected to an unexpected head-on collision scenario during distraction, at which point the intervention took place. The author was the main contributor to the planning and execution of the experiment, and the results have so far been used in [10] and in this thesis. A series of similar experiments were conducted in 2012 and 2013, both in the *Sim IV* driving simulator and on the Stora Holm test track. The author had an advisory role in these experiments, except for one driving simulator study in 2013, where the author had a leading role in the execution. These experiments are described further in Sect. 4.2.

In another experiment in 2013, 12 subjects were studied for the purpose of finding effects between driving behaviour and sleep deprivation on slippery roads. The author had an advisory role in the planning of the experiment and for the data analysis, and the results are presented in [97]. Then, in 2014, an on-road experiment involving a prospective long vehicle combination was carried out. In the experiment, a truck driver was asked to carry out multiple lane changes on the road between Göteborg and Malmö, for the purpose of studying driver behaviour. The author had a limited role in the planning and execution of the experiment, but was one of two main contributors in the data analysis. The results from the experiment were used when writing Paper F.

Finally, in 2014, the experiment involving children and their parents, briefly described in the previous section, was conducted. The experiment had two purposes, namely (i) to study the general driving capabilities of completely inexperienced drivers, and (ii) to test neuromuscular aspects of steering. The author had the main responsibility for planning and executing the experiment. Some of the results are presented here, and the experiment has been met with interest from mass media [33] and popular science [83, 105].

Chapter 2

Background

First there will be a brief review on the history of steering models. A similar review can be found in Paper A, where models of collision avoidance behaviour are discussed in detail. Here, a more general review is given, with focus on the important discoveries and events of driver modelling in general. At the end of the chapter, there is also a separate review on neuromuscular models of steering.

2.1 Models of lateral control

The first mathematical model of human manual control (i.e. steering) is the one published by Tustin in 1947 [111]. When examining the first recorded steering signal, Tustin described it as ‘a jerky curve with “flats”.’ The control was approximated with a linear transfer function, where the remaining non-linear part was referred to as the *remnant*. In the decades to come, several attempts were made to categorise the remnant in order to explain it in a model (see e.g. [66, 79]). Generally, at that time, researchers considered the remnant as noise or neurological artefacts induced by the driver. This view, however, will be challenged later in this thesis (see Sect. 3.1.2).

In the 1950s, the *Quasi-linear model* was developed by McRuer and Krendel [80, 79]. The model was designed from basic laboratory tracking experiments. A typical experimental setting was the tracking of a dot moving in a sinusoidal pattern, for example, using a pencil or a wheel. The purpose of the experiments, and the model, was to separate the linear and non-linear (i.e. remnant) properties of the human as a controller. The linear part of the behaviour was modelled as a scenario-specific transfer function with the operator output correlating linearly with the input. Since, by definition, the remnant consists of all output lacking a linear correlation with the input, a mathematical framework could then be formulated for its analysis. Consequently, even though the remnant could not be explicitly stated, its power spectrum could be compared to that of the known transfer function.

Meanwhile, in Japan, a vital step was taken in 1953 concerning the modelling of driver steering behaviour, when Kondo developed the first model using a **preview point** [59, 60]. It is rumoured that Kondo got the idea for the model when his car was towed with a very short rope, and therefore it is often referred to as the *shaft model*. The model applies steering by, for example, minimising the lateral offset between the preview point and the desired curvature path. Also, the angle between the heading of the vehicle and the preview point was mentioned as one possible minimisation criterion. As a side note, this measure was later recognised by Baxter and Harrison as a way to combine lateral and heading error, then referred to as an **aim point** error [9, 5, 65]. Interestingly, Kondo referred to the preview point as the *sight point*, in terms of where the driver actually looked. Furthermore, it was hypothesised that the distance to the sight point had a linear relationship with the vehicle speed. For their experiments, Kondo and Ajimine [60] developed a special apparatus in order to investigate the relative position of the actual sight point during driving. Similar experiments were independently carried out by Gordon in 1966 [37]. The purpose of Gordon's studies were not to create a descriptive model of steering, but rather to study perceptual aspects of the driving task. Importantly, it was found that drivers mainly look at the road edge or centre line while driving, knowledge which later proved very useful in driver modelling. To conclude, the preview point concept is used in most modern driver models. Moreover, it has been developed over the years through extensive experimentation, such as, for example, the well-known model of Sharp, Casanova, and Symonds [103], where the concept was extended to include multiple points along an axis. However, in such an arrangement, the preview points can no longer be considered to be measures of where the driver looks, but rather measures of where, along the axis, the information is extracted.

In 1962, an important finding was the *crossover model* by McRuer *et al.* [81]. The model was later used especially in the analysis of ground vehicle driving [118, 82]. Interestingly, the model does not represent the driver separately, but the combined driver and vehicle as one system. The main idea is that, for *any* vehicle behaviour, the driver will adapt so that the combined behaviour remains the same. Therefore, in many cases, the model is a very precise description of the behavioural dynamics [51].

Then, in 1969, Baron and Kleinman [8] presented the first operator model using an **internal model**. The model was defined as a general optimal control problem, allowing any linear and time-invariant internal model. Later, in the 1980s, the same framework was used in the well-known model of MacAdam [70]. In that model, the steering is chosen so as to minimise the path deviation along a preview interval. Furthermore, using different optimisation criteria (e.g. shortest driven distance), such models are able to generate different types of behaviour [96]. Behavioural variation of that kind can be referred to as **driver motivation** [107].

In 1978, Donges published his two-level model of steering [20]. The model divides driving into two parallel tasks, anticipatory open-loop control and compensatory closed-loop control. The open-loop component is calculated based on upcoming road curvature, and the closed-loop component is calculated using the current errors in heading and lateral lane position. Earlier, there were also very similar, but less influential, models [90, 26]. A kindred approach referred to as *dual-mode* had also been formulated before, incorporated in an advanced model by McRuer, Allen, Weir, and Klein [78].

During the 1990s, a few models were developed based on **fuzzy logic** [52, 45, 123]. Models of this kind are interesting when discussing **satisficing**[1] behaviour [107]. Such

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[1] From satisfy and suffice [104].

behaviour, in contrast to optimising, refers to an operator acting on compelling need rather than *any* small error. For example, driving with a small lateral offset on a road involves no risk, therefore no steering correction is needed.

In 1995, Land and Horwood convincingly argued that the driver uses information continuously from regions both near and far away [63]. The far region was found to be where the driver looked, and the near region was perceived peripherally. In a later publication, Land formulated a two-level driver model based on the experimental results [62]. However, the model relied on knowledge about the upcoming road curvature, something which has been found to be surprisingly hard for the driver to estimate [27]. Therefore, Salvucci and Gray in 2004 [101] formulated the *two-point visual control model of steering*, which represented the near and far areas as two points. The model applies control by minimising the movement of both points, and the angle to the near point, according to

$$\dot{\delta} = k_f \dot{\theta}_f + k_n \dot{\theta}_n + k_I \theta_n \tag{2.1}$$

where $\dot{\delta}$ is the steering wheel rate, and θ_f and θ_n the angles to the far and near points, respectively.

In work by Lee in 1998 [65], a driver steering model was developed based on the variable τ, defined as the ratio between optical angle (size) and expansion rate (looming) of an object [64]. In most cases τ can also be considered as the time headway. The variable has been used successfully in many models of driver *braking* behaviour, for example in Paper F. However, as indicated above, in his paper from 1998, Lee applied the same principles in a model of steering. Partly, inspiration was taken from very primitive animals, from which Lee observed the ability of advanced navigation despite limited neurological capacity. The dynamics of the proposed model was to couple two τs by keeping them at a constant ratio.

In the early 2000s, driver models based on retinal flow started to emerge. Such models are in fact quite general and apply to many navigational tasks, such as walking, running, or cycling. Extensive work along these lines had been carried out earlier [35, 17, 36], but it took some time until the theory was used in practice and evaluated in driver modelling [115, 22, 119]. The Fajen and Warren model uses the retinal flow explicitly for navigation, in a similar way as in artificial potential field theory [58, 98]. In contrast, the Wilkie and Wann model instead estimates a single navigational gain for an arbitrary target point in the visual field. The estimate is calculated as a weighted sum of (i) the retinal flow rotation, (ii) extraretinal information, which is the rate of change of the target direction [99], and (iii) the visual direction.

To conclude, in a previous discussion by Benderius in 2012 [10], three different modelling perspectives were defined: (i) control, (ii) behaviour, and (iii) cognition. The same partitioning may also be relevant for the historical review presented here. Many of the early models clearly studied the driver as a controller, and specifically the emergent properties in terms of frequencies and gains (see e.g. [111, 82]). At the same time, other researchers focused on the prominent behavioural features of the driver [59, 20, 9]. In parallel, the perceptual and cognitive aspects were also studied [37, 60, 62, 101].

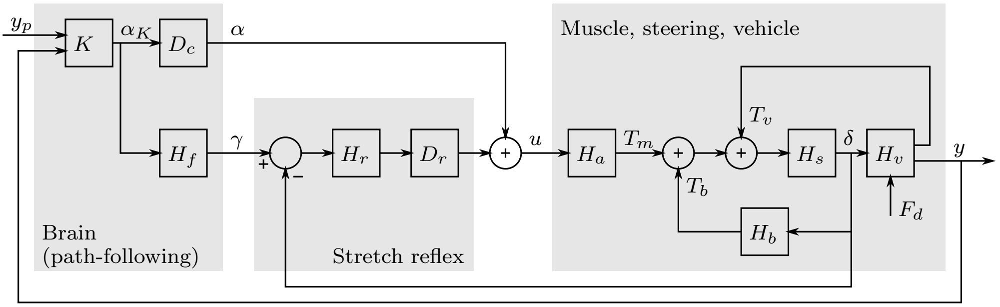

Figure 2.1: *The Cole et al. model. After [18].*

2.2 Neuromuscular models of lateral control

Compared to the models of lateral control presented in the previous section, there are relatively few models considering the neuromuscular aspects of steering. Even though neuromuscular models started to emerge during the 1960s, for example the λ *model* drawn from **equilibrium-point theory** [24], the first comprehensive model of *machine operation* was probably the one developed by Magdaleno and McRuer in 1971 [71]. Just like the early models, the Magdaleno and McRuer model was not explicitly designed for the operation of ground vehicles, but rather vehicle operation in general, including aeroplanes and spacecraft. The model is, in great detail, based on knowledge from physiology, and was designed using control theory as a framework. However, the model was verified using only two subjects, and the authors concluded that parts of the model need further work. Then, a refined model was given by McRuer in 1980 [77], which was later used for ground vehicle applications [124].

A relatively simple neuromuscular model, probably inspired by the McRuer model, was developed by Hess and Modjtahedzadeh in 1990 [44], and was later applied by the same authors in both lane keeping and obstacle avoidance [85]. In the model, the neuromuscular dynamics are represented by a simple second-order system, with proprioceptive feedback. Furthermore, this model was later used by other authors for the purpose of vehicle handling simulation [49], and the evaluation of torque assist systems [76, 25]. In order to enhance the level of perceptual realism of the model, it has recently also been combined [102] with the Salvucci and Gray model described in the previous section.

In 2004, Pick and Cole [93] presented yet another neuromuscular model of lateral control. The model is based on experimental data and, in particular, **electromyography** (EMG) measurements. The Pick and Cole model was later improved and applied in a variety of different scenarios [94, 50]. The most recent version [18], depicted in Fig. 2.1, puts special emphasis on **alpha gamma co-activation** (discussed further in Sect. 4.1). In the model, the α signal requests a goal-directed steering movement based on the upcoming road curvature. By contrast, the γ signal is a forward model of the D_c, H_a, H_b, and H_s components, effectively making γ equal to the steering wheel angle δ as long as the external torque T_v equals zero. Therefore, if an external torque is applied, the

stretch reflex will add to the motor command u resulting in an opposing muscle torque added to T_m. The torque component T_b originates from the intrinsic properties of the driver's muscles that are implemented, mainly, as a damping term in H_b.

Finally, many experiments have also been conducted in research on driver acceptance to haptic shared control [3, 4, 2, 53, 55]. A driver model that specifically considers shared *pedal* control was suggested by Abbink in 2006 [1]. The model was later converted and extended to treat steering behaviour [21, 54]. More recently, this research has been focused on **impedance control** [48], and it has been concluded that previous work on neuromuscular steering behaviour has often disregarded such control. However, to the author's knowledge, no detailed model addressing impedance control has been suggested so far.

Chapter 3

Realistic steering behaviour

In this thesis, driver behaviour has been studied in several different realistic traffic scenarios, both critical and non-critical ones. For each scenario, one or several driver models have been evaluated. It is hypothesised here that in order for a model to accurately and robustly describe real driver behaviour, it must be based on a sound theoretical framework of realistic human perception and control. Ultimately, with such a foundation, these models should become good enough for explaining the observed behaviour in an array of different scenarios. Furthermore, the behaviour of the model should be tunable in terms of simple and understandable parameters.

This chapter will discuss the realism of driver models from a neurological perspective. Thereafter, the validity of tested models will be discussed in terms of their ability to explain realistic steering behaviour. Finally, a novel model of such steering behaviour will be presented and demonstrated in three different scenarios.

3.1 Model realism and neurology

For many applications, a driver model does not need to mimic human control behaviour (see e.g. [103]), even though many of the ground-breaking new models (see e.g. [59]) did indeed have that exact purpose. However, when regarding the actual problem at hand, the focus was instead often on how to simply control the vehicle in an efficient way, in particular with the purpose of studying certain effects on the dynamics of the vehicle rather than the dynamics of the driver. However, although not entirely realistic from a neurological point of view, the behaviour generated from most driver models in specific scenarios may perhaps at least be considered plausible.

When discussing the realism or plausibility of a model of steering behaviour, it might prove useful to start discussing human steering in general terms, in particular the input heuristics that are available to, and used by, the driver, and the kinds of outputs that can be generated.

3.1.1 Heuristics

Before addressing different heuristics it is useful to discuss the **egocentric reference frame**, which is the brain's spatial representation of the own body. The concept has been established based on both experimental [23] and clinical [28] studies. Then, the theory has been incorporated into driver behaviour research [65, 119]. Basically, the spatial representation is a neural map that contains information about the heading and size of the own body in an egocentric coordinate system. Natural uses for such a construct include, for example, the lateral offset needed to walk past an obstacle, and the determination of body relative directions. Interestingly, the representation can also be altered by the use of tools, as convincingly shown by Berti and Frassinetti [14]. Anecdotally, in driving, one can especially notice this when parking in a tight parking slot or driving into a garage. One seems to *feel* the size of the car, as if it is one's own body. Furthermore, when still learning how to drive, this feeling is not yet developed, and maybe that is why parking is then much harder.

Since driver models in many practical settings do not specifically target the study of human behaviour, they can without large consequences make use of slightly unrealistic heuristics. For example, a preview model typically uses the metric *lateral deviation of the preview point* when applying steering. However, it has been shown several times that metric distances are perceptually hard to estimate [108, 42], especially outdoors. Even though such measures can, in principle, be used by the driver, they must be perceived from other low-level heuristics. For instance, the relative speed of a lead vehicle is neurologically determined by the looming effect (i.e. τ, see Sect. 2.1) [64]. The example is actually quite illustrative, since the looming, at a constant speed, in fact is non-linear unlike its metric counterpart (i.e. distance). Another metric which is hard to fathom is the curvature of a bend [27]. There are some models which rely on an accurate estimate of such a measure, for example the models of Donges [20] and Land [62]. It might be argued that driver models that use heuristics available on the lowest possible neurological level are likely to be the most realistic. In Paper D it is indicated that such models (e.g. the Salvucci and Gray model) in fact also result in the most realistic behaviour. Therefore, the driver model presented in Paper F uses neurologically available heuristics for both lateral and longitudinal control.

It is a well-known fact that directional angles are accurately assessed by human perception, even during locomotion. However, there have been discussions on how such assessments are actually done. Early on, it was hypothesised that, in the visual flow, the focus of the radial outflow was an important cue [16, 35]. However, the hypothesis was later falsified by Llewellyn [69]. Instead it was found that the **target drift** was mainly used for the estimation, a view also expressed in [100]. Target drift is the apparent motion of a target (i.e. aim point) in the visual field as the observer approaches it. A movement to the left corresponds to the observer having a heading towards the right of the target, and vice versa [116].

There is also a problem of redundancy in heuristics. The phenomenon is illustrated by Benderius [10], where the Sharp, Casanova, and Symonds model was parameterised for a double lane change manoeuvre. It was found that the model successfully captured the behaviour of all drivers, but with very different and unpredictable parameter values.

As another example, the model of Wilkie and Wann [120] uses three different heuristics: Retinal flow, visual direction, and extraretinal information. The authors conclude that these parameters contain redundancy, and post, as a research question, how those parameters should be weighted. It might be argued that a realistic model should contain as little parameter redundancy as possible, since any such redundancy adds uncertainty when it comes to selecting relevant heuristics.

Another heuristic that should not be forgotten, even though it is rarely discussed for existing driver models, is the internal state of the driver [107]. Ideally, a model should be able to capture different states, such as stress and inattention, in terms of tunable parameters. The new model presented in Sect. 3.3 below explicitly includes one such parameter.

3.1.2 Control

Since Tustin discovered his remnant (see Sect. 2.1) in 1947, researchers have generally considered it as a noise or neurological artefact which cannot be explicitly captured by a model. Even so, through several decades much effort has been put into finding its features in terms of control theory. As Jürgensohn in 2007 [51] explained it:

> But mostly the remnant has to be considered as an error signal, which has no special traits, and which cannot be described by means of simple mathematical methods.

Intriguingly, there have been a few voices against this view, however. For example, the following was stated by Baxter and Harrison in 1979 [9]:

> The question arises as to whether the source of the ‘remnant’ is wholly stochastic in nature or whether, alternatively, at least a portion of these fluctuations deterministically results from the characteristics of the driver ‘black box’ itself.

This thesis supports Baxter and Harrison by suggesting, as presented in Paper E, an explanation to the seemingly random behaviour. The theoretical background for the results is the neurological phenomenon of *reaching* [34]. Instead of smooth and continuous control of the steering wheel, the driver of a car or truck carries out small intermittent corrections with different magnitude. Therefore, one can actually claim that any model which predicts a smooth and continuous output never can reach a perfect result, regardless of the heuristics used. For example, even though the Salvucci and Gray model clearly manages to approximate realistic behaviour rather well, it is, from its mathematical definition, unable to produce small intermittent corrections. In fact, in the light of these new findings, one may conclude that previous driver models incorrectly regard steering as human *tracking* behaviour, rather than reaching.

The special behavioural features of reaching are, for example, discussed in a review by Georgopoulos [34]. Perhaps the most notable feature is the relationship between the velocity and displacement of the hand, in effect making the movement time constant. However, specific task constraints (e.g. due to instruction) may alter the duration of the movement, such that slow movements become more accurate than fast ones [56]. It has also been found, at least regarding blind reaching, that movements in front of the body are more accurate than movements in other directions, and that small movements are more accurate [31]. Furthermore, the velocity profile of a reaching movement is typically single-peaked and bell-shaped, suggesting a single large aimed movement. However, as also observed in Paper E, a reaching movement can in some cases be composed of two or more sequential (see e.g. [122]) or slightly time-overlapping such movements. Typically, the large initial movement relates to the *position* of the target and is actuated by the shoulder and elbow joints, whereas subsequent corrective movements relate to the *orientation* of the target and are actuated by the wrist and finger joints [106]. Additionally, it has been found that corrective movements might be added as a result of very fast movements, referred to as **Fitts' law**, for example in instructed experiments [30]. Several authors have made efforts to capture *Fitts' law* in a model referred to as the *deterministic iterative-corrections model* [57, 19, 84]. However, it might be questioned how relevant the law is to the driving task, since steering is typically not temporally forced, and since the target has no clear width. Finally, to assume that reaching is a natural response to a presented visual stimulus is not in any way unreasonable; reaching has, for example, been noted as the preferred behaviour selected by infants [47].

There is another important difference between traditional control theory and neurological control, which in effect was shown in Paper E. Traditional control is typically optimising, meaning that some error is minimised over time. Typical such errors include, for example, lateral position or vehicle heading. However, by observing an actual driver casually operating a vehicle one can conclude that the driving task is not, in contrast to most existing driver models, optimising. Therefore, neurological control can arguably often be considered satisficing, only acting on strong enough stimuli. In the model comparison of Paper D, all models except the Gordon and Magnuski model are optimising. Interestingly, even models defined in terms of human heuristics [62, 22, 101, 119] continuously apply control by minimising the perceived errors in an optimising fashion.

A moral from Tustin's remnant is that neurological control behaviour may not easily be explained by means of classic control theory. On the other hand, as Tustin also successfully showed, a linear transfer function might be a good *enough* approximation depending on the application at hand. Nevertheless, a complete understanding of the observed behaviour is always paramount, and therefore one should never rely on a single theoretical framework for its modelling.

The timing of control is also very relevant for a realistic steering behaviour. In driver model applications, a reaction time of 0.2 s is generally used. However, there are applications were such a convention might be unfortunate. For example, in Paper C it was observed that inexperienced drivers tend to steer later compared to more experienced drivers in a critical lead vehicle braking scenario. As a result, inexperienced drivers were involved in a larger number of collisions. However, even though experience seems to have an effect on the number of collisions, it does not mean that the actual *control* would differ, given the same manoeuvre time. In fact, by comparing the experience groups, no significant differences related to steering behaviour were identified. Similar conclusions were made from Paper B, where no significant differences could be identified from the control behaviour applied, first in an unexpected traffic event, and then in six repeated such events. The only effect observed was a significant difference in timing between the

Figure 3.1: *In a simulator experiment, young children (left panel) showed that they could (i) drive a car on a normal road, and (ii) regain control after an external disturbance applied to the steering wheel. Their overall performance was very similar to that of their parents (right panel).*

unexpected and expected events.

Another aspect of realistic control is that of *internal vehicle models*, motivated by the driver's understanding of the vehicle dynamics. Of course there must be some understanding involved, most basically the directional modality of the steering wheel. However, the internal representation typically refers to a deeper understanding, which in many classical driver models is implemented as a linear mathematical model. In contrast to most previous work, this thesis argues that no internal representation of the vehicle is required, nor used, when driving a car or truck in normal or critical conditions. The statement is supported by three results: (i) the new driver model presented later in this chapter, (ii) the driving simulator experiment depicted in Fig. 3.1, and (iii) the overall results of Paper D.

3.2 Modelling real driver behaviour

The choice of driver model always depends on the application under consideration. However, it was concluded in Paper A that models typically are defined for a specific purpose and that proper comparisons between existing models are practically non-existent in the literature. As a result of this observation, in Paper D several models were evaluated for the same driver scenario, with different drivers. Specifically, the scenario was a lead vehicle breaking scenario on a slippery road surface, where several truck drivers were forced to rapidly overtake the lead vehicle. For each recorded event, several existing and new driver models were tested independently.

In the model comparison in Paper D, it was found that no model could accurately account for all observed behaviour throughout the scenario. Therefore, the scenario was separated into two parts, namely collision avoidance and stabilisation. It was found that the sudden initial avoidance manoeuvre best could be explained by a single large open-loop steering correction. Furthermore, it was found that the swiftness of the correction depended on the urgency of the current situation, and that the urgency could be defined very well in terms of looming.

As for stabilisation, it was found, as shown in Fig. 3.2, that the Salvucci and Gray model (see Sect. 2.1) performed well. It was especially noted that the angular rate of the far point was the key component. The model behaviour can be explained as the driver trying to stabilise the world around the vehicle. The behavioural hypothesis was further strengthened when the automatic parameterisation of the MacAdam model resulted in virtually the same type of behaviour, due to a very long preview interval. Furthermore, other experimental work also indicates that the Salvucci and Gray model very well can account for observed driving data [75].

After the strong connection between realistic driving behaviour and the Salvucci and Gray model had been found, the model was used for other scenarios as well. For example, in Paper F, it was used for a lane change manoeuvre of a truck. The data used for parameterisation were collected on-road in an actual highway setting. As presented in Fig. 3.2, the model managed to capture the observed behaviour quite well.

Furthermore, in a master thesis project [7] supervised by the author, the Salvucci and Gray model was used for explaining the driver behaviour in a 90° left turn. In that case, the model was used in a slightly different way, by letting the car approach perpendicularly to the far and near points. Still, as seen in Fig. 3.2, the model could successfully account for the behaviour observed in **field operational test** (FOT) data.

The driver steering behaviour in a double lane change was considered by Benderius [10]. The behaviour was modelled using the Sharp, Casanova, and Symonds model, which also was included in the already mentioned comparison in Paper D. It was found that the model can generate a behaviour similar to what was observed from real drivers. On the other hand, it was argued that the model in fact can generate virtually any steering behaviour due to its many redundant parameters.

Finally, in Paper A a single lane change was chosen when comparing the behaviour from different models of steering. However, the comparison was carried out with standard model parameters, without the use of any actual driving data. Therefore, in that particular investigation, model realism was not studied.

3.3 The aim point correction model

In addition to the driver models considered in Papers A, D, and F a novel, general steering model will be introduced in this section. The model is illustrated schematically in Fig 3.3. During development, the aspects discussed in previous sections were considered in order to increase model realism. Especially, the two concepts of heuristics and control, as discussed in Sect. 3.1, were clearly separated. Furthermore, special care was taken in order to avoid parameter redundancy, and to ensure that each parameter can be motivated biologically. Finally, by using the mathematical framework presented in Paper E, the model was designed to exhibit a satisficing behaviour.

As shown in Paper D, Paper F, and in [7], the Salvucci and Gray model performed

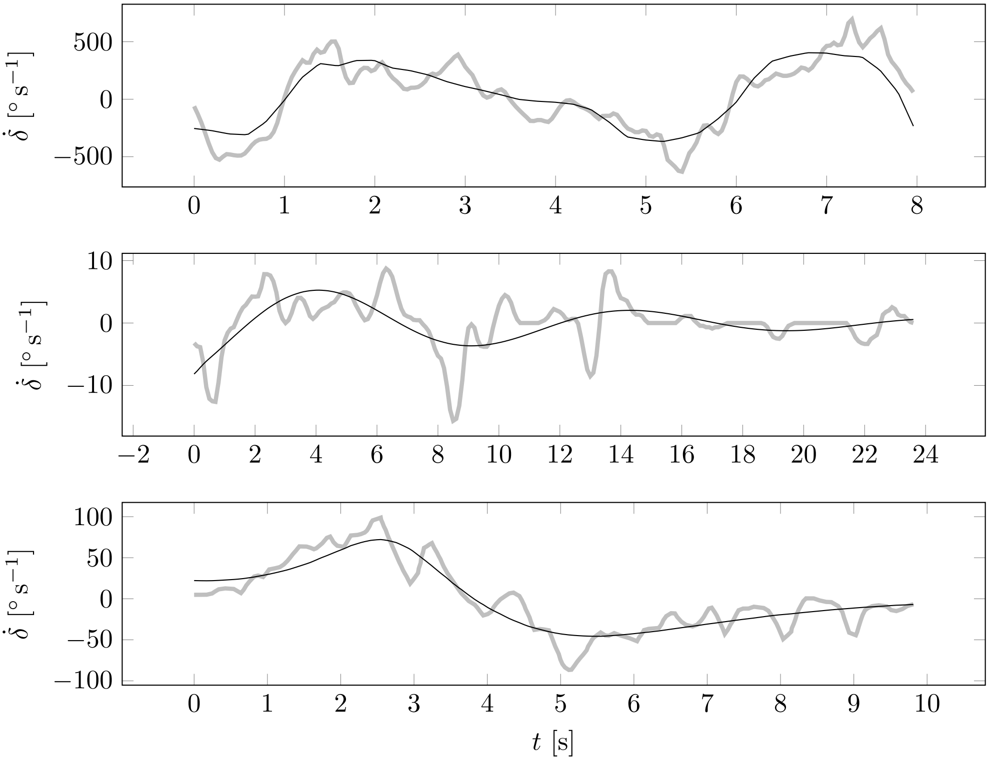

Figure 3.2: *In many of the studied scenarios, the two-point model of steering by Salvucci and Gray showed good performance. From the top: (i) stabilisation on a slippery road surface, (ii) a lane change, and (iii) a left turn. The thin black curves show the model output, and the thick gray curves show the observed data.*

reasonably well when explaining realistic driver behaviour. Furthermore, that model was initially intended as a practical incorporation of the promising theories put forward by Land and Horwood [63], Wilkie and Wann [120], and Fajen and Warren [22]. Therefore, particularly in terms of heuristics, it served as an inspiration for the new model presented here.

However, it was found that the Salvucci and Gray model exhibits parameter redundancy. Indeed, in Papers D and F it was concluded that the same model behaviour could be obtained using different sets of parameters. Specifically, the degree to which the near and far points accounted for different parts of the total behaviour was found to be dependent on their respective weights. In their paper, Salvucci and Gray are very clear in pointing out their use of two explicit aim points as a way to make the model more practical. However, it might be argued that such an arrangement adds redundancy to the model. In retrospect, the finding of Land and Horwood (see p. 7) should perhaps not be taken literally, as long as the far and near areas are implicitly included in the model.

The solution suggested for the model here is to replace the near and far point construct

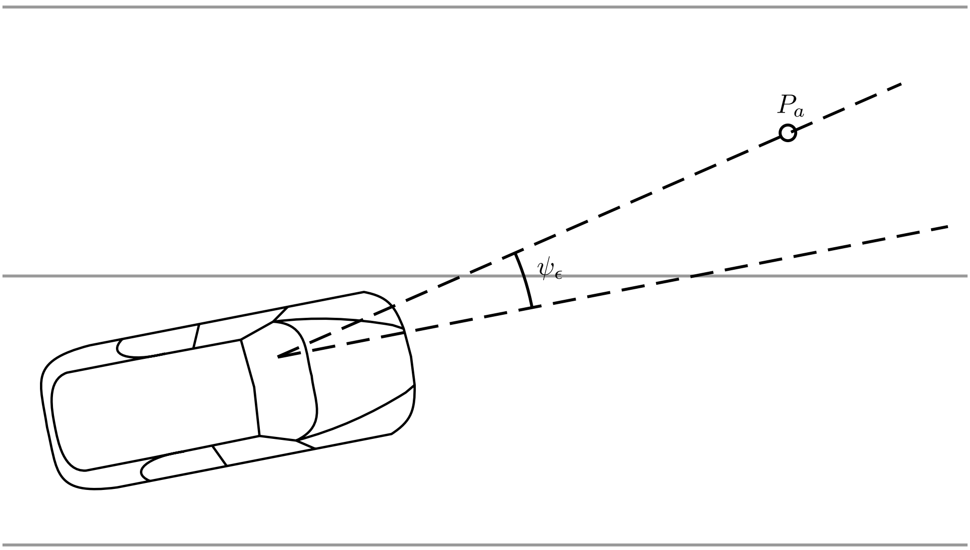

Figure 3.3: *A single lane change is performed where the driver fixates at the aim point P_a. In the new model presented here, the angle ψ_ϵ is used by the driver as the only heuristic for lateral control.*

with an egocentric reference frame and an aim point. The reference frame is aligned to the road and is used by the driver to establish the longitudinal and lateral directions of travel (i.e. a local road coordinate system). Accordingly, the aim point is a salient point positioned within the reference frame. From the driver's point of view, such a point is perceived as a horizontal and a vertical angle [63, 101]. However, the presented model only uses the horizontal angle, calculated from the driver-relative metric coordinates of the aim point. Furthermore, it is assumed that the perceived heading in the egocentric reference frame equals the vehicle road heading. It is therefore not, as in the Allen, Szostak, and Rosenthal model [5] and the Gordon and Magnuski model [38], assumed that the driver predicts the imminent vehicle path curvature.

During normal driving, the aim point is positioned at a long headway but in, for example, a lane change it is instead positioned at a short headway in the target lane, as exemplified in Fig. 3.3. To use the error between the current heading and the aim point seems quite realistic, since it can, from a driver's point of view, be described as the error between the current and desired headings. Simply put, the aim point is *where the driver wants to go*, typically towards the fixation point, or, alternatively, towards the spatial *memory* of such a fixation point. Furthermore, even though the near point is not explicitly defined, the same information is used by the driver in order to establish the egocentric reference frame, in that way making it possible to perceive the aim point angle. It should also be noted that the aim point, depending on the developing situation, might move at any moment. For example, in a single lane change, the aim point moves twice: (i) to the entry point of the target lane, and (ii) towards the horizon of the target lane.

In mathematical terms, the aim error ψ_ϵ at time t is formulated as

$$\begin{aligned} P_a(t) &= (x_a, y_a) \\ \psi_\epsilon(t) &= \arctan \frac{y_a - y(t)}{x_a} - \psi_h(t) \end{aligned} \tag{3.1}$$

where, in the current egocentric reference frame, P_a is the aim point, y the driver lateral offset, and ψ_h the vehicle (and driver) heading.

In contrast to the Salvucci and Gray model, the model formulated here lacks an integrating part. However, since the new model is satisficing rather than optimising, such error integration is not needed. In order to generate satisficing behaviour, the control part of the model was designed in line with the results presented in Paper E. The basic assumption is that steering behaviour originates from the brain acting, at appropriate times, on a physical stimulus always available to the driver. In that way, each time the brain requests a steering movement the magnitude would depend on the stimulus strength as well as the current driver sensitivity. Here, the stimulus is simply selected as the aim point angle defined above. However, the driver's *sensation* of the stimulus is defined as the perceived need of a steering correction. The need is modelled as the stimulus multiplied by a gain representing the driver's understanding of the vehicle as well as the situation urgency, which may, for example, depend on the driver's stress level. Therefore, the gain can change over time, even though such changes are expected to relate to specific events. The sensation η at time t is simply

$$\eta(t) = k_s(t)\psi_\epsilon(t) - \delta(t) \tag{3.2}$$

where k_s is the gain, and δ the steering wheel angle. In terms of reaching, as discussed in Paper E, one can view the sensation as the driver-predicted steering wheel angle (or distance) which would remove the aim heading error. Naturally, the driver's understanding of the vehicle steering is here assumed to be quite limited, which is intentional.

In Paper E it was found that a typical steering primitive lasts for about 0.4 s. It was also found that about 60–70% of all corrections are performed as a single primitive, and the remaining mainly as two superpositioned primitives. Another observation made in Paper E was that driving on varied roads seems to result in a higher degree of superpositioned primitives compared to highway driving. Thus, it seems plausible that a strong aim point offset, as when driving in a curve, more often results in two superpositioned steering primitives rather than one. Additionally, the minimum time between such primitives seems to be around 0.2 s (i.e. a reaction time). In the model, such behaviour is implemented as follows: (i) if the sensation is greater than a threshold, then (ii) apply a proportional steering correction and, at that point, (iii) inhibit any subsequent corrections for the immediate time after. The steering wheel rate $\dot{\delta}$ can therefore be formulated as a sum of all current correction primitives

$$\dot{\delta}(t) = \sum_{i=1}^{n} \dot{\delta}_i(t_i) \tag{3.3}$$

Table 3.1: The parameters used in simulation of the three different scenarios. The first is the lane change scenario, the second the head-on collision scenario, and the third the truck lead vehicle braking scenario. In the table, t_a is the time when a new aim point position P_a (in road coordinates) is selected. Note that a scenario may involve a sequence of such aim points.

Scenario	R^2	k_s	T_s	t_r	t_a	P_a
1	0.53	3	0.01	0.2	0.0; 3.2; 7.5	(80, -1.2); (80, 2.4); (80, -1.2)
2	0.82	6	0.01	0.2	5.7	(50, -1.2)
3	0.80	13	0.01	0.2	0.0; 4.5; 8.0	(50, -0.5); (50, 3.5); (75, -0.5)

where each correction, according to Paper E, is

$$\begin{aligned} \dot{\delta}_i(t_i) &= \dot{\delta}_m \exp -\frac{(t_i - b)^2}{2\sigma^2} \\ t_i &= t - t_{0i} \end{aligned} \tag{3.4}$$

where t_{0i} is the correction start time, and with the maximum steering wheel rate

$$\dot{\delta}_m = k\eta(t_{0i}) \tag{3.5}$$

and the activation criterion

$$\begin{aligned} t_{0i} &> t_{0(i-1)} + t_r \\ \eta(t_{0i}) &> T_s \end{aligned} \tag{3.6}$$

where t_r is the reaction time, and T_s the sensation threshold, and finally, again from Paper E,

$$\begin{aligned} k &= \frac{1}{2\sigma\sqrt{\pi}} \\ b &= \frac{\Delta t}{2} \\ \Delta t &= 2\sqrt{2\ln 10}\sigma \approx 4.29\sigma \\ \sigma &= 0.1. \end{aligned} \tag{3.7}$$

In total, the model uses four tunable parameters, the constants t_r and T_s in Eq. (3.6), and the variables P_a in Eq. (3.1) and k_s in Eq. (3.2). Of these parameters, only the sensation gain k_s is strongly driver-dependent. Additionally, k_s is scenario-dependent since it captures the stress level of the driver, which for example would be higher in a critical scenario. The reaction time t_r and sensation threshold T_s are expected to be roughly constant between drivers, where t_r is typically 0.2–0.3 s. The aim point P_a is strongly scenario-dependent, but in most cases intuitive as illustrated in Fig. 3.3.

In order to test the validity of the model, it was used in computer simulation of three scenarios previously described in this chapter, namely: (i) a double lane change during casual normal driving, (ii) an evasive manoeuvre in a head-on collision scenario, and (iii) a

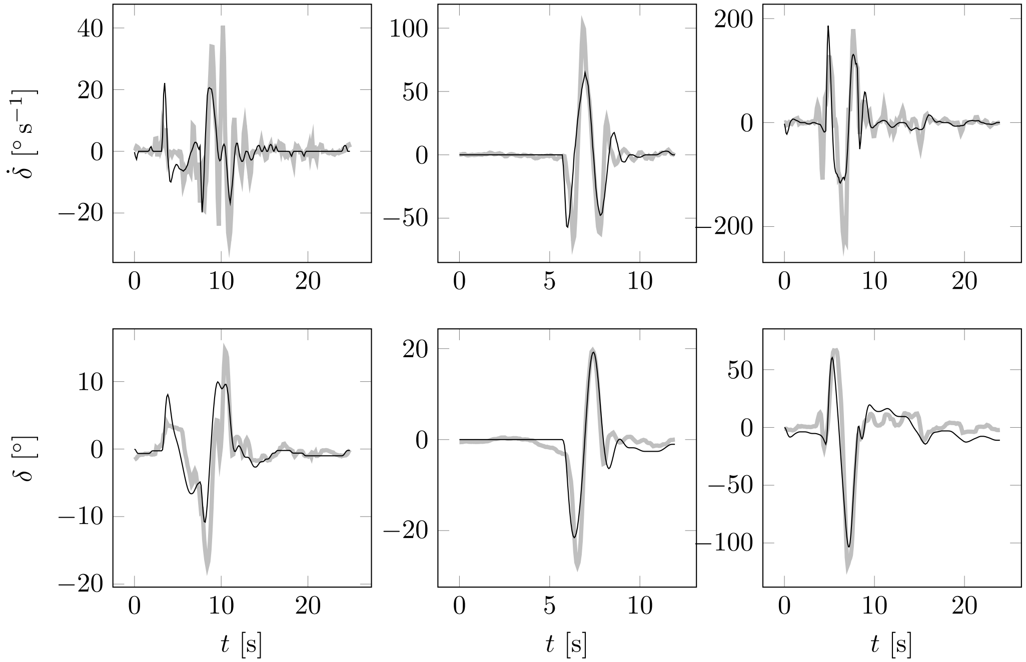

Figure 3.4: *The behaviour of the novel driver model (black) compared to real driving data (gray) in three different scenarios. The top row shows the steering wheel rate, and the bottom shows the steering wheel angle. The first column shows a double lane change scenario, the second a head-on collision scenario, and the third a truck lead vehicle braking scenario.*

truck lead vehicle breaking scenario (i.e. as in Paper D). Interestingly, unlike the case in Paper D, the latter scenario did not require separation into the two parts of avoidance and stabilisation, but could instead be treated in whole. It is also interesting to note that the data used here for the first two scenarios, namely the double lane change and the head-on collision scenario, in fact were collected from the same driver during the same drive. The simulation was carried out in open-loop (i.e. without simulating the vehicle) as in Paper D, where the measured vehicle state was used as input to the driver model in each time step[1]. For the head-on collision scenario, driver distraction was modelled as the absence of an aim point, in effect resulting in passivity. The model parameters were set based on the scenario or from predetermined values, except for k_s which was manually tuned. The model fit, given as the coefficient of determination R^2, as well as the used model parameters, are presented in Table 3.1. By relating the three different values of k_s to the three different scenarios, one can see that the parameter in fact does seem to indicate the stress level of the driver, and possibly also to some extent the vehicle type.

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[1] In Paper F, closed-loop simulation was employed, but in that case the vehicle state was not accurately measured due to on-road measurement constraints.

The results from the simulations are presented in Fig. 3.4. As is evident from the figure, the model behaviour closely matches the recorded steering, especially in the two critical scenarios. Importantly, the biologically inspired control methodology adopted for the model can represent the rapid and seemingly random rate peaks seen in the data. Based on this result, it appears that, contrary to the traditional views, the *remnant* discussed in Sect. 3.1 might be a highly predictable feature of human control.

Chapter 4

Neuromuscular steering and interventions

So far in this thesis, steering has been addressed in terms of steering wheel angles and rates. This approach is certainly the most common when explaining driver behaviour, and it is, in most applications, sufficient. However, when also considering external disturbances acting on the steering wheel one must instead explain the observed behaviour in terms of applied torque. In that way, the driver action and the external influence might simply be added and converted to a steering wheel angular acceleration by

$$\ddot{\delta} = \frac{T_R}{I} \tag{4.1}$$

where T_R is the net torque and I the moment of inertia of the steering system.

Typically, external torques acting on the steering wheel originate from road–vehicle interaction. For example, the so called **aligning torque** is, by design, continuously applied during steering with the purpose of aligning the front wheels of the vehicle after releasing the steering wheel. Moreover, the road might inflict undesired external torques due to various types of surface roughness. Even though driver behaviour in connection with road–vehicle interaction is an important field of study in itself, it might also be valuable to study the behaviour evoked by torques applied *artificially*. Such torques might, for example, be applied as an intervention in order to avoid a road accident.

In order to avoid a collision, typically caused by driver inattention or drowsiness, steering may be applied autonomously. Examples of accident types targeted in the development of systems for autonomous interventions include head-on collisions and run-off-road scenarios, both highly represented in accident statistics [88]. Even though head-on collisions are relatively rare, they account for a large portion of traffic fatalities[1]. Run-off-road accidents are not considered to be as fatal statistically speaking but, on the other hand, their representation in overall statistics and their economic cost are highly significant. By assisting the driver in such situations by means of lateral control

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[1] For example, in the US, 2 % of all traffic accidents are classified as head-on, but they still account for 10 % of all fatalities [88].

interventions, many accidents may be successfully mitigated or avoided. Mainly, there are two different ways of applying such interventions, either by adding a torque to the steering column, or by braking individual wheels. Looking to the future, one might also imagine technology and legislation allowing similar interventions using steer-by-wire. In such systems, the driver would more or less be bypassed.

However, even though the technical requirements for steering interventions to some extent already exist, there have been justified speculations on how a driver would react to such interventions, not least since the driver supposedly is unaware of the threat in the first place. Elsewhere, it has been shown that a steering intervention very well can help an *attentive* driver during obstacle avoidance [87]. Furthermore, due to the nature of the considered accident scenarios, a relatively swift intervention is required, which from the unsuspecting driver's perspective would be perceived as sudden. Therefore, in this thesis the driver's reaction to a sudden and unexpected steering intervention is considered.

The remainder of this chapter will focus on how drivers interact with the steering wheel on a neuromuscular level, both during normal conditions and during sudden autonomous interventions. First, the relevant anatomy of the driver is reviewed. Secondly, several experiments conducted within the framework of this thesis are described. Then, a few experimentally observed events will be explained using the provided theory. Finally, a discussion about the plausibility of unexpected steering interventions will be presented.

4.1 The anatomy of steering

The British Nobel prize winner Sir Charles Sherrington once said:

> To move things is all that mankind can do … for such the sole executant is the muscle, whether in whispering a syllable or in felling a forest.

Surely, this applies to the steering of a vehicle as well. When considering steering in general, there are two especially important components, namely: (i) the **central nervous system** (CNS) consisting of the spinal cord and the brain, and (ii) the **skeletal muscles**. The skeletal muscles represent the bulk of the body muscle mass, and are responsible for moving the body and maintaining its posture. For example, the human arm contains more than 50 such muscles.

The skeletal muscles are often categorised into **flexor** and **extensor** muscles, where flexion and extension refer to angular closing and opening of a joint, respectively. Typically, there is not only one muscle responsible for a specific flexion or extension movement; several muscles often work together in so called **synergistic** muscle groups. Note that muscles cannot push at a joint, only pull. Therefore, when carrying out a *directed* voluntary[2] movement, flexion and extension cannot be activated at the same time, but rather in sequence. Such pairs of flexion and extension muscles are referred to as **antagonistic pairs**, where one muscle, the *agonist*, initiates and drives the movement, and the other, the *antagonist*, finally slows down and stops the movement. In other words, during the entire movement, the agonist and antagonist muscles are sequentially contracted and

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[2] The term voluntary movement has been hotly debated amongst neuroscientists and psychiatrists [117, 40, 113]. Here, the term simply refers to a behaviour originating from upper motor neurons in the brain.

relaxed in a highly coordinated way. Furthermore, in order to hold a limb steady [48], for example during an external disturbance, both the agonist and the antagonist muscles may be contracted simultaneously, a process referred to as muscle *co-contraction*.

The skeletal muscles are innervated by the **somatic motor neurons** in the spinal cord. The innervation of the muscle fibres is limited to a specific area on the muscle, called the **innervation zone**. Motor neurons in the spinal cord are often referred to as the *lower* motor neurons to distinguish them from the *upper* motor neurons operating from the brain. However, skeletal muscles can only be innervated from the spinal cord. Therefore, using the upper motor neurons, the brain can only command the muscles indirectly by activating the lower motor neurons.

There are two different types of lower motor neurons, namely **alpha motor neurons** and **gamma motor neurons** (discussed below). The alpha motor neurons directly govern the force generated by the muscle by contracting its fibres. In static conditions, the generated muscle force changes with length in a springlike manner [48]. A single alpha motor neuron commands a large number of muscle fibres through multiple axon branches. One such motor neuron along with its muscle fibres is called a **motor unit**. In a large human muscle there are hundreds of motor units, and several hundred thousand muscle fibres [32]. Mainly, the motor units are of two different kinds, slow (red fibres) which can sustain contraction for a long time without fatigue, and fast (white fibres) which are responsive and powerful for short times. The human arm muscles contain many fast motor units. A collection of alpha motor neurons, referred to as a **motor neuron pool**, commands the entire muscle.

In order to control accurately the force generated by a muscle, the CNS carefully controls the length of muscle motor units by regulating the alpha motor neuron firing rate of **action potentials**. Each action potential causes the commanded muscle unit to *twitch* or, in other words, momentarily contract and then relax. Therefore, a sustained contraction of the motor unit requires a continuous barrage of action potentials. The high frequency activation of the muscle does, by summation, result in a smooth force profile. For fast motor units, the frequency is 30–60 Hz and for slow units 10–20 Hz. In order to generate even more force, the CNS may involve additional motor units within the muscle. The sensitivity, or resolution, of a muscle is related to how many muscle fibres there are, and how they are divided between the motor units. Depending on the exact number of muscle fibres, each motor unit generates a specific force. Furthermore, a muscle contains a repertoire of differently sized motor units that, if needed, are orderly recruited by the CNS from smaller to larger, according to the **size principle**. Therefore, the muscle is more sensitive when subjected to small loads compared to large ones.

An alpha motor neuron acquires input from three sources (see Fig. 4.1): (i) the upper motor neurons in the brain, (ii) the **muscle spindles**, and (iii) spinal interneurons. The spindle, which is connected to a dorsal root ganglion in the spinal cord, is a specialised sensory organ embedded into the muscle. When referring to the spinal cord, spinal interneurons are small local neurons often with inhibitory function. These small neurons represent the largest input to the alpha motor neurons.

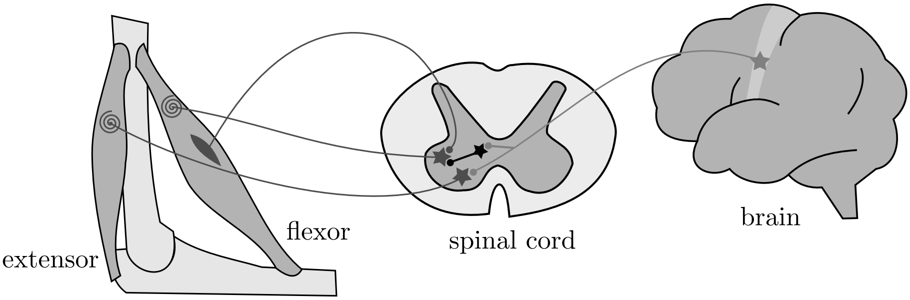

Figure 4.1: *The stretch reflex. By stretching biceps brachii (flexor) externally, the spindle (dark area) starts to send action potentials over the afferent (CNS input) axon to the spinal cord. The alpha motor neuron (dark grey star) then generates action potentials and sends them over the efferent (CNS output) axon to the innervation zone of biceps brachii, in effect contracting the muscle. The figure also exemplifies how action potentials sent from the motor cortex (i.e. a voluntary action) temporarily deactivates the antogonist muscle and its stretch reflex, by using an inhibitory spinal interneuron (black star).*

The muscle spindle, also known as the *stretch receptor*, consists of specialized muscle fibres incorporated into a small capsule. Inside the capsule a type Ia axon[3] is wrapped around the fibres, allowing the spindle to detect *changes* in muscle length. If the muscle is stretched, the firing rate of the Ia axon increases in proportion to the stretching, and if it is relaxed the firing rate decreases. The spindle is an example of a **proprioceptor**, which is an important component of the somatic sensory system, or *body sense.*

However, when a muscle is shortened as a result of alpha motor neuron activity, the special muscle fibres in the spindle must also be contracted in order to match the new length. The contraction is a result of action potentials sent from the *gamma* motor neurons (mentioned above) which are connected to the spindle muscle fibres. The activation of the gamma motor neurons is a result of the activation of the alpha motor neurons and is referred to as *alpha gamma co-activation.* The gamma motor neurons also possess the ability to alter the overall sensitivity of the spindle.

The **stretch reflex**, also referred to as the *myotatic reflex*, was first discovered by Liddell and Sherrington in 1924 [68]. It was noted that when a muscle is pulled externally, it tends to counteract. By cutting the Ia axon from the spindle, Liddell and Sherrington showed that the stretch reflex was disabled, even though the alpha motor neurons were left intact. The afferent (receptor) and efferent (effector) axons of the spindle and the alpha motor neuron together represent the so called **monosynaptic myotatic reflex arc**. The response time of the reflex arc is about 50 ms. In Fig. 4.1, the stretch reflex is illustrated. The figure also shows an example of how the stretch reflex can be disabled during voluntary movements commanded by the brain.

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[3] The type Ia axon is the largest type of axon, with a diameter of 20 µm and with a transmission speed of $120\,\mathrm{m\,s^{-1}}$.

Apart from the spindle, there is one more proprioceptor integrated into the muscle, namely the **Golgi tendon organ**. The organ is anatomically positioned at the attachment of the muscle and is sensitive to muscle tension. If the tension is dangerously high the **reverse myotatic reflex** is triggered, which inhibits the alpha motor neurons and, therefore, relaxes the muscle. However, even at lower levels, the tension is reported back to the spinal cord [95] in order to moderate the tension of the muscle when, for example, gripping an object.

Finally, there is one more type of proprioceptor highly relevant for steering, namely the actual joints, which can provide information about angles and the angular velocities of the limbs. In fact, the joints are the most accurate proprioceptors when determining the body pose. This is so, because the spindles cannot give the absolute length of a muscle, only the relative one, since they themselves are not fixed in length.

4.2 Experimental work

Several experiments, especially designed to study a driver's interaction with an applied steering intervention, have been carried out by the author. The results from these experiments have not yet been published.

The first study, conducted in late 2011, involved 40 subjects and employed a driving simulator[4] with 40 subjects in late 2011. It targeted a head-on collision scenario where the drivers were forced, during distraction, into a collision course with an oncoming car in the opposing (left) lane [29]. The distraction consisted of a reading task, compelling the drivers to look away from the road for a few seconds. Half of the subjects were given no help to avoid the collision, and, when looking back on the road, had to carry out a rapid manoeuvre to the right. The other half of the subjects were given a guiding torque intervention applied to the steering wheel, typically still during distraction. The intervention was designed to avoid the collision autonomously, provided that the drivers did not counter-steer. Based on the results of Paper B, the critical situation was repeated three times per subject.

The main result from the study was that drivers typically counteract an unexpected steering intervention while distracted. Therefore, two follow-up studies targeting a run-off-road scenario were conducted, one test track study in 2012–2013 involving 56 subjects, and one driving simulator study in 2013 involving 41 subjects. It was envisioned that a less violent intervention, as a result of the less demanding traffic scenario, would be accepted by the drivers. Additionally, as a separate part of the experiments, the intervention was combined with an audio-visual warning attracting the drivers' attention towards the road, right before the steering intervention was given. However, it was found that the majority of drivers, despite the changes, still counteracted the steering intervention. In fact, the same behaviour was also noted elsewhere [46], and described as

> Previously conducted studies within the EU project interactIVe showed that in critical rear-end collision situations, drivers tend to counteract steering interventions, such that low-level torque overlays hardly have any effect.

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[4] All driving simulator studies mentioned in this section were carried out in the VTI Sim IV simulator in Göteborg.

In their paper, the authors then evaluated a very strong torque intervention of 9.9 N m, and found that a few collisions could be avoided, but with the dangerous effect of some drivers losing control of their vehicles. The authors also tested versions of the system, with different warnings and where the driver was temporarily bypassed. In the end, the authors concluded that none of the tested versions worked well, and that further research is needed. No speculations were made regarding the cause of the observed behaviour, however.

Due to the adverse results considering the reaction to the intervention in the described experiments, the author engineered a new driving simulator experiment in 2014 with the sole purpose of acquiring a better theoretical understanding of the involved physiological aspects. In essence, the experimental arrangement was the same as in the previous experiments, but in a more condensed form. Importantly, the experiment involved two types of drivers, namely twelve-year old children and adults. In total there were 16 volunteer subjects, seven adults and nine children. The subjects were first asked to drive in the middle lane out of three, on a perfectly straight road. Occasionally, they were asked to carry out the same distraction task as used in the previous experiments. Then, towards the end of the drive, a steering intervention was applied to the steering wheel on two such occasions. The interventions were of fixed torque, first at 1 N m and then 3 N m, both with a duration of 1 s. During the experiments, EMG was taken to measure the activity of the *extensor digitorum* and *flexor digitorum superficialis* muscles in both forearms. Since the measured muscles are highly relevant when tensing the grip of the steering wheel it was assumed that such activity would indicate a cognitive effort. When attaching the electrodes, the innervation zones were avoided, in accordance with good practice. As mentioned in Chapter 1, the experiment also included a second part comparing the general steering behaviour observed on a normal winding road. Two subjects participating in the experiment, a child and an adult, are depicted in Fig. 3.1. In the picture, one can also see some of the attached EMG electrodes.

4.3 An illustration of neuromuscular steering

One can quite conveniently express individual steering corrections, as described in Sect. 3.1.2, in neuromuscular terms, by viewing a correction as an aimed movement carried out by an agonist-antagonist muscle pair, where the agonist muscle initiates the correction and the antagonist muscle terminates it. In reality most reaching movements use more than a single muscle pair, by instead involving synergistic muscle groups. For example, it has been found that up to ten muscles can be used for a single reaching movement [34]. However, in order to generate the distinct rate profile, the *work* carried out by each muscle group must still be the same. By extending the steering correction theory postulated in Paper E and used in Sect. 3.3 above, one can, by differentiation, simply express this muscular function as

$$\ddot{\delta}(t) = \dot{\delta}_m \frac{(b-t)}{\sigma^2} \exp - \frac{(t-b)^2}{2\sigma^2} \tag{4.2}$$

as exemplified in Fig. 4.2. Then, using Eq. (4.1) and assuming that the brain can accurately estimate the moment of inertia, the torque given by the driver from each

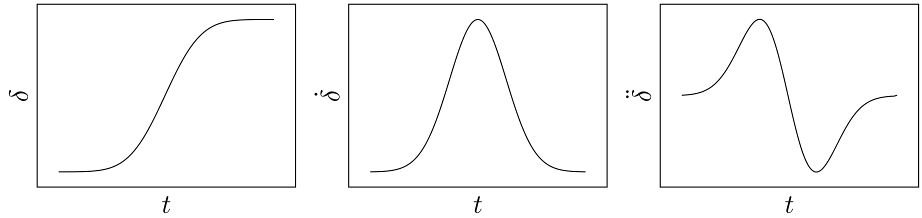

Figure 4.2: *An neuromuscular extension to the steering correction theory, where the acceleration profile relates to the activation of an agonist-antagonist muscle pair. In the rightmost panel, the positive first half corresponds to the behaviour of the agonist muscle, and the second part to that of the antagonist muscle.*

correction is

$$T_c = \ddot{\delta} I_E \tag{4.3}$$

where I_E is the inertia estimate. Once extended in this way, the aim point correction model will generate a torque instead of a steering wheel angle. Unlike other neuromuscular models of control (see e.g. [94, 3]), the neuromuscular aim point correction model applies steering as open-loop reaching movements. Therefore, the discussion whether control is driven by muscle co-contraction, or afferent feedback is somewhat unnecessary (see [3, p. 4]). However, the model given so far only considers the actual steering. It may not be sufficient for explaining the driver behaviour during an applied steering intervention. In order for the driver to hold the steering wheel steady during such an intervention, muscle co-contraction is expected.

Some vital clues regarding such behaviour can, however, be extracted from the final experiment described in the previous section. Generally, it was found that distracted drivers indeed can, and will, counteract an unexpected steering torque, as exemplified by Figs. 4.3 and 4.4. Both figures show clear examples of behaviour originating from the stretch reflex, as well as from cognitive actions. In both cases, the stretch reflex is triggered about 50 ms after the intervention was initiated, all in accordance with theory. Furthermore, looking at the time between the first indication of the stretch reflex and the cognitive action (i.e. the two thin vertical lines) it seems as though the stretch reflex is triggered at least once more, probably due to the ongoing build-up of the external torque.

Then, about 200 ms after the start of the intervention, some cognitive actions are initiated sequentially. In the first example, shown in Fig. 4.3, the rate of the steering wheel is first reversed (i.e. until around 400 ms after initiation), and then, when the driver contracts the muscles strongly enough to remove any further disturbances, the wheel is stabilised. In Fig. 4.3, this behaviour is especially noticeable since the *extensor digitorum* and *flexor digitorum superficialis* in both arms are forcefully tensed for the remaining part of the intervention. One should also note that, even for the child, the muscle tension is only about a fifth of the maximum, according to the EMG. The overall behaviour seen in the second example (i.e. Fig. 4.4) is similar, but with one addition: From the figure, it appears as though the second stretch reflex is strong enough to result in a steering wheel rate in the opposite direction of the intervention. Therefore, the driver, unable to detect the external torque due to the negative acceleration, then lets the steering wheel change

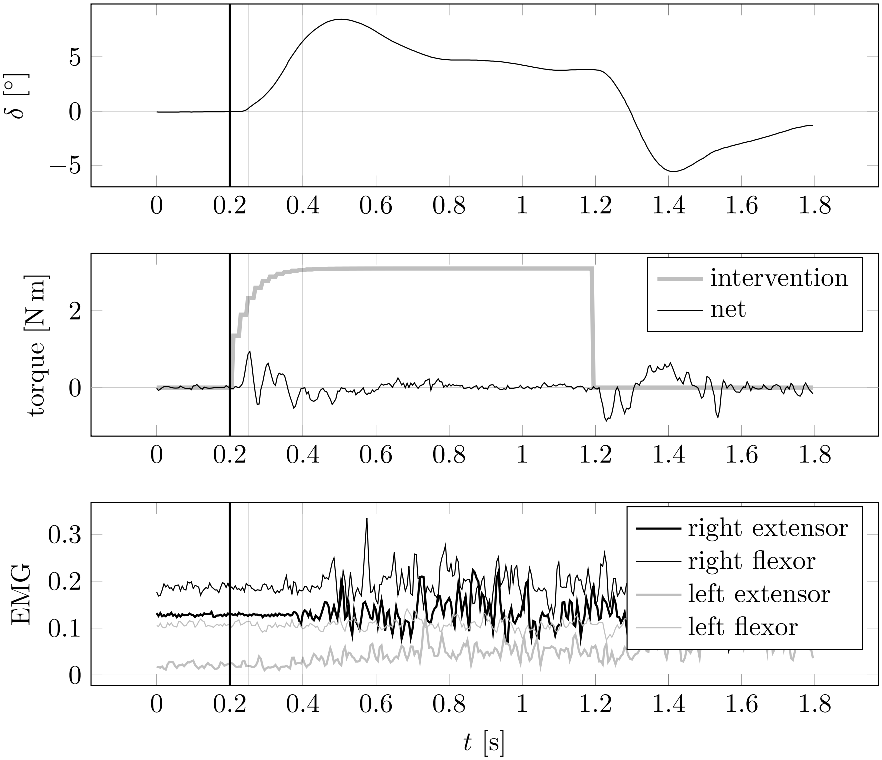

Figure 4.3: *Observed behaviour of a child exposed to a sudden and unexpected steering wheel intervention. The first vertical bar marks the initiation of the intervention, and the thin vertical bars indicate when (i) the first stretch reflex is triggered and (ii) the first cognitive action occurs. The EMG is presented as the absolute mean over a time window of* 0.05 s *(20 samples). Each channel was scaled by its maximum value, recorded during the maximum supervised voluntary contraction.*

direction once more, before initiating the same reversal and holding behaviour as seen in the first example.

Finally, when the intervention is terminated just before 1.2 s elapsed time, the same kind of behaviour is repeated but in reverse. In short, the subject is pushing the steering wheel against the intervention, and then, upon release, the steering wheel is unexpectedly rushing in the same direction. The stretch reflex is triggered to pull the wheel in the opposite direction, first about 30–40 ms after termination, and then once more. Then, about 150 ms after termination, the wheel is stopped by means of an automatic cognitive action, and the muscles are finally fully relaxed, about 400 ms after termination. It is interesting to note that (i) the behaviour looks very similar comparing the child and the adult, and (ii) the response times, both for the stretch reflex and the cognitive response, are shorter here compared to the when the intervention was initiated, possibly due to pre-activation of the involved motor neurons. The same relationship, between shorter

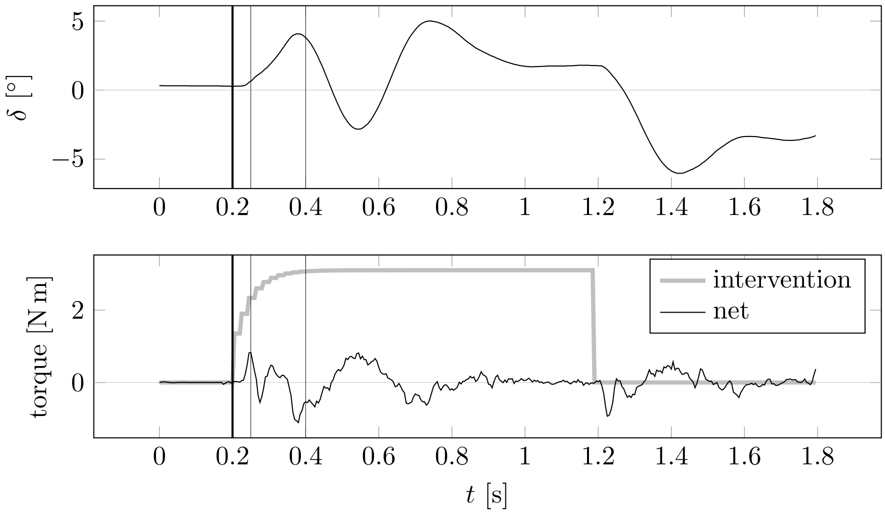

Figure 4.4: *Observed behaviour of an adult exposed to a sudden and unexpected steering wheel intervention. The first vertical bar marks the initiation of the intervention, and the thin vertical bars indicate when (i) the first stretch reflex is triggered and (ii) the first cognitive action occurs.*

response times and muscle tension, was first shown by Magdaleno and McRuer [71].

From these two examples, one observed from a child and one from an adult, it is quite clear that drivers are neurologically hard-wired in their response to unexpected steering wheel disturbances. At least here, it seems like the stretch reflex is applied in bursts, in a sense similar to the steering corrections identified in Paper E, and that muscle co-contraction is applied even before the driver is aware of the situation. Moreover, due to the *size principle*, one might suspect that any voluntary steering correction during such co-contraction would be of less accuracy compared to the normal case. Furthermore, if the stretch reflex is triggered strongly enough, as in the second example, the driver might temporarily steer in the opposite direction of the intervention. Therefore, for the particular scenario studied here, it can be concluded that such steering intervention would simply not work, and might, moreover, be dangerous.

Chapter 5

Applications

Apart from the research objective of understanding *driving* as a phenomenon, as mainly discussed so far in this thesis, there are of course also several practical applications where driver models are relevant. Typical examples include design of infrastructure [67], vehicles [92], and **active safety** systems that provide warnings or control interventions [15, 39, 61]. Originally, driver models were used in computer simulation, but more recently they have also been used as integral parts of embedded real-time systems, as exemplified in Paper F. In computer simulation, a driver model is typically used together with a vehicle model for different types of evaluations. In embedded systems, driver models can be used either to make real-time predictions, or to apply direct vehicle control. In this chapter, different applications of driver models will be discussed. The text will focus both on existing usages of driver models and potential near future applications.

5.1 Vehicle and system tests

Traditionally, driver models have been used in computer simulation for the purpose of testing vehicles in various ways. For example, such tests may target general vehicle dynamics [112], the performance of tyres [6], or evaluation of specific vehicle components. In the simulations, different aspects of the vehicle or tyres may be changed by varying model parameters, thus enabling the comparison of different solution candidates. The main advantage of using a closed-loop driver model when evaluating vehicle or tyre performance is that the simulated vehicle can be driven through standardised tests, such as the **ISO double lane change**, in a repeatable way. The alternative of using a driver models in such tests is to apply fixed open-loop steering commands, such as the well-known *sine with dwell* manoeuvre. When testing vehicle dynamics in simulation it may be argued that realistic driver behaviour, as emphasised in this thesis, is of less importance compared to test repeatability and model predictability.

In addition to computer simulations, driver models can be used in a similar way when testing physical vehicles at a test track, by utilising a **steering robot** [110]. The steering robot may be installed in conventional passenger cars or trucks in order to enable temporary autonomous control of the vehicle. Naturally, this kind of test is significantly

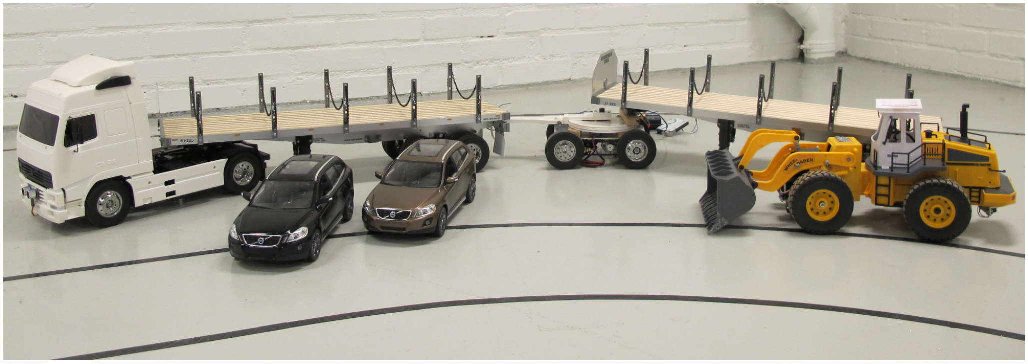

Figure 5.1: *Vehicles in the miniature lab, all in 1:14 scale. In the background: A truck with two trailers and an active dolly. To the left: Two passanger cars. To the right: A front loader.*

more expensive compared to computer simulation and is typically carried out under very specific conditions. However, Paper G describes a new specialised laboratory, developed by the Adaptive systems group at Chalmers University of Technology, with the purpose of performing inexpensive physical tests in a miniature scale arena. In this laboratory, scaled computer-controlled vehicles can be subjected to different traffic scenarios. Moreover, the laboratory framework constitutes a convenient way of mixing scaled physical vehicles with simulated virtual ones. Is is also possible to equip the scaled vehicles with virtual sensors. Therefore, the miniature laboratory can, in a sense, be considered as a testing paradigm positioned between traditional computer simulation and full-scale track tests.

Currently, a passenger car in 1:5 scale, and a truck and front loader in 1:14 scale are available to use in the arena. Furthermore, several passenger cars in 1:14 scale are currently under development. Apart from testing different driver models, the miniature laboratory has been a platform for various master theses partly supervised by the author. For example, the miniature **active dolly** shown in Fig. 5.1 was developed and evaluated [114]. The design of the dolly is somewhat unconventional, incorporating differential steering rather than steered axles, making its development as a scale model especially suitable. Even though the vehicle dynamics scale differently for miniature vehicles compared to full-scale vehicles, the use of the laboratory is motivated by the relatively inexpensive way of carrying out initial physical tests, in what one can call **embodied simulation**.

The new aim point correction model formulated in Chapter 3 is believed to be well suited for various vehicle testing applications. The initial model evaluation suggested better realistic behaviour compared to the models evaluated in Paper D, and the model contains very few parameters. Furthermore, to increase model predictability, the corrective behaviour can simply be replaced with a more conventional linear one acting directly on the aim point angle.

5.2 Accidents and safety

Even though it might be argued that traditional vehicle tests do not depend on realistic driver behaviour, such behaviour is, however, important when evaluating active safety systems with direct driver interaction. For example, in Paper C it was found that drivers with different levels of experience interacted differently with an ESC system. Therefore, when evaluating such systems in, for example, computer simulation it is of great importance to capture a representative sample of different drivers. In Paper D, it was shown that driver models differed much in allowing such behavioural variations. Thus, the choice of model is very important. Ultimately, one should aim to find a single model able to generate the full spectrum of typical driver behaviours seen in the traffic scenario at hand. Only then may the model generate accurate distributions of scenario outcomes, when exposed to different scenarios with different initial conditions and safety system parameters.

A prerequisite for designing new effective safety systems and safer traffic systems in general, is to develop a good understanding of actual road accidents. For this purpose, large amounts of field work and research [88] have been invested in creating large descriptive accident databases [91]. In such databases, information about accidents is often given as records of specific events typically coupled with the final position of the involved vehicles. However, driver models may be used as a way to reconstruct the accidents in order to obtain a more complete understanding of the scenario outcome. Furthermore, various active safety systems can then be tested in the reconstructed scenarios, in so called **what-if simulations**. In such simulations, different active safety systems and driver model parameters can be evaluated, with the purpose of finding conditions where the accidents are avoided or mitigated. By simulating a large enough population of different reconstructed accidents for a specific safety system, one can get an indication of the system's **safety benefit**.

5.3 Embedded systems

In embedded real-time systems, an integrated driver model can be used for a variety of different purposes, typically when needing to predict, in real time, driver actions or to generate vehicle control signals in specific situations. The most non-critical use of integrated driver models is probably as part of in-vehicle information systems capable of evaluating and suggesting driver actions. For example, one might imagine such a system suggesting a lane change to the driver and also supplying relevant timing information. Furthermore, if one uses the aim point correction model presented in Chapter 3 in such a system, one might even imagine the system guiding the driver by suggesting an aim point by means of a **head-up display**. Other similar, existing systems include support systems for parallel parking and reverse driving.

An example of an active safety function that could benefit from real-time *prediction* of forthcoming driver actions is the ESC system. As shown in Paper C, different drivers apply steering differently during skidding. Therefore, by understanding and possibly predicting driver behaviour, the safety system should be able to apply a more efficient intervention.

Table 5.1: Four basic conceptual control layers of fully autonomous vehicles.

Layer	Name	Description
1	Mission control	The selection of a destination.
2	Global path planning	The selection of an overall path, for example using a conventional GPS service.
3	Local path planning	The selection of a traversable path by the use of on-board sensors, and vehicle state estimation.
4	Control	The autonomous operation of the vehicle.

For instance, the aim point correction model is able to predict driver behaviour up to 0.4 s in advance due to the open-loop corrections. In practice, such prediction could be very valuable in order to break potential positive feedback loops between the driver and the system. Furthermore, if the system can detect a legitimate steering correction from the driver, it can begin preparing the next correction in the opposite direction, and in that way ensure a negative feedback loop. Another good example of an active safety system that could benefit from an accurate integrated driver model is the steering torque intervention discussed in Chapter 4. By using such a driver model in real time, the safety function can evaluate a large number of different steering interventions in advance in order to then apply the one resulting in minimal driver interference.

Some vehicular systems may use driver models directly to apply control. An example of such a system is shown in Paper F, where a driver model was developed for the purpose of changing lanes with a very long four-unit truck. In the paper, it was argued that an autonomous vehicle should be controlled in a human-like manner, for the purpose of gaining the trust of the driver, but also to be more predictable for other road users.

5.4 Autonomous vehicles

Driver modelling is also relevant for the development of fully autonomous, or self-driving, vehicles. When designing an autonomous system one can envision several *layers* of control, as exemplified in Table 5.1. In each layer, different types of artificial intelligence are involved. The first aspect is to determine the general direction, or *purpose*, of the drive, the second and third are to find a traversable path using maps and on-board sensors, and the fourth is to follow the selected path using driver models.

As an interesting example, the well-known autonomous vehicle *Stanley* that won the *2005 DARPA Grand Challenge* [109], clearly illustrates the four layers. In the challenge, the mission was given to the vehicle in advance as a sequence of predefined waypoints. Each waypoint contained the longitudinal and lateral position, the track width, and the maximum allowed speed. In the case of Stanley, this information was used in order to create a local road coordinate system, in which the longitudinal position corresponded to the travelled distance, and the lateral position to the offset from the centre of the road[1]. The conversion from global coordinates to road coordinates is in itself a type of global path planning, and in theory it would be enough simply to follow the road using a driver model. However, in order to adapt to an ever changing and, in many ways, stochastic real world, local path planning must be carried out in real time during the drive. For the Stanley vehicle, local path planning is conducted by simulation, using a vehicle model, for a large number of possible future paths (i.e. lateral offsets). Each simulation is evaluated based on, for example, how the simulated vehicle interacts with the sensed obstacles. Then, the best future lateral offset is selected and given to the driver model. The Stanley car uses a driver model of lateral control defined as

$$\delta_w(t) = \psi_h(t) + \arctan \frac{k y_e(t)}{u(t)}, \tag{5.1}$$

where δ_w is the angle of the front wheels, ψ_h the vehicle heading in road coordinates, u the vehicle speed, y_e the lateral offset from the desired path, and k a gain parameter. Since the authors assume the speed to have the same direction as the desired path, rather than pointing in the direction of the vehicle, the model does, in fact, reduce to the same kind of preview model as proposed by Kondo in 1953 [59], with the same type of linear relationship with speed. Furthermore, in order to successfully use the driver model for controlling the vehicle, a sufficiently accurate **state estimation** is needed. In this case, the estimation consists of determining the current lateral offset and heading in local road coordinates. For such an estimation, a positioning system, for example GPS, may be used as a starting point, but other sensors, and possibly **sensor fusion**, are needed in order to maintain accuracy over time.

The Stanley vehicle is a good example of a full-scale autonomous vehicle with strong capabilities in all layers of Table 5.1. However, from a driver modelling perspective there are a few improvements that could be made. The most obvious is to instead use a driver model based on human perception, as discussed in Paper F. In that way, the self-driving vehicle will show a more human-like behaviour, both for passengers and other road users. It is clear that the intention for the Stanley vehicle never was to realistically interact with other road users but if, in the future, one wishes to move such a vehicle to real traffic situations, a more human-like driving behaviour would be preferable.

The miniature vehicle laboratory, described in Paper G and mentioned in Sect. 5.1, has the main purpose of studying autonomous driving, in particular the dynamic behaviours needed for *local path planning* and *control* in Table 5.1. In a current master thesis project supervised by the author, the autonomous operation of a front loader, as shown in Fig. 5.1, is developed. The aim of the work is to equip the front loader with behaviours that will make it capable of autonomously approaching a pile of dirt, then load its bucket, and finally drive to a waiting truck to unload. On the mission control layer, the front loader gets approximate information about where the pile of dirt and the truck are located. On the global path planning layer, a path is generated by the use of a genetic algorithm. Then, on the local path planning layer, the on-board sensors are used in order to detect obstacles and possibly request a new path. Finally, in the control layer, the selected path

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[1] Local road fixed coordinate systems are typically used in computer simulation and driving simulators, as well as in the scaled vehicle laboratory; see also Paper G.

is followed by using a driver model. As illustrated by this project, the miniature vehicle laboratory is well suited for the design, development, and evaluation of algorithms in all four control layers. Furthermore, by using embodied simulation, as also discussed in Sect. 5.1, the evaluation of the autonomous system can be more comprehensive compared to traditional simulation, since physical obstacles can be included in the scene in an arbitrary way.

Chapter 6

Conclusions and future work

When developing a driver model of realistic behaviour in normal traffic situations, control and heuristics are both important factors. In this thesis, those two concepts have been treated as two separate issues.

Regarding the issue of *control*, the main findings are that human steering relates to *reaching* behaviour, rather than *tracking*. This statement is motivated by: (i) the results presented in Paper E, which show that steering generally consists of intermittent, and to some extent overlapping, individual steering corrections, (ii) the long-standing discussion originating from Tustin's *remnant* [111], which indicates that linear control (i.e. tracking) can accurately approximate human steering behaviour but with a consistent error, as illustrated in Fig. 3.2, (iii) the new aim point correction model, developed from reaching theory, indicating better performance compared to any other model tested in Paper D, and (iv) the neuromuscular theoretical explanation involving antagonistic muscle pairs. Furthermore, reaching behaviour can easily be used when forming a satisficing behaviour, rather than an optimising one, since corrections can be added whenever a stimulus reaches a threshold, something which is arguably more realistic than continuous, error-minimising control.

Regarding *heuristics*, a suitable example for motivating realistic driving behaviour has been found: From Papers D and F and from [7], it was concluded that the Salvucci and Gray model performed well when predicting actual steering behaviour, despite the fact that it is an example of linear optimising control, as criticised in the previous paragraph. Its good performance could therefore be attributed to its use of suitable heuristics. In particular it was found that the simple heuristic of an *aim point angle* gave very promising results. This angle can be explained as the angle between the driver's perceived vehicle heading relative to the road, and the direction in which the driver wants to travel (i.e. towards the aim point). This heuristic is especially suitable since it only uses angles, all perceived from the perspective of the driver. In order for the driver to determine the vehicle's heading relative to the heading of the road, the concept of an egocentric reference frame was incorporated. To support this addition, it might be argued that the visual information in the near region, as discussed by Land and Horwood [63], is used to form such a reference frame. Thus, unlike the case where one uses a near point, as in Salvucci and Gray [101], one can remove the requirement of using this visual information directly, thereby decreasing the number of model parameters.

Based on these findings, a new driver model rooted in correction theory and the aim point heuristic was developed, see Sect. 3.3. As exemplified in Fig. 3.4, this *aim point correction model* did well when compared to actual driving data, better than any of the models investigated in Paper D. It should also be noted that the model only uses one single gain parameter, which acts on the perceived angle to the aim point. It was found that the value of the gain correlates with the driver's arousal, which in normal driving was found to be lower than in critical situations. When discussing potential model applications, it was concluded that a model of realistic steering behaviour can be useful in a variety of different situations, such as when (i) evaluating the performance of vehicles and vehicle components in computer simulation, (ii) studying traffic accidents, in particular for accident reconstruction, (iii) designing vehicle safety systems required to predict the driver's behaviour, and (iv) controlling fully autonomous vehicles. Especially, it was envisioned that the model presented here would prove very useful if incorporated into an anti-skid system, such as ESC, since it essentially can predict, simply by measuring the steering wheel rate at the initiation of the correction, the driver's steering behaviour 0.4 s *before* it is applied.

In Chapter 4, the aim point correction model was extended also to consider neuromuscular aspects. Furthermore, since the original model only considers goal-directed antagonistic movements, an experiment targeting the dynamics of muscle co-contraction during driving was conducted. The experiment involved both adult and child drivers, for the purpose of identifying any learned behaviours. It was concluded, as in many other experiments, that *distracted* drivers automatically and unknowingly tend to resist an applied torque. By referring to the theory presented in Sect. 4.1, it was also shown that both the stretch reflex and an automatic cognitive mechanism were responsible for the observed behaviour, and it was therefore concluded that the applicability of steering wheel torque interventions is questionable. Instead, such an intervention should steer the vehicle by other means, such as steer-by-brake or steer-by-wire.

Some general conclusions were also made regarding data collection. In Paper C it was found that drivers with different levels of experience applied different control behaviour. However, it was concluded that the main reason is the timing of control. It is hypothesised that drivers subjected to an unfamiliar event were slower to react, since they needed time to neurologically incorporate a new response. To deal with these variations in driver modelling, one should use an experimentally determined distribution of reaction times for the specific event and conditions. Furthermore, since some model parameters may be sensitive to driver variability, it is crucial to have data from a sufficient number of drivers when evaluating a model. Therefore, when designing a driver model it is important also to avoid parameter redundancy. As a way to improve the collection of data for driver modelling, a new methodology was developed in Paper B, where it was found that a critical traffic scenario can be repeated several times, without any significant effects on the control behaviour of the driver. However, some modifications to the traffic scenario might be needed, since the *timing* of control is expected to differ in the repeated events. For example, in the studied scenario in Paper B, this effect was compensated by making the scenario more time critical (i.e. smaller distance to a braking lead vehicle).

6.1 Future work

First of all, the philosophical question of *how* driving is subjectively experienced by the driver, and how this relates to other manners of transportation, would benefit from further discussion. It can be argued that a better understanding of the *essence* of navigation would make its modelling easier. For example, the outcome of such a discussion could very well strengthen the case for using an aim point together with an egocentric reference frame. One can also imagine further experimental work involving, for example, other kinds of biological organisms.

Secondly, the aim point correction model, presented in Chapter 3, would benefit from a more rigorous evaluation in different driving scenarios. Fortunately, as exemplified in Sect. 3.3, the data for such an evaluation has been collected, so that such a study could therefore quite conveniently be carried out. In the proposed evaluation it could be relevant to compare, as suggested in Paper A, the model behaviour to the behaviour of existing models. From Paper D, one can conclude that the Salvucci and Gray model, and possibly the MacAdam model, would be suitable candidates for a comparison.

Thirdly, the neuromuscular aspects of steering could be further studied from additional *basic* experiments, for example by again involving people without driving experience (e.g. children) and carrying out further EMG measurements. In the end, the descriptive model given in Sect. 4.3 should be expressed in mathematical terms. By then using such a model in simulation, one can further study the driver's neuromuscular interaction with the vehicle. Moreover, since the steering wheel torque intervention proved to be problematic, other means of steering interventions should be studied and, especially, the evoked driver behaviour. In fact, preliminary tests have already been carried out in the driving simulator, in which adults and children were subjected to a visually undetectable (i.e. artificial) lateral acceleration during distraction. It was observed that the lateral acceleration resulted in some steering behaviour, but the data must be further analysed before drawing any firm conclusions.

Finally, by incorporating driver models into autonomous vehicles one can create self-driving cars with a realistic, natural steering behaviour. It would be interesting to test such systems, especially to compare different kinds of driver models and to study how the autonomous behaviour then is perceived by passengers and other road users. In this endeavour, miniature laboratories, of the kind discussed in Paper G, will be a valuable tool for initial tests. Further testing can then be conducted in the driving simulator and on a test track.

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