

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

# Driver interaction with vulnerable road users

Modelling driver behaviour in crossing scenarios

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*till Vilfred, Teodor, och Maria  
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# Abstract

Every year, more than 5000 pedestrians and 2000 cyclists die on European roads. These vulnerable road users (VRUs) are especially at risk when interacting with cars. Intelligent safety systems (ISSs), designed to mitigate or avoid crashes between cars and VRUs, first entered the market a few years ago, and still need to be improved to be effective. Understanding how drivers interact with VRUs is crucial to improving the development and the evaluation of ISSs. Today, however, there is a lack of knowledge about driver behaviour in interactions with VRUs. To address this deficiency and contribute to realising the full potential of ISSs, this thesis has multiple objectives: 1) to investigate and describe the driver response process when a VRU crosses the driver path, 2) to devise models that can predict the driver response process, 3) to inform Euro NCAP with new knowledge about driver interactions with crossing VRUs that may guide the development of their test scenarios, and 4) to develop a framework for ISS evaluation through counterfactual simulation and analyse the impact of the chosen driver model on the simulation outcome. The thesis results show that the moment when a VRU becomes visible to the driver has the largest influence on the driver's braking response process in driver-VRU interactions. Data gathered in driving simulators and on a test track were used to devise different predictive models: one model for the pedestrian crossing scenario, and three for the cyclist crossing scenario. The model for the pedestrian crossing scenario can estimate the moments at which key components of the driver response process (e.g. gas pedal fully released and brake onset) happen. For the cyclist crossing scenario, the first model predicts the brake onset time and the second predicts the experienced discomfort score given the cyclist appearance time. The third predicts the continuous deflection signal of the brake pedal based on the interaction of two visually-derived cues (looming and projected post-encroachment time). These models could be used to improve the design and evaluation of ISSs. From the models, appropriate warning or intervention times that are not a nuisance to the drivers could be adopted by the ISSs, therefore maximizing driver acceptance. Additionally, the models could be used in counterfactual simulations to evaluate ISS safety benefits. In fact, it was shown that driver models are a critical part of these simulations, further demonstrating the need for the development of more realistic driver models. The knowledge provided by this thesis may also guide Euro NCAP towards an improved ISS test protocol by providing information about scenarios that have not yet been evaluated.

**Keywords:** Active safety, counterfactual analysis, pedestrian, bicyclist, driver behaviour, driver model, Euro NCAP.



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Christian-Nils Boda  
Göteborg, November 2019



# List of Publications

- Paper I** - Marco Dozza, Christian-Nils Boda, Leila Jaber, Prateek Thalya, and Nils Lubbe (2019). “How do drivers negotiate intersections with pedestrians? Fractional factorial design in an open-source driving simulator”. Journal article. An earlier version of this paper was presented at the RSS2017 Road Safety & Simulation International Conference. After major revisions, a new version of the paper was submitted to Accident Analysis & Prevention
- Paper II** - Christian-Nils Boda, Marco Dozza, Katarina Bohman, Prateek Thalya, Annika Larsson, and Nils Lubbe (2018). “Modelling how drivers respond to a bicyclist crossing their path at an intersection: How do test track and driving simulator compare?” In: *Accident Analysis & Prevention* 111, pp. 238–250. ISSN: 0001-4575. DOI: <https://doi.org/10.1016/j.aap.2017.11.032>
- Paper III** - Christian-Nils Boda, Marco Dozza, Pablo Puente Guillen, Prateek Thalya, Leila Jaber, and Nils Lubbe (2019). “Modelling discomfort: How do drivers feel when cyclists cross their path?” Submitted to Accident Analysis & Prevention
- Paper IV** - Christian-Nils Boda, Esko Lehtonen, and Marco Dozza (2019). “A computational driver model to predict driver control at unsignalised intersections.” Submitted to IEEE Transactions on Intelligent Transportation Systems
- Paper V** - Jonas Bärgrman, Christian-Nils Boda, and Marco Dozza (2017). “Counterfactual simulations applied to SHRP2 crashes: The effect of driver behavior models on safety benefit estimations of intelligent safety systems”. In: *Accident Analysis & Prevention* 102, pp. 165–180. ISSN: 0001-4575. DOI: <https://doi.org/10.1016/j.aap.2017.03.003>





# List of Acronyms

ACAT	–	Advanced Crash Avoidance Technologies
AD	–	Automated Driving
AEB	–	Autonomous Emergency Braking
ATD	–	Arrival Time Difference
CLMM	–	Cumulative Link Mixed Model
DGPS	–	Differential Global Positioning System
FCW	–	Forward Collision Warning
FOT	–	Field Operational Test
IIHS	–	Insurance Institute for Highway Safety
ISS	–	Intelligent Safety System
NCAP	–	New Car Assessment Programme
NDD	–	Naturalistic Driving Data
NDS	–	Naturalistic Driving Study
NHTSA	–	National Highway Traffic Safety Administration
PET	–	Post-Encroachment Time
RTK	–	Real-Time Kinematic
TTA	–	Time-To-Arrival
TTC	–	Time-To-Collision
VRU	–	Vulnerable Road User



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# Chapter 1

## Introduction

### 1.1 Background

Pedestrians and cyclists account for a large number of fatalities on the world's roads. In the European Union, at least 5000 pedestrians and 2000 cyclists die every year (Strandroth et al. 2014) in road crashes, accounting for 27% of all road fatalities. In the USA, pedestrians killed by motor vehicles represent the third-highest number of deaths on the road. In 2015, pedestrians accounted for 14.5% of road fatalities and cyclists accounted for 2.2% (Washington DC 2016). In China, traditional and electric-powered bicycles accounted for 35% of road fatalities in 2013 (Sui et al. 2019), and pedestrians accounted for 25% (Chen et al. 2014). In the China in-depth accident study (CIDAS), cyclist crossing scenarios were shown to be the most frequent type of cyclist-car crash (Sui et al. 2019). Similarly, pedestrian crossing scenarios accounted for 79% of the pedestrian fatalities on the road, according to the data provided by CIDAS (Chen et al. 2014). In Europe, crash statistics from the German in-depth accident study show that around 75% of the pedestrian crashes between 1999 and 2008 were crossing scenarios (Ebner et al. 2011). The Swedish Volvo Cars cyclist accident database showed that the most frequent type of cyclist crashes on Swedish road was crossing scenarios (39% of all cyclist crashes) (Lindman, Jonsson, et al. 2015). These crash statistics show the preponderance of crossing crashes for pedestrians and cyclists regardless of the geographic region and motivate the development of safety countermeasures to reduce the number of these crashes.

Pedestrians and cyclists are categorized as vulnerable road users (VRUs), defined in an European directive as “non-motorised road users, such as pedestrians and cyclists as well as motorcyclists and persons with disabilities or reduced mobility and orientation” (European Parliament 2010). Although the general trend in Europe is towards a decrease in road fatalities, VRU casualties are not decreasing (European Commission 2016). Safety systems that are already on the market attempt to address this problem. Passive safety systems, such as soft car parts (bumper, hood, etc.) or, more recently, pedestrian airbag systems, are effective at reducing the number of fatalities or injuries when a crash is unavoidable (Jakobsson et al. 2013). Intelligent safety systems (ISSs), which include advanced driver-assistance systems and different forms of automated driving systems, strive to avoid crashes by warning drivers or taking control of the car (e.g., Toyota's Pre-Collision System with Pedestrian Detection function (Hayashi et al. 2013; Tsuchida et al.

2007), Volvo's Pedestrian and Cyclist Detection with Full Auto Brake system (Lindman, Ödblom, et al. 2010)). Although the traffic scenarios in which VRUs cross the drivers' travel path have been identified as the most critical for VRUs (Gohl et al. 2016), today's ISSs address the crossing scenarios only within a restricted operational design domain (Hayashi et al. 2013; Lindman, Ödblom, et al. 2010; Tsuchida et al. 2007)—probably because crossing scenarios are particularly challenging. Thus the present thesis focuses on crossing scenarios to support the development of appropriate ISSs.

The evaluation of ISS performance, essential for systems development, aims to determine how efficient the systems are and in which conditions they may perform suboptimally (Euro NCAP 2015; Euro NCAP 2017; Fildes et al. 2015; Hulshof et al. 2013). Several methodologies evaluating ISS performances exist. They may differ by the product's life status (in-development, after-market, etc.), the test environment (simulation, test track, field-operational test, etc.), or by the test party (suppliers, car manufacturers, third-party programmes, etc.). For instance, a well-known safety performance evaluation programme in the European Union is the European New Car Assessment Programme (Euro NCAP), which evaluates ISS using publicly available test protocols and issues a safety score for each of the tested cars. This type of programme exists in other parts of world as well (e.g., JNCAP for Japan, IIHS's NCAP in the USA, etc.<sup>1</sup>).

While NCAPs remain a great tool for evaluating ISSs' safety performances and raising public awareness of car safety while being a great advocate for the introduction of new ISSs in cars, NCAPs are only evaluating ISSs that are already on the market. Moreover, while ISSs may be performant in specific use cases, they might not be performant at reducing the number of crashes and fatalities, or the severity of injuries globally. This is the reason why it is important to evaluate how much impact the ISS would have when introduced onto the market. Safety benefits (e.g., the annual reduction in the number of crashes or injuries (Funke et al. 2011)) of an ISS represent a set of numerical indicators that describe how an ISS impacts the current crash statistics. For ISS designers, being able to estimate safety benefits prospectively helps them determine how much impact their system would have, even before its introduction onto the market. Safety benefit evaluation methodologies using counterfactual simulations were developed to serve this purpose. Multiple examples can be found in the literature (Lindman, Ödblom, et al. 2010; McLaughlin, Hankey, and Dingus 2008; Kusano and Gabler 2012; Kusano, Gabler, and Gorman 2014; Sander and Lubbe 2016; Sander 2018; Zhao et al. 2019). Although counterfactual simulation results depend on the chosen driver model (Lundgren and Tapani 2006), driver behaviour models implemented in the examples found in the literature are usually as simple as one single fixed reaction time to a warning and may not be describing a realistic behaviour given the driving scenario. Unfortunately, realistic driver models are quite sparse in the literature, especially those that focus on a specific driving interaction such as intersection encounters.

Not only is developing a detailed and realistic driver model for this specific driving interaction critical from the point of view of counterfactual simulations (Lundgren and Tapani 2006), but such a model could also be useful for ISS designers. Historically, drivers have been the ones controlling their cars, but with the introduction of ISSs the controls may be shared between drivers and ISSs. The interaction between drivers and ISSs is thus crucial; each ISS must take the driver's intent into consideration to maximize its safety

<sup>1</sup>see <http://www.globalncap.org/> for more details

performance (Rodrigues de Campos et al. 2017) without annoying drivers (Lubbe and Davidsson 2015). The need for models that can predict driver intent (or behaviour) for ISS threat-assessment algorithms is therefore obvious. This need and the lack of driver models for VRU crossing scenarios support one of the objectives of this thesis: to develop a more comprehensive and situation-dependent (e.g., in terms of kinematics, environment, etc.) computational driver model.

The present thesis focuses on these issues by investigating driver behaviour in VRU crossing scenarios and by devising driver behaviour models as well as an ISS safety benefit evaluation framework.

## 1.2 Objectives

The overall aim of this thesis work is to inform the development and evaluation of ISS by modelling how drivers interact with pedestrians and cyclists at intersections. Several objectives have been set:

1. *Investigate and describe the driver response process when a pedestrian or a cyclist crosses the driver's path.*
2. *Devise models that can predict the driver response process.*
3. *Provide new knowledge about driver interactions with a crossing pedestrian or cyclist that could be used by Euro NCAP to guide the development of their tests.*
4. *Develop a framework for ISS evaluation through counterfactual simulation and analyse the impact of the chosen driver model on the simulation outcome.*

The thesis is organized as follows. First, **Chapters 2-5** introduce the literature on driver behaviour in driver-VRU interactions, the test environments for data collection, the field of driver behaviour modelling, and ISS evaluation. Second, **Chapter 6** presents the overall research approach followed during the Ph.D. project. Third, **Chapter 7** presents the five papers produced during the thesis work. Fourth, **Chapters 8-9** present the discussion and conclusions about the outcome of the research performed during this Ph.D. project with respect to the above-mentioned objectives and how future research could address the remaining research gaps.

## 1.3 Scope of the thesis

The interaction between road users is complex as they communicate with, and react to, each other. In the ideal interaction, road users react to each other based on the outcome of their communication. Many studies have evaluated the extent to which non-verbal communication between road users can influence driver behaviour; for instance, it was shown that the appearance of a cyclist influences the driver's overtaking behaviour (Walker 2007; Walker et al. 2014), and that driver behaviour is affected if the pedestrian stares or smiles at the driver (Guéguen, Meineri, et al. 2015; Guéguen, Eyssartier, et al. 2016).

Non-verbal communication may be crucial to the whole interaction between a driver and a crossing pedestrian or cyclist. However, its study would require an extensive effort to include all road user's perspectives, including their communication and their reactions. Before addressing the role of non-verbal communication, the response process as a reaction to basic external cues needs to be understood.

Finally, with the introduction of automated driving (AD) systems, the contemporary notion of *driver* is evolving to include AD systems that can control the car autonomously. In this thesis, the term *driver* refers to the human occupant controlling the car.



## Chapter 2

# Driver behaviour in pedestrian and cyclist crossing scenarios

### 2.1 Factors influencing driver behaviour at crossings

Interest in the driver-VRU interaction is not new; in the mid-20th century, studies were already being undertaken in order to reduce pedestrian casualties on the road. For instance, in the pre-digital era, Barrett et al. (1968) demonstrated that automobile simulators could be useful for pedestrian-driver interaction studies. In a site-based observation study, Katz et al. (1975) examined which factors influence a driver's decision to yield at pedestrian crossings. In the case of cyclist-driver interactions, Kroll and Ramey (1977) investigated the influence of bicycle lanes on driver behaviour when overtaking a cyclist, while McHenry and Wallace (1985) looked at the effect of curb lane width on the same interaction. Research into the safety aspects of driver-VRU interactions has continued since then to better understand the relevant driver behaviour, in particular by identifying the relevant factors and evaluating the driver's role in making the driver-VRU interaction unsafe. A summary of these studies can be found in Tables 2.1 and 2.2. The investigated factors can be grouped into three types (Himanen and Kulmala 1988): 1) road user characteristics, 2) encounter configuration, and 3) physical environment. Note that only the studies which quantify the factors' effect on driver behaviour are presented here. Table 2.1 lists the studies which investigated crossing interactions with pedestrians, and Table 2.2 lists those with cyclists.

The literature review reveals that more information (i.e., more studied factors) about driver-pedestrian interactions is available compared to driver-cyclist interactions. For instance, one interesting factor that was only analysed in pedestrian crossing scenarios is the moment at which the VRU appeared to the driver for the first time (or *appearance time*) (Iwaki et al. 2015). Other factors were also shown to have a significant effect on drivers' response process: VRU conspicuity (Balk et al. 2008; Langham and Moberly 2003), car speed (Katz et al. 1975; Himanen and Kulmala 1988; Lubbe and Rosén 2014; Silvano et al. 2016), pedestrian speed (Lubbe and Davidsson 2015), pedestrian lateral position (Himanen and Kulmala 1988), cyclist speed (Petzoldt et al. 2015; Silvano et al. 2016), and crossing entry (Räsänen and Summala 2000)). Notably, the appearance time is a crucial point in the driving sequence that relates to all of those factors. Since only one study has quantified the effect of this factor on driver behaviour in pedestrian crossing scenarios, and none have

done so in cyclist crossing scenarios, the current thesis further analysed this factor for both types of VRU.

Table 2.1: List of factors investigated in driver-pedestrian crossing interactions by study

Type of factor	Factor	Reference
Road users' characteristics	Driver age	(Bromberg et al. 2012; Katz et al. 1975; Sun et al. 2002)
	Driver gender	(Sun et al. 2002)
	Vehicle type	(Sun et al. 2002)
	Headlamp type	(Bullough and Skinner 2009)
	Warning safety system	(Lubbe 2017)
	Pedestrian conspicuity	(Balk et al. 2008; Langham and Moberly 2003)
Encounter configuration	Oncoming traffic	(Sun et al. 2002)
	Crossing angle	(Iasmin et al. 2015)
	Number of pedestrians	(Katz et al. 1975; Himanen and Kulmala 1988; Sun et al. 2002)
	Car speed	(Katz et al. 1975; Himanen and Kulmala 1988; Lubbe and Rosén 2014)
	Pedestrian speed	(Lubbe and Davidsson 2015)
	Gap timing	(Várhelyi 1998)
	Pedestrian lateral distance	(Himanen and Kulmala 1988)
	Appearance time of the pedestrian	(Iwaki et al. 2015)
	Non-verbal communication	(Guéguen, Meineri, et al. 2015; Guéguen, Eyssartier, et al. 2016; Katz et al. 1975)
Physical environment	Crossing marking presence	(Katz et al. 1975)
	Road width	(Himanen and Kulmala 1988)
	Safety structures	(Himanen and Kulmala 1988; Bella and Silvestri 2015; Bella and Silvestri 2016)

Table 2.2: List of factors investigated in driver-cyclist crossing interactions by study

Type of factor	Factor	Reference
Road users' characteristics	Driver expectancy	(Phillips et al. 2011)
Encounter configuration	Crossing direction (near or far side)	(Räsänen and Summala 2000)
	Car speed	(Silvano et al. 2016)
	Cyclist speed	(Petzoldt et al. 2015; Silvano et al. 2016)
	Arrival time difference	(Silvano et al. 2016)
Physical environment	Cycle crossing location	(Räsänen and Summala 2000)
	Cycle lane width	(Räsänen, Koivisto, et al. 1999)
	Road traffic regulation	(Räsänen, Koivisto, et al. 1999)

## 2.2 Driver behaviour models in crossing scenarios

Three models covering the pedestrian crossing scenario and one covering the cyclist crossing scenario were found in the literature. In the pedestrian crossing scenario, the three models were designed to predict different facets of the driver behaviour. The first model (Sun et al. 2002) is a computational model that evaluates the probability of a driver's yielding. The second model (Bella and Silvestri 2016) is a braking-response model that predicts the deceleration-phase duration (from the initial speed to the minimum speed) given the type of safety treatment (infrastructure design), the car's initial speed, longitudinal distance to the crossing, minimum speed reached, and average deceleration rate. It is interesting to note that the authors concluded by saying that drivers could approach the intersection more smoothly when infrastructure design provided better visibility (i.e., longer appearance time). Finally, the third model (Iwaki et al. 2015) is a more complete computational model. It predicts the start of gas pedal release and brake initiation as well as jerk and maximum deceleration, with appearance time as a main factor. As for the cyclist crossing scenario, the only model found in the literature attempts to evaluate the probabilities of getting into a conflict and of yielding (Silvano et al. 2016), as functions of the lateral distance of the bicycle, the car and bicycle speeds, and the car and bicycle time-to-collision. The model was not developed to predict any part of the driver response process (e.g., brake initiation, steering, or any other type of control) other than the yielding decision. Previous research has not been able to develop a driver behaviour model in either pedestrian or cyclist crossing scenarios that predicts and quantifies driver response processes.

## Chapter 3

# Test environments for investigating driver behaviour

To support the development of ISSs, the analysis of driver behaviour is essential. Being able to predict driver intent helps the ISS intervene appropriately, in line with the driver's expectations. In order to analyse and model driver behaviour, driving data are required. Driving data include information related to the driver (demographics, gaze location, and secondary task, etc.) and the driving environment (including other road users' kinematics) as well as the driven car (pedals and steering wheel position, speed, and indicator light status, etc.). These data could be collected in one of the three test environments: 1) driving simulators, 2) test tracks, and 3) on-road studies.

### 3.1 Driving simulators

Driving simulators were already mentioned in the literature at the beginning of the 20<sup>th</sup> century; the work of De Silva (1936) was presented by Caird and Horrey (2011) as one of the first studies investigating driver behaviour in a simulator setup. In the 1960s, driving simulators were proposed for studying driver behaviour in interactions with VRUs (Barrett et al. 1968). Simulators provide a safe experimental environment as drivers drive a virtual car—an especially substantial safety advantage when studying specific medical conditions (e.g., post-stroke symptoms (Blane et al. 2018)). Fortunately, free, open-source driving simulators, such as OpenDS (Math et al. 2013), are now easily available.

The proliferation of simulators has resulted in a heterogeneous mix. For research purposes, a simulator can be classified as low or high fidelity, depending on how well it reproduces the real-world experience. Fidelity can be further defined in terms of three types of validity: ecological validity, the degree to which the test environment reflects the real-life on-road environment; behavioural validity, the extent to which a simulator elicits the same driving behaviour that occurs when driving on real roads; and physical validity, the extent to which the physical components of a simulated vehicle (i.e., layout, visual displays, and dynamic characteristics) correspond to real-world vehicles (definitions adapted from (Mullen et al. 2011)). Extensive research on simulator validity was conducted in 2011 (Mullen et al. 2011), containing most of the considerations that a researcher should keep in mind when using simulators. Ecological, behavioural, and physical validities in a simulator

setup define the extent to which the environment, driver, and vehicle, respectively, reflect reality. These validities are important when interpreting driver behaviour in a simulator and should be considered when generalising results to the real world.

## 3.2 Test tracks

In a test-track environment, participants drive a real car in a closed area. This method allows the researchers to control the scenarios under investigation in terms of other road users, traffic signals, etc. Test-track environments can be used for multiple purposes, including studying driver behaviour: for example, Kiefer et al. (1999) described evaluation procedures for ISS on a test track, and Najm and Smith (2004) presented a driver response model using data gathered on a test track.

A test-track setup may be a safer environment for the participants than on-road studies, as many unpredictable elements are eliminated. However, as a result, the ecological validity of the collected driving data may be questionable. This may influence the behavioural validity; drivers may not behave as they would on real roads.

## 3.3 Comparing driving simulators and test tracks

Driving simulators and test tracks are very similar: they both enable researchers to tightly control the participants' environment. Both have the benefit of costing less than large-scale on-road studies such as field operational tests (FOTs) and naturalistic driving studies (NDSs). These studies assess ISS performance or analyse natural driving behaviour by having participants drive instrumented cars that unobtrusively record daily driving data (Carsten et al. 2013). FOTs and NDSs usually require significant human and financial resources, so driving simulators and test tracks may be better suited for testing a single, specific empirical hypothesis. However, the benefits of their low cost and tight control must be weighed against their reduced validity.

Driving simulator setups range from low-cost fixed-base simulators to highly expensive and complex moving-base simulators. By increasing the complexity of the setup, researchers hope to obtain higher physical, ecological, and behavioural validity. For driver behaviour researchers, the most important of these is behavioural validity. As long as the test environment elicits valid driver behaviour, it should be sufficient for researchers studying driver behaviour. Unfortunately, it is an arduous task to evaluate how valid driver behaviour is in a given test environment. A recently published systematic literature review, Wynne et al. (2019), assessed the results of studies that compared the validity of driving simulators and real-world experiments (including test tracks). The variability of the results was quite large and showed that the level of complexity in simulators does not necessarily correlate with the level of validity.

One important methodological issue is the difference between a fixed-base driving simulator and a test track. While neither of these environments consists of real roads with real traffic, a comparison of their results may indicate which parts of driver behaviour are affected by the degree of physical validity. For instance, would driver braking behaviour be similar in an environment that does not provide acceleration cues (a fixed-base simulator)

and one that does (a test track)? If the braking behaviours are different, would some parts of the braking response process be similar anyway—and if so, which ones? Addressing these questions would help researchers choose the most appropriate test environment for addressing their research objectives.





# Chapter 4

## Modelling driver behaviour

### 4.1 Model definition

Thoroughly modelling driver behaviour is, if not impossible (Michon 1985), certainly arduous (Cacciabue et al. 2010). Markkula (2015) divides driver models into three categories: conceptual, statistical, and process. Conceptual models qualitatively describe how drivers interact with their vehicle and the environment (the models developed by Ljung Aust and Engström (2011) and Summala (1988) are this type). The other two model types quantitatively describe drivers' behaviour. Statistical models describe some limited aspects of driver behaviour using probability distributions. They are open-loop models, meaning their output does not depend on previous output (or *feedback*). This type of model was used by Kusano and Gabler (2012), for example. Process models (or *computational* models), like statistical models, are mathematical, but their output depends on previous and current data. Examples of these closed-loop models can be found in Plöchl and Edelman (2007) and Markkula (2014). It is noteworthy that statistical models can be components of process models (Markkula 2015; Bärghman et al. 2017).

### 4.2 Modelling framework

Several driver modelling frameworks are available in the literature and it is difficult to choose the most appropriate one for a given research aim. Each has its individual qualities: ACT-R (Anderson et al. 2004) provides a comprehensive architecture for modelling human behaviour (see (Salvucci 2006) for an application in a driving context), control theory (see (McRuer et al. 1977; Saleh et al. 2011)) can model dynamic systems (i.e., they can generate a continuous output depending on current and past data), and artificial neural networks (see (Lin et al. 2005)) can model complex non-linear systems (in this case, driver behaviour). All have a conceptual background and offer tools for modelling driver behaviour according to their specific paradigm, or cross-paradigm approach.

A recent human behaviour modelling framework, based on neuroscience, was proposed by Markkula, Boer, et al. (2018). It integrates three concepts from neuroscience: 1) motor primitives, 2) evidence accumulation, and 3) prediction of sensory consequences of motor actions (Markkula, Boer, et al. 2018). The mathematical implementation was derived from

control theory. Overall, the framework offers the possibility of quickly devising a model with a human-like intermittent control output, regardless of the number of perceptual cues given. Note that the control is considered *human-like* because it mimics the motions of the human body, in terms of the intermittency of the control adjustments and their form (the motor primitives) (Flash and Hochner 2005; Dégallier and Ijspeert 2010; Schaal et al. 2000).

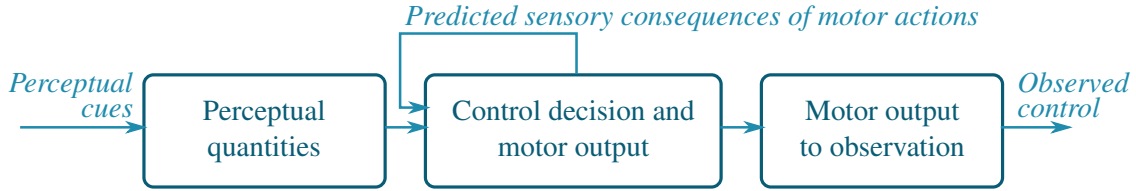


Figure 4.1: Main blocks forming the driver model adapted from the framework of Markkula, Boer, et al. (2018).

The overall structure of the framework is represented in Figure 4.1. The main part of the driver model is the *Control decision and motor output* block, in which the evidence is accumulated. Note that the way that neuronal evidence accumulation happens is still subject to debate in neuroscience: see, for example, the ramping (or diffusion-to-bound) accumulation model (Purcell et al. 2010; Schustek and Moreno-Bote 2014) versus the discrete stepping model (Latimer, Yates, et al. 2015; Latimer, Huk, et al. 2017). The ramping model was the first to be established, and the type of accumulation model might not significantly affect the results in predicting driver behaviour, so the evidence accumulation was modelled (as defined by (Purcell et al. 2010)) as a ramping process in the framework. One way to express the accumulation process mathematically is

$$\frac{dA(t)}{dt} = k \times \epsilon(t) + gate + \mu(t), \quad (4.1)$$

where  $A$  is the activity of the accumulator,  $k$  a gain,  $\epsilon$  the difference between the received and predicted perceptual quantities, *gate* a leakage term, and  $\mu$  a noise term (formula adapted from (Markkula, Boer, et al. 2018)). The generated motor output is transposed to the observed control (e.g., from steering rate to steering position in the example from Markkula, Boer, et al. (2018)). Each time the activity of the accumulator reaches a specific threshold (i.e., when enough evidence has accumulated), a control adjustment is made. The model generates a continuous control signal that is a combination of motor-primitive adjustments, resulting in a human-like intermittent control (Flash and Hochner 2005; Dégallier and Ijspeert 2010; Schaal et al. 2000).

One of the advantages of the framework is that the structure can be expanded—it does not depend on a single accumulation process. Several accumulation processes may be hierarchically structured, to create a more comprehensive driver model. For instance, Markkula, Romano, et al. (2018) describe a pedestrian behaviour model that interconnects different evidence accumulation blocks, accounting for different perceptual quantities. The pedestrian’s decision is made based on the accumulated evidence, giving priority to one accumulation process (i.e., enough evidence that the driver saw the pedestrian has

accumulated) over the others (i.e., the driver has made the decision to slow down, and the pedestrian has enough evidence to decide it is safe to cross before the car passes).

Markkula, Romano, et al. (2018)'s framework has been used when modelling driver steering and braking control in different traffic scenarios: rear-end (Svärd et al. 2017), and path-following (Markkula, Boer, et al. 2018). However, the implementation of the framework in crossing scenarios was not done and further research is required to better understand how this can be done.



# Chapter 5

## Evaluating intelligent safety systems

Among many ISS evaluation methodologies, the NCAPs' methodology and the safety benefit evaluation methodology with counterfactual simulations are particularly worth studying. Both methodologies are employed to evaluate ISSs, but they do not evaluate the same safety indicators so they are not in opposition and should be seen as complementary to each other. In fact, seeing the potential of prospective simulations, researchers have already suggested that Euro NCAP incorporate simulations into their assessment programme (Page et al. 2015). This addition seems to be under consideration by Euro NCAP, according to their roadmap towards 2025 (Euro NCAP 2018).

Several methodologies aim at evaluating ISS performance given a specific driving scenario. Performance is evaluated by comparing correct interventions or non-interventions against the unnecessary or missed interventions (Nilsson 2014). Several tools for the evaluation of ISS performances exist. Software or hardware in-the-loop (SIL or HIL) simulations (Zhou et al. 2016) or tests using driving simulators or test tracks could be used (e.g., NCAPs evaluate the ISS performances by means of test-track experiments). While the test environment may be different from one tool to another, it is not the only difference; the choice of tool mainly depends on the stage of the ISS's product life cycle. The SIL simulations are used at an early stage, enabling designers to refine the ISS's performance; at the other end of the product life cycle, NCAPs (such as Euro NCAP) evaluate ISSs that are already on the market. The test scenarios of NCAPs, including Euro NCAP, are often derived from crash statistics and attempt to provide the public with a car's safety rating. However, the test scenarios may not do justice to some ISSs because they would expect a warning or intervention at a certain time. For instance, if a forward collision warning (FCW) system is designed to issue a warning later than the time-to-collision awarded for the highest safety score by Euro NCAP, the system may be underrated even though its intervention was legitimate, in the sense that it enables drivers to avoid a crash. It is, therefore, important to develop further knowledge of driver behaviour. Doing so can help improve NCAP's test protocols by accounting for realistic behaviour and assessing the ISSs fairly.

While the performance evaluation addresses the operation of the ISS in specific driving scenarios, the safety benefit evaluation deals with the number of crashes (and, by correlation, of injuries and casualties) that the ISS would reduce in the real world if the fleet of vehicles were equipped with this specific ISS. Multiple methodologies have been

developed and proposed in the literature to evaluate ISS safety benefits before the ISS is introduced in the market. They rely mainly on virtual models (e.g., environment, vehicles, and road users), and on crash kinematics (e.g., kinematics reconstruction from crash statistics or from naturalistic driving data (NDD) collected in on-road studies). One of the largest efforts to set up a methodology for the evaluation of ISS safety benefits was led by the National Highway Traffic Safety Administration (NHTSA). During the NHTSA's advanced crash avoidance technologies (ACAT) programme, several methodologies using counterfactual simulations (Carter et al. 2009; Funke et al. 2011) were introduced and exemplified with different types of ISS (e.g., lane departure warning and backing-up crash countermeasure systems). While all the developed methodologies offer a solid platform for future ISS evaluations, many examples (Gordon et al. 2010; Van Auken et al. 2011; Perez et al. 2011) only include relatively naïve driver models.

Because they depend on the nature of the ISS to be evaluated, the evaluation methods found in the literature are all slightly different, but they all use simple driver models. However, accurate driver models are key for realistic simulations (Lundgren and Tapani 2006), in particular for the evaluation of ISSs that rely on driver reaction. In contrast, ISSs that do not expect driver control input, such as autonomous emergency braking (AEB) systems, may not require an evaluation method with a comprehensive driver model (Lindman, Ödblom, et al. 2010; Sander 2018; Zhao et al. 2019). However, driver models should be able to predict realistic driver control for ISSs that rely on driver intervention, such as warning systems. Unfortunately, studies that attempt to evaluate the safety benefits of warning systems usually implement naïve driver models that include a reaction time and a reaction intensity that are either deterministic or drawn from distributions (Sugimoto and Sauer 2005; McLaughlin, Hankey, Dingus, and Klauer 2009; Kusano and Gabler 2012; Kusano, Gabler, and Gorman 2014; Billicsich et al. 2016). Very few studies have implemented a driver model that was situation-dependent (i.e., the driver reaction depends on the environment, the kinematics, etc.), although Markkula, Engström, et al. (2016) suggested that reaction times may be correlated with the urgency of the situation (e.g., shorter times-to-collision would elicit shorter reaction times). One of the few studies that used a kinematics-dependent driver model, that of Roesener et al. (2017), proposed a methodology to evaluate the benefits of an automated driving (AD) system. Simulated driver control was predicted with a model that includes a reaction time (determined by a statistical distribution) followed by a kinematics-dependant reaction intensity, either for braking or steering. Those studies may not have put much effort into their driver model, and the impact of the driver model on the result of the evaluation is unknown.

# Chapter 6

## Methods

### 6.1 Overview of the research methodology

While each of the appended papers addresses different research interests, they are all interconnected via the overall methodology of this Ph.D. project. Table 6.1 demonstrates three ways of categorising the methodology: 1) test environments, 2) the number of factors analysed, and 3) the complexity of the devised driver models. The data used for the analyses in the five papers were collected in three types of test environment: driving simulator, test track, and real world (road). The simulators set up for this project's analyses were inexpensive fixed-based simulators. The initial assumption was that as the complexity of the test environments increased (i.e., resembling the real-world environment more) the participants would exhibit more genuine driving behaviour. However, the observations from the fixed-base simulators would still provide useful indications about how drivers behave. Additionally, the inexpensive fixed-base simulator setups provide a good way to investigate several factors without designing a complex experimental protocol; the simpler protocol can easily be preserved when switching between different trials. The first paper included several factors, to determine which had a significant influence on driver behaviour. Built upon **Paper I**'s results, the analyses carried out for **Papers II-III** focused on four specific factors. The driver behaviour model presented in **Paper IV** was, in turn, partly based on one factor related to one of those four in **Papers I-III**. **Paper V** did not analyse any factors on driver behaviour since its goal was to evaluate how driver behaviour models could affect the results of ISS safety benefit evaluations. **Paper V** implemented

Table 6.1: Methodological progression through the papers

Paper	Test environments	Number of factors	Driver model complexity
I	Fixed-base simulator	8	Low
II	Fixed-base simulator and test track	4	Low
III	Fixed-base simulator and test track	4	Low
IV	Test track	2	High
V	On-road	-	Low to high

five distinct driver models, ranging from simple to more complex. The models presented in **Papers I-IV** followed the same progression: while the driver models from **Papers I-III** were simply statistical models (i.e., linear mixed-effect models and cumulative link mixed models) or deterministic models (**Paper II**), the model in **Paper IV** is more complex. Benefiting from the knowledge acquired in **Papers I-III**, it may predict driver behaviour with higher fidelity than simpler models.

According to their 2025 roadmap (Euro NCAP 2018), Euro NCAP seeks to implement more simulations in their assessment protocols. The study presented in **Paper V** evaluates the extent to which the driver model influences the outcome of such simulations, while **Papers I-IV** aimed at providing driver models that could be used in crossing scenarios with pedestrians and cyclists. Note that **Papers I-IV** focused on crossing scenarios with pedestrians and cyclists; however, because a significant amount of NDD was available for rear-end scenarios (i.e., car-following scenarios that turned into rear-end crashes), **Paper V** presented rear-end scenarios as a use case.

## 6.2 Data collection

Except for the driving data from the SHRP2 naturalistic driving study, all the other data were collected during the Ph.D. project (Figure 6.1). Test protocols were designed to address the objectives of the project, test environments were set up according to the protocols, and participants naïve to the experiments were recruited.

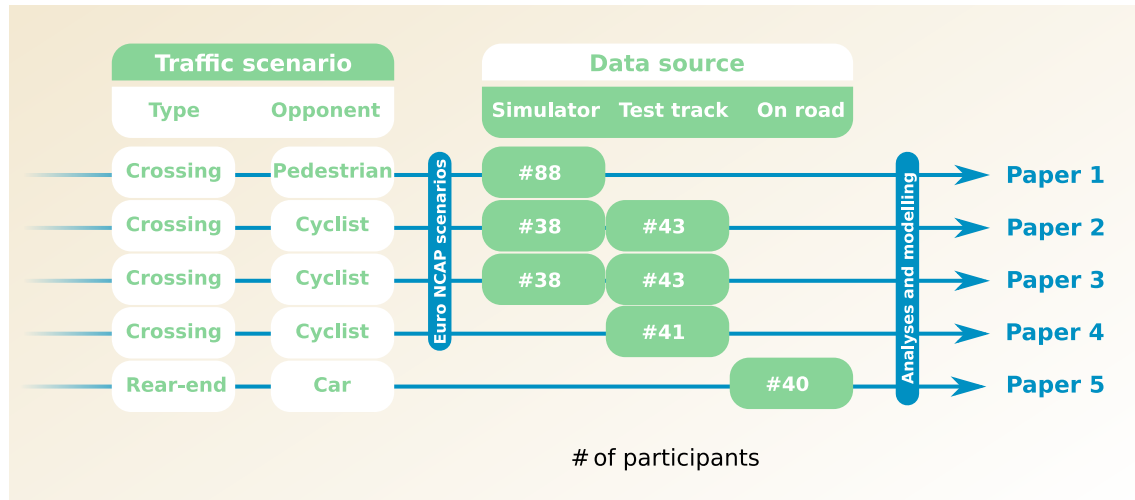


Figure 6.1: Driving scenarios and data sources for the studies presented in this Ph.D. thesis

### 6.2.1 Participants

#### Simulator experiments

Two driving simulator experiments were carried out using a fixed-base simulator located at SAFER (Vehicle and Traffic Safety Centre at Chalmers University of Technology,



Gothenburg). The participants answered an advertisement shared through SAFER's mailing list, through fliers that were distributed in public places (supermarkets, parking lots, etc.), and on social media (Facebook and Reddit). The recruitment criteria were that the participants should be over 25 years old and hold a valid driving licence. In the first experiment (data for **Paper I**), 107 persons signed up, 94 participated in the experiment, and the data from 88 of them were retained for the analyses. In the second experiment (data for **Papers II-III**), 47 persons signed up and participated in the experiment, and data from 38 were retained for the analyses.

### **Test-track experiment**

The test-track experiment followed the same experimental protocol and recruitment criteria as the second simulator experiment (see next sub-section). All the participants were Autoliv employees, recruited through an internal mailing list. Forty-four persons participated, data from 43 of those were retained for the analyses of **Papers II-III**, and data from 41 were used in **Paper IV**.

## **6.2.2 Experimental protocols**

### **Pedestrian crossing scenario**

The main motivation behind the pedestrian crossing scenario experiment was to estimate the effect of multiple factors on driver behaviour when approaching a crossing pedestrian. Seven factors (see Table 6.2) that were shown to be relevant in pedestrian crossing scenarios were chosen from the literature. Additionally, the levels of the factors were chosen to ensure that the Euro NCAP's pedestrian crossing scenarios were included. Because a full factorial design would result in 128 different combinations of those factors (with 2 levels each), a fractional factorial design was used to reduce the number of trials to 32 (using a  $2^{7-2}$  resolution V fractional factorial design (Box et al. 2005)). This design has the advantage of reducing the time and resources needed for the experiment while retaining the ability to study the main effects and the 2-way interactions of the factors. However, higher-level interactions cannot be evaluated due to the reduced number of trials.

Each participant went through 39 trials: 32 trials corresponding to the fractional factorial design, three trials reproducing trials analysed in previous studies (for comparison), and one trial that was reproduced four times at fixed time intervals to study longitudinal changes in driver behaviour.

### **Cyclist crossing scenario**

For the cyclist crossing scenario, the experimental protocol was carried out both in a fixed-base driving simulator and on a test track (more details about the setups are in the next section). To compare driver behaviour in both environments, they were modelled to be as similar as possible (see Figure 6.2) to provide the participants with the same driving experience regardless of the test environment.

This test scenario was also based on the Euro NCAP scenario CBNA-50, in which a cyclist crosses the vehicle path and, if no action is taken, the vehicle will collide with

Table 6.2: Factors studied reported in **Paper I**

Factors	Low level	High level
Crossing side	Far side	Near side
Car speed	20 km/h	60 km/h
Pedestrian speed	1 m/s	2 m/s
Crossing angle	90 degrees	45 degrees
Pedestrian size	176 cm	115 cm
Zebra-crossing presence	Yes	No
Lane width	3 m	2.5 m



Figure 6.2: Images displaying the physical environment from the test-track experiment and the driving simulator experiment.

the cyclist with a 50 % overlap. In the Euro NCAP test protocol, the car speeds increase from 20 to 60 km/h and the cyclist becomes visible around 4 s before the car reaches the potential collision point (Euro NCAP 2019). In the Ph.D. project's experimental protocol, three variables were controlled: 1) the instructed car speed, set to 30 or 50 km/h; 2) the cyclist speed, set to 10 or 20 km/h; and 3) the encroachment sequence, controlled so either the cyclist would pass before the car, the car would collide with the cyclist with a 50 % overlap, or the car would pass before the cyclist. Note that the encroachment sequence was not dynamically controlled; it was only respected if the conditions on the other variables were fulfilled (i.e., constant speeds and no avoidance manoeuvres).

A full factorial design was used, resulting in 12 trials. Of those 12 trials, four were reproduced, except that the cyclist would come to a full stop before entering the car's travel path. Additionally, four trials in which no cyclist would cross were added to limit driver expectancy. Finally, in the simulator experiment, an extra trial was added at the very end of the experiment, in which the drivers would find themselves in a critical crossing scenario (the cyclist would be visible around 1.5 s before the car would reach the intersection point).

### 6.2.3 Test environment setups

#### Driving simulator setups

The two driving simulator setups were similar, using the same hardware except for the display: a Hitachi CP X1 LCD video projector (1024x768 resolution) for the first exper-

iment and three Samsung 40" LED-TV screens (1920x1080 resolution) for the second experiment. The latter enabled a larger field of view (see Figure 6.3).

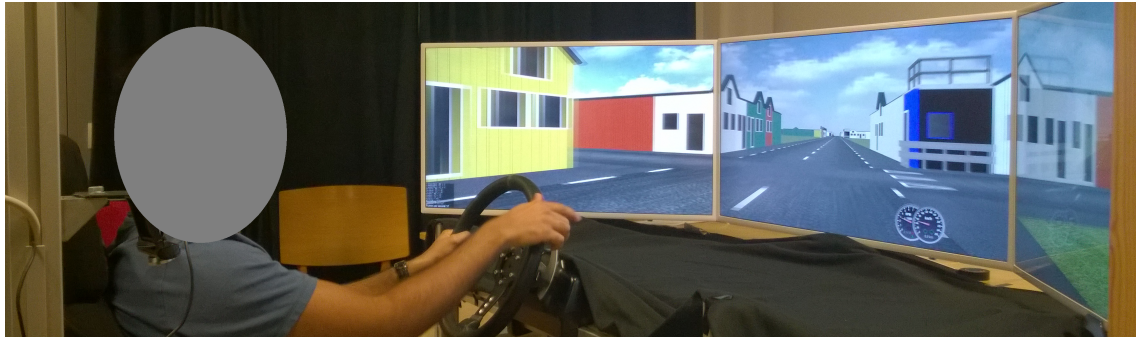


Figure 6.3: Setup of the second fixed-base driving simulator used in this thesis work.

Only open-source software was used for setting up the simulators. OpenDS, a driving simulator program based on jMonkeyEngine, was modified to record data from all the road users and MakeHuman and Blender were used to design and animate the 3D models, respectively. The position and speed of the road users were collected, as well as the positions of the participant controls (pedals and steering wheel). For the second driving simulator setup, the 3D models simulated the environment of the test-track setup as closely as possible to provide similar visual input to the participants, independent of the test environments (i.e., simulator or test track).

### Test-track setup

The data collection took place on the Carson City test track owned by Autoliv (see Figure 6.4), in Vårgårda, Sweden. All tests occurred in daylight on dry asphalt. The bicycle was constructed of light plastic and foam, and a lightweight dummy represented the cyclist. The bicycle and dummy were attached to cables which were pulled forward to obtain the desired position and velocity. The bicycle frame was linked to the track in the road to keep the bicycle vertical during the experiment. The data logger used was a VBOX 3 RTK (Racelogic Ltd.<sup>1</sup>, Buckingham, UK) equipped with a D-GPS RTK, recording at 100 Hz. The collected data provided information on vehicle position, speed, and acceleration. Two wire potentiometers were used to measure the gas and brake pedal positions. The analogue output signals from the potentiometers were sampled using the VBOX system.

## 6.2.4 Naturalistic driving data

In a project called SAFER Glances (Victor et al. 2015), in which the author took part, 46 rear-end crashes were extracted and analysed. The same crash dataset was used in **Paper V**; 12 crashes were dismissed due to low data quality or missing data. The speeds of the leading vehicle and the following vehicle (i.e., the instrumented vehicle) were used as well as the relative speed, the relative acceleration, and the distance between the two vehicles.

<sup>1</sup>[http://www.racelogic.co.uk/\\_downloads/vbox/Datasheets/Data\\_Loggers/RLVB3iSLRTK\\_Data.pdf](http://www.racelogic.co.uk/_downloads/vbox/Datasheets/Data_Loggers/RLVB3iSLRTK_Data.pdf)

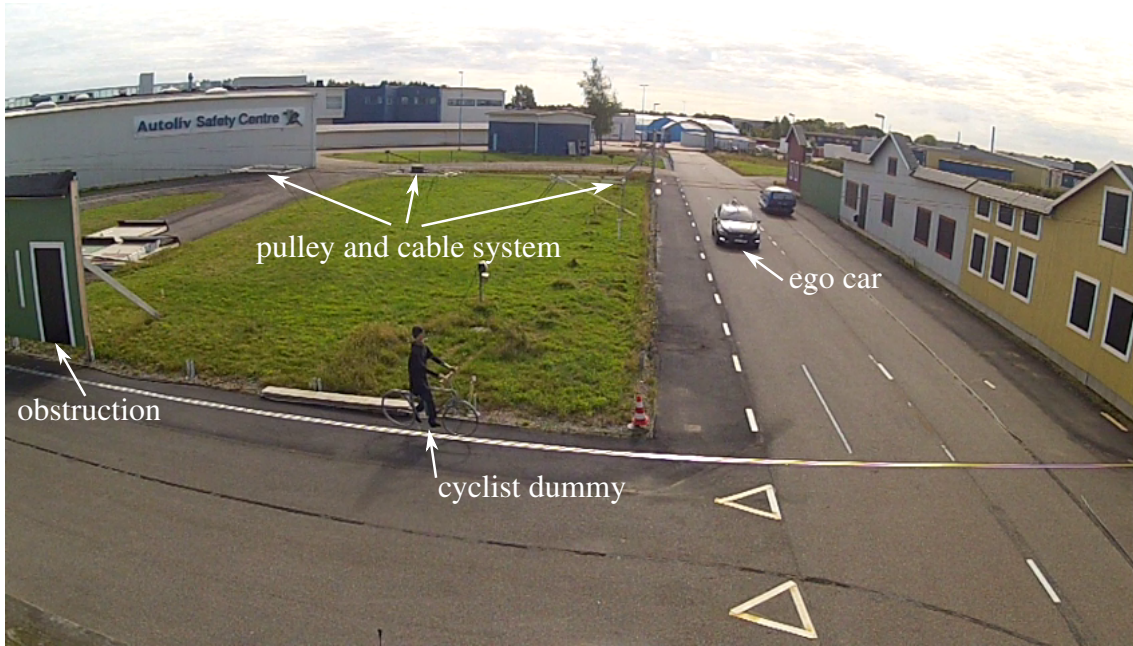


Figure 6.4: Autoliv's "Carson city" test track used to collect driving data in cyclist crossing scenarios.

Additional variables were extracted after manual annotation of the forward video (method described by Victor et al. (2015)): 1) the optical angle  $\theta$  formed by the left and right sides of the leading vehicle from the driver's perspective, 2)  $\dot{\theta}$  (i.e., the derivative of theta), and 3)  $\tau$  (the ratio  $\theta/\dot{\theta}$ ). These optically derived variables were used by most of the driver models implemented in the **Paper V**.

## 6.3 Driver behaviour modelling

As mentioned in the introduction of this Chapter, driver behaviour has been modelled to different degrees in all five papers (**Papers I-V**). Except for the model presented in **Paper IV**, the modelling methods used are simple statistical or deterministic methods (Figure 6.5).

The computational model in **Paper IV** was partly built on the deterministic model developed for **Paper II**, in which the time when drivers initiated their braking regulation (i.e., brake onset) could be expressed as a function of the bicycle appearance time (i.e.,  $TTA_{vis}$ ). As hypothesized in **Paper II**'s discussion section, the mechanism behind the deterministic model might be explained by the accumulation of cues providing evidence of the need for braking. In **Paper IV**, the cue used to describe the need for braking, longitudinal looming, is related to  $TTA$  (mathematical demonstration by Morando (2019)). The choice of looming was motivated by a substantial number of studies showing a relation between the need for braking and the looming cue (initially theorised by Lee (1976) and further analysed by Markkula, Engström, et al. (2016) and Victor et al. (2015), among others). Additionally, the looming cue was used in the Markkula, Boer, et al. (2018)'s modelling framework to predict braking regulation (Svård et al. 2017; Markkula 2015).

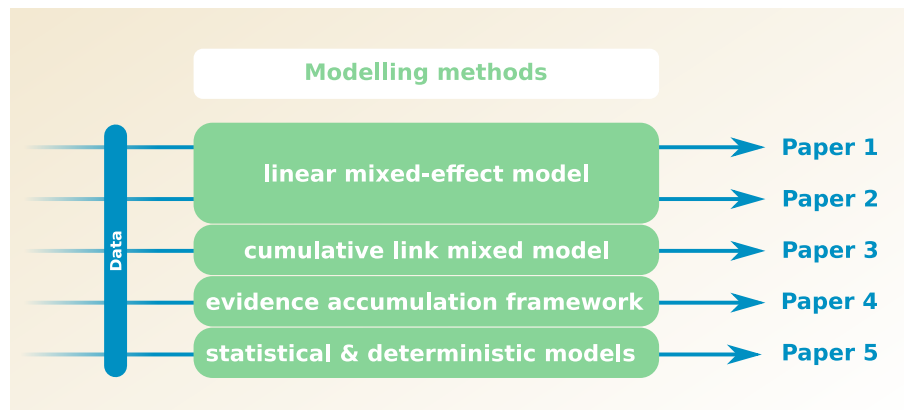


Figure 6.5: Modelling tools

Note that the looming cue in those studies differs from the longitudinal looming cue, which is defined as the ratio of the angle  $\gamma$  (see Figure 6.6) to its derivative (Fajen 2013). **Paper IV**'s model did not include just one cue describing the need for braking; it also included a variable describing when it was safe to pass, the predicted post-encroachment time ( $PET_{proj}$ )—defined as the predicted time between the moment one road user leaves the conflict zone (see Figure 6.6) and the other one enters it. While this variable is not a cue that drivers directly perceive, it is closely related to a cue that they can perceive: bearing angle ( $\beta$ , see Figure 6.6). A model proposed by Cutting et al. (1995), the constant bearing angle model (i.e.,  $\dot{\beta} = 0$ ), describes how humans may be intercepting (or avoiding) moving objects. In order to move safely, humans may try to maintain a  $\beta$  different from zero (i.e., so that the obstacle passes either before or after the moving human). A more recent model (Fajen 2013) extended that one to account for the obstacles' widths. The variable  $PET_{proj}$  is itself an extension of the constant bearing angle model's accounting for obstacle width.  $PET_{proj}$  accounts not only for obstacle's length and width but also for the driven car's dimensions. In fact,  $PET_{proj}$  is related to the bearing angle derivative: when  $PET_{proj}$  is close to zero the bearing angle derivative is also close to zero. When  $PET_{proj}$  is equal to zero, the car is on a collision course with the obstacle if the road users' speeds are kept constant. While  $PET_{proj}$  is certainly not a cue that drivers perceive, it can be seen as a metric that accounts for multiple perceptible cues, including the bearing angle, the visual angles from the obstacle's extremities to the drivers' eyes, and the drivers' knowledge of their own vehicle dimensions.



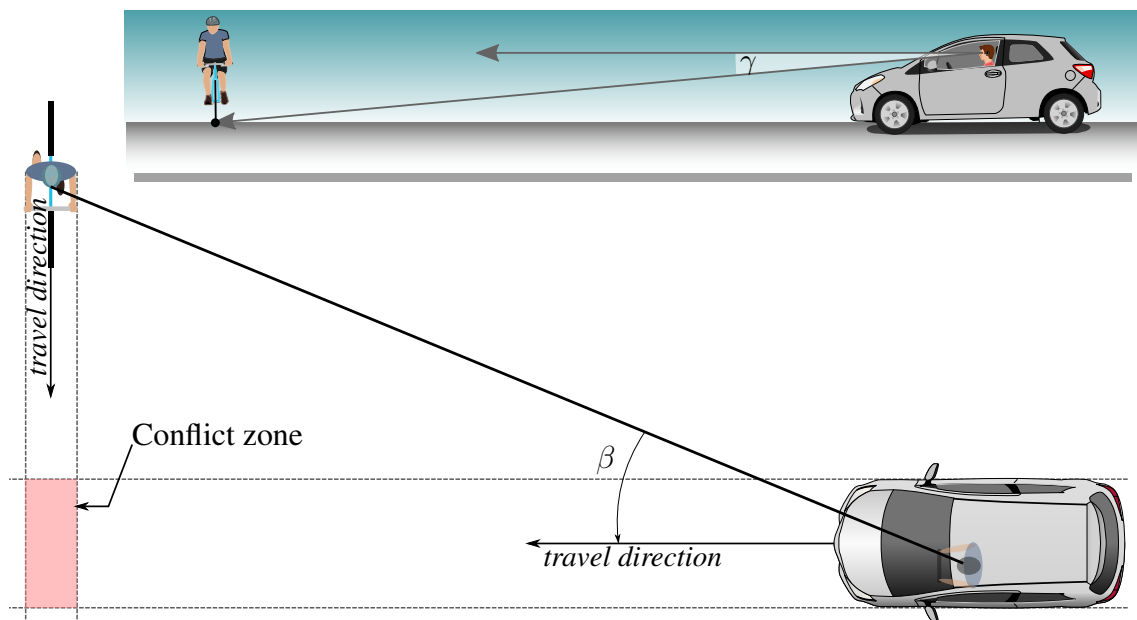


Figure 6.6: Definition of parameters used for modelling driver behaviour

# Chapter 7

## Summary of papers

The studies presented in the papers were organised to address the objectives of the thesis (Section 1.2). Devising a driver model requires that enough data on driver behaviour are available. If it is not the case, driver behaviour studies (i.e., analyses of driver behaviour) should be undertaken to provide the necessary data for the modelling. The new knowledge gathered by such studies needs to be disseminated, in particular (since it is one of the objectives of the present thesis) to ISS assessment programmes such as Euro NCAP to improve their existing test protocols. The driver models may be either used in ISSs' threat-assessment algorithm, or in virtual simulations such as counterfactual simulations for ISSs' safety benefit evaluation.

The first and second objectives of the Ph.D. work were addressed by the **Papers I-IV**, the third objective by the **Papers I-III**, and the fourth objective by the **Paper V**. The publications are summarized in the next section.

The contributions of the author to the five papers were as follows:

**Paper I** - The author took part in designing the experimental protocol. He modified OpenDS to match the study's requirements, ran most of the analyses, prepared the results, and participated in the paper writing.

**Papers II-IV** - The author played a major role in the design and implementation of the experimental protocol in the driving simulator and the test-track experiments. He conducted the analyses and prepared the results. He was the main author.

**Paper V** - The author participated in the analyses by acquiring, filtering, and post-processing the naturalistic driving data. The author assisted the main author, Jonas Bärghman, with the implementation of the counterfactual simulation in MATLAB, as well as, with writing the paper.

### **Ethical statement:**

All the participants who took part in the experiments were volunteers. The volunteers' involvement followed Swedish ethical guidelines. Before starting each experiment, the participants were informed how the experiment would unfold, what was expected from them, and that they could stop the experiment at any time without providing any reason. They then signed a consent form. All the collected data were anonymized. All the experiments were designed to ensure the participants would not be harmed, physically or psychologically.





## **Paper I — How do Drivers Negotiate Intersections with Pedestrians? Fractional Factorial Design in an Open-source Driving Simulator**

### **Introduction**

ISSs still need improvement to intervene at the right time; a compromise has to be found between degrading driver acceptance of the system (by intervening too early) and degrading the system's safety benefits (by intervening too late). However, the influence of factors such as lane width or pedestrian speed on the intervention timing of ISS for pedestrian crash avoidance is still unknown.

### **Aim**

The aim of the paper was to quantify the influence of seven factors (crossing side, car speed, pedestrian speed, crossing angle, pedestrian size, zebra-crossing presence, and lane width) on the driver response process in a driving simulator study.

### **Method**

Ninety-four volunteers participated in the study and drove through an intersection in a fixed-base driving simulator. A fractional factorial design was used to reduce the total number of trials while keeping the ability to study the main effects of the studied factors. Several parameters describing the driver response process were calculated.

### **Results**

Results of linear mixed-effect models show that the driver response process was based mainly on pedestrian time-to-arrival and appearance time. The other factors did not have a significant influence. Some longitudinal effects were present; more experienced drivers were more susceptible to changing their approach strategy to minimize driving effort than less experienced drivers were.

### **Discussion**

A greater understanding of the effect of pedestrian's appearance time and time-to-arrival on driver behaviour will facilitate the design of more precise and acceptable activation timings for FCW systems. The fractional factorial design was helpful in reducing the number of trials while retaining the ability to study the factors' main effects. However, this design did not allow in-depth analyses (i.e., analyses of a higher level of factor interactions). In the future, this study may guide the design and evaluation of FCW (perhaps with counterfactual analyses), by highlighting which factors deserve further investigation.



## **Paper II — Modelling how drivers respond to cyclists crossing their path at intersections: How do test-track and driving simulator experiments compare?**

### **Introduction**

Cyclist fatalities in the European Union are a great concern. Most are due to crashes between motorized vehicles and cyclists at unsignalised intersections. One countermeasure that has been introduced to reduce the number of crashes is ISS. In order to assist drivers without becoming a source of annoyance, these safety systems require a good understanding of driver behaviour to intervene at the appropriate time.

### **Aim**

This study was undertaken to quantify the effects of several factors (including car speed, pedestrian speed, encroachment sequence, and appearance time) on the driver response process when approaching a crossing cyclist. The results could be used to inform the design of test scenarios for assessment programmes such as Euro NCAP.

### **Method**

The influences of car speed and cyclist speed on the driver response process were assessed for three different crossing configurations. The same experimental protocol was tested in a fixed-base driving simulator and on a test track. A virtual model of the test track was used in the driving simulator to keep the experimental protocol as consistent as possible.

### **Results**

Results show that car and bicycle speeds did not directly influence the response process, and neither did crossing configuration—although the configuration did influence the strategy chosen by the drivers to approach the intersection. Bicycle appearance time (which depends on car speed, bicycle speed, and crossing configuration) had the most significant effect on the driver response process. Dissimilarities between the test-track and driving-simulator studies were found: 1) the participants did not follow the same strategy when it came to releasing the gas pedal, and 2) the braking profiles were drastically different. However, there were also interesting similarities: for example, drivers followed the same strategy to initiate braking.

### **Discussion**

These findings suggest that cyclist appearance time should be integrated into the threat-assessment algorithms of ISS, since it is such a predominant factor in the driver response process. Additionally, the findings suggest that it is acceptable for an FCW to be issued before an AEB. It is, therefore, suggested that Euro NCAP consider utilising FCW in cyclist crossing interactions as part of their test protocol.



## Paper III — Modelling discomfort: How do drivers feel when cyclists cross their path?

### Introduction

Many on-road cyclist fatalities occur when the cyclist crosses a vehicle's path. Although ISSs address these interactions, their driver behaviour models may not be optimal in terms of driver acceptance. Incorporating explicit estimates of driver discomfort might improve acceptance.

### Aim

The main aim of the study was to devise a computational model that predicts the degree of discomfort experienced by drivers when cyclists cross their travel path. Ideally, the model would be used to quantify the discomfort experienced by drivers and adapt the systems' intervention timing accordingly.

### Method

The data collected and presented in **Paper II** were used to analyse the effects of controlled variables (car speed, bicycle speed, and bicycle-car configuration), and a visual cue (the car's time-to-arrival at the intersection when the bicycle appears;  $TTA_{vis}$ ) on self-reported discomfort (on a 7-step scale). Cumulative link mixed models (CLMM) were used to quantify the level of discomfort experienced, depending on the variables of interest. The prediction performance of the CLMMs was estimated using the leave-one-out cross-validation method.

### Results

In both experimental environments (i.e., test track and simulator), the controlled variables were shown to significantly influence discomfort.  $TTA_{vis}$  was shown to have a significant effect on discomfort as well: the closer to zero  $TTA_{vis}$  was (i.e., the more critical the situation), the more likely it was that the driver reported great discomfort. The prediction accuracies of the CLMM with all three controlled variables and the CLMM with the visual cue only were similar; the exact discomfort score was predicted with an average accuracy between 40 and 50%, but the average accuracy rose to between 80 and 85% when the discomfort score was predicted with a tolerance of  $\pm 1$ .

### Discussion

The models successfully predicted the level of discomfort experienced by the drivers. The visual cue,  $TTA_{vis}$ , appears to be an important cue that drives discomfort, which can be related to the main result of **Paper II**: when  $TTA_{vis}$  was smaller, the braking reaction time was shorter. This observation can be related to previous literature by suggesting that the more discomfort the drivers experience, the faster they try to get back into their comfort

zones. It is therefore suggested that the proposed model be included in decision-making algorithms of ISS to improve driver acceptance.

## **Paper IV — A computational driver model to predict driver control at unsignalised intersections.**

### **Introduction**

Crash statistics show that cyclists are still vulnerable on roads, and that the number of cyclist casualties has been stable over the last few years. Crossing scenarios are a complex traffic situation in which cyclists are at high risk, but few ISSs address it at all. A computational driver behaviour model predicting drivers' braking behaviour in this traffic scenario is required to improve ISSs' threat-assessment algorithms.

### **Aim**

The aim of this study was to address this lack of appropriate models by proposing a predictive computational model for crossing scenarios. The study also sought to determine the principal cues that have a direct influence on drivers' braking behaviour.

### **Method**

The proposed model was implemented using a biofidelic human sensorimotor-control modelling framework based on the evidence accumulation principle. Two visual cues were used: 1) optical longitudinal looming ( $\tau$ ) and 2) projected post-encroachment time between the bicycle and the car ( $PET_{proj}$ ). The first was used as an excitatory cue (i.e., eliciting the need for braking), and the second was used as an inhibitory cue (i.e., repressing this need). The model was optimised using data from the test-track experiment presented in **Paper II**. The prediction performances of the model were evaluated by comparing the simulated driver-control process with the observed control behaviour for each trial, using a leave-one-out cross-validation method.

### **Results**

The cross-validation process showed that the model was able to predict a braking deflection signal similar to the observed one. Moreover, the model's braking control prediction reproduced kinematics that were also similar to the observations.

### **Discussion**

As shown by the veracity of the model predictions, the choice of cues was judicious—even though the implementation may be limited by the assumptions made (e.g., fully attentive driver or decelerating with brake pedal only). The use of this model in ISS implementations may help to increase its driver acceptance, either by advancing or delaying the intervention appropriately or by adapting the intervention effect (e.g., by increasing braking force).





## **Paper V — Counterfactual simulations applied to SHRP2 crashes: The effect of driver behaviour models on safety benefit estimations of intelligent safety systems**

### **Introduction**

Counterfactual simulations are a recently developed methodology, used primarily to evaluate the safety benefits of ISSs before the systems' introduction on the market. The simulations implement models from the joint driver-vehicle-environment system. However, so far, the inclusion of realistic driver models in counterfactual simulations has been limited. In the literature, most applications of counterfactual simulations use a simple driver model based on statistical distributions which does not consider the possibility that the urgency or the kinematics of the situation may affect driver responses.

### **Aim**

The aims of the paper were, firstly, to demonstrate the importance of the choice of driver model when evaluating two specific ISSs (FCW and AEB systems). Secondly, the paper shows how to perform sensitivity analyses on the settings of driver or ISS models using counterfactual analyses. The final aim of the paper was to evaluate how the choice of driver glance distribution influenced the safety benefit estimation.

### **Method**

For the demonstrations, the SHRP2 NDS dataset was used. Pre-crash kinematics and driver behaviour were obtained from 34 rear-end crashes. A counterfactual simulation framework was devised and compared with another counterfactual framework. Sensitivity analyses were done to evaluate the impacts of various driver models on the results of the new framework. Additionally, the devised framework demonstrated the safety benefits of an FCW with different settings, to demonstrate how counterfactual simulations can be used to fine-tune an ISS.

### **Results**

The results show that the percentage of crashes avoided due to the FCW's activation depended largely on the driver model; there was a large difference between the conceptually different models, while differences were small for conceptually similar models. On the other hand, the AEB safety benefit was not influenced much by the driver model. The devised framework showed the large influence of the FCW's settings on the system's efficiency.

### **Discussion**

The findings show that the choice of driver models greatly influenced the results of the simulation. Researchers and others who use counterfactual simulations with driver models

to evaluate ISS are therefore advised to choose the driver model carefully. Additionally, the framework demonstrated its potential for fine-tuning an FCW; clearly, it can be used in the future to improve ISSs in the early development stage.

# Chapter 8

## Discussion

### 8.1 Studying the driver response process

The exploratory study undertaken in **Paper I** demonstrated that the pedestrian's entry side when crossing (i.e., far (left) or near (right) sides), related to the pedestrian's appearance time, had a strong influence on the driver response process. In line with this result, **Paper II** showed that bicycle appearance time was the most predominant of the influential factors on the driver braking response (both in the simulator and on the test track). In previous studies, the appearance time was shown—directly or indirectly—to have a large effect on driver response. Iwaki et al. (2015), in a pedestrian crossing scenario in a test-track experiment, showed that the time-to-collision when the pedestrian appears has a great influence on how participants released the gas pedal and regulated their braking. Bella and Silvestri (2016), analysing different types of infrastructure design for pedestrian crossings by means of a driving simulator, showed that the participants reacted earlier when the design allowed the pedestrian to be seen earlier.

The analyses of driver response processes showed that brake onset time was found to be consistent across the two simulator studies in **Paper I** and **Paper II**, suggesting that it is the crossing scenario, and not the VRU type, which influences the initial driver response. In contrast, gas pedal release was not consistent across the studies. It may be that the different experimental protocols led to different throttle response (i.e., more expectation in one study compared to the other). Furthermore, the strategy of gas pedal release is drastically different in **Paper I** compared to Iwaki et al. (2015), suggesting that the participants in the former may have anticipated their reaction.

**Paper IV** further developed the idea that appearance time impacts the driver response process. In fact, the excitatory cue used by the computational driver model,  $\tau^{-1}$ , is closely correlated to the time left for the driver to reach the intersection point,  $TTA$ . Because the accumulation of this cue starts from the moment the cyclist is perceived, driver braking regulation is directly influenced by the cyclist appearance time (i.e.,  $TTA_{vis}$ ).

The first two papers showed the importance of the moment when drivers see the VRU in the intersection for the first time. **Papers III** and **IV** support the same conclusion in different ways. Indeed, **Paper III** showed that the discomfort reported by the drivers in the simulator and test-track experiments was highly influenced by  $TTA_{vis}$ . Drivers usually felt a higher discomfort for low  $TTA_{vis}$  (i.e., critical scenarios). With higher discomfort,

the drivers initiated braking faster (i.e., had shorter brake reaction times), which is in line with the literature. For instance, Markkula, Engström, et al. (2016) suggested that driver response is urgency-dependent: the more urgent the situation, the more likely it is that drivers react faster. This finding supports the results of **Paper III**, which quantifies the urgency of the situation with  $TTC_{vis}$ . In other words, the participants attempted to reduce their discomfort and stay in (or return to) their comfort zone by braking, and the farther away they were from their comfort zone the harder they braked. This result is in line with the conceptualisation of driving behaviour made by Ljung Aust and Engström (2011) and Summala (2007), which both described how drivers control their car by trying to stay in their comfort zone while completing their overall driving goal.

The analysis of the self-reported discomfort scores in **Paper III**, together with the results from **Paper II**, provides a better understanding about the cues which may cause driver discomfort in this crossing scenario. As discussed above, discomfort was shown to be highly correlated with  $TTC_{vis}$ , a visual cue that indicates how much time is left before a potential collision. This result was consistent across both test environments. The lack of deceleration cues in the fixed-base simulator did not seem to significantly affect driver discomfort suggesting that discomfort is due not only to high deceleration but can also be elicited by visual cues alone.

## 8.2 Modelling driver behaviour

The work presented in **Papers I-IV** provided four different types of driver models. **Paper I** provides a simple linear mixed-effect model quantifying driver response times (for gas pedal release, brake onset, and brake pedal fully released) in pedestrian crossing scenarios. **Papers II-IV** present three driver models in cyclist crossing scenarios: the brake onset prediction model, discomfort model, and brake pedal deflection model.

**Paper I** presents the analyses of the effects of seven factors on the driver response process. One of the analyses quantified the effects on the time-to-collision at which the participants initiated braking ( $TTC_{bo}$ ). Vehicle speed was shown to have a statistically significant effect on  $TTC_{bo}$ , unlike the findings of Lubbe and Rosén (2014) which did not show statistical significance. Similarly, the results of **Paper I** showed that pedestrian speed may not have a significant effect on  $TTC_{bo}$ , although it was deemed significant in Lubbe and Davidsson (2015). The crossing angle factor was shown to have a significant effect on  $TTC_{bo}$ , similar to a previous study (Iasmin et al. 2015). The crossing entry factor (i.e., near- or far-side entry) was shown to have a significant effect on  $TTC_{bo}$ , probably because the pedestrian appearance time was twice as long for the far side than the near side; this result agrees with the results of Iwaki et al. (2015), which used test-track data. **Paper I** suggested that pedestrian size, crossing-marking presence, and lane width have little impact on  $TTC_{bo}$ . Unfortunately, previous literature exploring these three factors could not analyse the time-to-collision metric due to limitations in the experimental setups (Himanen and Kulmala 1988; Katz et al. 1975), so a comparison with the literature is not possible. Overall, the linear mixed-effect model used in **Paper I** seems to generate valid results that are consistent with those in the literature. Nevertheless, the model needs to be used with caution since the driving data come from a driving simulator, and the model

would need to be verified with more ecologically valid driving data (e.g., from an NDS) before being used in an ISS.

Few models for the cyclist crossing scenario exist in the literature. The most relevant model, presented by Silvano et al. (2016), attempted to predict the same parts of the driver response process as the model in **Paper IV**. Their model was intended to predict the probability of yielding when a driver crosses a cyclist's path. Before predicting the yielding decision, the model estimates the probability that a conflict may arise. This conflict decision model is partially based on explanatory variables such as the car's arrival time and the difference between the bicycle and the car arrival times (ATDs). These variables are closely related to the inhibitory ( $PET_{proj}$ ) and the excitatory ( $\tau^{-1}$ ) cues used in **Paper IV**, respectively. The model from **Paper IV** is expected to predict that drivers do not brake when ATD is large. The advantage of the computational model presented in the present thesis over Silvano et al. (2016)'s model is that the former not only predicts whether drivers will brake or not—it also predicts the brake pedal deflection that follows brake initiation. Notably, the use of  $PET_{proj}$  in **Paper IV**'s model addressed a limitation of the brake onset prediction model from **Paper II**, that of assuming drivers always brake when approaching the conflict with the cyclist. Indeed, the main objective of **Paper IV** was to propose a computational driver model that is valid even when drivers do not need to regulate their speed when crossing the intersection (i.e., the bicycle crosses the driver's path long before or after the car). Notably, this model produces continuous braking control signal, intermittently updated to mimic human control processes, as output. The introduction of the inhibitory cue  $PET_{proj}$  was a judicious choice, since the model was able to predict that no braking regulation was needed in some of the observed trials. However, when drivers used engine braking to decelerate, the model had the tendency to predict that drivers would use the brake pedal, mainly because the model did not implement engine braking.

While looming,  $\tau^{-1}$ , has already been implemented in driver models in the past (Lee 1976), the model presented in **Paper IV** was one of the first attempts to use a looming cue in a crossing scenario. The idea was inspired by the work of Fajen (2013) in the human locomotion field. In **Paper IV**,  $\tau^{-1}$  was derived from the optical angle between the horizontal line of sight and the intersection point. This definition was not used previously in driver behaviour modelling; previous studies usually used the optical angle defined by the width of the leading vehicle in car-following scenarios (Markkula 2014; Victor et al. 2015; Markkula, Engström, et al. 2016; Engström, Bårgman, et al. 2017; Engström, Markkula, et al. 2017; Svård et al. 2017). Clearly, this definition of looming (based on another road user) could not be used in the crossing scenarios, since the travel of the crossing road user from one side of the road to another in itself would generate visual looming (even if the driver were standing still, looming would still occur).

### 8.3 Test environments

Driver behaviour may be studied with different setups. Two of them, driving simulators and test tracks, can be criticised because they are artificial; they may not represent natural driving, as in an NDS (see Section 3.3). These options remain, nonetheless, very useful because of their advantages (repeatability, low cost, and fast setup and execution). Test

tracks are expected to be more valid physically (because of vehicle dynamics) and ecologically than driving simulators (Mullen et al. 2011), but the behavioural validity needs to be carefully evaluated, because even if the physics of the car and the environment are the same as in real traffic, drivers may not behave naturally.

Setting up a test-track study requires more resources, time, and funding than setting up fixed-base driving simulators. Fortunately, as **Paper I** suggests, researchers do not have to use just one type of environment; they can use a combination. For instance, one option would be to use a low-cost driving simulator to run an exploratory analysis to determine which of seven factors studied in the literature were the most predominant (as was done in **Paper I**). The most predominant factors can be analysed further in a test-track experiment to quantify each factor's effect in a more ecologically and physically valid environment (**Paper II**). As suggested by Wynne et al. (2019), results derived from simulator experiments need to be validated with on-road studies before drawing conclusions. This validation work was partly carried out in **Paper II**; driver behaviour in the simulator experiment was compared to driver behaviour in the test-track experiment. While the results do not validate the driving simulator, it was demonstrated that the brake onset behaviours in the simulator and the test track were similar. This is consistent with other studies, such as Hoffman et al. (2002), which compared the driver response processes in a high-fidelity driving simulator and on a test track. Together, these results suggest that brake onset is stable between the simulator and the test track, strongly corroborating the suggestion made in **Paper I** that the use of a driving simulator as an exploratory technique (before investigating driver behaviour on test tracks) is legitimate. However, **Paper II** also demonstrated that after the brake onset, the braking profiles were very different for the two test environments; the participants in the driving simulator braked harder than the participants on the test-track. This behaviour is explained by the fact that the simulator did not provide deceleration cues, making the participants brake harder to compensate for the lack of perceived deceleration. And even though deceleration cues may be provided in some driving simulators (such as a moving-base simulator), the research presented by Ahlström et al. (2012) showed that participants tended to accelerate or decelerate with higher jerk values compared to an on-road study. The lack of deceleration cues may, therefore, not be the only cause of the higher deceleration or acceleration observed in simulators.

Researchers who use driving simulators should be very cautious when interpreting their results. As stated by Wynne et al. (2019), the validity of simulators is different from one simulator to another and it is not necessarily correlated with the level of complexity. Furthermore, the same authors recommend always verifying simulators' validity with real-world studies before interpreting results. In the setups used in the present Ph.D. project, some parts of the driver response process were similar in a driving simulator and on a test track, while other parts were drastically different because of the lack of deceleration cues in the driving simulator. The verifications in **Papers II-III** suggest that key components of the driver response process which are the results of visual cues only—such as brake onset—could be investigated in driving simulators. However, researchers should interpret even these process components with care, especially if they are part of a driver response that includes deceleration or acceleration cues.

## 8.4 Design of intelligent safety systems

Driver models are an important part of ISSs' threat-assessment algorithm; systems need to be able to predict drivers' intent in order to assist the drivers in the best way and at the appropriate time. The results from **Papers I-III** singled out appearance time, the time taken by the car to reach the intersection after the VRU appears, as the most predominant factor influencing the driver response process. This important result indicates that ISS designers should consider integrating appearance time into the ISS decision-making algorithm. More specifically, it was shown in **Paper II** that almost all drivers (97.5%) initiated braking before their time-to-arrival was equal to 1.8 s for long bicycle appearance times. For shorter appearance times, the brake initiation was linearly correlated with the appearance time, resulting in shorter brake reaction times (the time from when the bicycle was first visible to the brake onset). This result suggests that drivers would be likely to accept an FCW issued 1.8 s before the potential collision, since it would be given outside their comfort zone boundary (**Paper III**). A recent simulator study, based on the model in **Paper II**, seems to verify this hypothesis (Puente Guillen and Gohl 2019): participants tended to appreciate a late warning ( $TTC = 1.7s$ ) more than an early warning ( $TTC = 2.7s$ ) when the appearance time was the same ( $TTC = 4s$ ). Furthermore, as discussed in a previous section, the discomfort experienced in this cyclist crossing scenario was shown to be highly correlated with a visual cue. The deceleration cues do not seem to have much influence on discomfort, suggesting that for this scenario, ISSs should not only account for the maximum deceleration that drivers accept when the system intervenes, but they should also account for other cues, such as visual cues. By doing so, ISSs may be able to intervene earlier than they could if their threat assessment were only deceleration-based. Being able to predict driver discomfort by accounting for factors other than deceleration may increase ISSs' safety performance without decreasing driver acceptance.

The model from **Paper II** was extended in **Paper IV**. Although this more comprehensive model still has some limitations (e.g., steering and engine braking not implemented), it is a great leap forward in terms of ISSs' ability to predict drivers' intent. This ability is an important part of ISS's threat-assessment algorithms (Rodrigues de Campos et al. 2017). Further, it would enable ISSs to adapt their activation timings and choose which intervention is most adequate for the current situation. For instance, would the ISS autonomously brake the car or would it pre-charge the brakes to assist the driver in future speed regulation? The computational model from **Paper IV** would, in fact, be very useful for the second type of intervention, since the model would predict the brake pedal deflection the driver is aiming for and the ISS might decide that the resulting deceleration will not be enough to avoid the crash; therefore, the ISS may increase the brake force accordingly.

## 8.5 Evaluation of intelligent safety systems

The use of driver models is not limited to ISS design; they can also be used to evaluate ISSs. Two types of evaluation methodologies were described in this thesis: the NCAPs and the safety benefit evaluation with counterfactual simulations. Euro NCAP recently introduced new test scenarios to assess ISSs in VRU crossing scenarios (Euro NCAP 2017; Euro NCAP 2019). The scenarios were designed to rate the performance of a pedestrian

AEB system, a pedestrian FCW system, and a bicycle AEB system. The results of **Paper II** suggest that it is possible to design an FCW that could be triggered even before an AEB for cyclist crossing scenarios; therefore, it is suggested that Euro NCAP consider evaluating this possibility in the future. Additionally, results from **Papers I-III** also have a role in evaluating ISSs: these works indicate that Euro NCAP's required activation time for AEB systems is appropriate, because it corresponds to moments when drivers would be in their discomfort zone.

System performance is not the only important consideration when designing ISSs—they also need to have a real impact on crash statistics. Safety benefit evaluations are therefore important, and using counterfactual simulations may help carry out these evaluations prospectively. There is a great deal of literature proposing methodologies based on counterfactual simulations (McLaughlin, Hankey, and Dingus 2008; Carter et al. 2009; Gordon et al. 2010; Funke et al. 2011; Van Auken et al. 2011; Perez et al. 2011; Sander 2018). However, they only implemented a simple driver model (e.g., a single reaction time value to a warning) that does not account for the driving situation. To understand the impact of the driver model on the results, **Paper V** compared the safety benefit estimations of five different driver models for one FCW system and one AEB system. The driver models differed in their level of detail—ranging from a model considering only a single reaction time to one that includes a glance behaviour model and anchors its reaction to a metric describing the urgency of the situation. The results show that the safety benefit estimation depended strongly on the type of driver model. It is thus clear that the choice of driver model to be used in counterfactual simulations is important and should always be well-grounded. Modelling driver behaviour is therefore essential for improving the design and the evaluation of ISSs—at least ISSs that rely on some form of driver response.



# Chapter 9

## Conclusion and future work

### 9.1 Conclusion

The thesis aimed to inform the development and evaluation of ISS by modelling how drivers interact with VRUs at intersections. This overall aim was reached by addressing the four objectives (see Section 1.2).

**Objective 1: Investigate and describe the driver response process when a pedestrian or a cyclist crosses the driver's path.**

The appearance time of a crossing pedestrian or cyclist was shown to have a significant effect on driver behaviour, both in simulator and test-track setups. The relation between the driver's brake onset response and the bicycle appearance time was quantified and modelled. Further analyses were conducted and it was concluded that appearance time is also a key component in the discomfort experienced by drivers.

A comparison between a fixed-base driving simulator and a test-track setup showed that both environments elicited the same brake onset behaviour, as well as the same experienced discomfort. Research questions related to visual cues may, therefore, be addressed by the use of an inexpensive and highly controllable driving simulator instead of a test-track setup since it appears to elicit the same behaviour. In contrast, for investigations that don't rely solely on visual cues, such as an analysis of driver braking behaviour (e.g., brake pedal deflection), fixed-base simulators may be less well suited than test tracks—partly because of the lack of realistic deceleration cues. However, using both environments may be beneficial to decrease costs and narrow down research objectives by leveraging the results of test-track experiments to direct simulator experiments.

**Objective 2: Devise models that can predict the driver response process.**

The thesis presented four driver models that predict the driver response process: one model for the pedestrian crossing scenario and three for the cyclist crossing scenario. The model for the former scenario can estimate the moment at which key components of the driver response process (e.g., gas pedal release and brake onset) may happen, given seven different factors. For the cyclist crossing scenario, the first model predicts the brake onset time given the cyclist appearance time, the second model predicts the experienced

discomfort score given the cyclist appearance time, and the third model predicts the driver's continuous brake pedal deflection signal based on visually perceived cues. This third model was shown to perform well, predicting not only a continuous brake pedal deflection (including brake onset, regulation, and release of the pedal), but also whether drivers would apply the brakes at all. Although the model requires further validation, its use should enable ISS designers to improve ISSs' ability to account for the driver's intent.

**Objective 3: Provide new knowledge about driver interactions with a crossing pedestrian or cyclist that could be used by Euro NCAP to guide the development of their tests.**

For both pedestrian and cyclist interactions, Euro NCAP's required activation times for AEB systems were found to be appropriate because the times correspond to moments when drivers are in their discomfort zone. However, these activation times happen later than drivers' brake onsets. As a consequence, issuing a warning (for instance, an FCW) earlier than Euro NCAP's required activation times would be possible without creating a nuisance for drivers. Euro NCAP should therefore consider the introduction of FCW systems in cyclist crossing scenarios.

**Objective 4: Develop a framework for ISS evaluation through counterfactual simulation and analyse the impact of the chosen driver model on the simulation outcome.**

A framework for ISS safety benefit evaluation was developed, and exemplified with rear-end crashes extracted from the SHRP2 NDS. The counterfactual simulations implemented five driver models with different levels of detail. The results were highly dependent on the type of driver model chosen. The design of the driver model is thus crucial when using counterfactual simulations; the model should be detailed enough to capture most of the driver behaviour process.

## 9.2 Future work

Future research may be carried out in three main areas.

First, the work carried out in the present Ph.D. project focused primarily on the driver side of the interaction with the crossing pedestrian or cyclist. Future work should further investigate these interactions from the crossing pedestrian or cyclist perspective, which has not been explored. The other point of view is particularly important given that communication with the driver seems to be an essential part of a VRU's locomotion decisions in crossing scenarios (Guéguen, Meineri, et al. 2015; Guéguen, Eyssartier, et al. 2016; Markkula, Romano, et al. 2018). However, with the progressive introduction of automated driving systems or autonomous driven cars, VRUs will have fewer opportunities to communicate with human drivers, which may affect their decision-making in unforeseen ways.

Second, all the driver models that were devised and presented in the present thesis need to be validated with more ecologically valid data (e.g., from NDS). Note that using NDD

might not lead to causal conclusions (Bärgman 2016), but it would nonetheless help to assess whether the models could predict driver behaviour in real driving situations.

Third, as hypothesized in this thesis, ISSs may improve their performance of their threat-assessment algorithm—without decreasing driver acceptance—by adding a discomfort prediction model that is not based solely on deceleration cues. This hypothesis requires testing with drivers, preferably in a naturalistic driving environment.



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