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Driving in Virtual Reality

Investigations in Effects of
Latency and Level of Virtuality

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” Sed fugit interea,
fugit inreparabile tempus

Vergilius' *Georgica* 29 BCE

Abstract

When developing new active safety systems or improving existing systems, conducting performance evaluations is necessary. By performing these evaluations during early development stages, potential problems can be identified and mitigated before the system moves into the production phase.

Testing active safety systems can be difficult since the characteristic scenarios may have complex interactions. Using real vehicles for performing these types of scenarios is difficult, expensive, and potentially dangerous. Alternative methods, such as using inflatable targets, scale models, computer simulations or driving simulators, also suffer from drawbacks. Consequently, using virtual reality as an alternative to the traditional methods has been proposed. In this case, a real vehicle is driven while wearing a head-mounted display that presents the scenario to the driver.

This research aims to investigate the potential of such technology. Specifically, this work investigates how the chosen technology affects the driver. This investigation has been conducted through a literature review. A test platform was constructed, and two user studies using normal drivers were performed. The first study focused on the effects of visual time delays on driver behavior. This study revealed that lateral behavior changes with added time delays, whereas longitudinal behavior appears unaffected. The second study investigated how driver behavior is affected by different modes of virtuality. This study demonstrated that drivers perceived mixed reality as more difficult than virtual reality.

The main contribution of this work is the detailed understanding of how time delays and different modes of virtuality affect drivers. This is important knowledge for selecting which scenarios are suitable for evaluation using virtual reality.

Keywords: Virtual Reality, Augmented Reality, Mixed Reality, Latency, Driver Behavior, Active Safety Testing

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Björn Blissing

Linköping, September 2016

Abbreviations

ABS	Anti-lock Braking System
ADAS	Advanced Driver Assistance System
AEB	Autonomous Emergency Braking
ANOVA	Analysis of Variance
AR	Augmented Reality
AV	Augmented Virtuality
CAVE	Cave Automatic Virtual Environment
EBA	Emergency Brake Assist
ESC	Electronic Stability Control
FCW	Forward Collision Warning
FOT	Field Operational Testing
GPS	Global Positioning System
HMD	Head-Mounted Display
JND	Just Noticeable Differences
LCW	Lane Change Warning
LDW	Lane Departure Warning
LKA	Lane Keep Assist
MR	Mixed Reality
OST	Optical See-Through
PSE	Point of Subjective Equality
RMS	Root Mean Square
SLAM	Simultaneous Localization And Mapping
VR	Virtual Reality
VST	Video See-Through

Papers

The following four appended papers are arranged in chronological order of publication and will be referred to by their Roman numerals. All papers are printed in their original published 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] and [IV], 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] Björn Blissling, Fredrik Bruzelius, and Johan Ölvander. “Augmented and Mixed Reality as a tool for evaluation of Vehicle Active Safety Systems”. In: *Proceedings of the 4th International Conference on Road Safety and Simulation*. October. Rome, Italy: Aracne, 2013.
- [II] Björn Blissling and Fredrik Bruzelius. “A Technical Platform Using Augmented Reality For Active Safety Testing”. In: *Proceedings of the 5th International Conference on Road Safety and Simulation*. Orlando, FL, USA: University of Central Florida, 2015, pp. 793–803.
- [III] Björn Blissling, Fredrik Bruzelius, and Olle Eriksson. “Effects of Visual Latency on Vehicle Driving Behavior”. In: *ACM Transactions on Applied Perception* 14.1 (Aug. 2016), pp. 5.1–5.12. DOI: 10.1145/2971320.
- [IV] Björn Blissling, Fredrik Bruzelius, and Olle Eriksson. “Driver behavior in mixed and virtual reality – a comparative study”. In: *Proceedings of the Driving Simulation Conference 2016 VR*. Paris, France: Driving Simulation Association, 2016, pp. 179–186.

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

- [V] Jonas Andersson Hultgren, Björn Blissing, and Jonas Jansson. “Effects of motion parallax in driving simulators”. In: *Proceedings of the Driving Simulation Conference Europe 2012*. Paris, France, 2012.
- [VI] Lars Eriksson, Anne Bolling, Torbjörn Alm, Anders Andersson, Christer Ahlström, Björn Blissing, and Göran Nilsson. “LDW or rumble strips in unintentional lane departures: Driver acceptance and performance”. In: *Advances in Human Aspects of Road and Rail Transportation*. CRC Press, 2013, pp. 77–86.
- [VII] Jonas Jansson, Jesper Sandin, Bruno Augusto, Martin Fischer, Björn Blissing, and Laban Källgren. “Design and performance of the VTI Sim IV”. In: *Proceedings of the Driving Simulation Conference Europe 2014*. Paris, France, 2014, pp. 4.1–4.7.
- [VIII] Lars Eriksson, Lisa Palmqvist, Jonas Andersson Hultgren, Björn Blissing, and Steven Nordin. “Performance and presence with head-movement produced motion parallax in simulated driving”. In: *Transportation Research Part F: Traffic Psychology and Behaviour* 34 (Oct. 2015), pp. 54–64. DOI: 10.1016/j.trf.2015.07.013.

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Part I

Context of the Work

1

Introduction

When testing vehicles during development or during driver training, there may be a need to perform scenarios that are too dangerous or too complex to perform using real target vehicles. Traditionally, these types of tests are conducted using driving simulators. These simulators use a computational model of the vehicle dynamics, and high-end simulators also use advanced motion systems to replicate the expected motion feedback from a real vehicle. These models and motion systems cannot exactly reproduce the driving experience, which may result in altered driving behavior and/or motion sickness. This can make the results from such studies questionable or even invalid.

To overcome this problem, one option is to use a real vehicle on a test track while replacing the targets with virtual objects. The goal is to combine the advantages of proving ground testing and driving simulators. These virtual objects must be displayed to the driver in a believable fashion and affect driver behavior in a similar way as a real target. The increase in the number of driver support systems introduced in recent years has increased the interest in performing these types of tests while still achieving high validity.

1.1 Research Aim

The aim of this research is to evaluate the use of virtual reality and mixed reality as a potential tool for use during the development of active safety systems. Before such a tool is introduced in the development process, understanding how the tool may affect the results is necessary.

The current head-mounted display technology poses limitations on what can be achieved in terms of realism. Previous research has focused on the use of optical see-through devices. These devices have the benefit

of always providing a direct view of the real world, but they suffer from issues due to latency and cannot have virtual objects occlude real objects. Rather, this work has primarily focused on using video see-through devices. Naturally, these devices come with their own limitations, and the main goal of this work is to attempt to identify and quantify these effects on driver behavior because the usefulness of these types of devices in the development process would be impaired by possible adverse effects.

1.2 Research Questions

The following main research questions have been identified:

- RQ1** – *Can the testing of active safety systems using virtual reality inside a real vehicle be a complement to using driving simulators?*
- RQ2** – *Are there certain types of scenarios that are more suitable for virtual reality testing?*
- RQ3** – *What are the technical requirements for such systems in terms of visual latency and its effect on driver behavior?*
- RQ4** – *In this context, is augmented reality preferable to virtual reality?*

1.3 Thesis Overview

This thesis is divided into two parts. The first part, which includes chapters 2–3, provides the context for this research. The second part, chapter 4, summarizes the results and provides a discussion of the appended published papers.

Chapter 2 explains virtual reality technology in general. This chapter presents details about display systems, tracking systems and the concept of latency.

Chapter 3 is dedicated to the testing of active safety systems. This chapter explains the concept of active safety systems, as well as describes ways to test such systems during different development phases.

Chapter 4 introduces the aims, results, and individual contributions of each of the four papers included in this thesis.

Chapter 5 summarizes the findings published in the appended papers and discusses the results and contributions. This chapter also attempts to look ahead to suggest interesting future research topics.

2

Virtual Reality

The term Virtual Reality (VR) has been used to describe technology that replaces sensory inputs with artificial inputs to make the user believe that he or she is part of an artificial world. No strict definition of VR exists, but three components are generally required [1]:

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

It is also possible to combine the real world and the virtual world. The amount of virtuality can be expressed as a continuum from fully real to completely virtual (see figure 2.1). The area in between the completely virtual and the completely real worlds is denoted as Mixed Reality (MR). When virtual objects are added to the real world, the term Augmented Reality (AR) is generally used. A typical example of AR is to add annotations to objects in the real world, but it can also be to add a virtual object to the real world, such as a virtual teapot placed on a real table or a virtual vehicle in a real traffic environment. On this continuum is also (*the more uncommon*) Augmented Virtuality (AV), which means to add real objects to an otherwise virtual world.

VR has been used in research, product development, education, training, therapy and for entertainment purposes. Examples include aeronautical, automotive, architectural, medical, and military applications [2].

In the automotive sector, VR has been used for design and development, and there have also been experiments with the training of both drivers and for servicing and maintenance crews [3].

Figure 2.1 *The reality-virtuality continuum proposed by Milgram et al. [4]*

2.1 Display Systems

Some form of display system is required to present an immersive experience to the user. These systems can be categorized into three main variants: *world fixed displays*, *handheld devices*, and *head-mounted displays*.

2.1.1 World Fixed Displays

There are many options for world fixed displays, such as a simple monitor on a desktop capable of presenting an oriented view to the user, occasionally called *fishtank VR* [5]. If there is a requirement for multiple users, one option is to use an *infinity wall* [6], which is a large screen where multiple digital projectors are used to achieve very high-resolution images. By using synchronized stereo projectors, these screens can have multiple users at the same time (see figure 2.2). If there is a need for an even more immersive experience, the projection can be made on multiple sides of a room-sized cube, also known as a Cave Automatic Virtual Environment (CAVE) [7]. Another option is to have a cylindrical or dome-shaped screen, which covers a large part of the user's field of view. These are most common for seated experiences, such as flight simulators or driving simulators. The main drawbacks of fixed displays are that they often require a large footprint and are quite expensive.

2.1.2 Handheld Devices

Handheld devices are most common in the case of AR [8]. For example, they allow a user to use a tablet or a mobile phone pointed toward an object in the real world, which then receives oriented annotations or 3D animations displayed on the screen of the device.

Figure 2.2 Fixed display systems with different levels of immersion. (a) Infinity wall, (b) cylindrical screen, (c) 4-sided CAVE, and (d) dome display

2.1.3 Head-Mounted Displays

Head-Mounted Displays (HMDs) are probably the device most commonly associated with VR. The HMD can be completely opaque and only display a completely virtual world. However, it is also possible to have HMDs that combine virtual information with the real world. These can be of two different variants, using either Optical See-Through (OST) or Video See-Through (VST).

In an OST system, the virtual information is displayed on some form of optical combiner (see figure 2.3 a). This provides the user with a direct view of the environment without any delay or distortion. However,

Figure 2.3 Schematic illustration of HMD with optical see-through (a) and video see-through (b)

this solution often suffers from registration errors, where the generated image and the real-world objects are out of alignment [9]. Optical see-through systems also suffer from low brightness and contrast, which can be important when using in a bright outdoor environment.

The VST system uses video cameras, and the information of the real world is combined inside the electronics of the system (see figure 2.3 b). A VST HMD can display graphics that completely occlude the image from the cameras since the display can completely replace parts of the captured image with the computer-generated graphics. However, one of the major shortcomings of VST is the latency of cameras that provide visual sensory input of the real environment [10].

2.2 Tracking Systems

To be able to present an oriented view to the user, some form of 3D tracking technology must be used to track the position and orientation of the user. There are multiple technologies available, as described in the survey by Bhatnagar [11]. The information from that survey has been further expanded in the book chapter by Foxlin [12]. The most commonly used technologies for tracking position and orientation are as follows:

Mechanical trackers – By connecting the tracked object to rigid rods, which in turn are connected to rotary encoders, the current position and orientation can be calculated using forward kinematics.

Acoustical trackers – The position can be calculated by measuring the time of flight of a sound signal from a fixed reference position.

Electromagnetic trackers – Magnetic trackers work by having a base station that emits magnetic fields. The tracked object is fitted with sensors that can measure this generated magnetic field. This results in measurement of both position and orientation.

Inertial trackers – Inertial trackers work by measuring angular velocities and linear accelerations. Angular velocity can be measured using a gyroscope and then integrated to obtain a relative orientation change since the last measurement. An accelerometer can measure linear accelerations. The acceleration information must be integrated twice to obtain a position. Any error due to noise or bias in the gyroscopes or accelerometers will lead to drift since errors will accumulate over time.

Optical trackers – Optical trackers work by projecting patterns of light over the tracking volume. The tracked object is fitted with light sensors that can detect changes in light. Knowledge of the light pattern and the information from the light sensors can be used to calculate a position.

Video trackers – Video trackers utilize cameras and image processing to track objects. The camera can be placed on the tracked object to look at fixed objects in the environment. This type of tracking is known as inside-out tracking. Another option is to have the camera fixed and look at the tracked object, which is known as outside-in tracking. Outside-in tracking is more susceptible to occlusion problems, but it has the benefit of not having to equip the tracked object with a potentially heavy camera.

Each tracking technology has its own strengths and drawbacks; thus, hybrid solutions are often used to combine the best aspects of different tracking technologies.

To track vehicles over large areas, the most common technology is to use some form of satellite-based tracking system, such as Global Positioning System (GPS). Satellite-based systems provide absolute positions with reasonable accuracy and precision. However, if higher precision is desired, these systems can be combined with some form of odometry. This can be achieved using optical measurement systems or

laser Doppler velocimetry, which uses the Doppler shift in a laser beam to measure the velocity of the ground surface relative to the vehicle.

An alternative to using GPS is to use image-based Simultaneous Localization And Mapping (SLAM) techniques, which can calculate positions and orientations with high precision [13]. However, these techniques can have high latency due to image processing delays.

2.3 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 (see figure 2.4). Each subsystem can cause time delays [14]. The tracker may have some latency when measuring the current position and orientation, occasionally using multiple measurements. Then, the image generator processes this tracker data, runs a simulation step, and generates a new image, which 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 [15].

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 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. The time delay is from when the cameras capture the image of the real world until this image is displayed to the user inside the HMD. This can be called *photon-to-photon* latency or *visual latency*.

Figure 2.4 *The possible sources of latency.*

2.3.1 Effects of Latency

Low latency has been proven to be important for cognitive functions such as sense of presence, spatial cognition, and awareness [16, 17]. When latency increases, the user experiences decreased visual acuity, decreased performance, decreased presence and is less susceptible to training [18]. Increased latency is also associated with increased levels of simulator sickness [19]. Stress effects also increase with added latency [20].

2.3.2 Measuring Latency

Several methods have been developed to quantify the latency in VR systems or subsystems. To measure the latency in the tracking system, one option is 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 [21]. A common method to measure the time delay in the full VR system is to record the HMD with a high-speed video camera. The latency can then be estimated by counting frames between HMD movement and the corresponding change in the display inside the HMD. This method was introduced by He et al. [22], and an automated variant of this method was presented by Friston and Steed [23].

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, which causes the display inside the HMD to illuminate the light-sensing device. By feeding the signals from the pulse generator and this signal from the light-sensing device into an oscilloscope, the latency can be measured as the time difference between the two signals [14].

2.3.3 Latency Detection

There have been a couple of studies related to 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 of 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 [24] and Ellis et al. [25], who reported JND in latency levels ranging from 14 ms to 77 ms. Even stricter requirements were found by Jerald and Whitton [26], 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. [18] reported acceptable latency levels between 60 and 200 ms, and in the study by Moss et al. [27], latency levels reaching as high as 200 ms (mean 148 ms) were reported 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 [28]. In OST systems, the real world is viewed directly, which makes the latency detectable at considerably lower levels. A study by Ng et al. [29] 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. By using a closed-loop system to continuously measure the resulting registration error in each frame and using that information to correct the next frame, Bajura and Neumann [30] showed that it was possible to reduce the visible registration errors.

3

Testing of Active Safety Systems

Traditionally, the automotive industry has focused on passive safety, i.e., how to best protect the occupants inside the vehicle in the case of an accident. Three-point seat belts, crumple zones, and side impact protection are good examples of passive safety systems, and the use of these types of systems has decreased traffic-related injuries and fatalities. Testing of passive systems was traditionally performed as crash tests, which measure the forces exerted on crash test dummies. This may involve crashing a vehicle against another vehicle or against a very heavy stationary object. Today, the majority of crash tests are conducted using advanced modeling and simulation tools, which has reduced both development time and costs and increased the crash performance of vehicles [31]. Compared to active safety systems, it is more straightforward to test passive safety systems using virtual simulations since they do not need to consider the actions of the human driver.

3.1 Active Safety Systems

Active safety systems use another approach. Here, the goal is to construct systems that completely avoid accidents or at least minimize the impact of accidents. Their level of automation ranges from simple systems designed to aid the driver in his actions, such as Anti-lock Braking System (ABS), Electronic Stability Control (ESC) or Emergency Brake Assist (EBA), to systems that warn the driver of potential dangers, such as Forward Collision Warning (FCW), Lane Change Warning (LCW), Lane Departure Warning (LDW) or blind spot monitors, to Advanced Driver Assistance System (ADAS), which can assume control of the vehicle at critical situations, such as Lane Keep Assist (LKA) or Autonomous Emergency Braking (AEB) [32].

The majority of these systems require advanced sensors to continuously capture the environment surrounding the vehicle. This can be radar, lidar, cameras, GPS sensors and *vehicle-to-vehicle* or *vehicle-to-infrastructure* communication.

Various accident-prone scenarios have been identified that may benefit from the introduction of ADAS, such as the scenarios proposed by Najm and Smith [33] (see figure 3.1). The complexity of testing ADAS is tightly coupled with the complexity of the interactions in the scenario. As interactions become more complicated, the difficulty of evaluating these systems increases. However, before a ADAS can be implemented in a production vehicle, it must be tested meticulously.

Figure 3.1 Examples from Najm and Smith [33] of accident-prone scenarios with increasing level of complexity: (a) Vehicle departs road edge to the right. (b) Approaching a slower moving vehicle. (c) Vehicle cutting in at overtake situation. (d) Vehicle turns left and encroaches adjacent vehicle. (e) Vehicle approaching a slower vehicle, attempts to change lane and encroaches vehicle on adjacent lane.

3.2 Development Process

Many descriptions of generic product development processes exist. According to Ulrich and Eppinger [34], the development process can be divided into the phases planning, concept development, system-level design, detailed design, testing and refinement, and finally production ramp up.

The aim of this thesis is to develop methods that use VR that can enable the testing of active safety systems using real drivers. By performing these tests using VR, the aim is to use these methods in concept development and system-level design, as well as during the testing and refinement phase.

Although many generic product development processes exist, there are few publications regarding the specific development process when engineering active safety systems. This is probably due to the secrecy between the competing companies within the automotive sector. However, there are some publications that outline the process used. Toyota [35] has described their overall process for safety as a V-model (see figure 3.2) using the following steps:

1. *Macro traffic accident analysis* — Perform macro analysis of accident data to identify accident-prone scenarios.
2. *Micro traffic accident analysis* — Analyze the identified scenarios in detail to find root causes of the accident.
3. *Driver behavior analysis* — Analyze the typical driver behavior in the identified situations.
4. *System concept* — Design a system that attempts to prevent the accident.
5. *System requirements* — Specify the requirements for the system concept.
6. *Function test* — Perform function tests of the system prototype.
7. *System evaluation test* — Perform evaluation tests of the system prototype.
8. *Effectiveness estimation* — Computer simulations are used 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 from statistics.

The technology and processes within this work can be used in many of these steps. It can be used as a tool when performing driver behavior analysis by subjecting drivers to typical accident-prone scenarios and studying the resulting behavior to better understand which type of intervention would be most suitable. The knowledge from this analysis can be used as input for both the concept design and the system requirements. The technology can also be employed for prototyping during functional tests, as well as during system evaluation.

Figure 3.2 The development process according to Toyota [35].

3.3 Test Environments

Testing of ADAS can be addressed in multiple ways depending on which property of the system is desired to be evaluated. The most common environments are described below.

3.3.1 Proving Grounds

Traditionally, most of the testing has been performed at proving grounds. These have the benefit of being controlled environments where tests can be setup and performed under relatively safe conditions. Trained test drivers are often used to perform the maneuvers, but if the maneuver is deemed too dangerous or if stricter repeatability is required, then driving robots must be used. These are robots that may control pedals, steering wheel, and/or gear shifter (see figure 3.3).

Figure 3.3 *The VTI driving robot mounted in a Volkswagen Passat (Image courtesy of VTI/Anders Andersson).*

Unfortunately, this eliminates the possibility of studying the interaction between the driver and vehicle.

Testing of ADAS often requires complex interactions with other vehicles. At the same time, collisions are undesired since the subject vehicle may be a preproduction vehicle, which cannot be damaged. Some maneuvers that are desired to be tested are performed at such high speeds that it may cause serious damage to vehicles and drivers.

To be able to perform these types of tests with reasonable safety, a multitude of alternatives to using real target vehicles have been employed. The traditional variants use static targets: either foam targets or inflatable targets. These targets can be manufactured such that their dimensions and radar signature match those of a real vehicle.

If movement of the targets is desired, then these targets must be attached to something that can propel them. One option is to have the target as an outrigger or trailer, which is towed by a proxy vehicle. There are also installations that employ an advanced wire system to drive the targets, particularly when the targets are pedestrians or cyclists. Another option is to use a low profile remote controlled vehicle, which is so low that it can safely pass under the subject vehicle in the case of a collision.

3.3.2 Field Operational Testing

For micro traffic accident analysis, there is a need to observe naturalistic driving behavior, and thus, Field Operational Testing (FOT) is used. Here, normal drivers are assigned to a vehicle that is fitted with equipment able to log their driving behavior. This can be video loggers, GPS loggers or other data loggers that store the current state of the vehicle.

The main drawback associated with FOT is that there is generally no possibility of choosing specific situations to study. It is often necessary to have a multitude of vehicles equipped to be able collect sufficient data to include enough critical situations to be able to perform meaningful data analysis. One example is the *euroFOT* project [36], which used more than 1000 vehicles over a period of one year. This resulted in several hundred terabytes of data that had to be analyzed. This also reveals the time-consuming and expensive nature of FOT.

3.3.3 Offline Computer Simulations

Offline computer simulations are typically used to study the effectiveness of the ADAS algorithms, particularly to find error cases. The first type of errors are *false positives*, which are when the vehicle would react to a non-existent threat. Too many false positives could make the driver lose confidence in the system and actively shut it down. The other type of errors are *false negatives*, which are when the vehicle would fail to react to a real threat.

Performing computer simulations is very cost effective since this process can be parallelized once a scenario is setup, and it can easily be modified to produce hundreds or thousands of variants of the same scenario [37]. However, since it is an offline simulation, there is no possibility of having any real driver interactions.

3.3.4 Scale Models

One option is to use R/C scale model vehicles, either fitted with similar sensors as real vehicles or using simulated sensors [38, 39]. By equipping the scale model with a video camera, the vehicle can be controlled via telepresence, thus enabling studies involving driver-system interactions. The main drawback of using scale models is that the vehicle dynamics of a scale model is quite different from that of a real vehicle.

Figure 3.4 *The VTI Driving Simulator IV featuring an advanced motion system (Image courtesy of VTI/Hejdlösa Bilder AB).*

3.3.5 Driving Simulators

High-end driving simulators use immersive display systems and high-performance motion systems to recreate a believable driving experience (see figure 3.4). The benefits of driving simulators are that they provide a safe way of performing scenarios that are too dangerous, costly or impractical to perform on real roads or even on proving grounds. Driving simulators can also be used to perform scenarios that contain complex interactions between multiple targets such that their setup would be next to impossible to perform in reality. The number of variables can also be reduced in simulators, streamlining the scenarios in such a way that only the desired factors are studied. Another benefit is the repeatability; every test subject can be exposed to the exact same conditions as the persons performing the test before them.

However, driving simulators can suffer from drawbacks, such as motion sickness and driver adaptation, which can lead to questionable validity of results [40].

3.3.6 Virtual Reality

Rather than using a driving simulator, Sheridan [41] proposed a new method that uses VR or MR. By using a real vehicle, no computational model of the vehicle dynamics is needed. Moreover, the vehicle will subject the drivers to real force feedback, hopefully reducing motion sickness. The objective is to be able to use the same repeatable and complex scenarios as driving simulators.

This method has been tested with different display systems and the earliest examples used OST HMDs [42, 43]. There have also been studies that employ opaque HMDs, where the drivers performed the task inside an entirely virtual world [44, 45]. Another display system configuration consisted of cameras and screens mounted fixed relative to the car [46]. A variant of this configuration is to use the windshield as a projection surface for the virtual environment [47]. There has even been a concept system using VST HMD to produce an AV solution, where the real dashboard of the vehicle is included in the virtual environment [48].

This thesis involves studies concerning a system that uses a VST HMD, but this system was used inside a moving vehicle in contrast to the concept by Berg, Millhoff, and Färber [48]. Another difference is that the system was used in an AR mode, which consists of including virtual objects in the real world, whereas the previous concept only replaced everything outside the vehicle with a completely virtual world.

3.4 Evaluation of User Studies

When studying humans with respect to technical systems, it is necessary to consider that human behavior may vary greatly from person to person. To test whether a technical system has the desired effect, there is a need for a method that can distinguish between the effects of the system and those caused by individual variations. The most common method is to use *statistical inference*, which is used to find properties associated with a selected population. Data can be collected either by using devices that record objective data, such as time, position, velocity, acceleration and so forth, or by using questionnaires or interviews to collect subjective data from the test subjects.

A *population* is every object that matches some specified criterion. Examples from an automotive context could be *all drivers on the planet*, *all owners of a premium car* or *all female drivers in Sweden*.

It may be impractical or impossible to test every object in a population. Conversely, a *sample* representing the total population can be used as test subjects. A sample is defined as a subset of the main population selected using a specified procedure. Using the above automotive populations, this could be *20 drivers*, *15 premium car owners* or *50 Swedish female drivers*.

To avoid *bias*, it is important to select the sample from the population that does not depend on the attribute that is about to be studied. For example, only selecting drivers who have had their driver's license for more than 10 years would probably bias the results when studying factors that depend on driving experience for the population of all drivers.

For further reading on this topic, see the work of Kutner et al. [49].

3.4.1 Hypothesis Testing

When testing whether a system has a certain effect, there is a need to formulate a hypothesis, that is, a presumption about the state of the system. The hypothesis should be formulated prior to the evaluation. The null hypothesis (H_0) is typically the state when there is no discernible difference with or without the studied system. In contrast, the criterion for the alternative hypothesis (H_1) is the state when there is a difference with and without the studied system.

When testing which of these two hypotheses are more likely to apply, there are four possible outcomes (see table 3.1). Either the alternative or the null hypothesis has been correctly selected or one of two possible errors has occurred. The first type of error occurs when the null hypothesis state applies to the population, but based on the sample, a decision is made to reject the null hypothesis. By making this type of error, the assumption may be to believe that a studied system has an effect where there is none. This is called a Type-I error or false positive. The other type of error is when the alternative hypothesis state applies to the population, but based on the sample, a decision is made to not reject the null hypothesis. Making this type of error can result in rejecting an effect that actually exists. This is called a Type-II error or false negative.

Table 3.1 Possible outcomes from hypothesis testing

		Actual population state	
		H ₀	H ₁
Decision based on sample from population	H ₀	Correct Decision	Type-II error
	H ₁	Type-I error	Correct Decision

To test whether the populations are significantly different, a T-test can be used. If there are more than two sample sets, then Analysis of Variance (ANOVA) can be used to perform significance tests. The result from ANOVA only indicates whether there is a significant difference between any of the populations. To determine which of the populations differ from each other, additional *post hoc* analysis must be performed. The results from T-tests or ANOVA are commonly reported as *P*-values. These values describe the probability of attaining a result equal to or more extreme than the observed, when the null hypothesis is true. *P*-values lower than 5% are generally considered statistically significant. In conjunction with the significance tests, the arithmetic mean (3.1) and variance (3.2) of the sample sets are typically reported. The mean describes the general level within the group, whereas the sample variance describes how spread out the individuals are within the group.

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (3.1)$$

$$s^2 = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2 \quad (3.2)$$

3.4.2 Study Design

When performing user studies, the goal is to determine whether and how the *explanatory variable* affects the *response variable*. The response variable is the studied measurement, for example, *the time to complete a task* or *the force applied to the brake pedal*. The explanatory variable is the variable that is changed between the studied sample sets, for example, *the enabled state of an active safety system* or *the sound volume level of an audible warning*. When designing studies, the goal is to vary the explanatory variables, while keeping the other variables constant. Typically, the test subjects are denoted as *random factors* since they are a random sample from a larger population.

The study design must be adapted to the population, sample set, studied phenomena and hypotheses. Studies can be *experimental*, *observational*, or a mix of the two. Experimental studies are designed to show a cause-and-effect relationship between one or more explanatory variables, and researchers can divide the samples into groups depending on the state of the explanatory variables. In observational studies, researchers have no control over the explanatory variables and can only observe and draw conclusions from a random sample of the population.

Experimental studies can be performed using either a *between-group design* or a *within-group design*. In between-group design studies, the participants are divided into groups, and each group is then subjected to one level of the testing factor. This design is common in medical studies, where one group is administered the active treatment and the other group is the control group, which may be given a placebo.

Within-group design implies that all participants in the study are subjected to all combinations of testing factors (explanatory variables). The main benefit of a within-group design is that it requires fewer subjects to reach the same statistical power as a study using a between-group design. Another benefit is that individual differences in subjects' behavior are carried over between the different tested factors. The drawback with using a within-group design is that the order of the testing factors must be considered. If all subjects perform the same test in the same order, the results may contain learning effects since the experience from one testing factor may affect subsequent measurements. To correct for these types of effects, the order of testing factors can be varied between the subjects. This process is called counter balancing, and ideally, all possible orders between factors should be represented.

Part II

Contribution

4

Summary of Studies

This chapter introduces the objectives, methods, and results of the four papers included in this thesis. The scientific contributions are also summarized in a more concise form at the beginning of chapter 5.

4.1 Paper I

Paper I describes the state-of-the-art in how Augmented Reality is used in the automotive sector. This paper also contains a more general part regarding display technology and tracking technology, but with a focus on their benefits and drawbacks for automotive use.

4.1.1 Objectives

The objective of paper I is to compile the knowledge from previous research regarding Augmented Reality in vehicle driving situations, focusing on the technical limitations and their possible implications for driver behavior.

4.1.2 Method

A literature review was performed by searching in scientific databases using keywords related to Virtual Reality, Mixed Reality and Augmented Reality within automotive applications. This search resulted in a wide range of papers from scientific journals and conferences. The results were reviewed and sorted by relevance to the intended application. Additional papers describing tracking technologies and HMDs were also added to the literature review to provide a detailed background.

4.1.3 Results

The paper provided a current literature review of the uses of augmented reality within the automotive sector, with a focus on head-mounted displays and tracking technologies. The conclusions favor HMDs compared to windshield-mounted display systems. It also suggests using VST rather than OST since the former can present objects with arbitrary levels of occlusion and the potential to minimize registration errors. The effects of latency in VST systems are highlighted as a future research topic.

4.2 Paper II

Paper II presents the design process for constructing a custom VST HMD intended for use inside a vehicle. It also presents a technique for measuring visual latency with high precision.

4.2.1 Objectives

To be able to perform the desired user studies, some form of VST HMD was needed. Paper II investigated whether it was possible to construct an augmented reality solution from commercial off-the-shelf components that is viable for use as a test platform.

4.2.2 Method

The available VST HMDs options on the market were either deemed too expensive, had a field of view that was too narrow, used a monoscopic camera, or used monochromatic cameras. Since there was no available technology on the market ready for use, it was decided to construct a custom unit using parts available on the open market.

The paper describes how the camera and optics were selected. It also describes how they were mounted to the HMD, with the motivations, benefits, and drawbacks of each option. Two different iterations of the HMDs were constructed: one based on the *Oculus Rift Development Kit 1* and the second based on *Oculus Rift Development Kit 2*.

It also details how tracking was implemented for tracking both the driver inside the cabin and the vehicle on the test track. Additionally, a summary regarding the implementation of the custom image generator

responsible for presenting the automotive scenarios for the user is presented.

This paper also contains a section regarding latency measurements, presenting the multiple options for measuring motion-to-photon and photon-to-photon latency in VR systems. Our custom latency measuring device is described, as well as the latency results from our custom VST HMDs.

4.2.3 Results

This paper shows the process of constructing a technical platform, which can be used for automotive testing. The paper also describes a method for measuring the total latency in the VST HMDs system.

The term *photon-to-photon latency* is introduced to describe the visual latency for VST HMDs.

It also presents how to automate the latency measurement method presented by Jacobs, Livingston, and State [14]. This greatly simplifies situations where a vast number of measurements are needed, which is beneficial for measuring asynchronous systems where latency may vary from frame to frame.

4.3 Paper III

Using the first iteration of the technical platform described in Paper II, a user study was performed to study the effects of latency on driver behavior.

4.3.1 Objectives

The objective was to study how driver behavior changes when drivers are subjected to different levels of visual latency. Since visual latency is present in all VST HMDs, there is a need to quantify the effects that this may have on the user, which in this case are the effects on driving performance.

4.3.2 Method

A user study using 24 drivers was performed. A within-subject design was used since normal driving behavior varies among individuals and because by using a within-subject design, the effect of latency can

be studied per driver. Each driver drove a slalom course while being subjected to three levels of latency. They also performed the task without wearing the HMD to record their driving behavior in an unaffected state. Each task was repeated three times for each level. The driving behavior was recorded and analyzed for changes in lateral and longitudinal behavior, in both the local and global cases. The following objective measurements were used:

Time to completion Defined as the total time the driver took to perform each run. The hypothesis was that increased latency would result in the participants choosing a slower speed to compensate for the increased cognitive load due to the delay.

Acceleration changes The number of changes in acceleration during the task. The hypothesis was that increased latency would lead to a jerkier driving pattern because the driver would feel any acceleration or deceleration before seeing the effects, leading to overcompensation.

Lateral path deviation This is defined as the mean lateral deviation from the ideal path. The ideal path was unique for each driver and calculated from when they completed the task unaffected by added latency. The hypothesis was that the subjects would compensate for higher latency by performing wider turns in the slalom course.

Steering wheel reversals This is defined as the number of times the participants changed the direction of the angular velocity of the steering wheel. The hypothesis was that the participants would be forced to correct their steering more as the latency increased.

In parallel to the objective measures, the subjective opinions of each driver were recorded via a questionnaire. In this questionnaire, the driver had to assess both the difficulty of the task and their own performance. The objective data were recorded using an assisted GPS and a sensor attached to the steering wheel. A statistical model was constructed to test the hypotheses, and the model was analyzed using a three-way ANOVA.

4.3.3 Results

The results show that the use of the HMD affected all measurements, but only the *lateral path deviation* showed a statistically significant effect when considering the difference between the levels of added visual latency. For the highest latency level, the *steering wheel reversals* also increased. Neither *time to completion* nor *acceleration changes* showed any significant effects, which suggests that drivers neither compensate for added latency by changing their velocity nor accelerate and brake more. Instead, they compensate by using a wider lateral driving pattern.

4.4 Paper IV

Using the second iteration of the technical platform described in Paper II, a study was performed to investigate the effects of the selected mode of virtuality.

4.4.1 Objectives

The objective was to study how different VR modes affect driver behavior.

4.4.2 Method

A within-group study was performed using 22 drivers. Each driver drove the same type of slalom course as in Paper II, but rather than changing latency levels, the modes of virtuality were changed. Their driving behavior was recorded and analyzed for changes in lateral and longitudinal behavior. Four different conditions were used:

1. Direct view of the environment - used to record the driving behavior in an unaffected state.
2. Mixed Reality using real cones (*pure video feedback*)
3. Mixed Reality using virtual cones
4. Virtual Reality driving in a completely virtual world.

Similar measurements as in Paper III were used:

Time to completion Same as in Paper III.

Acceleration changes Same as in Paper III.

Maximum curvature Since no steering wheel sensor was available during this study, the local lateral behavior was quantified in the maximum curvature, that is, the maximum value of the ratio between the vehicle yaw rate and the vehicle velocity. The hypothesis was that modes of the maximum curvature will increase if any of the VR modes are perceived as more difficult.

Lateral deviation The lateral deviation was calculated as the Root Mean Square (RMS) of the lateral position of the vehicle trajectory. The hypothesis was that the subjects would compensate with a wider lateral driving pattern if any of the VR modes were deemed more difficult.

The same type of questionnaire as in Paper III was used to record the subjective opinion of each driver.

4.4.3 Results

In this study, it was found that the participants altered their braking and accelerating behavior when using the HMD compared to the unaffected state. The differences between the different VR modes were smaller for both *time to completion* and *acceleration changes*. Only the Mixed Reality mode differed with a significantly lower average speed compared to the other modes.

For the steering behavior, a similar difference could be observed as for the longitudinal case. The direct view runs without the HMD differed compared to those with the HMD for both minimum radii and average lateral margin to the cones. For the other VR modes, *maximum curvature* was higher with mixed and virtual reality modes, whereas the *lateral deviation* was not significantly different in all cases wearing the HMD.

The self-assessment measures were consistent with the other measures regarding the difference between wearing and not wearing the HMD, but Mixed Reality with virtual cones was perceived as the most difficult mode of virtuality.

5

Discussion and Conclusions

This thesis consisted of two user studies in four papers. The following section will discuss the conclusions of the individual papers from a collective perspective.

The initial literature review summarized the existing research regarding VR and AR in the automotive sector. It was found that HMD systems were preferable to fixed windshield-mounted display systems, simply because HMDs require less effort to install and use inside a vehicle. Another drawback with windshield-mounted displays is their problems with image contrast. They also suffer from large registration errors unless head tracking is used.

The literature study also concluded that VST HMDs have clear benefits compared to OST HMDs since the former can display virtual objects that are capable of fully occluding real objects. Another benefit of VST HMDs is that they allow for some rectification of registration errors. Several tracking systems were also evaluated for potential use in automotive applications. Furthermore, it was identified that no previous research had been performed regarding the effects of latency on driving behavior, suggesting a need for further research on this topic.

The knowledge acquired from the literature review was used to construct a customized technical platform for further research. The main works consisted of selecting and assembling suitable hardware, as well as developing the vital software components for interfacing between the different subsystems. A correctional algorithm that allowed for the use of an inertial tracking system inside a moving vehicle was also written and integrated in the platform. The system was also optimized to minimize visual latency. This work also included constructing a latency

measurement device capable of automating a previously developed method [14].

The developed platform was then used to study the effects of latency on driving behavior. The necessary software for introducing the desired latency was developed, and its effect on longitudinal and lateral driving behavior was determined by conducting a user study with untrained drivers. Their driving behavior was recorded using a GPS system, and the test subjects were also allowed to self-assess the difficulty and performance at different latency levels. Surprisingly, the added latency did not affect longitudinal behavior; rather, the drivers attempted to compensate by making larger lateral movements. There was a similar study by Cunningham et al. [50], who investigated visual latency effects using a driving simulator. The results from this driving simulator study were similar to the results presented in this thesis, that is, lateral behavior changed due to latency, whereas the longitudinal behavior was unchanged. These types of results can potentially be explained by the findings of Jerald and Whitton [26], who showed that latency discernibility increases during head rotations. It is plausible that increased discernibility is connected with an adjustment in behavior.

Finally, a study comparing the effects of different modes of VR on driving behavior was conducted. The results showed that using MR visualization was assessed as the most difficult by the test subjects, although their longitudinal driving behavior was not affected. Notably, the HMD itself affected all measured parameters.

5.1 Answers to Research Questions

Using the obtained knowledge, the formulated research questions can be addressed:

***RQ1:** Can the testing of active safety systems using virtual reality inside a real vehicle be a complement to using driving simulators?*

The HMD platform was developed to produce a cost-effective alternative to driving simulators for certain types of scenarios, as well as an attempt to circumvent the issue of simulator sickness since the driver would experience more realistic feedback cues from a real vehicle. However, some test subjects reported feeling nauseated when using the HMD platform. Although the cause of the nausea was not determined in

that particular study, it would be justified to study the effects of HMD systems on motion sickness and what causes it. The effects of latency are inherent to any HMD system, and it would likely cause discrepancies between visual and perceived cues that could trigger simulator sickness.

The current HMD technology is still limited, mainly in regards to latency, field of view and image resolution. In fact, the image resolution of the current generation HMDs is so low that a person exhibiting visual acuity comparable to the maximum possible resolution of a current HMD would be considered unfit to drive by today's safety regulations. These regulations require a visual acuity of at least 0.5 and a minimum of 120 degrees of horizontal field of view to be allowed to apply for a driving license within the European Union [51]. The HMD systems tested herein have a visual acuity closer to 0.2 and a horizontal field of view between of 90 degrees and even lower when using the developed VST HMD. Thus, before virtual reality testing can complement testing in driving simulators, there is need for improvement of the HMD technology, particularly in terms of latency.

***RQ2:** Are there certain types of scenarios that are more suitable for virtual reality testing?*

To choose suitable scenarios, it is important to consider the potential validity of the results. The tool used may have absolute validity or relative validity [52]. Absolute validity means that both the direction and the magnitude of the results match the real case, whereas tools that expresses relative validity only show the same direction while the magnitude of the results may be scaled.

The results from the user studies suggest that the lateral behavior is more affected than the longitudinal behavior, both by latency level and mode of virtuality. Additionally, the narrow field of view of the current HMDs forces the users to exaggerate their head rotations while using the HMD. Previous studies have also shown that increased head rotations increase latency detection, which makes the HMD systems unsuitable for scenarios that require the driver to shift their gaze from side to side. Hence, the natural conclusion would be to exclude scenarios that require extensive lateral motion.

RQ3: *What are the technical requirements for such systems in terms of visual latency and its effect on driver behavior?*

Even when using the lowest latency capable by the tested platform, driving behavior is affected in all measured parameters. The current technical solutions cannot achieve low enough latency to be unnoticeable to the user.

One participant in each user study had to abort due to motion sickness, but many reported minor levels of nausea or dizziness. This would indicate that motion sickness is an issue even though a real vehicle is used. The causes for this motion sickness have not been studied specifically, but previous research points to latency as a major cause for motion sickness [53].

RQ4: *In this context, is augmented reality preferable to virtual reality?*

The results suggest that VR is preferable to AR. However, the studied VST HMD had a narrower field of view compared to when it was used in pure VR mode, which may explain some of the differences in driving behavior between the studied VR and AR systems. Furthermore, due to both the internal latency and the accuracy of the tracking system, the AR system was displaying quite severe registration errors, which can also be an explanation for why the drivers preferred VR over AR.

5.2 Outlook

The current generation of HMDs are already being updated with newer versions that support higher resolution, wider field of view and lower latency. One possible research direction is to continue exploring the effects of latency and field of view on driver behavior. The current research has limited the user studies to low-speed maneuvers for safety reasons, but if the technology becomes mature enough, it would be reasonable to expand the tests to more natural velocities.

There will always be technological limits to what can be achieved, but as the technology behind VR improves, the testing methods should also evolve. At present, the planning and preparations of tests can be very time consuming. One possible research direction is to improve the procedures behind these preparations, thus enabling even more complex scenarios.

Another potential research focus is to study the development processes used for the design of the vehicle cabin. It is conceivable that the introduction of VR in these processes can shorten the iteration cycles during development and reduce the number of physical prototypes.

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