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Driving in Virtual Reality

Requirements for Automotive Research and Development

Björn Blissing

LINKÖPING UNIVERSITY

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To Annica & Gustav

Abstract

In the last decades, there has been a substantial increase in the development of complex active safety systems for automotive vehicles. These systems need to be tested for verification and validation to ensure that the system intervenes in the correct situations using the correct measures. There are multiple methods available to perform such testing. Software-in-the-loop and hardware-in-the-loop testing offer effective driverless testing. Other methods increase the fidelity by including human drivers, such as driving simulators and experiments performed at test tracks.

This thesis examines vehicle-in-the-loop testing, an innovative method where the driver of a real vehicle wears a head-mounted display that displays virtual targets. This method combines the benefits of driving simulators with the benefits of using a real vehicle on a test track. Driving simulators offer repeatability, safety, and the possibility of complex interactions between actors. In contrast, the real vehicle provides the correct vehicle dynamics and motion feedback.

There is a need to know how the technology behind the method might influence the results from vehicle-in-the-loop testing. Two techniques for vehicle-in-the-loop systems are studied. The first involves video-see through head-mounted displays, where the focus of the research is on the effects of visual latency on driving behavior. The results show that lateral driving behavior changes with added latency, but longitudinal behavior appears unaffected. The second system uses an opaque head-mounted display in an entirely virtual world. The research shows that this solution changes speed perception and results in a significant degradation in performance of tasks dependent on visual acuity.

This research presents results that are relevant to consider when developing vehicle-in-the-loop platforms. The results are also applicable when choosing scenarios for this test method.

Populärvetenskaplig sammanfattning

Dagens fordon innehåller fler och fler säkerhetssystem. Vissa av dessa system ger varningar i potentiellt kritiska trafiksituationer. Det finns också mer komplexa system som tillfälligt kan ta kontroll över fordonet för att förhindra en olycka eller åtminstone mildra effekterna. Komplexiteten hos dessa system innebär att man måste genomföra omfattande tester. Både för att se att systemen reagerar vid rätt tidpunkt, men också för att se att valet av åtgärd är korrekt.

Det finns många olika sätt att testa dessa system. Man börjar vanligtvis med simuleringar av programvara och hårdvara. Därefter kan systemet introduceras i ett fordon för att se vilka effekter systemet har när det interagerar med en riktig förare. Att utföra tester med förare ställer dock höga säkerhetskrav, och det är ofta svårt att samordna komplexa trafiksituationer på en testbana. Traditionellt har körsimulatorer varit ett naturligt alternativ eftersom de kan utföra komplexa scenarier i en säker miljö.

Denna avhandling undersöker en testmetod där man utrustar föraren med en virtual reality-display. Genom att presentera omvärlden med hjälp av virtual reality, så kan man genomföra scenarion som tidigare varit omöjliga på en testbana. Det kan dock finnas inbyggda begränsningar i virtual reality tekniken som kan påverka körbeteendet. Det är därför viktigt att hitta och kvantifiera dessa effekter för att kunna lita på resultaten från testmetoden. Att känna till dessa effekter på körbeteendet dessutom kan hjälpa till att avgöra vilka typer av scenarier som är lämpade för denna testmetod. Det är också viktig information för att avgöra var man bör fokusera den tekniska utvecklingen av testutrustningen.

Acknowledgments

The main part of this work was funded through the two VINNOVA/FFI projects *Next Generation Test Methods for Active Safety Functions* and *Chronos II.* Additional funding was provided by the Swedish National Road and Transport Research Institute (VTI).

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I also would like to thank my parents for their encouragement and support. And finally, my wife Annica, and our son, Gustav, for showing me what is most important in life. I dedicate this thesis to you.

Björn Blissing

Linköping, August 2020

Abbreviations

ABS	Anti-lock Braking System
ACC	Adaptive Cruise Control
AEB	Autonomous Emergency Braking
ANOVA	Analysis of Variance
AR	Augmented Reality
AV	Augmented Virtuality
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAN	Controller Area Network
CAVE	Cave Automatic Virtual Environment
DGPS	Differential-GPS
DIL	Driver-in-the-loop
EBA	Emergency Brake Assist
ECU	Electronic Control Unit
ESC	Electronic Stability Control
FCW	Forward Collision Warning
FMSS	Fast Motion Sickness Score
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
HIL	Hardware-in-the-loop
HMD	Head-Mounted Display
JND	Just Noticeable Differences
LCW	Lane Change Warning
LDW	Lane Departure Warning
LKA	Lane Keep Assist
MR	Mixed Reality
NCAP	New Car Assessment Program
OST	Optical See-Through
PDP	Product Development Process
PSE	Point of Subjective Equality
RTK GPS	Real-Time Kinematic GPS
SIL	Software-in-the-loop
SSQ	Simulator Sickness Questionnaire
VIL	Vehicle-in-the-loop
VR	Virtual Reality
VST	Video See-Through

Papers

The following six appended papers are arranged in chronological order and will be referred to by their Roman numerals. All papers are printed in their original state with the exception of minor errata and changes in text and figure layout in order to maintain consistency throughout the thesis.

In papers I, II, III, IV, V, and VI, the first author is the main author, responsible for the work presented, with additional support from the co-authors. A short summary of each paper can be found in chapter 4.

[I] B. Blissing and F. Bruzelius. "A Technical Platform Using Augmented Reality For Active Safety Testing". *Proceedings of the 5th International Conference on Road Safety and Simulation*. October. Orlando, FL, USA: University of Central Florida, 2015, pp. 793–803.

[II] B. Blissing, F. Bruzelius, and O. Eriksson. "Effects of Visual Latency on Vehicle Driving Behavior". *ACM Transactions on Applied Perception* 14.1 (Aug. 2016), pp. 5.1–5.12. DOI: 10.1145/2971320.

[III] B. Blissing, F. Bruzelius, and O. Eriksson. "Driver behavior in mixed and virtual reality – A comparative study". *Transportation Research Part F: Traffic Psychology and Behaviour* 61.1 (Feb. 2019), pp. 229–237. ISSN: 1369-8478. DOI: 10.1016/j.trf.2017.08.005.

[IV] B. Blissing and F. Bruzelius. "Exploring the suitability of virtual reality for driving simulation". *Proceedings of the Driving Simulation Conference 2018*. September. Antibes, France: Driving Simulation Association, 2018, pp. 163–166.

[V] B. Blissing, F. Bruzelius, and O. Eriksson. *The effects on driving behavior when using a head-mounted display in a dynamic driving simulator*. 2020. Submitted for journal publication.

[VI] B. Blissing, B. Augusto, F. Bruzelius, S. Gupta, and F. Costagliola. *Validation of driver behavior in the Driver and Vehicle in the Loop platform*. 2020. Submitted for publication.

The following papers are not included in the thesis but constitute an important part of the background.

[VII] J. Andersson Hultgren, B. Blissing, and J. Jansson. “Effects of motion parallax in driving simulators”. *Proceedings of the Driving Simulation Conference Europe 2012*. Paris, France, 2012.

[VIII] B. Blissing, F. Bruzelius, and J. Ölvander. “Augmented and Mixed Reality as a tool for evaluation of Vehicle Active Safety Systems”. *Proceedings of the 4th International Conference on Road Safety and Simulation*. Rome, Italy: Aracne, Oct. 2013.

[IX] J. Jansson, J. Sandin, B. Augusto, M. Fischer, B. Blissing, and L. Källgren. “Design and performance of the VTI Sim IV”. *Proceedings of the Driving Simulation Conference Europe 2014*. Paris, France, 2014, pp. 4.1–4.7.

[X] L. Eriksson, L. Palmqvist, J. Andersson Hultgren, B. Blissing, and S. Nordin. “Performance and presence with head-movement produced motion parallax in simulated driving”. *Transportation Research Part F: Traffic Psychology and Behaviour* 34 (Oct. 2015), pp. 54–64. DOI: 10.1016/j.trf.2015.07.013.

[XI] B. Blissing. *Tracking techniques for automotive virtual reality*. VTI notat 25A-2016. Department of Driving Simulation and Visualization, VTI, Sweden, 2016.

Contents

Appended Papers

1
Introduction

Many initiatives have been used to reduce the number of fatalities and injuries in traffic accidents. To increase road safety, governments have changed infrastructure and implemented laws that address driving hazards. For example, Sweden intends to implement the *Vision Zero* strategy [1].In addition, automobile manufacturers have increased the safety of vehicles with improved seat belts, crumple zones, laminated windshields, airbags, and reinforced passenger compartments. These systems are usually denoted as *passive safety systems* since they are designed to be a reactive solution to a collision. More recently, automobile manufacturers have attempted to prevent collisions using proactive systems, known as *active safety systems*. These systems are designed to detect potentially hazardous situations and act by issuing warnings to the driver or temporarily assuming control over the vehicle. The line between active and passive systems are not always clear as passive systems can be equipped with active functions such as seatbelt tensioners and pre-crash systems. A comprehensive review of passive and active safety systems can be found in the TRACE project report [2].

Active systems use sensors that continuously monitor the surrounding environment to detect potentially dangerous situations. The information from these sensors needs to be processed to recognize critical situations and to implement the most appropriate response. The complexity of these algorithms requires extensive testing to ensure they reach the correct conclusion since incorrect interventions could be dangerous [3].

The algorithms and hardware can be tested employing computer simulations. These simulations can be used for functional tests where no driver is needed or include a model of a driver's behavior. However, computer models of a driver can never capture the full complexity of human behavior [4]. Consequently, testing needs to include a real human driver; however, these tests must ensure the driver's safety as the scenario might include potentially dangerous situations.

Traditionally, testing is performed in a driving simulator as simulators offer a safe and reproducible environment. Driving simulators use a model of the vehicle's dynamics and replicate the motion feedback using large motion systems. However, even high-performance motion systems have trouble realistically reproducing the motion of a real vehicle. In addition, other sensory cues are also simulated such as sounds, vibrations, and the visual environment. The difference in sensory feedback between simulation and reality can lead to altered driving behavior and even motion sickness [5].

An alternative to driving simulators is driving on a test track using inflatable targets or targets made of foam. These targets need to be placed on a moving platform when used in a dynamic scenario [6]. The platform is programmed to intercept the test vehicle at the exact moment to render a successful test. This programming can be complicated as the test vehicle is driven by a human who might perform unpredictable speed changes and steering maneuvers.

This thesis investigates the combination of a real vehicle on a test track with the reproducible environment in driving simulators. This combination is achieved by equipping the driver of the test vehicle with a virtual reality display. These types of setups have been denoted as Vehicle-in-the-loop (VIL). The virtual reality display can be an opaque display that shows an entirely virtual world. There is also the option of using mixed reality displays that augment the real world with virtual targets. The simulated environment is presented to the driver while driving a real vehicle. This method allows for complicated scenarios involving multiple actors while keeping the vehicle's original motion feedback.

1.1 Scope

There are many classes of virtual reality displays, each with their strengths and weaknesses. This thesis focuses on head-mounted displays, both the traditional opaque displays that offer a completely virtual environment and displays that include a view of the real environment using video cameras. Consequently, this thesis does not consider semitransparent displays or displays fixed to the vehicle.

Virtual reality can be used for many purposes in an automotive context, including design reviews, production planning, and investigations of ergonomics and visibility. In addition, automotive virtual reality can be used for pure entertainment purposes. However, this thesis focuses on using this type of technology as a tool for automotive research and development, particularly functional tests and system evaluation tests of active safety systems and autonomous driving systems.

1.2 Motivation

Introducing virtual reality displays as a part of the toolset of active safety system testing can allow for tests that are too complicated or too dangerous to perform otherwise. The technology also promises to make the testing process more effective since the time needed for preparing each experiment is reduced. However, there is a possibility that the introduction of a virtual reality display in the test method will have a negative impact on driver behavior, which may affect the outcome of the test. Consequently, it is important to identify and quantify any of these potential adverse effects to verify this test method.

1.3 Research Aim

This thesis investigates the inherent effects of head-mounted displays on driving behavior. These effects need to be identified and quantified to determine the technical requirements. These requirements can then be used to direct the technical design of virtual reality test platforms. The knowledge of these effects can also guide the planning of suitable test scenarios for such platforms.

To determine these requirements, the following research questions were formulated:

RQ1 – *How does a head-mounted display affect driving behavior?*

RQ2 – *How do visual time delays affect driving behavior?*

RQ3 – *What requirements should be put on the scenarios used during vehicle-in-the-loop testing?*

RQ4 – *What are the technical requirements for vehicle-in-the-loop platforms?*

1.4 Research Approach

The research performed in this thesis is connected to two VINNOVA funded projects within the *Strategic Vehicle Research and Innovation Programme (FFI)*: *Next Generation Test Methods for Active Safety Functions* and *Chronos 2*. Both projects involved collaboration between universities, research institutes, and industry partners. A timeline of these projects is shown in figure 1.1.

The goal of the *Next Generation Test Methods for Active Safety Function* project was to increase the efficiency in virtual test methods by combining physical testing with virtual simulation environments. The project started with a literature review, followed by the design and development of the custom head-mounted displays (paper I). These displays were then used to perform two user studies (paper II and paper III).

The goal of the *Chronos 2* project was to develop the virtual test methods by extending the capabilities of injecting virtual targets into a real vehicle. The project also focused on validating these methods. The work in the *Chronos 2* project was organized similarly: a literature review (paper IV) followed by a user study (paper V). Finally, the author included an interview study and an experiment using experienced engineers (paper VI).

The primary purpose of the literature reviews was to select the appropriate scenarios to study in the user studies. To understand users' general behavior, one must consider a larger group and then use statistical methods to find significant patterns. Hence, user studies were used as the principal method to research the behavior in virtual reality.

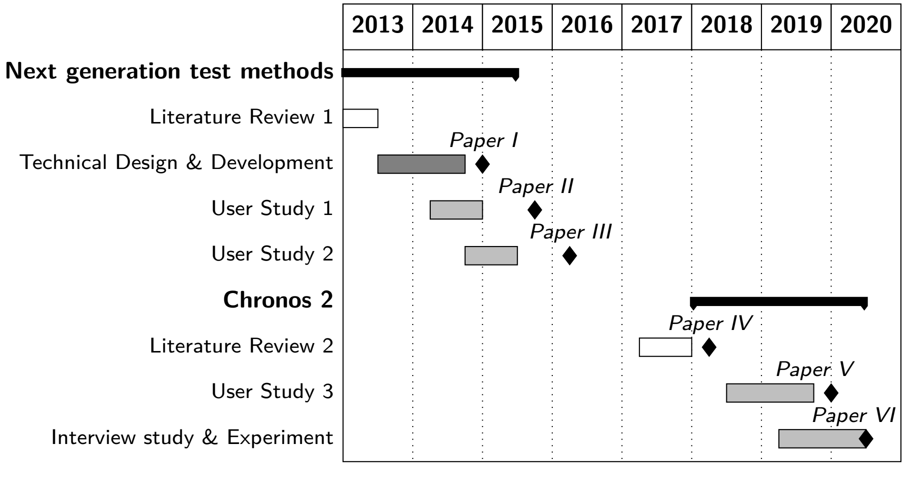


Figure 1.1 *Project timeline detailing the major activities in the two projects; Next Generation Test Methods for Active Safety Functions and Chronos 2. Black diamonds signify the submission date of each paper.*

1.5 Outline

This thesis starts by providing the context for this research in the first chapters. The following chapters summarize the results and provide a discussion of the appended published papers.

Chapter 2 provides an overview of virtual reality technology in general, presenting details about display systems, tracking systems, and latency. It also includes previous use in the product development process with use cases from the automotive industry.

Chapter 3 explains the concept of active safety systems and describes ways to test such systems during the development phases.

Chapter 4 summarizes each paper with a brief description of the content and result. This section also describes the individual contribution of the thesis author to each paper.

Chapter 5 discusses the broader implications of the presented research from both the product development and the research perspective.

Chapter 6 presents the main conclusions of this thesis and provides an outlook for future research topics in this area.

2
Virtual Reality

This chapter briefly introduces the field of virtual reality to give the background needed for the upcoming chapters. The chapter starts by defining relevant concepts. This section is followed by a description of available display technologies together with their potential use-cases. The next two sections summarize tracking technologies for user tracking and vehicle tracking, focusing on the technologies used in the research presented in this thesis. These sections are followed by a detailed section regarding latency and an overview of simulator sickness. The final section outlines industrial applications, with a focus on product development.

2.1 Definition

The term Virtual Reality (VR) describes technology that replaces sensory inputs with generated data to make users believe they are part of an artificial world. It is also possible to combine the real world and the virtual world. Milgram et al. [7] proposed that the level of virtuality can be expressed as a continuum from fully real to completely virtual (figure 2.1). The area in-between the completely virtual and the completely real is known as Mixed Reality (MR). When virtual objects are added to the real world, the term Augmented Reality (AR) is generally used. The most common example of AR is to add annotations to objects in the real world. However, it can also involve adding virtual objects in a real-world scene, such as a virtual teapot placed on a real table or a virtual vehicle placed in a real traffic environment. Although less common, Augmented Virtuality (AV), can also be found on this continuum. This mode involves adding real objects to an otherwise virtual world.

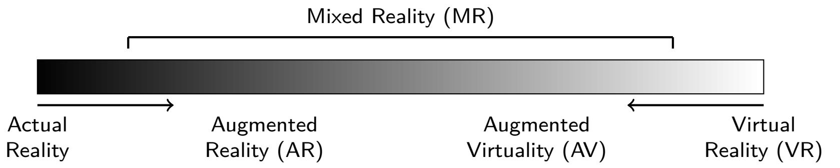


Figure 2.1 *The reality-virtuality continuum proposed by Milgram et al. [7]*

There is no strict definition of VR that has achieved universal acceptance within the scientific community [8]. This thesis uses the definition proposed by Bishop and Fuchs [9], which requires the following components:

1. Present an interactive computer simulation
2. Use of a display technique that immerses the user
3. A view that is oriented to the user

2.2 Interactive Computer Simulations

The first requirement of VR stipulates an interactive computer simulation. This simulation can be a specifically designed application developed for the intended use case. However, it can also be an extension to an existing software package, such as, plugins to existing CAD/CAE software to visualize components and assemblies.

To feel responsive, the simulation should execute at interactive update rates. Miller [10] estimated that this update rate should require a response to user input within 100 ms to feel immediate. This estimation was based on *"best calculated guesses by the author"*, although more recent experiments have arrived at similar requirements for response rates [11]. The update rate of the interactive simulation should not be confused with the update rate of the image presentation. Experiments have shown that updating the generated image in the display to correspond to a user's perspective requires updates between 10 ms to 20 ms to remain unnoticed [12, 13].

2.3 Immersive Display Systems

There are different categories of displays available to present the immersive experience to the user. These systems belong in three principal classes:

1. World-fixed displays
2. Handheld devices
3. Head-mounted displays

2.3.1 World-Fixed Displays

As the name implies, world-fixed displays are fixed to the world so they do not move when the user moves. As the user moves independently of the screen, there is a need for some form of user tracking to present a view with the correct perspective. The simplest immersive version is a standard monitor with connected tracking equipment allowing an oriented view relative to the user. This setup is sometimes referred to as *Fish tank VR* [14].

If there is a need to observe objects in a 1:1 scale, there might be a need for a screen larger than a typical computer monitor. This demand can be solved using digital projectors, preferably on a back-projected screen. The benefit of using a back-projected screen is that it allows the user to move close to the screen without causing shadows [15].The display resolution can be increased by dividing the projected screen into parts with each part controlled by one projector. This arrangement allows for setups where image resolution meets the limits of the human eye. It also allows for screen areas only limited by the available volume of the installation facility and the available budget. For a more immersive experience, multiple projection walls can be used, including projecting the image on the floor and roof. This setup has been named Cave Automatic Virtual Environment (CAVE) [16]. These installations require rooms large enough to accommodate all the needed equipment. Other options include having a cylindrical or dome-shaped screen that covers a large part of the user's field of view. These are most common for seated experiences, such as flight and driving simulators [17].

Stereoscopic Displays

Many technologies can produce stereoscopic images [18]. A display can present a stereoscopic image using either active or passive technology. The active stereo mode requires the display to switch between rendering an image for the left and right eye. In this set up, users wear special glasses that block or allow light to reach the either the left or right eye. These glasses need to be synchronized with the display for the correct image to be visible for the corresponding eye. This technology halves the available framerate and reduces the perceived display brightness since half the light gets blocked from reaching the eye.

The passive stereo mode requires the user to wear glasses equipped with either polarizing filters or narrow bandpass filters. These filters allow for projecting two simultaneous images for the left and right eye. Each image is projected with a specific filter setting, which allows the glasses to pass the correct image to the corresponding eye. These filters block some of the light from reaching the eyes, and the technology places special demands on the projector screens.

There are also glasses-free (autostereoscopic) technologies available for monitors. These monitors use lenticular lenses mounted on the display surface to separate images depending on viewpoint (left or right eye). This technology has the drawback of not allowing the user to move without causing the image intended for one eye being displayed for the other eye. The technology also divides the available pixels between the left and right eye, effectively cutting the available resolution in half. The image intended for one eye must not reach the other eye as this will produce a double-image effect known as crosstalk or ghosting [19]. Although depth perception is retained, the ghosting effect results in the user perceiving the display as blurry and reduces visual comfort in general.

There is also a relatively new class of autostereoscopic displays, light field 3D displays [20]. These displays rely on tens or hundreds of views of the generated scene rather than just two views. All views are displayed simultaneously and filtered on the screen surface, only allowing the correct view to reach the correct direction. This design allows for relatively free movement in front of the display. The major drawback is the increased computational power needed to render all these additional views.

2.3.2 Handheld Devices

Another class of immersive display devices is handheld displays, usually a tablet or a mobile phone. The most common mode is to use these types of displays for AR [21]. Using the built-in camera in the phone or tablet provides tracking of the position and orientation of the device. Knowing the position and orientation allows for adding annotations or 3D objects that integrate with the environment in a real world camera stream. These displays are usually used for training, remote guidance, computer games, and virtual tour guides.

2.3.3 Head-Mounted Displays

The Head-Mounted Display (HMD) is probably the device that is most commonly associated with VR. The HMD can be completely opaque and display a completely virtual world. However, it is also possible to have HMDs that combines virtual information with the real world in two ways: Optical See-Through (OST) or Video See-Through (VST) [22].

In an OST system, the virtual information is displayed on some form of optical combiner (figure 2.2 a). This display provides the user with a direct view of the environment without any delay or distortion. However, this solution can suffer from registration errors, where the generated image and the real-world objects are unaligned [23]. OST systems also suffer from low brightness and contrast, which can be important when using in a bright outdoor environment. The optical design of most OST devices also limits the available diagonal field of view to approximately 50° [24].

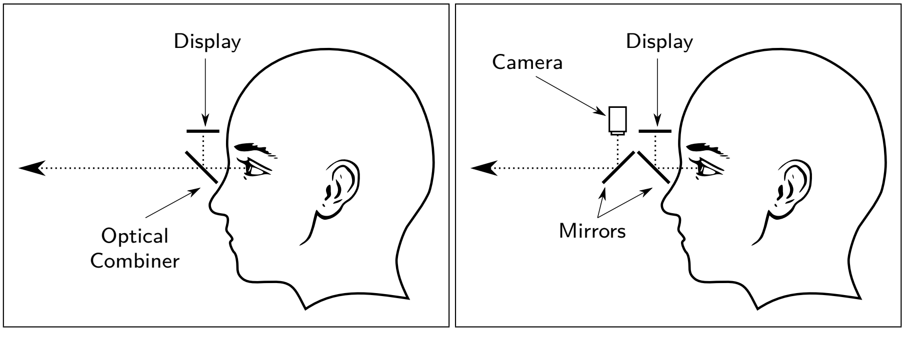


Figure 2.2 *Schematic illustration of head-mounted displays with optical see-through (a) and video see-through (b)*

The VST system uses one or more video cameras, and the information from the real world is combined inside the electronics of the system (figure 2.2 b). A VST HMD can display graphics that occlude the image from the cameras as the display can completely replace parts of the captured image with computer-generated graphics. However, one of the significant shortcomings of VST is the added latency from the cameras that provide visual sensory input of the real environment [22].

2.3.4 Visual Perception

The limits of human visual perception must be considered when selecting the appropriate display technology. Visual perception is a vast research field. Consequently, this thesis focuses on the parts of visual perception that have the most significant impact on driving behavior-i.e., visual acuity and field of view. These two factors have clearly stated legal requirements in most US states [25] and the EU [26].

Visual acuity

Visual acuity is essential for detecting and recognizing objects. There are several types of visual acuity: *detection acuity*, *separation acuity*, and *Vernier acuity* [27]. These acuities are measured in the subtended angle from the viewpoint to the object of interest. These angles are so small that they are usually expressed in arcminutes or arcseconds: one arcminute is 1/60 of a degree, and one arcsecond is 1/60 of an arcminute.

Detection acuity specifies the smallest subtended angle from the viewpoint that an object can have to be detectable. In an empty environment, this is close to 0.5 arcsecond. In contrast, the *separation acuity* describes the smallest subtended angle from the viewpoint where two objects can be separated. This angle is approximately 1 arcminute. The *Vernier acuity* represents the detection limits of line alignment (1–2 arcminute). An optician measures visual acuity using a chart with optotypes, symbols with equal line thickness and internal line separation. For "normal" vision, the optotype subtends a visual angle of 5 arcminute, and the separation distance between the features is 1 arcminute [28]. The size of the optotypes progressively increases, expressing the resulting visual acuity as fractions of "normal" vision. The Commission Directive 2009/112/EC [26] requires that any applicant applying for or renewing a driving license needs to have the minimum binocular visual acuity of 0.5. Most US states have similar requirements [25].

The resolution of digital displays is usually specified as the number of horizontal and vertical pixels. There is a need to calculate the angle a pixel subtends to compare the display resolution of digital displays with the theoretical limits of human vision. This angle depends on the width of the display as well as on the viewing distance. The resolution can be expressed as either the subtended angle per pixel or as the pixels per degree. The average subtended angle for a pixel is calculated using equation 2.1.

$$\alpha_{pixel} = \arctan\left(\frac{w_{display}}{d_{screen} \cdot n_{pixels}}\right) \tag{2.1}$$

This calculation assumes that all pixels on the screen are at a uniform distance from the viewpoint, which may be true if the screen is curved so that the observer remains at a constant distance to the screen. However, most screens are flat, resulting in larger subtended angles for pixels in the center of the screen compared to pixels at the edges. Small angles per pixel result in an increased angular resolution at the edges of the screen. Consequently, the angular resolution is lowest in the center of the visual field, where it is needed the most. This effect gets more pronounced if the screen is moved closer to the observer (figure 2.3).

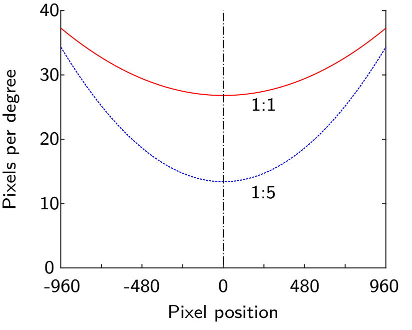
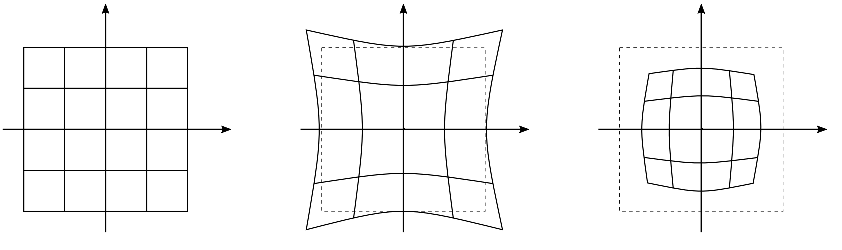


Figure 2.3 *The difference in angular pixel density depending on pixel position. The figure shows the horizontal angular resolution of a Full HD (1920 × 1080 pixels) display seen at two distances. The solid red line shows angular resolution for a screen observed at a distance equal to the screen width (ratio 1:1). The dashed blue line shows the pixels per degree if the screen is moved closer to the observer with a 1:5 ratio of distance from screen and width of screen.*

The display inside a HMD is very close to the eyes to allow for a large field of view. This design has the additional benefit of keeping the center of gravity close to the center of the head. The drawback is that the distance to the screen is too close for the eyes to focus. Therefore, lenses are needed that can gather (collimates) the light and move the focus distance outwards. These lenses cause aggressive pincushion distortion (figure 2.4b). This pincushion distortion can be corrected by applying an inverse distortion, known as barrel distortion, during the graphics rendering stage. This distortion correction is done by the software and results in loss of visual acuity in the outer part of the display as multiple pixels will merge into one pixel on the display (figure 2.4c).



(a) **(b)** **(c)**

Figure 2.4 *Visualization of lens distortion effects – (a) Ideal lens without distortion, (b) Pincushion distortion, and (c) Barrel distortion.*

The current generation of HMDs used in the research in this thesis has displays and lenses that give them a resulting angular resolution of 10-15 pixels per degree [29]. The low resolution inside a HMD can make objects hard to discern at distances where they would be clearly identified in real life. These values can be compared to projector-based simulators, which usually have between 20-30 pixels per degree [30, 31]. There are even simulators with a resolution that rival the separation acuity limit of the human eye [32].

Field of view

A healthy individual has a horizontal field of view of about 200° [24]. However, the outer parts are only visible to one eye at a time. Accordingly, the binocular field of view is limited to about 120°. The maximum visual acuity also is limited to the most central portion of the fovea of the eye, decreasing exponentially towards the peripheral parts of the visual field.

The horizontal field of view of most current generation HMDs are between 90–100°,(e.g., the *Oculus Rift* or the *HTC Vive*) [33]. This limited horizontal field of view makes any task where the user is instructed to detect objects in the peripheral vision challenging to perform when using a HMD. In addition, limiting the field of view can have consequences for the perception of self-motion, leading to underestimation of the current speed [34].

2.4 Tracking

A tracking system is required to present a view that adapts to the user's movement. This thesis distinguishes between technologies used to track a human observer and tracking technologies used to track a vehicle.

2.4.1 User Tracking

There are many tracking systems available, including inertial trackers, optical trackers, video trackers, and hybrids of these technologies. Other more niche technologies rely on mechanical, acoustical, or electromagnetic tracking. The following sections provide a brief overview of these systems. See [35, 36] for in-depth descriptions.

Mechanical trackers

These systems rely on connecting the tracked objects with mechanical rods that are connected to rotary encoders. The tracked object's position and orientation can be calculated by measuring the rotary encoders' angles. However, the mechanical rods may limit the users' natural movement and the system may gimbal-lock when two axes of the systems align, effectively locking the one degree of freedom.

Acoustical trackers

Acoustical trackers use sound emitters mounted at fixed locations to emit periodic sound pulses. These pulses are picked up by microphones attached to the tracked object. The distance from the microphone to the sound emitter can be calculated by measuring the delay from when the sound was emitted to when the sound was detected. This distance can be used in a method known as Trilateration (or Multilateration) to calculate the position using distances from other already known positions [37]. Having three or more sound emitters allows for the calculation of a position in 3D-space. Acoustical trackers can be sensitive to acoustic noise and occlusions as well as changes in temperature, humidity, and wind as these inputs affect the speed at which sound travels.

Electromagnetic trackers

These types of trackers use a base station that emits a magnetic field. This magnetic field is cycled between three orthogonal axes. The tracked object is outfitted with sensors that can measure the magnetic field. The resulting measurement contains both the position and orientation of the tracked object. Electromagnetic trackers are accurate in small volumes, but the accuracy degrades with the cube of the distance to the base station. The tracker sensors can also be sensitive to other magnetic fields.

Inertial trackers

Inertial trackers measure angular velocities and linear accelerations. Angular velocity can be measured using a gyroscope and integrated to obtain a relative orientation change from the last measurement. An accelerometer measures linear acceleration. These acceleration measurements are integrated twice to obtain a position. Inertial trackers measure orientation and position relative to an initial starting condition. Any error due to noise or bias in the gyroscopes or accelerometers will lead to drift as errors accumulate over time.

Optical trackers

Optical trackers project structured patterns of light over the desired tracking volume. The tracked object is fitted with optical light sensors that can detect light levels. The absolute position is calculated using knowledge of the light pattern and the information from the light sensor. Other systems use a sweeping light pattern and the timing information to triangulate the position. A drawback with optical trackers is that the user may end up in positions that occlude the light sensor on the tracked object; however, multiple light projection engines may be used to emit light from different directions to remedy this problem. Another option is to use multiple light sensors.

Video trackers

This technology uses cameras and image processing to track the position of objects. The camera can be placed on the tracked object looking at fixed objects in the environment, which is known as inside-out tracking. Another option is to have the camera fixed and looking at the tracked object, which is known as outside-in tracking. Outside-in tracking is more susceptible to occlusion problems, but it does not have to equip the tracked object with the added weight of a camera.

Hybrid trackers

Hybrid solutions take advantage of the specific strengths of a particular tracking technology while remedying its drawbacks using a complementary technology. For example, reducing drift can be accomplished by using a relative tracker with a high update rate combined with an absolute tracker with a lower update rate. Reducing occlusion effects can be accomplished by combining trackers that are sensitive to occlusion with trackers that are not.

2.4.2 Vehicle Tracking

Using a VR system inside of a moving vehicle puts unique demands on the tracking technology. The vehicle cabin is a relatively confined space, which is challenging for both mechanical and acoustical systems. The electronics in the vehicle also create an environment inside the cabin that interferes with electromagnetic trackers. The entire vehicle is moving, making inertial systems hard to use without introducing compensatory algorithms [38]. The vehicle movement also causes the daylight sun to create shifting light conditions inside the cabin that are challenging for both optical and camera-based systems.

There is also a need to track the entire vehicle in order to make the corresponding movements in the virtual environment. Most traditional tracking systems are designed to room-scale tracking volumes or smaller. To track objects in larger spaces, other technologies must be used, such as satellite navigation or dead reckoning methods [39].

Satellite navigation

The most common technology to track vehicles is to use some form of tracking system based on Global Navigation Satellite Systems (GNSS), such as Global Positioning System (GPS). The accuracy of these types of systems is approximately 10 m, which can be further improved by using either Differential-GPS (DGPS) or Real-Time Kinematic GPS (RTK GPS). DGPS uses a ground base station positioned at a well-known position to correct for the atmospheric effects, which affects the accuracy of a traditional GPS. The resulting accuracy is approximately within 0.1 m. A RTK GPS can improve accuracy by measuring the carrier phase of the GNSS signal, which can enhance the accuracy down towards 0.01 m.

Dead Reckoning

Tracking via GNSS will result in absolute positions and orientations. For some applications using a relative measurement will suffice. By starting from a previously determined position, the new position can be estimated by adding the relative movement, a method known as *dead reckoning*. One option for acquiring relative movement is to use odometry data from the vehicle. Odometry data can be captured by measuring wheel rotations. The quality of tracking depends on the precision of this data and can be easily disturbed if the wheels slip or skid. Another option is to use non-contact measurements of speed-over-ground velocities such as Laser Doppler velocimetry, which uses the doppler shift in a laser beam to measure the ground surface's velocity relative to the vehicle. A third option is to employ image-based systems that calculate the relative movement in position and orientation [40].

2.5 Latency

Latency is the time delay from the input to output in a system. In a VR system, there are many potential sources of latency. Each subsystem can cause time delays [41]. The tracker may have some latency when measuring the current position and orientation, occasionally using multiple measurements. The image generator processes this tracker data and runs a simulation step to generate a new image. This image is sent to the graphics card. The graphics card processes the information from the image generator before sending the image to the display. The display has a scan out time that needs to be considered. For VST MR systems, the camera attached to the HMD can introduce latency in the image acquisition phase [42].

For opaque VR systems, full system latency is specified as the time delay from the tracker input until the corresponding graphics are presented to the user. This delay includes both the latency in the tracking system and the latency in the visual presentation. This type of latency is occasionally called *motion-to-photon* latency or *input latency*.

For VST MR systems, this can be extended to include the cameras. This delay is calculated from when the cameras capture the real world image until this image is displayed inside the HMD. This is called *photon-tophoton latency* or *visual latency*.

2.5.1 Effects of Latency

Low input latency has been proven to be essential for cognitive functions such as the sense of presence, spatial cognition, and awareness [43, 44]. When input latency increases, the user can experience decreased visual acuity, decreased performance, decreased presence, and decreased response to training [45]. Increased input latency is also associated with increased levels of simulator sickness [46]. Stress effects also increase with added latency [47].

2.5.2 Measuring Latency

Several methods have been developed to quantify the input latency in VR systems or subsystems. One of the first methods to measure the latency in the tracking system was to attach the tracker to a pendulum and then use a LED and a light-sensing diode to measure the periodicity of the pendulum and compare this signal to the tracker output [48].

A common method for measuring the time delay in the full VR system is to record the HMD with a high-speed video camera while displaying a grid pattern. The latency can then be estimated by counting frames between HMD movement and the corresponding change in the display inside the HMD. He et al. [49] introduced this method, and Friston and Steed [50] presented an automated variant. A simplified variant of these methods was presented by Feldstein and Ellis [51], which uses the actual virtual environment instead of a grid pattern. A novel method relies on human cognitive latency and compares the result from a human triggered measurement from an unknown system with similar measurements from a system with known latency [52].

To measure the visual latency of VST HMDs, the above frame counting method can be used. Another method is to attach a light-emitting diode to a pulse generator and attach a light-sensing device inside the HMD. The light emitted from the diode is captured by the cameras in the HMD. This camera image is transferred and displayed inside the HMD illuminating the light-sensing device. The signals from the pulse generator and the signal from the light-sensing are fed into an oscilloscope. The latency can be measured as the time difference between the two signals [41].

2.5.3 Latency Detection

A couple of studies have investigated the discernibility of latency in humans. Here, two different measurements are interesting: the absolute detection threshold and the differential threshold. The absolute detection threshold can be quantified using the Point of Subjective Equality (PSE) value, which is the point when 50% of observations can detect a change in latency. Just Noticeable Differences (JND) is a measure of how sensitive participants are to changes around the PSE. This has been studied by Adelstein, Lee, and Ellis [53] and Ellis et al. [13], who reported JND in latency levels ranging from 14 ms to 77 ms.

Even stricter requirements were found by Jerald and Whitton [54], who claims a mean JND of 16 ms and a minimum of 3.2 ms. Other studies have reported considerably higher levels; Allison et al. [45] reported acceptable latency levels between 60 ms and 200 ms, and in the study by Moss et al. [55], latency levels as high as 200 ms (mean 148 ms) as unnoticeable by untrained subjects.

For MR systems, the latency requirements are different since the user has the real world as a reference, and registration errors are magnified as latency increases [56]. In OST systems, the real world is viewed directly, making the latency detectable at considerably lower levels. A study by Ng et al. [57] found the JND of latency to be as low as 2.38 ms for OST systems.

For VST systems, some correction of the perceived latency is possible since the real-world view has some minor delays resulting from the video capture process. Registration errors can be reduced using a closed-loop system to continuously measure the resulting registration error in each frame and using that information to correct the next frame [58].

2.6 Simulator Sickness

Several theories attempt to explain why simulator sickness occurs inside virtual reality: sensory conflict theory [59], evolutionary theory [60], postural instability theory [61], rest-frame hypothesis [62], and eye movement theory [63]. The susceptibility to simulator sickness can be influenced by individual factors, such as age, gender, health status, previous experiences, and the user's own expectations [64]. In addition, hardware factors can contribute to motion sickness in virtual reality, such as flicker, latency, tracking errors, field of view, ergonomic factors, display refresh rate, and the accommodation-vergence conflict. The presence and quality of a motion system may also have a significant effect on simulator sickness.

The most common way to measure simulator sickness is via the Kennedy Simulator Sickness Questionnaire (SSQ) [65], where the users are asked to rate 16 common symptoms on a four-point scale (*none*, *slight*, *moderate*, or *severe*). The questionnaire divides these symptoms into three groups: nausea, oculomotor, and dizziness. The resulting measurement can be reported as a total score, but can also be presented as a score per symptom group. The potential issue with the questionnaire is that it is time-consuming to perform. Another option is to use the Fast Motion Sickness Score (FMSS) [66], where the user is asked to rate their level of motion sickness on a scale from 0 (*no sickness at all*) to 20 (*frank sickness*), once per minute.

2.7 VR in the Product Development Process

Since the early 1990s, VR has been used in industries such as energy, military, aerospace, agriculture, automotive, entertainment, construction, and consumer goods [67]. However, during the last several years, the field has seen a drastic expansion due to the development of virtual reality devices targeted for consumers. This expansion has led to low cost and relatively high-performance software and hardware being available to a more general market.

VR can be used as a tool in most phases of product development [68]. The technology enables users to explore a problem space in a virtual environment, an approach that can be beneficial during both the analysis and synthesis phase.

During the simulation phase, VR can be used to visualize complex multidimensional data [68]. VR can also be used to introduce a real human into the simulation. Modeling all the intricate details of human decision making can be next to impossible. Consequently, a real human in the loop can reveal unknown emergent behavior. Another significant benefit is safety as virtual reality allows for experiments that would be too dangerous to perform in a real-world setting either due to the risk to the equipment or the well-being of the human [69].

VR can also be used to improve decision making as it allows multiple users to experience a proposed design. These meetings can improve the cross-functionality among teams, even when they are in different locations [70, 71].

Virtual environments can also be used to analyze both manufacturing and end-of-life scenarios by studying the ergonomics and design of both assembly and disassembly. Virtual production planning early in the design phase allows the assembly line staff to experience manipulating a component that only exists in a CAD-model, allowing for the identification of problems before actual production begins [72, 73].

Use cases from the automotive industry

Since the early 1990s, the automotive industry has been using VR [74]. Many of the previously mentioned use cases were adopted in the automotive industry such as incorporating findings from studies of driver and assembly line worker ergonomics. Other early examples include using VR to evaluate the aesthetic quality of a vehicle. Experiencing the design in immersive stereoscopic 3D provides engineers and designers the possibility to view a vehicle in real-life scales, which may provide new insights compared to looking at a 3D-model on a traditional monitor. VR is also well suited for space planning due to the stereoscopic viewing, which gives unmatched depth cues compared to ordinary computer monitors. These added depth cues help designers position buttons, levers, and other instruments in optimal locations.

Later use cases include VR to test systems that need to be evaluated under specific conditions. For example, VR can be used to create a virtual environment that resembles night driving and simulates various headlight configurations [75]. Another typical use case is to evaluate visibility factors- i.e., testing how well a driver can perceive the outside environment. It could be a simple task such as studying the design and placement of the A-pillars in vehicles or the more complex task of evaluating the best location for instruments to reduce glare in the vehicle side windows [68]. In addition, VR has been used extensively with driving simulations. The most common use cases include studies of human factors, vehicle tuning, and driver training. There have also been experiments concerning preliminary engineering design for active safety systems [76].

This thesis aims to investigate the effects of VR on driving behavior, with a focus on VIL setups for validation and verification of active safety systems.

3 Active Safety Systems

This chapter begins with a definition of what constitutes an active safety system and how it differs from traditional passive safety systems. This definition is followed by an introduction to the product development process and system engineering concepts and how these relate to the design, development, and, most of all, testing of active safety systems. This chapter then describes the available methods for functional and systems verification and the benefits and drawbacks of each test method with particular focus on vehicle-in-the-loop as most of the research in this thesis is connected to this method.

3.1 Definition

Active Safety Systems are designed to prevent accidents from happening or to mitigate the potential effects of an accident. These systems actively monitor the driver, vehicle, or road environment. The action could warn drivers of potential risks or perform active interventions [2].

Active safety systems include Anti-lock Braking System (ABS), Electronic Stability Control (ESC), and Emergency Brake Assist (EBA), systems that help the driver maintain control of the vehicle in critical situations. In addition, active safety systems provide warnings in certain situations, such as Forward Collision Warning (FCW), Lane Departure Warning (LDW) and Lane Change Warning (LCW). Active safety systems also include more complex components that assume some or full control over the vehicle: systems that automatically keep a fixed distance from another car (Adaptive Cruise Control, ACC); systems that automatically brake if needed (Autonomous Emergency Braking, AEB); and systems that maintain the vehicle in the current lane (Lane Keep Assist, LKA) [77].

Passive safety systems in a vehicle are components designed to help the occupants survive a crash, such as airbags, crumple zones, and side-impact protection. These systems can be combined with active components to improve their function in a crash. These types of combined pre-crash systems prepare the vehicle for an imminent collision by pre-tensioning the seatbelts, quickly adjusting seat positions to optimize airbag performance, and by closing windows to prevent ejection [78].

3.2 Developing Active Safety Systems

The general Product Development Process (PDP) has been described in several ways. Ulrich and Eppinger [79] specify a generic process starting with the planning phase. This phase is followed by the concept development phase, system-level design phase, detail design phase, testing and refinement phase, and the production ramp-up phase. Similarly, the design process described by Roozenburg and Eekels [80] is characterized as a feedback process that starts with the desired function and ends in an approved design. The steps in-between include the four methodologies: analysis, synthesis, simulation, and evaluation.

Developing active safety systems requires integration between multiple systems inside the vehicle. A system design might contain interactions between software, electronic, and mechanical systems. Consequently, this development is guided by a systems engineering approach. This approach is generally described using a V-model of the system development life cycle from the project definition to test and operation. Each step in the definition side of the V-model is linked to the corresponding verification or validation method used in the V-model's test and operation side [81]. For example, an extended V-model is used by Toyota systems engineers to develop safety systems [82](figure 3.1).

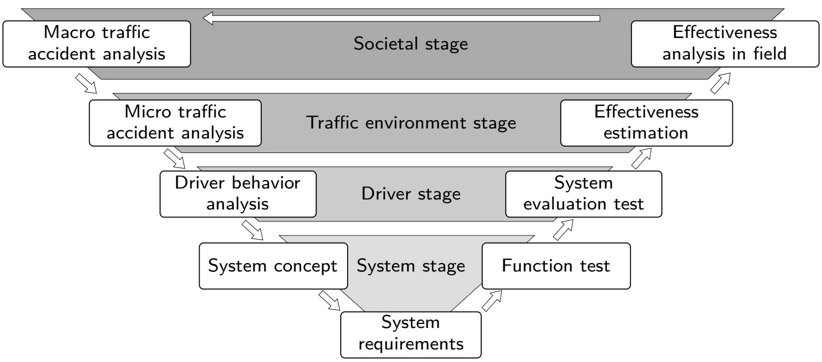


Figure 3.1 *The development process used at Toyota according to Murano et al. [82]*

This extended V-model contains the following steps:

1. *Macro traffic accident analysis* — Perform macro analysis of accident data to identify accident-prone scenarios. This analysis can be done using statistics available from government agencies.
2. *Micro traffic accident analysis* — Analyze the identified scenarios in detail to find the root causes of the accident.
3. *Driver behavior analysis* — Analyze typical driver behavior in the identified situations, for example, by studying detailed descriptions of accidents or studying data from field-operational testing where selected vehicles have been instrumented to record data over long periods.
4. *System concept* — Design a system that attempts to prevent the accident or at least mitigates the potential effects of the accident.
5. *System requirements* — Specify the requirements for the system concept. In this phase, the product developers decide which sensors will be needed to solve the task.
6. *Function test* — Perform function tests of the system prototype. These tests can be performed using different closed-loop tests (see section 3.3.1).
7. *System evaluation test* — Perform evaluation tests of the system prototype. These system evaluations often require the introduction of a human driver in the tests, either on a test track or in a driving simulator (see section 3.3.2).
8. *Effectiveness estimation* — Using computer traffic simulations to estimate the reduction of accidents using the designed system.
9. *Effectiveness analysis in field* — The effect of the system is tested in the field either by recording data from installed systems or collecting open statistics.

The PReVAL project suggested a similar V-model as the assessment procedure for advanced driver assistance functions [83]. This model includes the *Test Definition* step for both *Verification* and *Validation*. However, most importantly, it introduces a step for producing *Evaluation Specifications* (figure 3.2). These specifications tie together the functional and technical specifications for all test types: pure technical and human factor tests.

Both the Toyota and the PReVAL models highlight technical and functional assessment of the designed system. These tests can be performed using a broad set of available test methods.

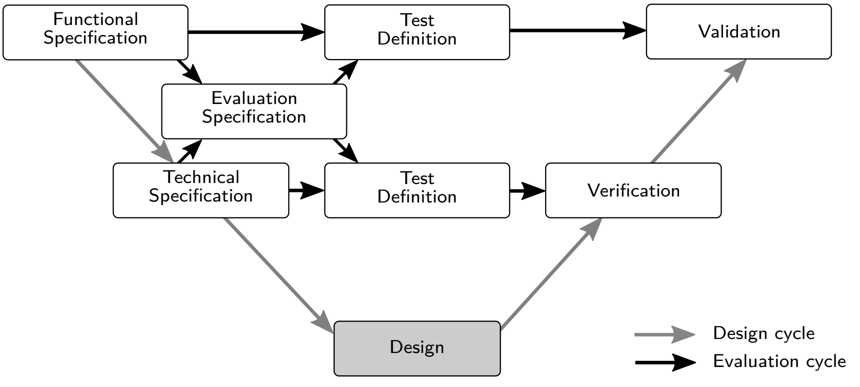


Figure 3.2 *The PReVAL procedure for the assessment of advanced driver assistance functions [83]*

3.3 Test methods

Testing of passive safety systems usually happens via crash testing with crash test dummies inside the vehicle. By measuring the forces exerted on the dummies, quantitative measurements can be obtained for each vehicle type, simplifying the comparison of passive safety levels between vehicle types. These tests are performed on a large scale by vehicle manufacturers as well as by governmental institutions, such as the National Highway Traffic Safety Administration New Car Assessment Program (NCAP) [84] in the United States and the corresponding non-profit organization Euro NCAP [85] in the European Union. These institutions administer these tests to issue safety ratings. These ratings promote safe vehicles for consumers, thus encouraging vehicle manufacturers to improve their safety.

Tests of active safety systems are harder to design and compare since these systems solve dynamic scenarios. Different manufacturers may use different strategies to solve the same type of hazardous scenario. Some scenarios are performed at high speed or involve multiple actors, making them hard to reproduce with sufficient accuracy. Nevertheless, there have been some active safety system tests added to the Euro NCAP test suite, for example, LKA and tests involving AEB for other vehicles as well as for vulnerable road users. These rating tests are standardized to provide a fair system independent of individual manufacturers. During the development of a new active safety function, the manufacturers can choose their method. Once the system concept and requirements have been fixed, the algorithms are put through rigorous testing using several test methods.

3.3.1 Closed-loop Methods

Validation and verification of safety systems and subsystems can be performed without the need for a complete vehicle. These tests are designed to run in a closed-loop without the need for input from a real driver. A safety system concept can be put through Software-in-the-loop (SIL) or Hardware-in-the-loop (HIL) testing, which involves running the concept algorithm implementation or Electronic Control Units (ECUs) through a selected set of test cases. Both SIL and HIL have the benefit of producing repeatable results, which can be important when evaluating different solutions.

Software-in-the-loop

SIL benefits from being a pure software method; that is, it is possible to run as many parallel glssil test cases as there are simulation computers available. It is also possible to run the simulation faster than real-time, allowing for massive test-suites to be executed within a short timeframe [86].

Hardware-in-the-loop

HIL uses the intended hardware for a selected part of the system. The real part can be a single component or an entire subsystem, whereas the rest of the vehicle is simulated. The fidelity of the test increases compared to SIL as actual hardware is used. However, the efficiency decreases since the tests are constrained to run in real-time. The real-time constraint arises from the hardware components used in the test [87].

3.3.2 Driver-in-the-Loop

By performing Driver-in-the-loop (DIL) tests, it is possible to include a human in the test suite. The algorithms run in SIL or HIL mode, and with simulated vehicle dynamics, but now there is an actual human controlling vehicle input. These tests use either driving simulators, scale models, or test tracks.

Driving simulation

Driving simulators can range from small static simulators using computer monitors to high-end driving simulators [88]. High-end simulators use immersive display systems and high-performance motion systems to create convincing feedback for the driver (figure 3.3). The simulator provides a safe environment to perform tests that are too costly, dangerous, or impractical to perform on a real road or a test track. The simulator can also perform scenarios that involve complex interactions between actors. The scenarios can be reduced to only include the desired factors to be studied, a configuration that can help with interpreting the results. The scenario can also be repeated with the same conditions for all drivers, eliminating undesired variables that may affect the result.

However, as users of driving simulators know that their actions will not result in any harm, they might adopt a more dangerous driving style. Another drawback may be the motion feedback (or lack thereof) in the simulator. The mismatch between the actual and the expected motion may cause motion sickness. This motion sickness may cause the driver to adapt behavior to alleviate the symptoms, ultimately affecting the results [5].

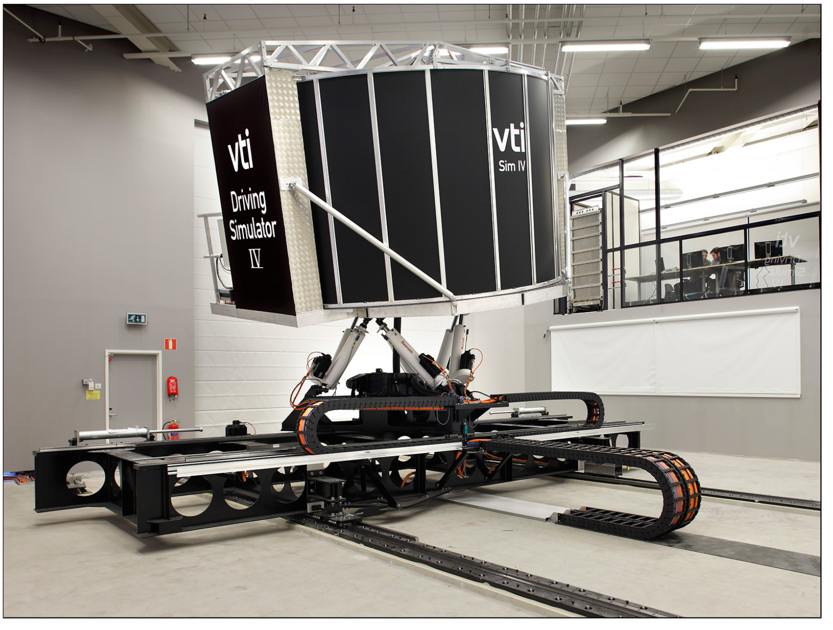


Figure 3.3 *The VTI Driving Simulator IV featuring an advanced motion system. The black rails in the floor allow for realistic linear accelerations in the lateral and longitudinal direction. The platform containing the vehicle cabin is positioned on a hexapod, which permits both linear and rotational movement (Image courtesy of VTI/Hejdlösa Bilder AB).*

Scale models

Another option is to use radio-controlled scale models fitted with similar sensors found in the real vehicles or simulated sensors [89, 90]. The scale model can either be controlled by algorithms or controlled via telepresence using an onboard video camera. However, scale models have quite different vehicle dynamics compared to real vehicles, differences that can affect the results. Nevertheless, these models can be a tool for rapid prototyping and for designing verification scenarios.

Test tracks

Test tracks, also known as proving grounds, have been the standard environment for testing since the early days of automotive engineering [91]. These tracks are closed roads where tests can be performed under safe and controlled conditions. Trained test drivers perform specific maneuvers to test the entire vehicle or the proposed system. Some active safety systems are tested in high-speed scenarios. In these scenarios, the targets are usually not real vehicles as a collision may be dangerous for both drivers and vehicles. These test use inflatable targets or foam targets that have the same visual appearance and radar signature as real vehicles [92].

The artificial targets can either be used as static targets or attached to a mechanism that can move them. One alternative is to put the target on a trailer towed behind a proxy vehicle. Another option is to use a remote-controlled vehicle to drive the target. This remote-controlled vehicle must have a low profile to allow the test vehicle to pass over it in case of collision. A third option is to use overhead wire systems to move the targets; these systems are most common for smaller targets such as artificial pedestrians or cyclists [93].

Vehicle-in-the-Loop

Bock, Siedersberger, and Maurer [94] introduced the concept of VIL as a way to transfer the repeatability and safety from the driving simulators to the test track. They suggest that active safety systems could be simulated and tested by fitting the driver with some form of virtual reality display and driving a real vehicle on a test track. Sheridan [95] describes a similar idea with a real vehicle using an augmented reality display to add virtual targets as a way to perform scenarios that would be dangerous to perform with real target vehicles. Because a real vehicle is used, the vehicle dynamics do not have to be simulated, so the driver receives motion feedback without any added latency. This solution reduces potential miscues in perceived motion dynamics, which may contribute to more realistic driving behavior and decrease motion sickness compared to driving simulators.

This VIL method has been tested with different display systems and the earliest examples used glsost HMDs [96, 97]. There have also been studies that employ opaque HMDs, where the drivers perform the task seeing an entirely virtual world [98, 99]. Another display system configuration consists of cameras and screens mounted fixed relative to the car [100, 101]. A variant of this configuration uses the windshield as a projection surface for the virtual environment [102]. These fixed display configurations have been limited to non-stereoscopic displays. There has even been a concept system demonstrated that uses VST HMD to produce an AV solution. In this AV solution, the real dashboard of the vehicle is included inside an otherwise virtual environment [103].

3.3.3 Selection of Test Method

The choice of test method depends on the phase of the product development process. The selection of the test method is also a trade-off between fidelity and effectiveness. Testing a subsystem might not require the same level of fidelity as testing an integrated system, allowing for a test method with lower fidelity but higher effectiveness. Consequently, *function tests*, as described in the extended V-model (see section 3.2), are more suitable to perform with close-loop methods.

The opposite applies to *system evaluation tests* as these require higher fidelity, which usually requires the introduction of a human driver. Traditionally, system evaluation tests have been done using test tracks or driving simulators. The introduction of VIL testing promises more effective testing compared to traditional test track testing. The cost is slightly reduced fidelity, but the available fidelity is still higher than driving simulators (figure 3.4). However, before VIL is used on a large scale, the method needs to be evaluated. The bulk of this thesis is related to finding the effects and limitations of the technology behind the VIL method.

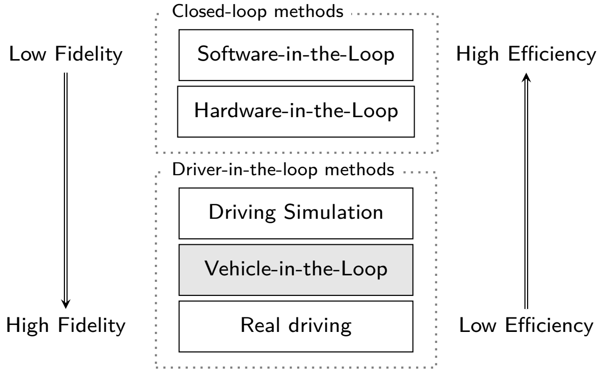


Figure 3.4 *The fidelity increases when moving towards real driving but at the cost of efficiency.*

4

Summary of Included Papers

This chapter summarizes each paper included in the thesis and specifies the contributions to each paper by the author of this thesis.

Paper I

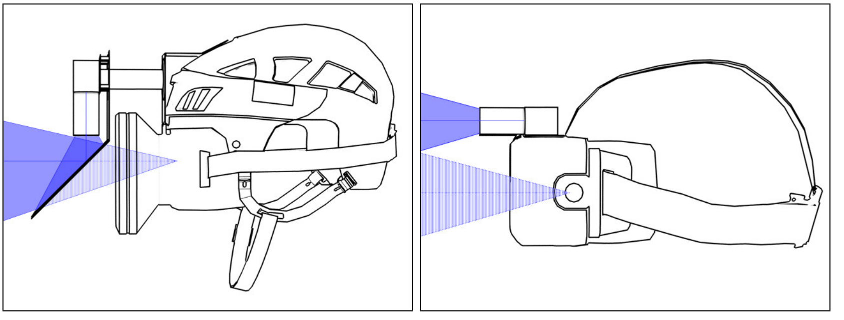
> B. Blissing and F. Bruzelius, "A Technical Platform Using Augmented Reality For Active Safety Testing", *Proceedings of the 5th International Conference on Road Safety and Simulation*, pp. 793–803, Orlando, FL, USA, 2015

This paper describes the design of the custom VST HMDs used to perform the research in papers II and III. Before building the custom device, the market was surveyed for VST HMDs. Most of the available devices were ruled out because their field of view was too narrow. Some devices only used monochromatic cameras and others only used one monoscopic camera. Therefore, it was decided to build a custom device using commercial off-the-shelf components.

The first iteration was based on the *Oculus Rift Development Kit 1* with dual high-resolution cameras. The optics were mounted and reflected in a first-surface mirror so that the camera's optical node points corresponded with the eyes' positions. Because the device was large and heavy, it had to be fitted on a hockey helmet to distribute the weight (figure 4.1a).

For the second iteration, there was a need to support both VR and MR. Hence some form of tracking system that supported both orientation and position was needed. The *Oculus Rift Development Kit 1* only supported orientational tracking. The first attempt used a third party magnetic tracker, advertised to be usable in environments containing metal. This tracker worked well when the vehicle was at a standstill; however, the magnetic environment changed as soon as the engine was engaged, resulting in non-linear disturbances in the tracking output.

The HMD was replaced by a *Oculus Rift Development Kit 2*. This HMD offered a hybrid tracker based on an inertial tracker that was supplemented with a video tracker to counter drift. The optical tracker negated the possibility to use the mirror solution from the first iteration, as it would block the LEDs on the HMD, which the tracker camera uses as reference. Consequently, the cameras were moved to the top of the HMD, which resulted in a minor perspective issue. This solution, although not ideal, was less bulky and did not require a hockey helmet (figure 4.1b).



(a) **(b)**

Figure 4.1 *(a) First iteration of HMD with Oculus Rift DK1 and a first surface mirror to give on-eye axis optical path. (b) The second iteration with the Oculus Rift DK2. This iteration placed the cameras on top of the HMD, changing the perceived perspective.*

The Oculus hybrid tracker is not designed to be used inside a moving vehicle as movement of the vehicle is incorrectly interpreted as the head movements of the user. The solution to this problem was to use the inertial information from the vehicle captured by the DGPS system used to track the vehicle. The tracking errors were corrected by subtracting the inertial information originating from the vehicle from the inertial information captured by the HMD, a method that resembles one proposed by Foxlin [38].

This paper also presents a method for measuring visual latency with high precision. Measurement of visual latency was performed by recording the delay from the illumination of a LED positioned in front of the cameras until the corresponding light increase can be detected on the digital display. This method is an automated version of the latency measurement method proposed by Jacobs, Livingston, and State [41]. Automating the method means a large number of measurements can be made, which is advantageous for measuring asynchronous systems where latency may vary from frame to frame.

This paper also describes the custom image generator designed to use these two HMD devices. This image generator was required to capture the live image from the cameras and combine these images with computer graphics with minimal latency. The image generator also needed to change the latency as requested.

This paper also includes a solution for the MR use case where real objects occlude virtual objects. This method requires that the real objects are modeled and added to the virtual environment, but these models are only rendered to the depth buffer in the image generation step. As the pixels from the real objects' models are only present in the depth buffer, any pixels from pure virtual objects behind these pixels will be rejected, requiring these pixels to use information from the camera feed.

Author contribution

The author of the thesis designed the two VST HMD devices. This design process included the selection of hardware and the software implementation of the image generation and the latency measurement device. The author was also responsible for writing the paper.

Paper II

B. Blissing, F. Bruzelius, and O. Eriksson, "Effects of Visual Latency on Vehicle Driving Behavior", *ACM Transactions on Applied Perception*, 14.1, pp. 5.1–5.12, 2016

As all VST HMDs have more or less visual latency, this paper investigates the effects of added visual latency on driver behavior. That is, if these types of HMDs are to be used to study driver behavior, the effect of the equipment on the user needs to be determined.

This user study, which included 24 drivers, deployed the first iteration of the custom VST HMD designed in paper I (figure 4.1a). Each driver drove a slalom course while being subjected to three levels of visual latency (127 ms, 186 ms, and 349 ms). The lowest latency level was the minimum latency achievable with the first iteration of the custom VST HMD. The subjects also drove the task without wearing any HMD to record an individual baseline to be used for comparison. Each task was repeated three times for each latency level.

The participants' driving behaviors were recorded using a DGPS and an angular sensor connected to the steering wheel. The objective measurements were divided into longitudinal and lateral behaviors. These behaviors were split into local and global behaviors. Each driver was also asked to give their subjective opinion regarding their performance and perceived difficulty after each latency level.

The recorded data were analyzed using a three-way Analysis of Variance (ANOVA). The results clearly show that wearing a HMD affects driving behavior. All measurements showed statistically significant effects compared to the baseline, except for the local lateral behavior (*number of steering wheel reversals*). However, it was only the global lateral behavior (*lateral path deviation*) that showed significant effects between the different latency levels as the drivers used wider paths as latency increased (figure 4.2). For the subjective self-assessment, there was a trend of decreased perceived performance and an increase in perceived difficulty with increased latency. However, the difference between the latency levels was only significant between the highest and lowest levels.

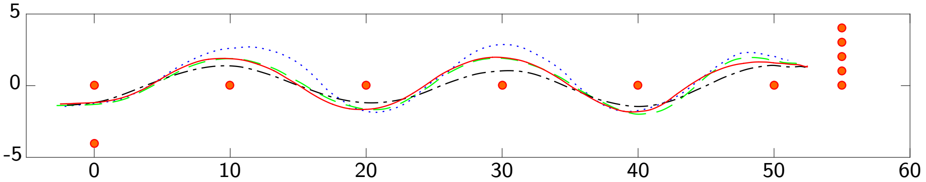


Figure 4.2 *The test track set up with four trajectories from one test subject. The black dashed line denotes the baseline, the solid red line denotes the lowest latency level, the dashed green line denotes the medium latency, and the dotted blue line denotes the highest latency level.*

Author contribution

The author of the thesis was responsible for designing the scenario, the data acquisition, interpreting the results, and writing the paper.

Paper III

B. Blissing, F. Bruzelius, and O. Eriksson, "Driver behavior in mixed and virtual reality – A comparative study", *Transportation Research Part F: Traffic Psychology and Behaviour*, 61.1, pp. 229–237, 2019

This paper investigates how different modes of virtuality affect driving behavior. The primary motivation was to see whether the benefits of having a view of the real world as a reference in MR would outweigh the potential issues with the registration errors.

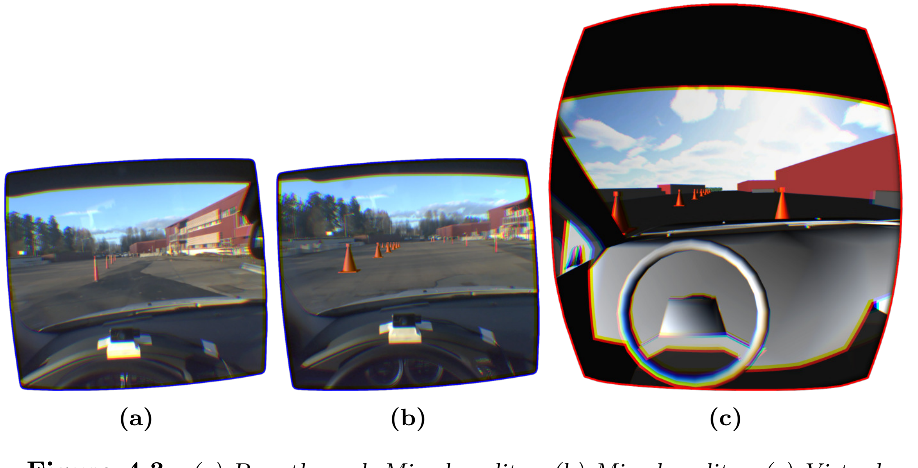
The research method was similar to the one used in paper II, a user study with 22 drivers. Each driver performed the task in four modes of virtuality:

Direct View The subjects drove without a HMD to provide a baseline measurement of their default behavior.

Pass-through Mixed Reality In this mode, the VST HMD was used in pass-through mode (figure 4.3a). The subjects drove through a real cone track. This condition was similar to the conditions used in paper II.

Mixed Reality In this mode, the subjects saw the real world through the VST HMD, but the cone track was virtual (figure 4.3b). The virtual cones were superimposed using the techniques described in paper I. These cones suffered from registration errors due to a lack of tracking precision of the vehicle and the latency of the video feedback. These registration errors were most prominent in rotational movements.

Virtual Reality A completely virtual mode where everything was rendered as virtual objects (figure 4.3c). This mode offered a wider field of view as the MR-modes were limited by the available field of view of the video cameras.



(a) **(b)** **(c)**

Figure 4.3 *(a) Pass-through Mixed reality. (b) Mixed reality. (c) Virtual reality.*

The subjects' driving behaviors were recorded using the same type of DGPS as in paper II. No angular sensor for the steering wheel was present, but similar measurements were derived directly from the DGPS data. The same subjective self-assessment was used as in paper II.

The results, analyzed using the same type of three-way ANOVA as in paper II, show that the drivers used more acceleration changes and used a more significant lateral deviation when wearing a HMD. However, no statistically significant effects were observed between the modes of virtuality for these measurements. The drivers drove significantly slower in all conditions where they used a HMD, but they drove even slower in the VST condition with the virtual cones. This condition was also rated significantly more difficult than the other HMD conditions, most likely, due to the present registration errors. The local lateral behavior (*maximum curvature*) was most significant for the two conditions that used virtual cones.

Author contribution

The author of the thesis was responsible for designing the scenario, the data acquisition, interpreting the results, and writing the paper.

Paper IV

> B. Blissing and F. Bruzelius, "Exploring the suitability of virtual reality for driving simulation", *Proceedings of the Driving Simulation Conference 2018*, pp. 163–166, Antibes, France, 2018

A literature review was performed in preparation for paper V and VI. This literature review focused on finding scenarios that had been identified as problematic to perform using a HMD. Another goal was to investigate the feasibility of using HMDs for current simulator studies. All publications from the last five years from the *Driving Simulator Conference* and the *Road Safety and Simulation Conference* were examined. All papers that included some form of interactive driving simulator study were reviewed to identify which maneuvers were performed. Information regarding the study's scope was noted, especially information regarding simulator sickness. Additionally, the review was extended using scientific journal publications of known benefits and drawbacks using HMDs in a broader context. The review identified the low resolution and narrow field of view of the current generation of HMDs as a potential issue for driving simulator studies. Specifically, three types of scenarios were judged problematic for HMDs:

1. Scenarios that include high-dynamic lateral motion of the vehicle.
2. Scenarios that demand numerous head turns.
3. Scenarios that require interaction with hardware inside the cabin.

The primary conclusion from this review was that a noticeable amount (40%) of the current simulator studies could have been performed using HMDs instead of traditional display technology.

Author contribution

The author of the thesis was responsible for performing the literature review and writing the paper.

Paper V

B. Blissing, F. Bruzelius, and O. Eriksson, “The effects on driving behavior when using a head-mounted display in a dynamic driving simulator”, *Submitted for journal publication*, 2020

This paper investigated the difference in driving behaviors between driving a simulator with a HMD and with a traditional projector-based graphics. The primary motivation was to evaluate the technology in preparation for the study planned on the test track. An additional motivation was to examine how a current generation HMD performs in a dynamic driving simulator.

A simulator study was performed using a current generation HMD (*Oculus Rift Consumer Version 1*). This HMD, which uses a hybrid tracker that combines an inertial tracker with a video tracker, could not be used inside the dynamic simulator due to interference from the external motion. Therefore, this tracker was disabled and replaced with third-party video tracker.

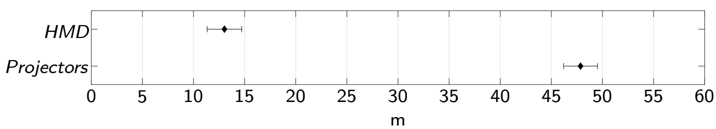
The study, performed in the VTI simulator III (figure 4.4), had 25 subjects perform selected driving tasks with and without the HMD. These tasks were selected using the results from paper IV. The first task, a speed perception task, required the subjects to drive at various speeds with the speedometer disabled. The second task required the subjects to navigate a double-lane change maneuver at low speed (below 20 km/h). The third task was the same double-lane change maneuver, but at a medium speed (40 km/h). The final task required the subjects to detect and react to road signs. As the subjects drove on a narrow hairpin curve between each task, they were required to keep the vehicle centered on the lane in the curve.

The simulator recorded their driving behavior such as speed, lateral position, and steering wheel angle. Information regarding head movements was retrieved from the HMD and stored. The subjects also responded to a SSQ questionnaire before the study and after each driving condition.

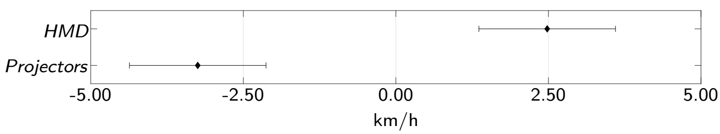
(a) **(b)**

Figure 4.4 *(a) The exterior of VTI simulator III with the large linear acceleration track visible. This track allows for realistic lateral accelerations. The platform housing the vehicle cabin can be tilted to simulate longitudinal acceleration. (b) The interior of the simulator platform. The vehicle cabin is placed on a vibration table to simulate the high-frequency movement of the vehicle.*

ANOVA was used to determine the effects of HMD and projector-based graphics. As expected, the largest difference was found in the task that depends on the display resolution: the subjects reacted earlier when using the projector-based graphics (figure 4.5a). The subjects underestimated their speed when using the HMD in the task designed to assess speed perception (figure 4.5b). This difference is most likely due to the lower field of view in the HMD. The tasks designed to force head turns and high dynamic lateral motion showed no statistically significant effect between the conditions. However, the subjects used fewer steering wheel turns in a maneuver designed to benefit from the added depth cues in the HMD.



(a) *Sign Detection Distance*



(b) *Speed Perception*

Figure 4.5 *The difference in (a) sign detection distance and (b) speed perception between the HMDs and projector-based graphics.*

There was no significant difference between the conditions regarding the SSQ assessed simulator sickness. However, the subjects who scored higher for oculomotor symptoms also had reduced head turn range. This reduction might be an unintentional approach to prevent simulator sickness from increasing.

Author contribution

The author of the thesis performed the development of the needed software integration of the video tracker and graphics environment. The author was also responsible for designing the scenario, interpreting the results, and writing the paper.

Paper VI

B. Blissing, B. Augusto, F. Bruzelius, S. Gupta, and F. Costagliola, "Validation of driver behavior in the Driver and Vehicle in the Loop platform", *Submitted for publication*, 2020

Paper VI investigates two iterations of a VIL platform. The first iteration was developed internally at Volvo Cars using knowledge acquired from the papers I–III. This iteration was evaluated by interviewing three automotive engineers who had experience driving the platform at a demonstration event at the Volvo Cars test track. The engineers tried the platform in an AEB scenario. The engineers all agreed that this platform is ready to use as a tool for evaluating specific active safety systems.

The second iteration was developed in partnership between VTI and Volvo Cars. The first iteration of the platform did not track the driver's head, only orientation. Because the compensatory algorithms used to correct the heading signal introduced some drift during dynamic maneuvers, the second iteration included the same type of third-party video tracker used in the simulator study in paper V. This tracker introduced positional tracking of the driver's head and remedied the issues with drift. A schematic view of both iterations of the platform can be seen in figure 4.6.

The second iteration was evaluated by four of the authors performing the same driving tasks as in paper V. However, the medium speed double-lane change maneuver had to be removed due to space constraints at the test track. The tasks were performed with and without a HMD. The vehicle position and orientation were recorded using the RTK GPS unit already present in the platform.

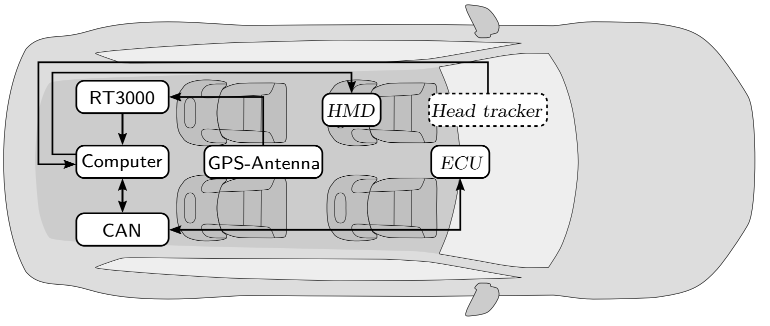


Figure 4.6 *The schematic overview of the Driver and Vehicle in the Loop platform displaying the data flow directions. The optional third-party head tracker introduced in the second iteration is shown with dashed lines. The main computer communicates with vehicle ECU via a CAN interface. The vehicle position and orientation information are received via an Oxford Technical Solutions RT3000 unit.*

The results from the experiment with the second iteration show few changes in driving behavior between driving with and without a HMD. The drivers drove 5% slower when wearing the HMD compared to the simulator study in paper V. This result may be explained by the drivers' hesitation to drive a real vehicle wearing an opaque HMD. However, it could also be a consequence of driving in an open space with few available points of reference in the peripheral vision.

As in the simulator study in paper V, the task depending on display resolution showed the most distinct results. This results indicate that high display resolution is a vital feature for these types of VIL platforms. However, none of the interviewed engineers considered that display resolution as a high priority for improvement.

Author contribution

The author of the thesis developed the VR part of the second iteration of the platform. The author was also responsible for designing the scenario, interpreting the results, and writing the paper.

5 Discussion

This thesis describes the work performed in two research projects – *Next Generation Test Methods for Active Safety Functions* and *Chronos 2*. The first project researched the effects of mixed reality for vehicle-in-the-loop testing. The second project focused on vehicle-in-the-loop testing using virtual reality. This chapter discusses the broader implications and limitations of this work.

5.1 Virtual or Mixed Reality?

The choice between a VIL system using VR or some form of MR is not obvious as both have their benefits and drawbacks. VR provides an entirely virtual environment that can be fully adapted to the needs of the test. On the other hand, VR requires the entire environment to be modeled in the virtual environment. The most significant drawback of using an opaque HMD is that the real world is not visible, which makes interactions with the vehicle interior more difficult. Not seeing the real world also forces strict safety requirements when driving a real vehicle. A sudden loss of tracking accuracy might unintentionally guide the driver off the test track. The view will also be blocked entirely if the device suffers any hardware failure, which would require the driver to remove the HMD quickly to operate the vehicle safely.

MR devices offer a view of the real world. In the case of optical see-through HMDs, this view is without any delay. The device can suffer complete hardware failure and still show the real world view. However, OST devices cannot show virtual objects that completely block out the real view, making all virtual objects semi-transparent. This phenomenon will hurt realism, which might affect the results of the test. The virtual view inside an OST device is also fixed at a certain focus distance. This fixed focus distance can make interactions with objects at different distances problematic.

The other type of MR device is the video see-through HMD. This device's sensitivity to hardware failure is similar to an opaque HMD, but it still offers a view of the real world in case of tracking degradation. The view of the real world is delayed due to the technology's design, which might affect driver behavior (see paper II). The cameras used in the device might also be sensitive to rapid changes in environmental lighting conditions due to limited dynamic range, leading to whiteout or blackout in the video-feed.

The most significant issue with any mixed reality device in this application is that they suffer from registration errors. These errors can originate from time delays or tracking errors. The current tracking technology available is not sufficient to support MR for any scenario with any sizable lateral movement (see paper III). Instead, the MR technology is currently limited to scenarios with mostly longitudinal motion, as described by Bock, Maurer, and Färber [96].

5.2 Requirements for Research and Development

The technology readiness level of the VIL platform has moved from proof of concept via validation and demonstration to a working prototype. It is now time to move into qualified usage where the technology can be evaluated in real automotive projects, as stated by the engineers during the interviews in paper VI. As the platform moves into an operational phase, the technology platform will need to be transformed from loosely fitted components in a prototype system to a more unified system. The platform also needs to simplify preparation procedures, such as position synchronization and automation of calibration between computers.

The result of this research needs to be considered when selecting and designing validation scenarios. Any task that depends on visual acuity must be adapted to fit the resolution in the HMD used for the test. Such adaptations might include increasing the scale of significant objects in the virtual environment. The difference in speed perception must also be considered. Increasing the number of objects visible in the peripheral vision may help drivers better assess their speed.

During this project, there has been significant development in HMD performance. The resolution has increased, latency has decreased, and tracking accuracy and precision have improved. At the same time, the manufacturers of the devices have chosen to move a broad set of features inside closed implementations. Because the share of these closed implementations has increased as the project proceeded, the development of the VIL platform progressively became more difficult. Therefore, priority should be given to developing good relationships with the HMD manufacturers to ensure that enough of the hardware and software stack is available for the developers of the platform.

One limitation of the tested platform is the assumption that the vehicle only moves in one plane. No testing was performed on roads with steep inclines or roads containing overpasses. Consequently, vehicle tracking did not require measurements of altitudes, roll angles, and pitch angles. The introduction of such roads would require detailed tracking of the vehicle in six degrees of freedom. The same requirement would be needed for high-dynamic maneuvers using any mixed reality HMD, as these maneuvers display distinct pitch and roll motions. Consequently, any mixed reality devices will need a precise world tracking in all six degrees of freedom to avoid disruptive registration errors.

The VIL platform has principally been developed for use in the automotive industry. However, researchers might be able to use VIL to replace or complement driving simulators. A VIL setup requires a smaller investment compared to a high-performance dynamic driving simulator. The setup can also be moved quickly from one vehicle to another, although it does require access to a test track to perform research in a safe environment. For research projects, the scenarios might be more strict, and the safety considerations even higher because the subjects might not be trained test drivers.

The drivers of traditional driving simulators may change their driving behavior because they know that they are driving in a safe simulator environment [5]. Transferring the experiment to a real car may prompt a more realistic driving behavior even when driving in a virtual environment with virtual targets. However, the analysis of any result from a study performed using VIL technology should consider the results of this research.

6 Conclusions

The main scientific contribution resulting from this work is the result of the presented user studies and experiments. These studies have given new insights into how real driver behavior changes when VR technology is introduced inside a real vehicle. The following sections present answers to the previously posed research questions and ends with an outlook on suggested research directions.

6.1 Answers to Research Questions

RQ1: *How does a head-mounted display affect driving behavior?*

The research performed in user studies in this thesis shows that lateral driving behavior is relatively unaffected. The longitudinal behavior was affected in the simulator study in paper V as the drivers underestimated their speed. Previous research indicates that this effect may depend on the limited field of view in the HMD as a limited field of view results in underestimating the perception of self-motion [34]. Nevertheless, this behavior was reversed in the experiment on the test track. The drivers on the test track used a lower speed when wearing the HMD, which may be a consequence of the drivers' hesitance to use an opaque display that hides the view of the real world.

RQ2: *How do visual time delays affect driving behavior?*

The time delays investigated in paper II affected the driving behavior in all measured variables. However, the lateral behavior and the subjective self-rating were the only measurements that degraded as the latency increased. These results might indicate that the changes in longitudinal behavior are less dependent on latency and more dependent on other factors related to the HMD, such as the limited resolution and field of view.

RQ3: *What requirements should be put on the scenarios used during vehicle-in-the-loop testing?*

There is often a desire to test a specific scenario for the proposed active safety system. This scenario must be analyzed before selecting VIL testing as the appropriate test method. Scenarios that depend on visual acuity should be avoided since the visual acuity of the current generation of HMDs is noticeably lower than the legal requirements for vehicle driving. The research in paper II and paper III shows that maneuvers with dynamic lateral motion are inappropriate when using a mixed reality system due to the effects of the visual latency on driving behavior. It is also advisable to refrain from scenarios that depend on maintaining precise speeds as the results show that speed perception is affected by a HMD.

RQ4: *What are the technical requirements for vehicle-in-the-loop platforms?*

Mixed reality devices need very high tracking accuracy and precision to avoid registration errors, which is challenging even for stationary applications. The VIL application is situated on a moving vehicle, making the problem even more challenging. Previous research has tried to simplify this problem by reducing degrees of freedom for the tracking either by using a display technology that does not require tracking of the user's movement inside the vehicle [100, 104] or by disregarding this movement altogether [97]. The result is a solution that only displays the correct perspective on a single point inside the vehicle.

OST devices can be desirable for safety reasons as they offer a real-time view of the real world. However, the tracking problem becomes even harder for OST devices because the real world is visible without any latency. Any error or delay in tracking will be visible instantaneous [96]. These errors depend on the tracking difficulty inside a moving vehicle and the accuracy level of the tracking of the vehicle itself. The registration errors in the current systems are too large to make OST devices useful for VIL testing.

Using a video-see through device remedies some of the problems identified above. Nevertheless, the video-see through devices used in this thesis have too high latency and too narrow field of view for anything but simple scenarios. There are upcoming video-see through head-mounted devices that promise sub 10 ms latency, a property that might make the video-see through option more viable [105, 106].

The most viable technology is to use an opaque HMD as this technology does not suffer from registration errors and smaller errors in vehicle tracking are usually not noticed by the driver. A potential problem might be the low visual acuity, although it was deemed less critical by the interviewed engineers in paper VI. A potential solution would be to use a more recent HMD that offers a resolution higher than used in this research.

6.2 Directions of Future Research

The limits of the currently available technology also limit the possible studies that can be performed. In an ideal world, HMDs would have zero latency and a resolution and field of view that matches the physiological capabilities of human vision. Such devices are not available today. However, the technology in the virtual reality field is developing fast, resulting in new devices with improved performance being released to the market at an increasing pace. These devices promise lower latency, higher resolution, and a wider field of view.

Repeating the latency study in paper II with a device that supports lower baseline latency may reveal insights into when increased latency starts affecting driving behavior. The results from such a study would be relevant for remotely operated vehicles because these vehicles would be affected by network latency in addition to the camera-display latency. Further investigations of the effects of the field of view and visual acuity can also be done with these new devices to answer questions about reaction distances as well as speed perception.

However, the most imminent need is to compare traditional real testing and VIL testing for real applications, as indicated in the interview with the engineers in paper VI. Although the evaluation experiment in paper VI indicated that driving behavior would be relatively unaffected, a new experiment should be extended to a more comprehensive study using real active safety systems and more test drivers.

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