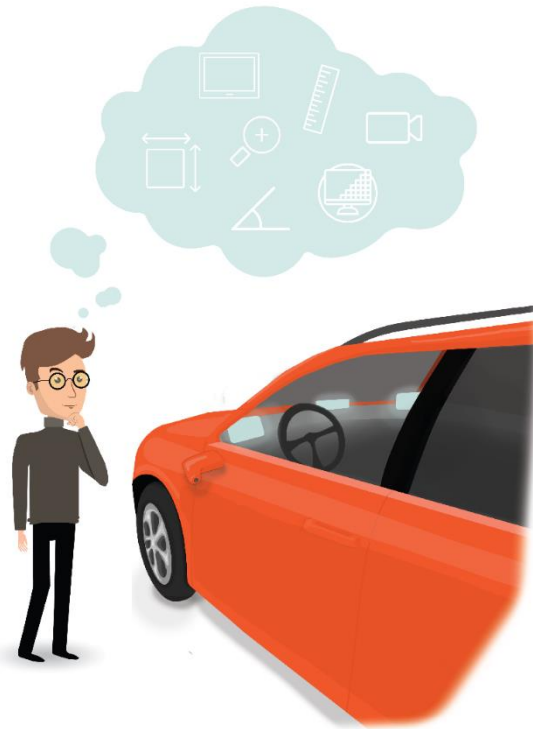




CHALMERS
UNIVERSITY OF TECHNOLOGY



Designing Camera Monitoring Systems in Cars for Enhanced User Performance

Exploring parameters' impact on user performance and providing guidelines for designing CMS

Master thesis in Industrial Design Engineering

PONTUS JOHANSSON & SARA JONASON

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE
Division of Design & Human Factors

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
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MASTER'S THESIS 2021

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Master of Science Thesis 2021
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ABSTRACT

This Master Thesis was conducted at the Industrial Design Engineering program at Chalmers University of Technology in collaboration with Volvo Cars. The aim was to investigate which – and how- design parameters impact user performance (includes the ability to perceive the image, detect objects and estimating the distance to them), when Camera Monitoring Systems (CMS) replace rearview mirrors in cars and which benefits and drawbacks related to the user performance that a specific CMS prototype posed compared to driving with traditional car. It was furthermore to develop guidelines for how to apply this knowledge when designing CMS for increased user performance in cars. Literature studies, expert interviews, workshops, FMEA and user tests were some methods used for discovering this knowledge.

The project resulted in a compilation of 20 design parameters that could affect user performance for CMS and which ten driving situations that are most relevant for the context of CMS. It also resulted in general guidelines for how to apply knowledge regarding researched design parameter's impact on user performance in CMS that any industry party could apply in their work, but also in specific guidelines for how to develop the CMS prototype with regard of enhancing the user performance and experience.

The literature studies led to knowledge regarding the impact that vertical and horizontal placement of the sideview camera, magnification, field of view, distance between the driver's eyes and displays, image resolution and update rate, as well as pictorial depth cues have on distance estimations. Furthermore, how the lateral display placement, number of displays, field of view, presence of vehicle references, viewpoint as well image resolution and update rate impact overall control and object detection when driving.

A parameter user test explored the impact zoom level (which depends on the parameters magnification and field of view) as well as vertical placement of the virtual inner rearview mirror's camera have on distance estimation. Lower camera placement and zoom level made the user perceive distances as longer compared to higher ones. The users however experienced difficulties when estimating the distance using any configurations for the camera, due to the lack of present vehicle reference and since the direct vision through the rearview window was covered.

Many design parameters affect the overall user performance and each design decision must therefore be made considering the others. There is no right or wrong way of how to perform this process, but the general guidelines present an order of which the decisions could be made to make the process more practically implemented based on the parameter characteristics.

A user test comparing the user experience of driving the CMS prototype to a regular car led to insights and guidelines regarding which driving situations that the user experience needs to be improved, namely during lane changes, overtakings and driving in roundabouts. The CMS prototype guidelines also contains suggestions for how to reduce inconsistencies between the different display types and improvements regarding size, shape, surface finish, resolution, magnification and FOV of the displays, and some system functionalities that should be included.

ACKNOWLEDGEMENTS

This Master Thesis was conducted at the Department of Industrial and Materials Science at the Industrial Design Engineering program at Chalmers University of Technology.

Before reading in on how this thesis was conducted and the findings it resulted in, we want to express our appreciation and say a few thanks to the people making the thesis possible.

First of all, we want to thank Gustav Kumlin Groth who was our main supervisor at Volvo Cars for giving us a thorough introduction to the company, connecting us with the right stakeholders, for your expertise concerning rearview mirrors and CMS as well as guiding and supporting us throughout this work. And of course, for now and then easing up the atmosphere with just the right meme at the right moment! We also want to thank Pernilla Nurbo who was our secondary supervisor at the company, for your guidance and especially expertise input concerning conducting our user studies. Thank you also Lars-Ola Bligård who was our supervisor and examiner at Chalmers, for your academic expertise but especially for your commitment, patience, support and encouragement throughout this process. We are so grateful for it and value you highly!

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A few last thanks are dedicated to all twenty-one test persons at Volvo Cars for giving us your time, thoughts and engagement when participating in our user tests, which were prerequisites for carrying out the tests. And of course, a great thank you to Volvo Cars for the opportunity of writing this thesis in collaboration with you.

Thank you so much!

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ABBREVIATIONS

BLIS – Blind Spot Information System

CMS – Camera Monitoring Systems

FMEA – Failure Modes and Effects Analysis

FOV – Field of View

GG – General Guideline

HTA – Heuristic Task Analysis

HUD – Head Up Display

LED – Light Emitting Diode

RPN – Risk Priority Number

SG – Specific Guideline

SUV – Sport Utility Vehicle

TP – Test Person

VIRM – Virtual Inner Rearview Mirror

WEM – Windscreen Electronic Module

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1 INTRODUCTION

This introductory chapter describes the overall background to the project, and clarifies why it is interesting to investigate this area further. The aim, deliverables, delimitations and disposition of the report are described here as well.

1.1 Background

The automotive industry is constantly searching for solutions to reduce the energy consumption of cars, and especially since the industry had started to adjust to the main energy provider being electric energy. Electric cars cannot carry as much energy on board compared to gasoline and diesel cars, which is why the incentive of being energy efficient in the automotive industry is more pronounced.

Camera Monitoring Systems (CMS) replacing rearview mirrors is one way of improving the car's aerodynamic performance, save cost and with the right design also improve the indirect visual field of view (FOV). CMS briefly means substituting the rearview mirrors in cars with cameras that take up visual information from the side- and rear environment of the vehicle and projects it in real time on displays inside the vehicle at appropriate placements. Integrating CMS in cars would decrease aerodynamic related energy consumption since CMS would allow for removing the exterior sideview mirrors, but also to alter the rear shape of the car when the indirect vision no longer is depending on it. (Terzis, 2018)

Integrating CMS into cars also provide possibilities of increasing the user performance and experience of driving if it is integrated in the right way, like for example providing a greater FOV, placing the indirect vision provider at more accessible positions and by integrating digital driving tools like augmented reality in it. (Terzis, 2018)

The concept of CMS in cars has actually existed for decades (Daimler AG, 2021) but it has until now not been integrated into existing cars due to lack of legislative framework that allowed integrating it into series production for cars; it simply has not been allowed. However, in 2015 the international standard ISO16505; “*Road vehicles - Ergonomic and performance aspects of Camera Monitor Systems - Requirements and test procedures*”, was published and in combination with recent versions of UN Regulation No.46 (Terzis, 2018), which provides the legislative regulations concerning how indirect vision in cars must be implemented within the European Union (UNECE, 2016). The possibilities opened up for the car industry within EU of replacing the previously mandatory side- and rearview mirrors with CMS (Terzis, 2018). A few car makers; Audi, Honda and Lexus, already have models available on the European market with implemented CMS instead of rearview mirrors, and since – if implemented successfully – CMS could be the future of indirect vision in cars. Integrating CMS in cars could be a way of staying on the frontline of the car development and signaling just that to customers.

However, the integration of CMS also brings about some challenges concerning the user performance and experience. The most recognized ones are that the perception of the surrounding environment and objects decreases when removing binocular depth cues. This implies a transition of switching from a three-dimensional (the mirrors) to two-dimensional images (displays) and making the otherwise dynamic FOV (due to head movements) into a static one on the display (Terzis, 2018). Since there are benefits of integrating CMS into cars that the car industry wants to utilize, but that currently pose difficulties for the user performance of driving and hence increases the safety risks of driving, it is crucial to understand how to overcome them.

Previous research explores the impact of some design parameters for CMS have on user performance. The existing research is spread out in numerous different articles, books and reports where the findings are expressed in different terms compared to each other. This makes it difficult to get an overview of the findings and to put them in context and relation to each other, which is necessary when designing CMS with the aim of maintaining or increasing the user performance when replacing rearview mirrors. It is particularly important to collect the findings and put them into context since decisions inevitably will have to be made regarding all parameters when designing CMS, and it is the interaction of all these decisions that will determine what total impact the system will have on user performance and experience.

1.2 Aim

The aim of the master thesis is to identify which parameters affect the user performance when using CMS for rear- and sideview sight (indirect vision) in cars. It is furthermore to define or identity in what way they affect the user performance, and to deliver guidelines on how those can be altered in order to maintain or improve user performance compared to traditional mirrors for indirect vision in future development of CMS.

1.3 Deliverables

The deliverables of the project are:

- A compilation of design parameters that possibly affect user performance when driving, related to indirect vision in cars equipped with CMS
- A compilation of previous researched design parameters' impact on user performance in CMS
- A list of guidelines and recommendations for how different design parameters could and should be used in future CMS development in order to alter user performance
- A list of guidelines and recommendations for how the CMS prototype should be developed further to increase user performance

1.4 Delimitations

The period of which this thesis was performed the Covid-19 pandemic was highly present, which restricted the possibilities of carrying out user tests and limited the amount of people that took part of them.

1.5 Disposition of Report

The report is built upon the ten steps which are illustrated in Figure 1. The introduction contains a background, aim, deliverables, delimitations and this subchapter (disposition of report). It is mostly to get an understanding of what the report concerns. Next step is the chapter of theory, where all necessary information is collected to let the reader understand the report. The chapter of methodology theory (chapter 3) provides more specific explanations about the used methods. Thereafter, the process (chapter 4) is presented, which presents the progress of the project. Thereafter, the chapter 5 (phase I) is presented. In phase I the previous findings from literature are presented, which provided a basis for the upcoming focus within CMS and an understanding of the today's knowledge. In phase II the findings from phase I were used as a basis, to understand what was needed to be focused on and the process of identifying scenarios and parameters for doing that. In phase III, it was decided from the output from phase II that some user tests were to be conducted. Everything regarding the user tests are presented in phase III. In the last phase, phase IV, the output from phase I-III were summarized and concluded into guidelines and recommendations. Thereafter, a discussion of all the previous work and everything that concerns the project are presented in the chapter 9. Lastly, the discussion leads to the last chapter, conclusion, where the final conclusions of the thesis are presented.

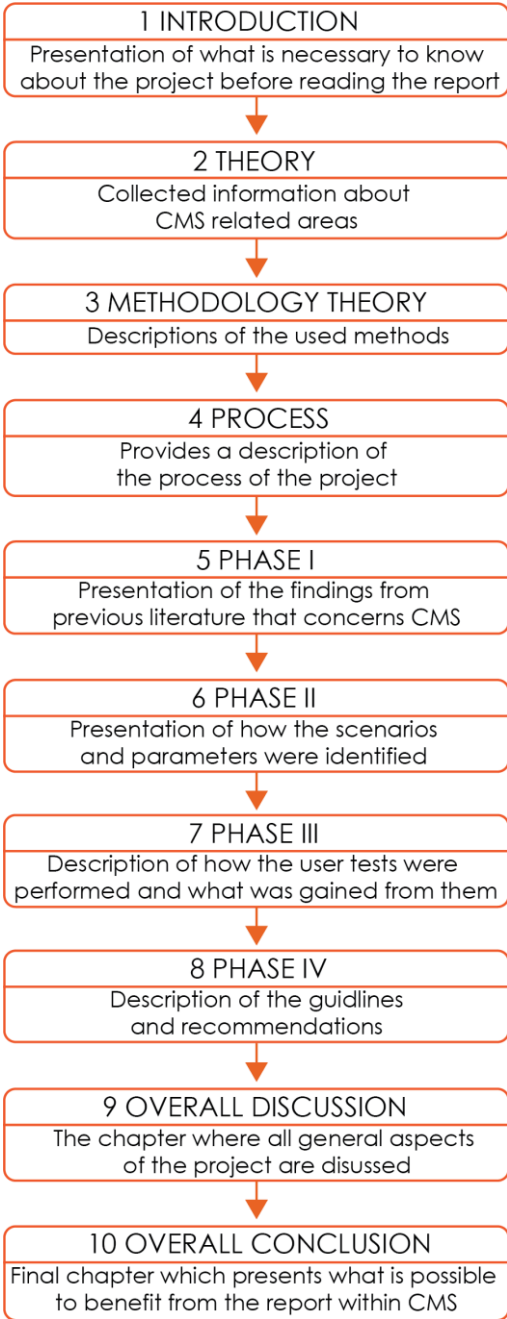


Figure 1 - Disposition of report.

2 THEORY

In this chapter, all the necessary theory needed to follow the report will be presented. It concerns areas such as indirect vision in cars, the human visual sensory, depth perception and geometric optics. These areas are highly appropriate to gain knowledge about to better understand the possibilities and challenges of CMS. Furthermore, technical definitions, standards and regulations are presented to enable understanding parts of the thesis.

2.1 The Human Visual Sensory

In this subchapter, there is theory regarding the eye's anatomy, accommodation of the eye and visual impairments presented.

2.1.1 The Eye's Anatomy

The vision is the dominant sensory intake for humans. About 70 % of the sensory receptors in the body are located in the eyes meanwhile about 40 % of the cerebral cortex in the brain handles and processes visual information. The eye is the visual organ and consists of a spherical structure of three main layers; the fibrous, vascular and inner layer (see Figure 2). The fibrous layer in turn consists of the posterior layer, corneas, and anterior layer sclera which protects the eyeball and acts as anchoring sites for the extrinsic eye muscles. Light enters the eye through the sclera where it starts to refract and then travels through the iris, which is a colored part of the eye containing pigment whose size can be regulated to adjust the amount of light entering the eye. The iris, together with the choroid and ciliary body make up the vascular layer (Figure 2). The ciliary body consists of the thickened ring of muscles that encircles the lens and determines the focus of it. (Brady et al., 2020)

The light then goes through the vitreous humors and fall on the innermost layer, consisting of the retina and optic nerve. It then stimulates the photoreceptors by modifying light sensitive vision pigment, which eventually generates nerve impulse potentials through the cells that converge posteriorly out from the eye through the optic nerve which is connected to the brain. The photoreceptors consist of two types of cells: cones and rods. Cones enable color and sharp vision. Rods are light sensitive and enable dim vision. The patterns of lights are then interpreted by the brain which applies meaning to it. (Brady et al., 2020.)

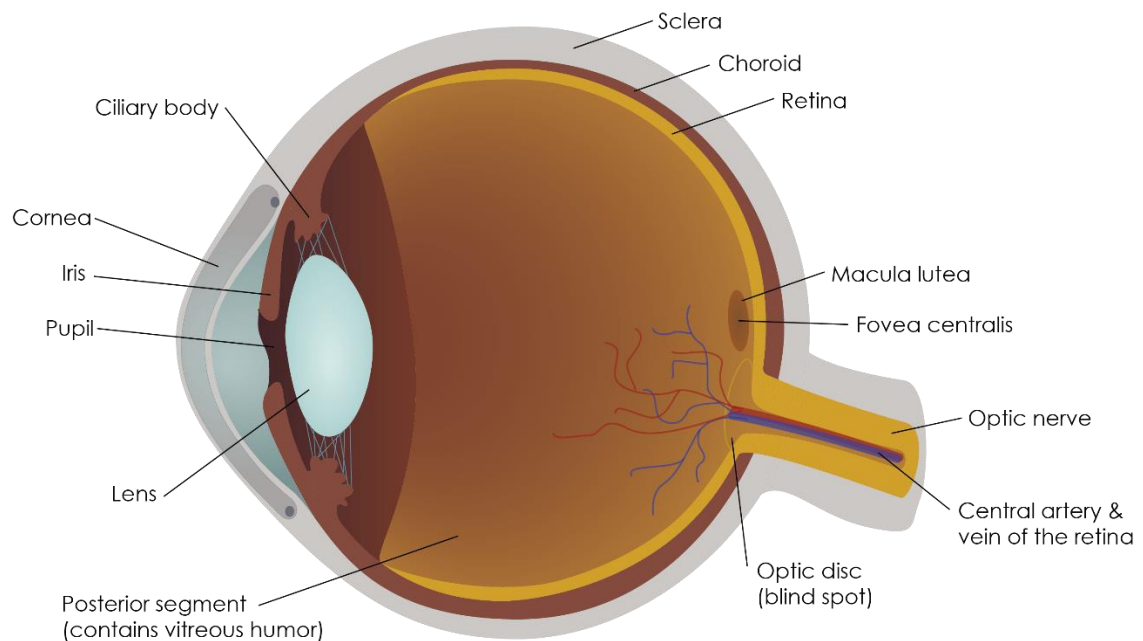


Figure 2 – Simplified human eye. (Brady et al., 2020)

2.1.2 Accommodation of the Eye

There are several different areas on the posterior parts of the retina that are important when it comes to vision. One of them is the area macula lutea (Figure 2), which contains a small pit called fovea centralis. Fovea centralis contains only cones which is why this provides maximum visual acuity, and since it is located straight in line with the anterior-posterior direction of the eye, one tends to see the clearest when looking straight forward. Macula lutea contains mostly cones but the number of cones decreases with an increased radius macula, which is why one is to see less sharp in the peripheral sight. Another important area is the optic disc (blind spot) since the optic nerve exits the eye there, why no photoreceptors are located there and this spot hence does not provide vision from light focused on it. (Brady et al., 2020)

To see an object clearly, one must bend the light from it, so it falls at the single focal point of the retina. Since rays from far away are almost parallel to the eye when entering the cornea, the resting state for the eye is when focusing on objects far away. The rays from closer objects however diverge significantly when entering the eye, so the light must be bent for the person to see it clearly. The cornea breaks the light the most and the humors the least, while the lens breaks them the second most but in an adjustable way. The lens is hence the reason to why it is possible to focus on objects at different distances. This is done by contracting the ciliary muscles surrounding the lens (Figure 3), which results in relaxation and less tension of the lens attached to the ciliary muscles, and the lens becomes more round and thick (convex) due to the elastic recoil. By increased age, the disc however becomes more dense, convex and less elastic, which is why the ability to change shape in order to focus light on the retina decreases. (Brady et al., 2020)

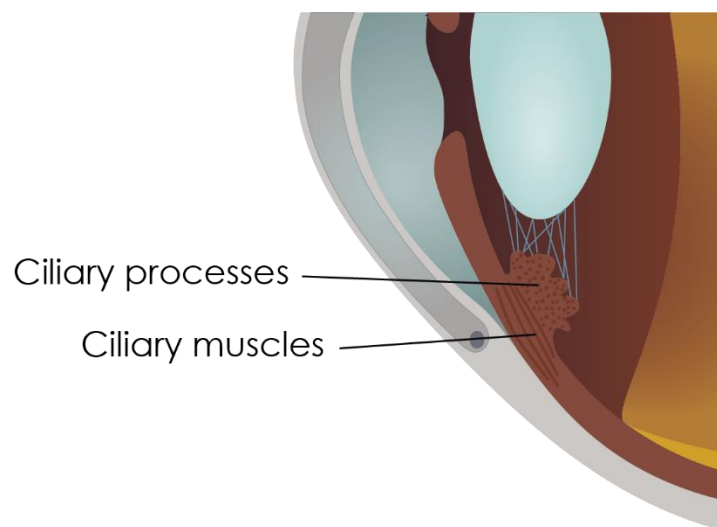


Figure 3 - The human eye, zoomed in on the ciliary muscles and processes. (Brady et al., 2020)

2.1.3 From Light to Image

When the cells connected to the retina exit the eye through the optic nerve, they travel through the visual pathway of the brain. Axons (ends of the cells) that originate from the medial parts of the retina then travel to the optic chiasma (Figure 4) where they cross each other and go through the optic tract, while the axons originating from the lateral parts of the retina compared to the

fovea centralis continue to the optical tract. Simplified, the axons continue from the tracts to the primary visual cortex where the conscious perception of the images projected on the retina occurs. That the axons from the medial parts of the retina deviates and crosses over in the optic chiasm is what enables depth perception, also called three-dimensional sight since the eyes provide slightly different images that are merged in the brain. (Brady et al., 2020)

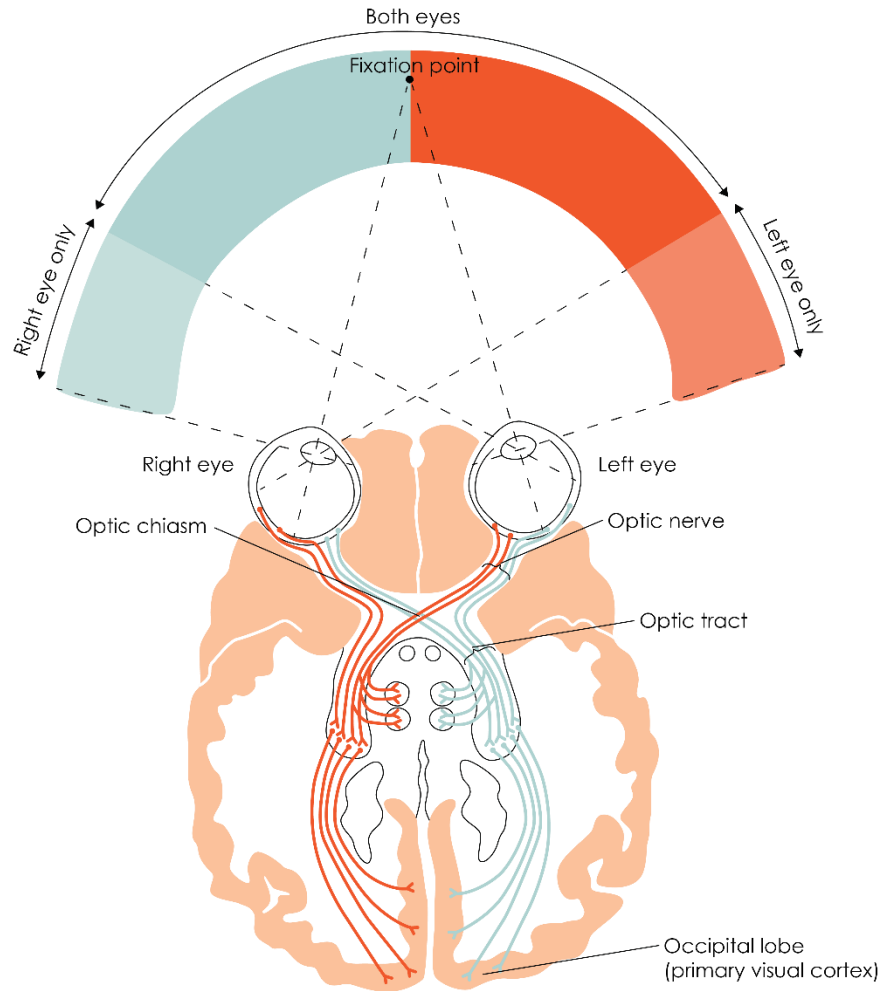


Figure 4 - The visual pathway through the brain from the eyes to the primary visual cortex. (Brady et al., 2020)

2.1.4 Visual Impairments

In this subchapter of human visual sensory, some relevant visual impairments are presented, such as myopia, hyperopia and presbyopia.

Myopia - Near-Sightedness

Myopia, also known as nearsighted, means that the eye has normal vision at shorter distances, but experiences a blurred image at farther distances. The refractive status is determined by the balance of the optical power of the lens and cornea, but also from the axial length of the eye.

More specifically, the anterior chamber length, lens thickness and vitreal chamber depth.

Usually, myopia is the effect of an eye that has become too long. As can be seen in Figure 5, in a normal eye (emmetropic eye) the rays from a distant object are focused on the photoreceptors of

the eye (image A). If focusing on a close by object (image B), the lens accommodates and converge the rays onto the photoreceptors (image C) for a sharp vision. In image E, for a myopic eye, (Figure 5) the rays of a distant object fall in front of the photoreceptors, which causes a non-focused sight. This cannot be brought into focus through accommodation and is therefore in need of external correction, image G in Figure 5. Myopia can be corrected with glasses, contact lenses and refractive surgery. Though, as seen in image F, objects at closer distances are seen sharply by the eye since the rays converge onto the photoreceptors. (Morgan et al., 2012)

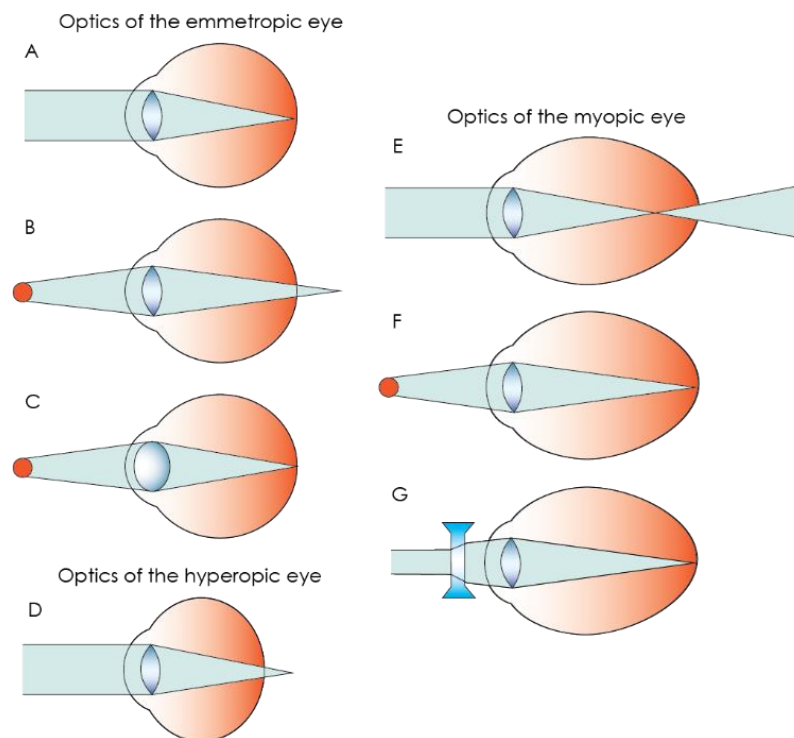


Figure 5 - Optics of emmetropic, hyperopic and myopic eyes. (Morgan et al., 2012)

Hyperopia - Far-Sightedness

In opposite to myopia, this eye condition often originates from a too short eye or the cornea is curved too little. The degree of hyperopia influences the eye's focusing ability. People with more severe hyperopia might only be able to get a clear image of object at a far great distance, while people with milder degree might see clearly at shorter distances as well. With hyperopia it is possible to focus on distant objects with a sharp image, but not for close objects. As can be seen in Figure 5 (image D), the eye is too short which makes the rays from distant objects to be focused behind the photoreceptors, though this is adjusted by accommodation. The issue appears when trying to observe a close by object, since the lens cannot accommodate that much. Therefore, blurry images will appear when observing nearby objects. This can be corrected to a normal vision by using glasses, contact lenses or surgery. (*Farsightedness - Symptoms and Causes*, 2020)

Presbyopia - Age Related Worsened Vision

When getting older, presbyopia is a common condition of the eyes. It means that the eye's lens gets stiffer and loses the ability to accommodate on short distances, which implies blurred

images while observing closed-up objects. The stiffer the lens gets, the more difficult it gets to focus the light rays on the photoreceptors. Presbyopia is a part of human aging and usually begins when around 40 years old and continues getting worse until 60 years old. (*Ålderssynthet - Memira Eyecenter*, 2020)

2.2 Depth Perception

This subchapter of theory includes some categories of depth perception that are necessary to have an understanding about when reading the report. The concerned categories are distance perception, binocular depth cues and monocular depth cues.

2.2.1 Distance Perception

Distance perception refers to the process of when an observer perceives the distance between two points in space. One distinguishes between the terms egocentric and exocentric perception, and the first mentioned refers to the distance between an object and the observer, while later refers to the distance between two objects, and the perception for these two different types show different characteristics. There is also a distinction between the two terms distance perception and depth perception (which are commonly used as synonyms), and the latter refers to the exocentric perception along the line of sight of the observer. (Yamamoto, 2017)

According to Andre and Rogers (2006) through Daum and Hecht (2009), research has found that the method of expressing distances using words leads to less accurate estimations compared to using action-based methods i.e. blindfold walking. They found that verbalizing distances led to users underestimating distances when the distance was greater than several meters (up to about 30 meters) while the action-based methods caused more accurate estimations.

2.2.2 Binocular Depth Cues

Physiological depth cues such as retinal disparity and convergence are described in the following section.

Retinal Disparity

The axons originating from i.e. the medial part of the left eye cross over to the right part of the brain to the visual cortex through the chiasm, and the lateral part of the right eye will go to the right visual cortex, and the opposite way around for the right eye. (Brady et al., 2020.) This hence provides each eye with two versions of the same image, from two different angles and with slightly different backgrounds which makes it possible to understand where in the room the object is located. This depth cue is called retinal disparity, and makes us understand depth (Stangor & Walinga, 2014). When objects are farther away from a person, the retinal images vary less compared to when they are closer, and by judging the amount of disparity, one can understand the relative distance to them. (Levitin, 2002).

The effect retinal disparity has on distance estimation is however limited, as the disparity between two images becomes smaller the farther away an object is located. The disparity will then eventually be too small to fall on different relative photoreceptors in the two eyes. Different studies have reached somewhat different results regarding until what distance the binocular disparity cue is efficient, but agrees that it is at less than 5-10 meters. (Röbbing, 2016)

Convergence

Another depth cue is convergence, and the visual cortex simply uses the angle size between the visual images that is created when turning the eyes more and more inwards when focusing on an object (otherwise the image would not fall on the fovea in both eyes when being closer to the person (Levitin, 2002), closer than 15 meters away, and the eyes then uses this angle to judge the distance to the object (Stangor & Walinga, 2014). This depth cue is only efficient up to 3 meters though, since the angular differences become too small to detect when looking at more distant objects, since the eyes more or less then are parallel. (Levitin, 2002)

2.2.3 Monocular Depth Cues

Within the category of monocular depth cues, there are pictorial depth cues. They make the perceiver understand depth when looking at something in two-dimensions, i.e. when looking at a picture. The pictorial depth cues are therefore relevant for the CMS. The pictorial depth cues are presented and explained in the findings in phase I. Furthermore, there are other non-pictorial depth cues (though monocular) presented in the following theory, concerning conventional mirrors.

Accommodation

One monocular depth cue is the accommodation, and the fact that the lens is more convex and relaxed when focusing on a close-up object is used, since this is related to how much the ciliary muscles attached to the lens are contracted. The accommodation cue is however only useful at very close up distances, such as shorter than 2 meters and not while driving. (Teittinen, 1993)

Relative Motion Parallax

Another cue that makes us perceive distance is the relative motion parallax. This cue causes depth perception since the objects that are located closer to the observer appear to move more, compared to objects located farther away. The reason for this is that the perceived motion of the objects is determined based on the relative motion they have on the retinal image of the scene, which will be larger for objects that are closer (both when it comes to using one or both eyes). (Levitin, 2002)

Angular Declination

Another monocular depth cue is the angular declination cue, which simply explained is that an observer is able to estimate the distance to an object on the ground from the angle of which it is seeing the object, as in Figure 6. The distance (D) to an object resting on the ground can be described as a trigonometric function of the eye height (h) of the observer, and the angular declination to the object from the observer's eyes (α) if the ground plane is accurately represented. The angular declination can then correspond to several different distances, depending on the slant (n) of the surface. (Gajewski et al., 2014)

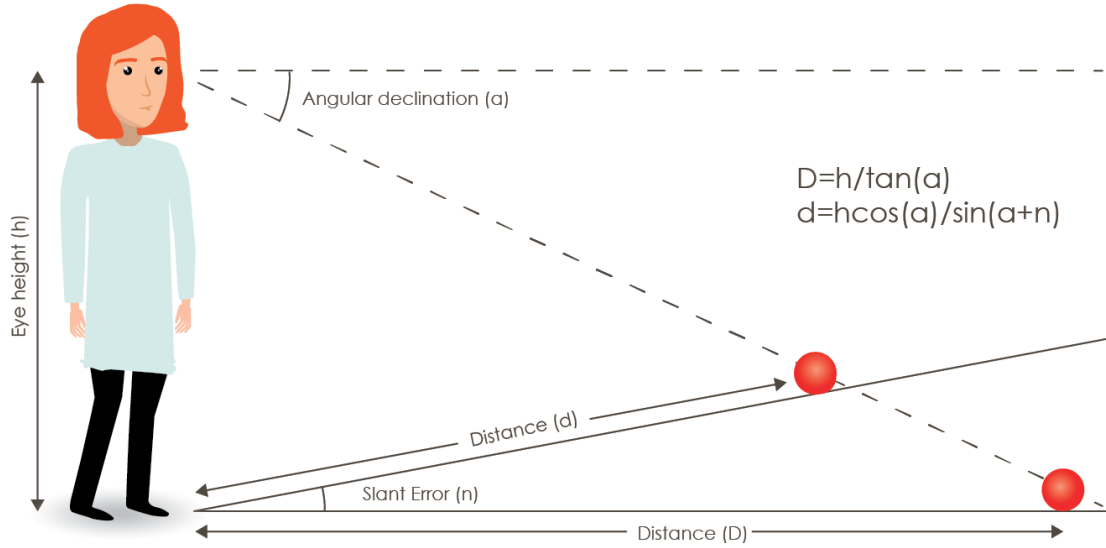


Figure 6 - Illustration of angular declination, adapted from Gajewski et al. (2014).

2.3 Geometric Optics

Geometric optics is what is referred to as ray optics and is applicable in scenarios where the dimensions of the object that the light interacts with are so large that one can disregard the render diffraction effects. In this area of light, light is being treated as infinite rays of lights diffusing from an object that travels on straight lines through transparent media, until it reaches a non-transparent surface where it then changes direction abruptly and then travels to a straight line until it reaches another non-transparent medium. Since the light eventually enters the eye, it is possible to see light emitted by different sources. A ray of light that encounters a non-shiny surface will bounce off into an infinite number of rays in different directions, resulting in *diffuse reflection*. A ray that instead encounters a perfectly shiny surface, bounces off as a single ray in one new direction, which is called *specular reflection*. (Schnick, 2020)

One example of specular reflection is the reflections of a mirror, see Figure 7. According to the *law of reflection*, the angle of which the incident ray of light will be reflected when bouncing off a mirror, will be the same angle from the normal that the ray comes into the mirror at ($\theta_{inc} = \theta_{ref}$).

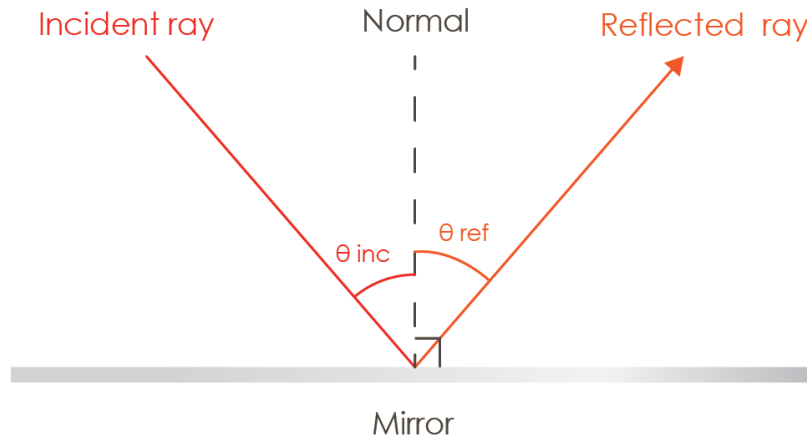


Figure 7 - Demonstration of law of reflection on a flat surface. (Potter & Webb, 2019)

When it comes to curved mirrors, one uses tangents in order to understand what the normal of an incredibly small segment of the surface is, see Figure 8. The normal is then the line perpendicular to the normal. (Potter & Webb, 2019)

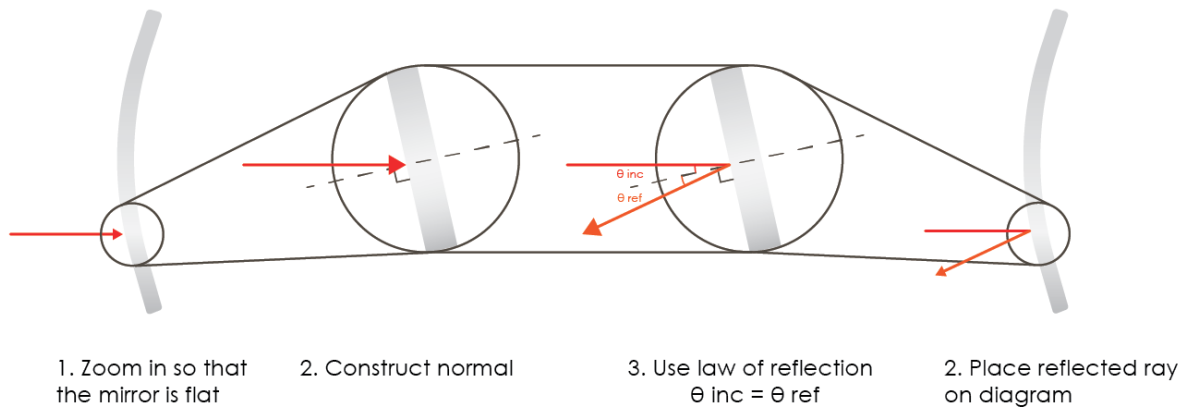


Figure 8 - Demonstration of law of reflection on a curved surface. (Potter & Webb, 2019)

A convex mirror is defined as a spherical surface that has been sliced away, where the silver surface makes it reflective. The mirror has a principal axis which is defined as going through the center of the surface and the center of the center of curvature is the same point that was the center of the original sphere. The mirror's focal point is located on the principal axis at half the distance from the surface to the center. An image is defined as the location in space that it appears as if the light diverges, comes, from. The observer will see the same image independently from where in the room the observer is located. When someone is determining where an object is, it really means that the observer needs to determine at what location the light rays intersect. (Potter & Webb, 2019)

When a mirror is flat, it means that the rays will bounce right out from the surface the images that are formed appear to be the same size at the real object but located behind the mirror. The rays of light hence seem to originate from a common point behind the mirror, so that is where the

image seems to be located. This is however a virtual image, since the image there cannot be projected, see Figure 9, where d_1 is equal to d_2 . (Ling et al., 2016)

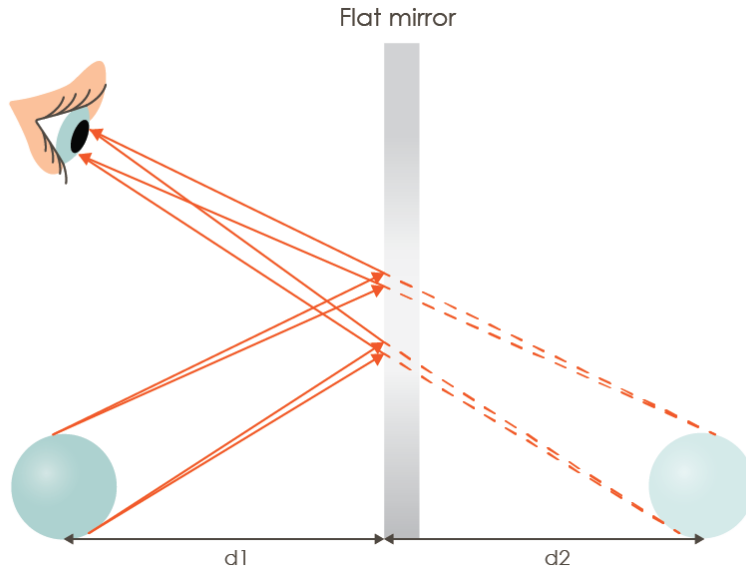


Figure 9 - Illustration of virtual image when object is reflected. (Ling et al., 2016)

2.4 Indirect Vision in Cars

While driving a car it is completely necessary to have control of the situation the driver and its car is positioned in at any given time. Otherwise it would be completely dangerous to be in car. To perceive the surroundings when driving a car, the driver uses its senses, such as hearing, vision and haptics. Though, vision is the overwhelmingly most used due to its accuracy and fast response time. According to Strasburger and Pöppel (2002) the visual field of a human is around 180 degrees along the horizontal meridian. This implies that there are 180 degrees horizontally field of view that is not viewable when focusing on the road straight ahead. This issue has partly been solved throughout the years by adding rearview mirrors, but it is not the only way. When discussing car mirrors, it is relevant to address them consequently, as UNECE (2016) states, the inner mirror or display which provides straight rearward view as in Figure 10 (with its minimum required view) , is categorized as Class I. The mirrors or displays that provides the sideview as in Figure 11 (with its minimum required view) is called Class III.

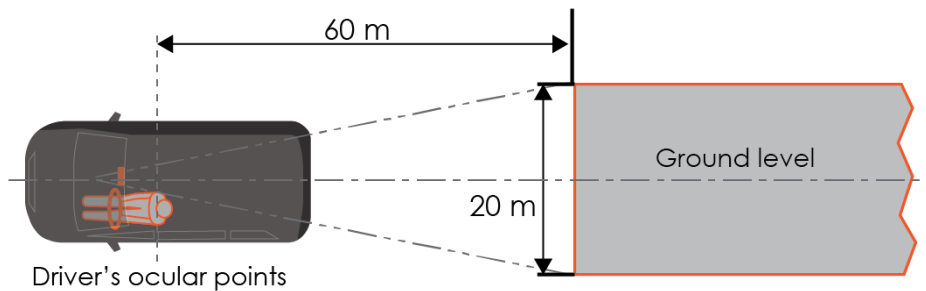


Figure 10 – Required FOV in Class I. (UNECE, 2016)

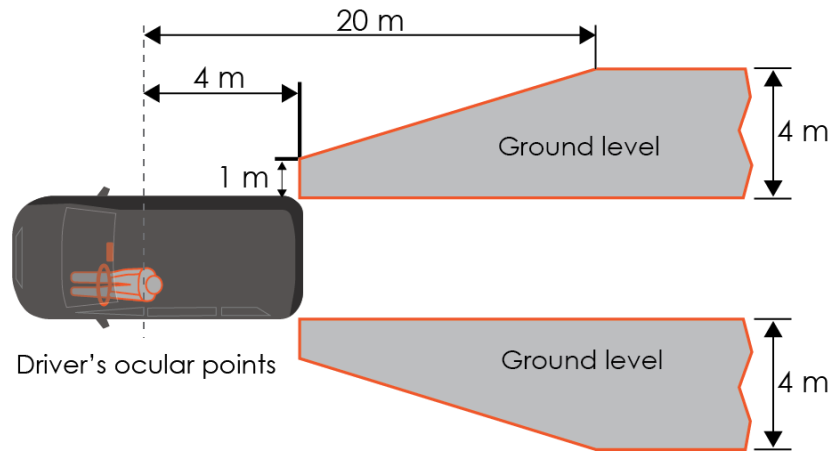


Figure 11 – Required FOV in Class III. (UNECE, 2016)

2.4.1 Tradition Rearview Mirrors

It is good to sort out what function traditional sideview mirrors fill for users when driving Cars. According to Therzis (2016), rearview mirrors are mandatory equipment in cars in order to follow the safety legislation. Their primary function is to cover visual angles that are behind the ocular reach for the driver with the aim of providing a greater view of the environment surrounding the user than what would have been accessible by just using the driver's direct vision (see Figure 11). A complement to these sideview mirrors is the inner rearview mirror that is located in the interior part of the car, which covers the rearview straight rearwards (see Figure 10). There is however an area that is not covered by the user's direct vision nor by the rear- or sideview mirrors and this is called the blind spot. Blind spots could have various sizes depending on the car's mirrors and design. The driver uses the mirrors as a way of being aware of the front- and rearview at the same time, and this is considered as the primary function of the traditional mirrors. There are however functions that are secondary; functions that support the primary one, and they are not mandatory. Secondary functions could be to fold the rearview mirrors, dimming technologies, visualize objects that appear in the blind spot, tilt options, housing of lamps and 360-degree cameras, heating regulation and finally esthetic contributions to the vehicle. (Therzis, 2016)

2.4.2 Camera Monitoring Systems (CMS)

Implementing CMS is increasingly being considered by car manufacturers, which means to remove the conventional rearview mirrors and replace them with displays and coherent cameras (Bernhard & Hecht, 2020). CMS provides an indirect rearview through cameras and displays in real time. The image being captured by the cameras becomes a signal that is transmitted to a control unit (ECU) for processing. In the ECU the signal is being prepared so the image is optimally presented in the displays. (Therzis, 2016)

By implementing CMS there are potentially many benefits, such as improvement of fuel economy and reduction of CO₂ emissions, which lead to longer range of driving. By removing the mirrors and their cowls, some weight is removed simultaneously as it increases the

aerodynamical shape of the car, which contributes to i.e. faster driving. This also leads to enhanced properties regarding the aeroacoustics. Further, the driver will not be blinded by reflected sunlight or other cars' headlights in the displays. Regarding the vision of the driver, it will become better when it rains and during nighttime and the cowl and mirror will not anymore disturb the direct vision in sideways. There is an ergonomic advantage because the driver does not have to turn their body to the same extent to check blind spots, which could be a problem for users with less range of upper body motion. CMS also contributes to a wider range of design freedom regarding the exterior body, with the placement and design of the camera housings. Regarding the interior design, there are many aspects to be considered, placement, shape, size etc. of the displays. It also enables integration with other support systems to a higher extent than possible through conventional mirrors. (Therzis, 2016)

The drawbacks and challenges of implementing CMS could be some as well. As mentioned in the previous paragraph, the placement of screens in the car is an opportunity and challenge to maintain or increase the user experience of keeping control of the rearview through the displays. From having the exterior mirrors on the car body, it needs to be fitted somewhere in the already narrow space in the interior in a smooth way. The cost aspect is also to be considered, due to its high level of technology compared to conventional mirrors and thereby potential technical issues such as latency, quality of screens, adaptation of light changes etc. As mentioned in chapter 1.1, there could potentially be an issue with accommodation, since the eye accommodates on the close by screen instead of far away at the observed object in the mirrors. Furthermore, the two-dimensional image could potentially lead to other problems such as the static FOV, compared to the dynamic FOV in the mirrors, by leaning forward. The two-dimensional screen also lacks the depth perception compared to three-dimensional mirror. Lastly, no visual communication is possible through the screens, which is possible with mirrors. (Therzis, 2016)

2.4.3 Usage Areas for Indirect Vision

The usage areas of indirect vision (either mirrors or CMS) can be described as very extensive. The purpose of having an indirect rearward vision is to gain control of what is happening live around the driver. This includes to identify objects and surroundings, distances and speed of objects. Everything that potentially could become a threat is necessary to have control over. Some driving situations that indirect vision is more useful in are obviously reverse driving, since it almost completely relies on the mirrors or screens to keep track of what is behind. Other driving situations could be intersection, roundabout, overtaking, changing lane, parking and exiting a car. In general, they are useful in almost all situations, due to having control rearward is a part of driving, to detect incoming objects, speed and location of them to decide if actions are needed to be taken to avoid collision.

2.5 Technical Definitions

To better understand the presented concepts in the report, there are technical definitions described in this subchapter. The technical definitions describe magnification, distortion, flickering and the relation between FOV, magnification and screen size.

2.5.1 Magnification/zoom level

When talking about optics, magnification is referred to as the size of an image compared to the size of the object creating it. Linear magnification is the ratio between image length and object length when measured in planes that are perpendicular to the optical axis. (Britannica, 2011)

Magnification, which also can be referred to as zoom, can be divided into two kinds of zooms. There are optical zoom and digital zoom. When using optical zoom, the lens is physically changing location which means that the focal length changes. Focal length is the distance between the light rays' convergence point (from lens) to the sensor that records the image. This changes the apparent closeness of the object, which is referred to as zoom or magnification. Adjusting the lens so it is positioned farther away from the sensor, means a larger focal point, which in turn implies that the image will be magnified and the FOV narrower. Though, since the light rays physically are converged and captured by the image sensor, no reduction in image quality appears when using optical zoom. (*What's the Difference Between Optical Zoom and Digital Zoom?*, 2021)

Digital zoom, however, uses another technology to magnify object in the image. There is no adjustable lens to change focal point. The technique is to use the original captured image and to crop out and enlarge some area of the total image. In this way, the new magnified image will consist of a smaller number of pixels compared to the main image. This implies that the image resolution gets worse and provides a blurred image when digitally zooming in, which can be a problem if the original image does not consist of an extremely high number of pixels. (*What's the Difference Between Optical Zoom and Digital Zoom?*, 2021)

2.5.2 Relation between FOV, Magnification & Screen Size

Field of view (FOV) for CMS, which is the view that is captured by a camera that can be displayed in the screen when discussing CMS. There is a relation between the FOV, magnification level and screen size. If the FOV is decided to a certain view, then the other two parameters are changeable in regard of each other. Having a FOV and choosing a magnification level (assuming the distance from screen to ocular point is constant), then a specific minimum screen size will be the result. This works the other way around as well and is important to consider.

2.5.3 Distortion

Distortion is more often referred to as aberration when it comes to optics, which means deformation of an image as a whole. Common fundamental aberrations are barrel, pincushion and mustache (see Figure 12), where rectilinear lines appear as curves (which is hence the reason for calling aberration curvilinear distortion). In barrel distortion, the lines appear bulging while they appear to bend inwards for pincushion distortion. The mustache distortion is a combination of the two previously mentioned ones, rectilinear lines appear curved inwards towards the center of the frame, while curved outwards in the corners. (Mansurov, 2020)

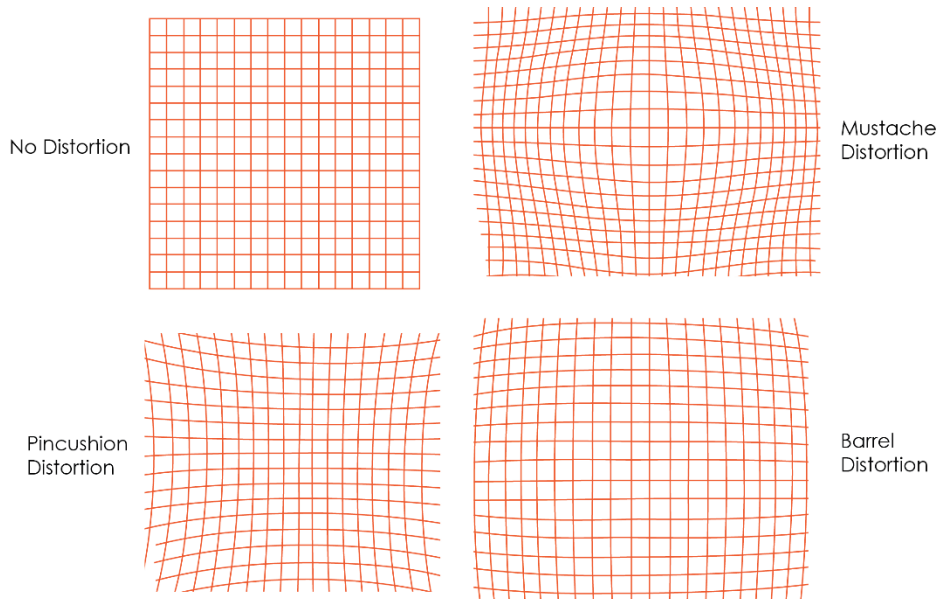


Figure 12 - Illustration of the different kinds of distortion. (Mansurov, 2020)

2.5.4 Flickering

The motion picture that is being shown in the displays are images that are being displayed one by one, with a certain speed frequency. Many light sources in traffic such as road lights, car headlights and digital road signs are often using light emitting diodes (LED) as light source due to its high energy efficiency. While the alternating current driven LED emits light, it turns itself on and off extremely fast, impossible to be detected by the human eye. In Sweden, the electrical frequency is at 50 Hz, which means that the LEDs turn on and off 50 times every second. Therefore, the eye interprets the light as a constant flow rather than blinking lights. The problem could be when trying to capture the blinking (flickering) on camera and to show it on the display. If the camera's recording frames per second do not align with the frequency of electricity, flickering will appear, which is called the strobe effect. The reason for that is that some of the images in the video will be captured when the LED is turned off, which will be displayed as a dark image. This in turn will lead to that the display appears to flicker. (Eugen, 2020)

In the case of CMS, the camera captures a potential flickering light source out in the traffic, to then be displayed inside the car. This display probably uses LED or similar technology, which means that the screen itself could provide a flickering footage. Even though the blinking happens fast enough to not be able to be perceived as flicker by the human eye, the brain still picks up the unnatural light, which could lead to nausea, headaches and sight problems. (Eugen, 2020)

Another perspective regarding the visible flicker is that it will alert the driver of incoming cars in the CMS. If the lights are blinking it would probably call for attention more efficient than if the lights would be constant. On the other hand, Lehman and Wilkins (2014) discuss the general flickering problems, though not precisely for displays, mentioning the distraction as an important aspect in the matter, which is highly relevant when it comes to CMS and driving cars. It is further mentioned the health issue, since flickering could provoke headaches and in extreme cases even epileptic seizures. The level of severity mostly depends on the area of retina being exposed to the flicker, frequency and other factors. (Lehman & Wilkins, 2014)

2.6 Regulations

The ISO16505:2019 (SIS, 2019) determines a lot about what is suitable regarding CMS. According to the standard, the definition of perception in CMS is summarized as

- *view of the field of vision of the intended mirror class;*
- *observation of traffic situations;*
- *observation of the near and far environment around the vehicle;*
- *perception of objects (e.g. vehicles, cyclists, pedestrian, traffic signs, signal lights, etc.);*
- *perception of location, distance and velocity of objects. (SIS, 2019)*

2.6.1 Types of View

For the default view of CMS, it should enable the driver to observe the surroundings needed for the most common driving situations. CMS should provide a default view, mostly because of homologation, which means that it will be certified, or law approved based on the default view. There could also be an adjusted default view, which means that the user should be able to adjust the settings of the CMS in a preferred way. This adjusted view might actually not fulfill all the requirements in SIS (2019) (field of view), but the rest of the requirements, though it is important to note that the settings may be restored for the next user. (SIS, 2019)

There is also a possibility to have a temporarily changed view for the user, which could be useful in specific driving situations, such as parking or merging lanes. The changed view could happen either automatically or manually, and the temporarily adjusted view should be indicated to the user in some way. Examples of temporary adjusted view could be a change in magnification, FOV, overlays, luminance or contrast. Overlays are any driving-related visual information depicted in the CMS over the original image, such as icons, colored areas, labels etc. Within the required FOV, only temporary transparent overlays are allowed. (SIS, 2019)

2.6.2 FOV

The CMS should cover the same FOV or more, compared to conventional mirrors in the same mirror class. The requirement applies to both horizontal and vertical directions. Class I mirrors have the minimum FOV as can be seen in Figure 10. 60 m behind the driver's ocular point, a 20 m wide rectangle should be seen on the road. The requirements for class III mirrors can be seen in Figure 11. (SIS, 2019)

2.6.3 Image Quality

There are directions concerning luminance such as ratios between luminance contrast (ratio between highest and lowest luminance level) for four different scenarios;

- Direct sunlight (2:1)
- Day condition with confused ambient light (3:1)
- Sunset condition (2:1)
- Night condition (5:1, 10:1 for older drivers) (SIS, 2019)

It also says that there are some specific rules during nighttime driving when it comes to background luminance of the monitor, and that the manual has to warn the user that intense light

sources can decrease the luminance contrast on the monitor. There are also some rules about what color ranges that each color is allowed to be represented by. (SIS, 2019)

Furthermore, there is directions regarding factors that lead to partial occlusion of the FOV, which is smear, blooming and flare (flare artefacts can cover up to maximum 25 % of the display area), see Figure 13. (SIS, 2019)

There are also rules about sharpness, describing it as a key parameter for perceiving an image faster. Furthermore, there are regulations regarding the maximum flicker allowed (90 % of the population shall not experience flicker). The monitor should be free from other visual artefacts, as well as there is a maximum gloss level for the monitor housing unit. There are minimum requirements regarding frame rate and latency since the system should be able to render the environment nearly at the same time. (SIS, 2019)

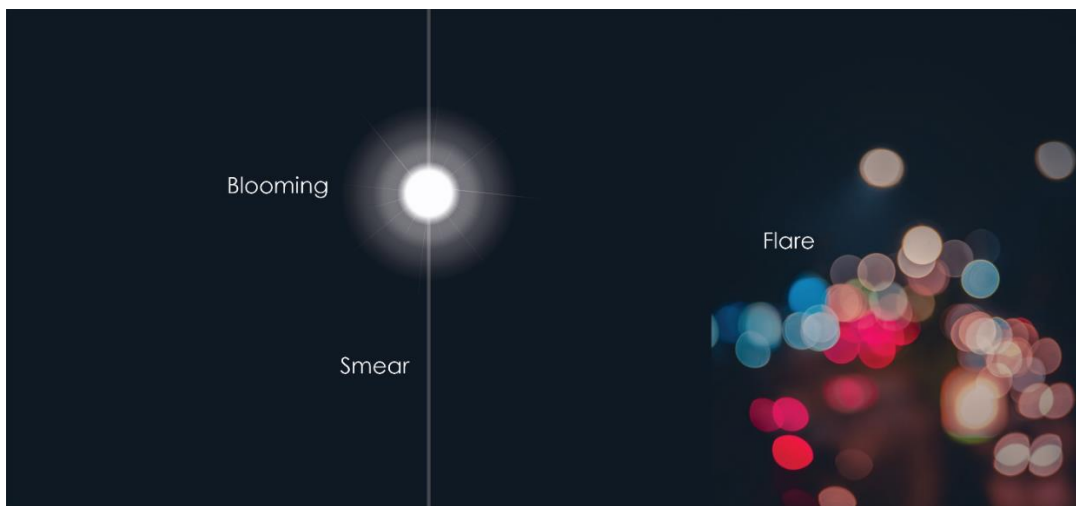


Figure 13 - Illustration of blooming and smear as well as flare. (Ryan, 2020)¹

2.6.4 Needs of Older People

SIS (2019) further described that older people might have problems with accommodation and that the user manual should instruct the person about how sight is affected and how to take this into consideration. It could also be that the monitor should be placed at a suitable location that meets the user needs.

2.7 Summary

With the presented theory from this chapter, enough knowledge is gained to enter the following phases. Knowledge concerning indirect vision in cars, technical definitions, the human visual sensory, depth perception, geometric optics and regulations are received and provide a basis to follow the rest of the project.

¹ Published and edited according to the UnSplash license at UnSplash.com.

3 METHODOLOGY THEORY

In the following chapter, the methods used in the project and how to implement them are explained.

3.1 Mindmapping

Mindmapping is a method to visually represent an area, ideas, subjects or aspects that are related to a given theme and can be used to show how different factors are related to each other (Ericson et al., 2016). Mindmapping can preferably be used in the beginning of a project to create a general structure and overview of what the theme or task includes and is useful to clarify what factors, questions, solutions and aspects to consider.

The process starts by writing down the theme in the center of a paper or whiteboard which is followed by a brainstorming session where sub-categories within the theme are written down as outgrowths from the main theme. The sub-categories can then continue like branches on a tree. Explanations can also be added to the mindmap, but the aim is to keep it concise, so it does not decrease the visual overview. Arrows can then be drawn between related categories, factors, aspects and solutions to clarify the dependence between them.

3.2 Hierarchical Task Analysis (HTA)

A hierarchical task analysis (HTA) is a way of splitting up a main task into several smaller steps in a structure that is easy to follow (Hornsby, 2010). The sub-steps can then be split into even smaller ones if necessary. The amount of sub-steps could theoretically continue to an infinite number of levels, but the number of levels should be reasonable for the task, and only cover steps that matter in the context. Every sub-task on the deepest level should then be extended with an activity for how to perform the given task. This creates a tree like structure with all the sub-tasks growing out from the main task at the top. The HTA hence provide an overview of what steps are included in a task and a sequence of performing it.

3.3 Failure Mode & Effect Analysis (FMEA)

Failure Mode and Effect Analysis (FMEA) is a tool for assessing risks and effects within tasks, relative to each other (Arabian-Hoseynabadi et al., 2010). The analysis consists of subjectively identifying possible root causes, failure modes and estimating the relative risks they bring. From a predefined numerical scale for rating severity, risk of occurrence and likelihood of detecting a root cause before the failure occurs are three factors that each are assessed. The product of these three factors is called *risk priority number* (RPN) which can be used to compare different risks with each other.

3.4 Use Case

A use case is the method that is used in system analysis to identify, clarify and organize the system requirement in a structured way (Brush, 2020). In a use case, there is always a system, a goal to carry out and an actor who carries out the goal by using the system. It hence describes the way of reaching the goal for the actor in the system from the user's perspective, and in a way that is easy to follow. Documenting the use case and the actions needed to carry it out can facilitate identifying where errors may occur in the chain of actions. When writing a use case, it is possible to describe it by using a sequence diagram that models the interaction between single actions in the system and chain of actions, and in what order the actions take place.

3.5 Literature Review

A literature review is the method of systematically reviewing and synthesizing previous research made within a specific field (Snyder, 2019). If the work is made effectively and well conducted, it creates a stable foundation for continued work and developing knowledge and theories. Literature research can be used to get an overview of a researched areas, to uncover what areas that have yet not been researched or that needs to be researched further. Using previous knowledge from many empirical findings can also be a method by itself of answering research questions that no previous study has answered before.

3.6 Interviews

Performing interviews is a method of retrieving information through asking questions to another person (Longhurst, 2003). There are typically three types of interviews, which can be placed along a continuum. The categories are non-structured, semi-structured and structured interviews. Non structured interviews are performed through an unprepared free conversation and using no predetermined questions. Structured interviews blindly following prepared questions and offer no flexibility for follow up questions, which guarantees a more equal interview independent from the person performing it. Semi-structured interviews can be placed in the middle of the continuum and contains starting off with some predetermined questions but is flexible and allows for asking probing and follow-up questions to make the interviewee elaborate more on interesting findings.

3.7 Parameter-Diagram

A parameter diagram (P-Diagram) is a structured tool for identifying the inputs of a system and relating them to the desired outputs of it, see Figure 14 (Reliability Engineering Resources, 1992-2006). It has been described as a “*structured tool to help teams understand the physics related to the function(s) of the design*”, and the analysis made when performing a P-Diagram can be a useful preparation prior to performing system or design FMEA:s. In P-Diagrams the *input* refers to the energy needed for the item to fill the intended functions. There is also performance as the *output* of the system (which is divided into the sub-categories *ideal responses* that are intended and *error states* that are undesired outcomes of the function). Furthermore, *control factors* can be changed by the design team which should be chosen to reduce the impact that noise factors have on the system. Lasty the *noise factors*, are things that could reduce the effectiveness of ideal responses. The noise factors can be broken down to five sub-categories; *piece to piece variations, change over time, usage, environment and system interaction*.

P-Diagrams can be developed at any level of the system hierarchy, from system to component level. The P-Diagram for performing FMEA:s by making the ideal responses in the P-Diagram functions in the FMEA, error states can be used as failures modes and the noise and control factors can be used as causes of the errors.

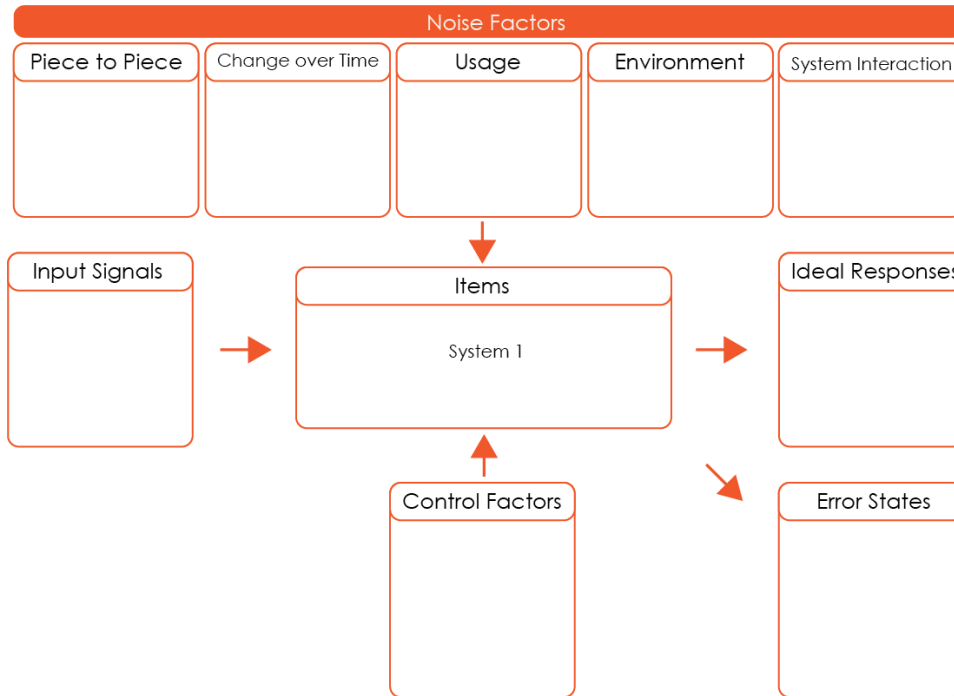


Figure 14 - A template of a P-Diagram. (Reliability Engineering Resources, 1992-2006)

3.8 Benchmarking

Benchmarking is a method of measuring and comparing own performance towards other companies' performance in the same or another industry (Lankford, 2000). By using knowledge, experience and assessing competitors strengths and weaknesses, one can make judgements of what is needed to improve the own company.

3.9 User Test

To test certain tasks, products, interfaces, systems or situations, it can be beneficial to perform usability tests (Moran, 2019). These tests are often referred to as user tests, but it is important to stress that in usability tests, only the interaction between the user and product is evaluated and not the user itself. A user test consists of a facilitator, participants and tasks to execute. The facilitator or test leader guides the participant to perform certain tasks or asks the person questions in the test. The test participant is supposed to be a realistic user of what is tested, to provide as meaningful input as possible. The participant may or may not be informed regarding what the test is about, depending on the layout of the test. Participants are often told to think aloud during the test to better understand their behaviors, goals, thoughts and motivations. What the tasks are in the user tests vary depending on the purpose of it, but the tasks are usually realistic activities that the users potentially might encounter in real life using the certain product. The tasks could be very specific or general depending on the test and research questions.

User tests can also be categorized into qualitative and quantitative tests. Qualitative tests focus more on gaining insights, findings and comments from the user regarding the product being tested. It is often used to discover usage problems in the user experience. There is also the kind of quantitative tests which focus on collecting metrics from the user that describe the user

experience. (Moran, 2019) Quantitative tests usually require a sample of at least 30 persons, comparing to qualitative testing which only require five to eight participants. (Budi, 2017)

3.10 Observation

Observation is a method for data collection by observing the behavior of a subject (Bhasin, 2020). Through observations, the researcher puts himself/herself in the subject context to live record and take notes of what is happening, to later analyze the notes. An observation can be structured, meaning that data is collected according to a pre-defined schedule. An observation can also be non-structured, which means noting down behavior as it occurs if it appears to be interesting.

3.11 Pilot Test

Before performing user tests, it is beneficial to perform one or two pilot tests to make sure that the plan works practically (Schade, 2015). Pilot tests do usually not contribute with result in the user study since its purpose is to find out where the real user test needs to be improved prior to performing them. The pilot test can also be used to find out if questions or tasks are formulated in ways that the participants will understand. By distinguishing the problems in the pilot tests there are still time for changes and retrial before the real tests take place. Shortly, one can describe them as tests testing the test. Pilot tests are always a good way of understanding how the test will be perceived, but it is also an important way for the facilitator to practice the routine if it takes place in an unfamiliar area or if the facilitator is not used to the role.

3.12 ANOVA-Analysis

Analysis of Variance (ANOVA) tests the statistical significance of the differences between the mean values in two or more independent groups (Tabachnick & Fidell, 2006). If a difference between means are significant, it means that it is likely to appear again with a certain probability if the same tests repeated. If the differences between the means are not significant, it means that one cannot rule out that the differences appeared by coincidence.

When performing ANOVA analysis, one assumes that the independent variable (IV) is what causes the dependent variable (DV) in the experimental test. The ANOVA analysis simply put is a way of finding out if that is true or not. There can be multiple IV:s, but each one has to have at least two levels that are tested. Most commonly, one-way ANOVA are used for testing three or more IV:s, since a T-test can cover less (T-tests are explained in the next subchapter).

Furthermore, preconditions of performing ANOVA tests are that the measurements come from experimental test, which means that:

- The order of which the levels of the IV:s are tested must be assigned randomly. This can however be done in a structured way, if it makes sure that the order that the levels of IV:s are presented varies randomly for different test participants
- The levels of the IV:s have to be manipulated, meaning that they must be actively chosen. The order and exposure of the test cases must be actively determined as well.
- Other variables must be controlled during the tests.

There are several different types of ANOVA tests depending on the type of experimental test that the results come from. In this thesis however, only One-way ANOVA tests are used. One-way ANOVA tests explore the independent variable's effect on the dependent variable in one direction; thus, how the IV affects the DV, and not the opposite way around.

Since a one-way ANOVA test show if there is a significant difference in a group, but not specifically between which ones, complementary tests are usually needed in order to pinpoint between which groups the difference is located. An example of such complementary tests are T-tests.

3.13 T-Test

T-test is a method used to understand if the average difference between two groups are caused by coincidence or an independent variable (Chieh, 2012). In a two-sample T-test, the purpose is to compare and hence understand whether or not two means come from the same population, which it is if the difference between the mean values is considered small enough. The T-value is the ratio between the differences between the groups and the differences within the groups. A high T-value hence means that the difference between the means is large and hence are more likely to occur again if the test is to be repeated, while a low T-value means that the results come from the same population. Every T-value also has a P-value, which is the probability that the results occurred by chance, and a low P-values means that is most likely did not occur by coincidence. (Goulden, 1956) Two mean values are interpreted to come from two different populations if the P-value is less than 0.05 (5%).

3.14 KJ-Analysis

To analyze a large amount of data gathered from for example interviews, performing a Jiro Kawakita (KJ) analysis can be suitable (Bligård, 2015). The KJ-analysis provides a structured way of getting a clear overview and categorizing lots of data. The method means putting interesting and relevant quotes from transcribed interviews on post-it notes, enabling easy rearrangements of them. All the post-it notes are then put on a board according to the message they contain, with the results of different categories arise from the cluster of post-it notes that are grouped together. The advantage of this method is that theme of the groups will not be distinguished until after or a while into the analysis, using a bottom up-approach instead of top-down. The output of the method is the categorization of the large amount of data, making it easier to interpret and use it.

4 PROCESS

This chapter describes an overview of the chronological order of which the thesis was conducted. It also explains where in the report each parts' description and results are located.

The thesis work started with an introduction that included identifying stakeholders that could contribute with input to the work. Initially the topic of the thesis was quite wide, and the work parallel to that therefore continued by performing literature research to read in upon the area; understand what it was, included and to get an overview of what had previously been researched and not. Part of the knowledge encountered at this time is required for anyone reading this report to understand the scope and enable following later discussions in the report. That information is therefore presented early in the report in chapter 2 and 3. The information that was gathered at this time that is more detailed and was used as content for the project deliverables are presented in chapter 5 and phase I (Figure 15), which cover the literature findings about design parameters' impact on user performance in driving.

Continuing, interviews with experts at Volvo within different areas in close connection to CMS were carried out to increase the understanding of what could be of interest to investigate in the further work. A benchmark was also conducted and cars with different types of rearview mirrors or CMS implemented for indirect vision were tested in order get a feeling of what driving scenarios that were critical out of a visual perspective. When discovering more and more parameters that could impact the user performance of CMS, the insight was reached that one way of continuing the thesis work was to clarify what function rearview mirrors fill for the driver during different scenarios, and what parameters that could increase or decrease that function. The following question was therefore formulated to guide the preceding work; *“What design parameters could possibly affect the user performance of using CMS?”*.

After this insight, the work continued with reading in on more literature and taking the experts' opinions into consideration regarding what scenarios and parameters that would be most important to research when designing CMS. A mindmapping session was conducted to summarize these activities and also to complement them with our own thoughts from the benchmarking session. The results were then used as a base for performing a P-Diagram workshop together with some of the experts that had previously been interviewed as well as a few other persons working at the Ergonomics department at Volvo Cars.

Since the P-Diagram workshop focused more on identifying the parameters affecting the user performance when driving but did not show which were the most important ones and why, there was a need for a methodical way of evaluating these parameters. An HTA was therefore performed on each of the identified driving scenarios. The HTA:s were then used as a base on which an FMEA was performed, where the most critical use cases for using CMS was identified as well as the most likely reasons for them to occur. This work, some findings from literature, the expert interviews, mindmapping, P-Diagram workshop, HTA:s and FMEA:s are thoroughly described in Chapter 6 (Phase II – Identifying Situations and Parameters).

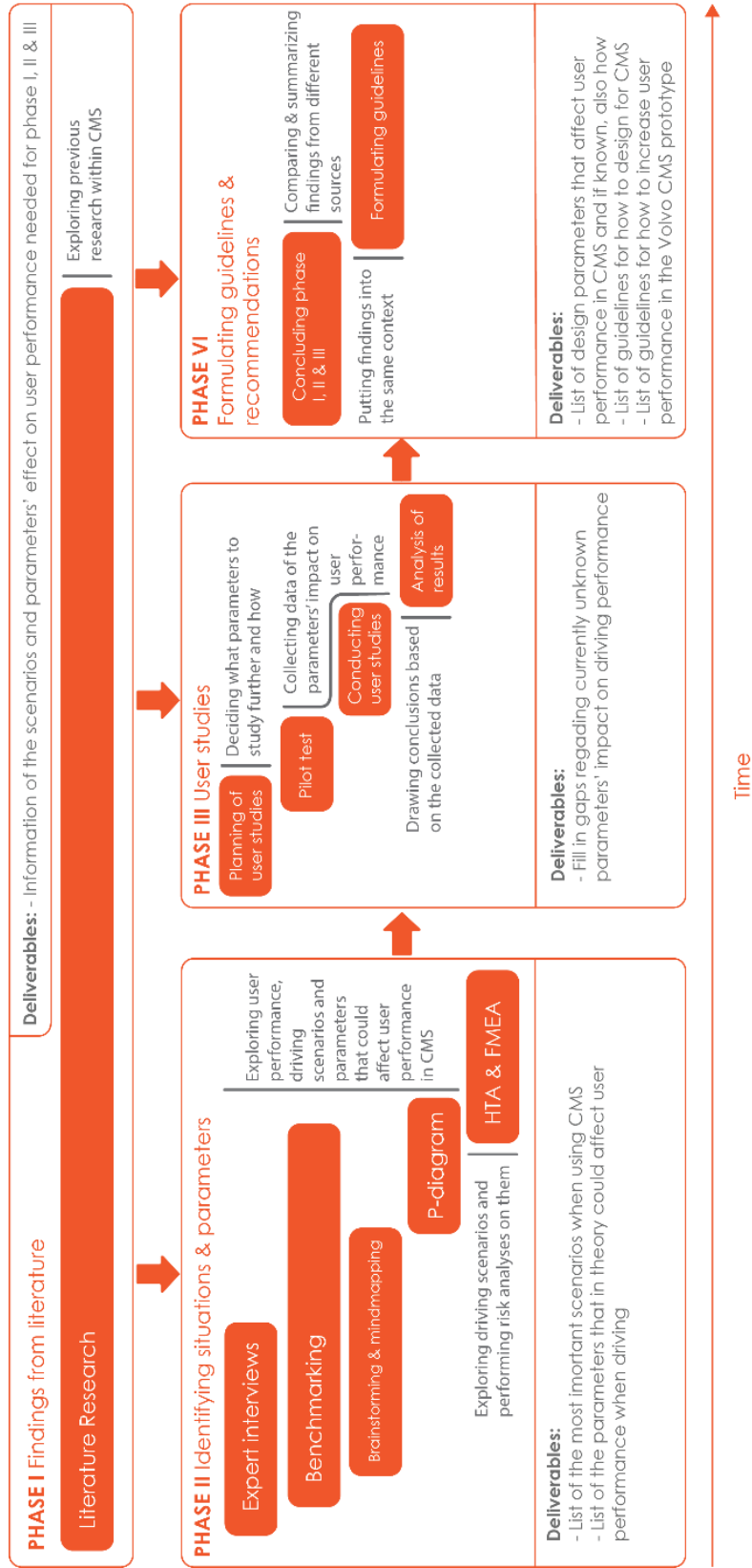


Figure 15 - Process of the project.

After understanding which of the scenarios and aspects of user performance that were the most important ones for CMS to be integrated successfully, and knowledge had been discovered concerning some design parameters' impact on user performance, the following question was formulated to guide parts of the continued work from hereon; *“What parameters have previously been researched/investigated and how do they affect the user performance in CMS?”*. To answer that question, parts of the continued work meant continuing to perform more thorough literature studies in parallel to other work. The method for- and findings from the thorough literature study is described and discussed in chapter 5 (Phase I – Findings from Literature).

The findings from phase II regarding what scenarios, aspects and parameters that are most critical when designing CMS, together with the gaps discovered early in phase I and limitations of this thesis (time, competence and physical equipment) were then used to select some parameters' that could impact user performance in CMS that would be explored further by performing user tests. The following question was used to guide that work: *“What are a few parameters' effect on user performance that previously has not been researched?”*. This resulted in a parameter user test being carried out.

At this time, it was established that one further important aspect for Volvo's continued work with CMS was to identify which factors to improve in relation to an already developed CMS prototype. A comparative user study was therefore also carried out, comparing the user experience of driving a CMS prototype to driving traditional rearview mirror car. The method for- and results from the user tests are described thoroughly in chapter 7 (Phase III – User tests).

To summarize and put the findings in a useful context, the following questions were formulated to guide the last work *“What are general guidelines for designing CMS with the aim of enhancing user performance?”* and *“What are guidelines for enhancing the user experience based on the CMS prototype and what driving situations should be prioritized in future work”*. The findings of phase I, II and III were then used to develop guidelines for how to design CMS for increased user performance. The process of formulating the guidelines along with the guidelines themselves can be found in chapter 8 (phase IV – Guidelines & Recommendations). In chapter 9 and 10 follows an overall discussion and conclusion of the project.

5 PHASE I

FINDINGS FROM LITERATURE

In this phase, all the gathered previous findings are presented and discussed. The goal of the phase was to find out what is known within the field of CMS from previous research and where there is a need for further studies.

5.1 Procedure – Literature Studies

This phase consisted of performing literature studies on previous findings that included both webpages, peer reviewed articles as well as books. To structure the literature research, a search table was used initially where the search engine, search words and sources were documented. The most used search engines were Chalmers Library, Google and Google Scholar. Throughout the literature studies, the summaries or abstracts were read through for at least two results for each search, and if the findings were interesting regarding the subject, the article or chapters from the books were read through more carefully and summarized into the search table. Two physical books were also used in the literature study, whose content was known from before.

5.2 Findings

In this subchapter, the findings from previous literature are presented. The findings are categorized into findings that regard the distance perception and findings that regard control and object detection.

5.2.1 Distance Perception

This subchapter presents the findings regarding distance perception. Furthermore, it is categorized into speed, camera magnification and FOV, longitudinal display placement, pictorial depth cues and image resolution and update rate.

Speed

The following findings were encountered concerning speed related to distance perception.

Replacing Mirrors with Displays' Effect on Distance Perception at Velocities Lower than 50 km/h

In a study conducted by Schmidt et al. (2016) one of the aims was to understand if distance and speed perception were changed when receiving visual support from CMS instead of regular mirrors. The aim was also to understand if a person's previous experience of CMS affected its ability to make estimations more in line with those of the mirror. The tests were therefore carried out on two different test groups; novices that had never encountered CMS and experts that got to try CMS in traffic before performing the tests. For these tests, the "last safe gap" method was used to understand the user's perception of the distance and speed, testing CMS and conventional exterior sideview mirrors as a reference. The last safe gap method was performed as follows. The person sat in a static vehicle that another vehicle approached from behind. The person was not allowed to glance rearwards or use the interior rearview mirror, and was then asked to press a button when the approaching car was no longer at a distance where he/she would feel safe pulling out in front of the vehicle for performing an overtaking. The tests were done at three different velocities (20, 35 respectively 50 km/h) for each system (CMS and mirrors) and a multivariate analysis of variance was then used to interpret the results and conclude whether or not the systems or velocities affected the time until the button was pressed.

The results showed no significant difference in last safe gap using CMS compared to traditional sideview mirrors. A significant main effect was however found related to the velocity factor. Furthermore, there was no significant effect for the interaction of system type and speed.

There was however a slightly larger last safe gap when using CMS instead of for mirrors, starting with a difference of 12.7 m at 30 km/h, continuing with 4.6 at 35 km/h and 0.5 m at 50 km/h. The difference in distance between CMS and mirrors converged at increasing velocities, but the last safe gap distance increased with higher velocities. The authors pointed out that these results show no signs of the user pulling out at a shorter distance when using CMS compared to a regular mirror, making CMS non-critical regarding safety since that rather increases road safety.

Furthermore, it showed that the speed factor had significant effect on the last safe gap distance (increasing distances with increasing velocities) which could indicate that the user can in fact perceive differences in object speed using CMS. It was however also pointed out that it is important to investigate what happens with the speed estimations in CMS compared with mirrors at velocities above 50 km/h as the estimations seemed to converge reaching that speed. If the perception would change at higher speeds and vehicles would appear farther away than what they really are, it would be of great importance to become aware of since that would decrease road safety.

Concerning if experience affected estimating speed more realistically using specifically CMS, the study showed no statistical evidence for this. It did however show a main effect of the users pulling out later if they had trained before, irrespectively to the system type. The authors recommended further investigation concerning training effects on CMS. (Schmidt et al., 2016)

Distance to Still Standing Traffic Cones – Underestimations when Using CMS

Another part test in the Schmidt et al. study was to estimate the distance to still standing objects behind, using CMS respectively mirrors at the distances of 5, 12.5 and 20 m. The results then showed that all distances were underestimated when using CMS, but when using the mirror the 5 m distance was underestimated, 12.5 was estimated correctly and for the longest distance of 20 meters, the distance was actually slightly overestimated using the mirrors. (Schmidt et al., 2016)

Reversing to Still Standing Traffic Cones – Overestimations when Using both Mirrors & CMS

Another test performed by Schmidt et al. (2016) was to ask commercial vehicle drivers to reverse drive towards still standing traffic cones and stop at a distance of 4 m when using CMS respectively mirrors. The results here showed that there was no significant difference between using the two systems, but a clear tendency was shown that drivers tend to overestimate distance more using the mirrors compared to CMS, and a few times using CMS even lead to underestimations of the distance. (Schmidt et al., 2016)

Replacing Mirror with Displays' Effect on Distance Performance at Velocities beneath 150 km/h

In another recently published article, distance and speed perception was studied by using the last safe gap method at seven different stimulus vehicle speeds (20, 25, 50, 70, 90, 120 and 150 km/h), where the results compared using CMS respectively mirrors. The results showed that there was no significant difference in the distance estimation depending on if the user used the mirror or the display for estimating the last safe gap in front of a vehicle approaching from behind. In the subjective measurements from questionnaires however, the results showed that the participants experienced depth representation better using the mirrors compared to the displays. (Berberich et al., 2021)

Camera Position

In the following part of the chapter, the findings belonging to the sideview camera position are presented, including both vertical and longitudinal placement.

Vertical and Longitudinal Placement of Sideview Cameras

In a study by Bernard and Hecht (2020), the effect that sideview cameras' longitudinal and vertical placement had on users' distance perception was investigated through user tests. In conjunction with that, how the approaching vehicle's size as well as the visibility of the subject vehicle's rear effected the driver's distance perception were explored. The hypothesis was that placing the camera at higher vertical positions would lead to relative distance underestimations and the opposite way around. The hypothesis regarding the longitudinal placement of the camera was that it would cause no significant effect, since seeing the back of the car would make it easier for the user to compensate for the displacement using that information. (Bernard & Hecht, 2020)

The study measured three egocentric distances (distance from the perceiver to the object) and three exocentric distances (distance between other objects than the perceiver) (5, 14 and 23 m) at five different camera placements (low: 35 cm below the conventional, conventional, high 35 cm above the conventional, front: 45 cm farther to the front, and back: 45 cm farther to the back). In these tests, the participants had two trial tests for two of the settings where they received feedback on their estimations in order to allow them to calibrate the distance. They were then shown an image on the display with a reference car in it and afterwards asked to estimate the distance to it (rear bumper of subject car to front bumper on reference car) verbally. An ANOVA analysis was then used to find correlations between the placements and distance estimations. (Bernard & Hecht, 2020)

In general, the results showed that the participants overestimated the egocentric distance with 2.71 m (9.57 %) and the exocentric distance by 4.30 m (30.73%). The results furthermore showed that camera position has significant effects on both egocentric and exocentric distance. The lower camera position led to greater overestimations compared with the conventional placements. The higher camera position led to underestimations compared to the conventional placements. The conventional camera placement did not cause significant differences in distance estimation compared with the other placements. Participants did however overestimate shorter distances and underestimate longer distances. (Bernard & Hecht, 2020)

The results also showed significant effects between the interaction of egocentric distance and exocentric distance. Exocentric distances were then strongly overestimated when two reference vehicles were placed with close distances between them, and the most at an egocentric distance of 30 m. (Bernard & Hecht, 2020)

Presence of Vehicle Reference

In the part of the Bernard and Hecht test (2020) that evaluated the impact presence of a vehicle reference had on distance estimations, two more sideview camera placements were added; one extremely low and one extremely high, and this part was only performed on egocentric distance estimation. The size of the target vehicle and the visibility of the test vehicle were also two

factors that were varied throughout the test. The hypothesis was that the rear reference would lead to increasing distance underestimations. It furthermore suggested that there would be an interaction effect between the camera placement and presence of the rear reference, and that the estimates would differ more strongly without the reference present. (Bernard & Hecht, 2020)

This time six different distances were used (13, 26, 39, 52, 65 and 78 m), five vertical camera positions, two vehicle reference options (with or without showing part of the car in display) and two target sizes. The participants were asked to estimate the egocentric distance to the target cars (bumper to bumper or from their viewpoint to the target bumper). (Bernard & Hecht, 2020)

The results for this second experiment showed that distance is generally underestimated by 1.15 m (2.54 %). It furthermore showed significant effect on distance perception caused by camera position, vehicle reference and target vehicle size. The conventional camera position distance estimation differed significantly from the extremely low respectively high camera placements, but the other two placements did not. The larger the actual distance was – the stronger the underestimation. Visible vehicle reference furthermore led to an increased underestimation and a larger target vehicle also lead to stronger underestimations of the distance. (Bernard & Hecht, 2020)

The interaction between camera placement and egocentric distance also showed a significant effect; the differences were stronger for closer distances and smaller for the longer. The interaction between camera placement and vehicle reference also showed a significant effect, and without the reference present, the estimations differed more strongly. The interaction between camera placement, egocentric distance and vehicle reference also showed significant effect, and with the vehicle reference present, the distance estimation differences disappeared – even for the shortest distances. (Bernard & Hecht, 2020)

The interaction between the camera positions and target vehicle size also showed significant effect on distance estimation; and the vehicle size caused more differences in estimated distance at the lower placements than the higher ones. Also, the interactions between egocentric distance and vehicle reference respectively egocentric distance and target size showed significant effect. (Bernard & Hecht, 2020)

To conclude the Bernard and Hecht article – moving the camera position up and down does affect the rearward distance estimation if there is no reference point. When it is moved downwards, participants overestimate the distance, and if it is moved upwards – distance is increasingly underestimated. The effect of varying the perspective is increased when the distance to the object is decreased – for shorter distances to the object the estimations are increasingly overestimated at lower positions and underestimated at higher positions. The size of the vehicle also caused greater differences in distance estimations (underestimations) at lower heights than at higher. And finally, the differences in estimations between the different camera heights almost disappeared when there was a vehicle reference present. Possible explanations of the effect of adding a vehicle reference is according to the authors that one of the most important depth cues is angle of declination, which is changed for different camera positions, and that it might not be as important when a reference is shown in the image. Another explanation is that the distance to

the object is a function between the eye height and declination point of the perceiver and that the perceived eye height (vertical camera placement) is altered when presenting different vehicle references in the images. (Bernard & Hecht, 2020)

Van Erp and Padmos (2003) did however show in a study that integrating spatial orientation aids into the image (that precisely indicated the exact distance from the bumper to the transverse line) did not have significant impact on the longitudinal distance performance. Their explanation was that the number of runs might not have given the participants the time to use the tool properly, or that there were other cues available that dominated the perception more, and that other concepts should be evaluated in future research. (Van Erp & Padmos, 2003)

Camera Magnification & FOV

The following findings concern the impact magnification level and FOV have on distance estimation.

Magnification of Sideview Cameras during Dynamic Stimuli

In a study by Flannagan and Mefford (2005), the distance estimation for using two levels of magnifications for a sideview camera was compared to using a mirror in a test where both the stimuli and test vehicle were in movement (dynamic stimuli). The test measured the “*last safe gap test*” (the last distance of which the test person would feel safe pulling out in front of the approaching car to execute an overtaking). The test vehicle was driving in 40 km/h and the stimuli vehicle was driving in 56 km/h. The magnifications used were unit magnification (1:1) and 0.5, the latter making objects appear smaller than 1:1 in the image. (Flannagan & Mefford, 2005)

The results showed that the viewing condition of the road (display with unit, 0.5 magnification or using a mirror) had significant impact on distance estimation. The longest distances were obtained using unit magnification, the second longest when using the 0,5 magnification and the shortest when using the mirror. The distance was however only slightly larger when using the 0.5 magnification compared to using the mirror (27.5 m compared to 27.2 m). The authors point out that using either display magnification leads to more conservative judgements which hence would not be critical from safety perspective, cause larger gaps in overtaking situations. Since the 0.5 magnification leads to distance estimations so close to using the mirror, the conclusions suggest that this could be the recommended magnification for CMS. They however also point out that this finding is limited to the velocities used in this test and that further evaluations would be necessary to draw more definite conclusions. This however conflicts with previous research and recommendations concerning the advocated magnification for CMS by Roscoe (1984) (through Flannagan & Mefford, 2005) who recommend 1.25 and Hicks et al. (1999) (through Flannagan & Mefford, 2005) who recommend 0.33. (Flannagan & Mefford, 2005)

Magnification Factor Correcting Distance Perception Compared to Direct Vision during Static Conditions

Roscoe (1984) conducted a study to understand which magnification factor that the corrected the perception to best correlate with the distance estimations when using direct vision within the aircraft sector. A static test was conducted, where the participants (among other tasks) got to

look at an oak from a distance on 183 meters through a frame. The participants were then asked to look at the oak again, but this time through a periscope screen using different magnifications. They were then asked to say whether the oak appeared to be further or closer away compared to viewing it directly through the frame. By altering the magnifications accordingly to the participants responses, the preferred magnification for each participant was determined. (Roscoe, 1984)

In this test, the magnifications evaluated were nine ones between 0.8 and 1.7. The results showed that the best magnification factor was approximately 1.25. They did however also point out that to determine the specific optimal magnification level for specific synthetic imaging system, one must look at them one by one. (Roscoe, 1984)

Magnification & FOV

An article review by Van Erp and Padmos (2003) showed that displayed images can provide users with support during poor visibility conditions, but that the differences compared to using direct vision can result in speed and distance overestimations. The authors identified (through previous literature studies) and tested six image parameters that affect the driving by conducting user tests. Those were FOV, image magnification, availability of reference point, viewpoint, image quality and image update rate. According to this article, previous findings suggest that peripheral view and reduced FOV affects speed perception (different sources have however reporting both underestimations and overestimations) as well as decreased accuracy of time-to-contact estimations. (Van Erp & Padmos, 2003)

Magnification is an important factor since it affects size and distance invariance. Several sources have shown that unit magnification does not have to represent the most accurate size and distance perceptions of objects, and some suggest that some level of magnification might be necessary for objects and distances to appear accurately compared to using direct vision. The level of magnification recommended does however vary depending on the source. These authors do however point out that it would be interesting to investigate magnification smaller than unity since that would favor a greater FOV. They also stress that the trade-off between FOV and the magnification are important topics to research. (Van Erp & Padmos, 2003)

Concerning the FOV, the results showed that it has no impact on the longitudinal distance perception. The level of magnification, which was isolated from FOV, does however affect the speed and distance perception; both magnification 1.0 and 0.5 lead to overestimations of speed and distance, but the distance and speed overestimations were larger for the 0.5 magnification. These findings regarding the distance estimations in relation to the magnification are not conflicting against the findings from Roscoe (1984). The authors suggested that the magnification level should be higher than unit to interpret distances in images in accordance with reality. The authors also encourage others to be cautious when translating the optimum magnification level from a simulator setting onto driving settings as other factors may affect what is optimal in that situation. (Van Erp & Padmos, 2003)

Van Erp and Padmos (2003) also showed that the driving performance for taking sharp curves increases with the wide FOV (100° compared to the lower one of 50°, but that it does not affect

speed estimations. The magnification level of 0.5 furthermore leads to deterioration when driving in sharp curves or making lane changes, and also leads to distance overestimations as well as speed overestimations (compared to the magnification factor of 1.0). (Van Erp & Padmos, 2003)

According to Roscoe (1984), the findings of the role that the physiological depth cue convergence has on distance perception are inconsistent, and suggests that the reason why this depth cue's impact is exaggerated by some might be that it is one of the easiest to manipulate and measure. (Roscoe, 1984)

Longitudinal Display Placement

In another study conducted by Flannagan et al. (2002), the effect that distance to a screen or mirror had on the distance estimation when driving was examined. The tests used static stimulus, and each person was then asked to estimate the distance to a car behind them that would be placed in one of six available positions (at the distances of 30, 40 or 50 meters behind, and either 3 m to the left or right of the subject car's longitudinal midline), by having the indirect vision provided by either a set of two displays or mirrors. The distance to the mirror/display was varied by placing the seat at two different longitudinal positions. (Flannagan et al., 2002)

The results showed that the estimates of the distance is linear to the increased actual distance, but that there is always a slight error in the estimation (underestimation) that seemed to be more significant when using the display, and particularly when the display was placed on the passenger side. The distances are thus perceived to be longer on the passenger side. (Flannagan et al., 2002)

Furthermore, the distances from the most forward position lead to longer distance estimations compared to the back position when using the mirror (surprisingly since the distance from the eyes are actually shorter when looking in the mirror from at the forward position). When comparing the estimated distance to the actual distance using the screen at different seating positions, the estimations made from the most forward position caused a somewhat smaller distance estimations compared to the distance estimations in the back. This finding was hypothesized by the authors, since previous findings (Roscoe, 1984 through Flannagan et al., 2002) indicate that the image size of an object presented artificially on a display affect the perceived distance to them. The difference was however much smaller than hypothesized, and definitely not proportional to the differences in distance to the displays but rather negligible. (Flannagan et al., 2002)

Pictorial Depth Cues

According to Rößing (2016), the depth cues are accumulated into forming a total impression of depth and distance perception in a scene, and the depth cues that dominate the perception depends of the quality and availability of them. If some cues are not present, the perceiver will use the available ones or interpret the scene and base the distance perception on it. Several empirical findings have also found that the weighting of the depth cues is dynamic and depends highly on the distance to and strength of the stimulus - even if they lead to unrealistic image perceptions, called optical illusions. (Rößing, 2016)

Relative Size

When the size of an object is remembered through previous experience, the observed object size will be compared with the remembered one by the brain. Thereby, the brain makes interpretations about the distance to the perceived object that will make the object appear in the remembered size. An object that is remembered as large, but portrayed small on the retinal image, will hence be interpreted as located far away. (Teittinen, 1993)

Linear Perspective

Linear perspective means that parallel lines that converge towards a point on the horizon that is located on the retinal image, will by the visual system be interpreted in a way that gives rise to the *ponze effect*. That means that two objects of the same size will be interpreted as larger if it is closer the point where the lines converge, and objects located farther away from it will appear to be smaller. The reason is that the distance to the spot where the lines converge is interpreted as farther away, and an object that takes up the same retinal space will hence be interpreted as bigger for it to make sense that it is located farther back. (Levitin, 2002) This cue also go under the name *Elevation*, with the explanation is that objects that are located closer to the horizon line will be perceived to be further away. (Braunstein & Ozkan, 2010)

Light & Shadow

Another depth cue to determine depth and distance concerns lighting and shading, and the way lights fall onto an object as well as the amount of shading on it can be important for the depth perception. Objects that are dark and obscure appear to be located farther away and lighter objects appear to be closer. (Pinna, 2012)

Interposition (Overlap)

The depth cue of interposition or overlapping is rather straight forward. An object that is overlapped or partly obscured by another object is perceived as farther away than the overlapped object. (Durand et al., 2002)

Aerial Perspective

Aerial perspective is a cue that refers to the contrast of the perceived object. When observing an object from far distance, the object appears a bit blurred or hazy due to atmosphere conditions such as rain, fog, smoke or dust. In the opposite way, object very close to the observer appear as more distinct, having a higher contrast. (Cherry, 2021)

Texture Gradient

Another depth cue is texture gradient. When observing a two-dimensional image or screen, it is possible to estimate depth based on how apparent the texture of an object is. When driving a car, it is possible to observe the roughness of the asphalt when it is close to the observer. In the opposite way, observing asphalt from for example 100 meters away will only provide a black or grey image without any texture possible to distinguish. Thereby it is possible to estimate distances through texture gradients of objects. (Cherry, 2021)

Image Resolution & Update Rate

The quality of the image is often times discussed in terms of resolution and contrast, and reducing the quality affects the size and distance perception to objects far away as well as tasks

that are mediated predominantly of acuity, like for example changing lane. It will however not affect driving tasks concerning peripheral vision like lateral control or navigating. The findings regarding the image update frequency showed speed and distance estimation tasks only require about 3 Hz. At breaking the resolution can be as low as 256x242 pixels and lower than these that will lead to performance degradation, more specifically overestimation distances. (Van Erp & Padmos, 2003)

5.2.2 Control & Object Detection

In this subchapter findings regarding control and object detection are presented. More specifically it concerns findings about display placements, FOV, reference and viewpoint, image quality and update rate and external/physical/light and weather conditions.

Placement of Displays

A study regarding the sideview displays' placement for CMS was made by Beck et al. (2017), where three different layouts and one control (mirror) were analyzed (see Figure 16). The experiment was conducted by letting participants use a driving simulator and perform lane changes to avoid an approaching collision. The five variables investigated were eye-off-the-road time, response time, ratings of perceived workload, preference and perceived safety. (Beck et al., 2017)

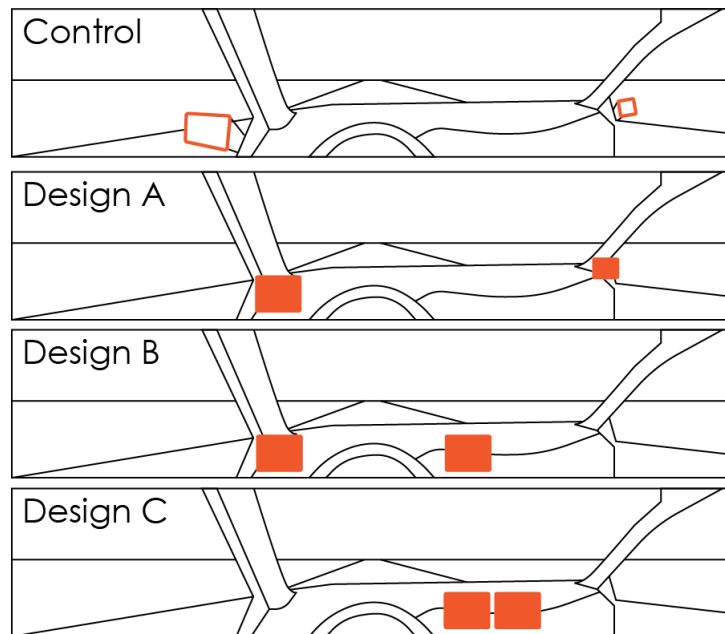


Figure 16 - Placement of the displays in the three suggestions, compared to conventional mirrors. (Beck et al., 2017).

The following results were found in the study:

- The Control layout (conventional mirrors) was the worst design regarding all the five measures.
- Design A performed better than the Control design, but worse than Design B regarding all five measures.
- Design B performed best of all layouts, regarding all five measures.
- Regarding eye-off-the-road time and response time, Design C was similar to Design B.
- Regarding the subjective ratings (perceived workload, preference and perceived safety), Design C was consistently worse than Design B, but similar to Design A.
- Design C did not significantly differ from the Control design regarding preference and perceived safety. (Beck et al., 2017)

Takeaways from the study was that the best placement (regarding eye-off-the-road time, response time, and, ratings of perceived workload, preference and perceived safety) was having both sideview displays on each side of the steering wheel. The result indicated that reducing eye gaze travel distance and remaining compatibility was affected by the placement of the screens. (Beck et al., 2017)

In a study by Berberich et al. (2021), the display positions were also studied with the focus on its effect on user experience and performance, by finding out which position was most pleasant to use and which one was the most safe in comparison to using the exterior mirrors. The experienced safety was measured by asking the participants to subjectively rate this with regard of psychological aspects (such like stress) of using the mirrors or CMS, and the level of safety was translated into measuring the object recognition time, dynamic discrimination performance (ability to separate objects from each other) and the situation overview was also studied. (Berberich et al., 2021)

Four display positions were analyzed; one with the displays on the left respectively right hand side A-pillars, in the middle in front of the center console of the vehicle and in front of the center mirror and in front of the instrument cluster. The images from the sideview cameras were then displayed on either two of the displays in the car, or together on one screen, creating a combination of six layouts that were tested (see Figure 17). The tests were carried out on public roads. (Berberich et al., 2021)

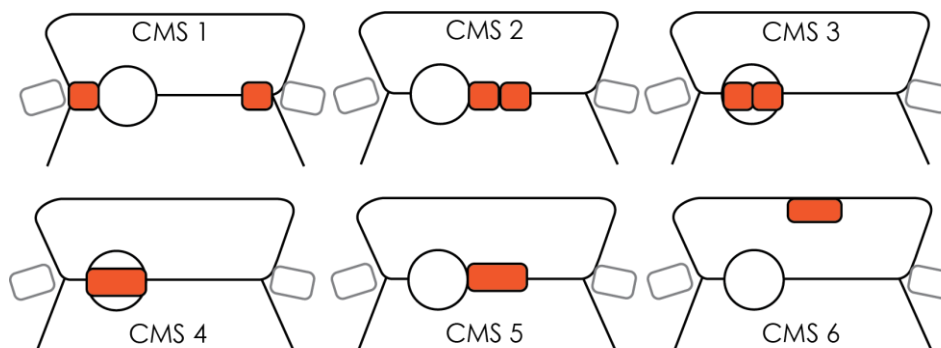


Figure 17 - Display layouts for the Berberich et al. (2021) user test.

The results showed that the display position in the instrument cluster (CMS 4) was the most favored one. For the situation overview, this display position was rated even higher than the exterior mirrors were. The object detection was the same when using CMS 2 and 3 as for mirrors, but worse when using CMS 1. For CMS 6, the stress level was significantly higher compared to using the mirror or any of the other two merged displays. CMS 4 and 5 were rated higher than the mirror concerning the overview, and furthermore there was no difference in object detection for CMS 4, 5 and 6 and the mirrors. (Berberich et al., 2021)

The participant's confidence using CMS was however not as high as when using mirrors, and the level of stress was higher using CMS compared to mirrors. The authors do however point out that this is most likely due to the habit (which was strengthened since the confidence ratings increased while the stress ratings decreased with the increasing number of tests the participants had gone through using CMS). This system did however not have any effect on the number of blind spot checks, but it did cause significant reduction or complete omission of the head movements, which was considered positive. The authors also stress that one must take into consideration aspects such as distractions from the forward driving scene caused by for example lights from the display. They also discuss the quality of the image when sunlight shine directly into the camera causing problems since that cancels the image for the user. The quality of the image and headlights was also discussed since it made objects "*melt*" together in the image, preventing the user distinguishing vehicles from each other. (Berberich et al., 2021)

In a study by Schmidt et al. (2006) regarding the display placement it was also found that the right CMS display should be placed on the right-hand side of the driver and the left screen should be placed on the left-hand side, i.e. around the steering wheel since it provides less head movements and makes the image more recognizable. Though, it was not at all desired to have the screens too far down vertically from the central visual field. The farther down from this forward line of sight, the smaller number of glances were namely measured during the tests. The lower placement scored the lowest number of glances, indicating a decrease of situation overview during the driving. (Schmidt et al., 2016)

FOV

According to Van Erp and Padmos (2003), peripheral view plays a role when it comes to lane keeping and general control. A limited FOV will hinder the perception of objects and vehicles that could be obstacles in the driving since they might disappear from the image before they are reached and that driving in curves might be affected by the limited FOV if the tangent line of the curve would fall out of the FOV. (Van Erp & Padmos, 2003)

Viewpoint & Vehicle Reference

In the study by Van Erp and Padmos (2003) where FOV, viewpoint and spatial reference aids' impact on user performance was evaluated, the results showed that the viewpoint had no significant impact on lateral distance estimation, but the interaction of viewpoint and FOV affect this performance significantly. With the 50 degrees FOV, the lower viewpoints led to better performance compared to the higher viewpoint. For a wider FOV of 100 degrees, the higher viewpoint however led to significantly increased performance while the lower led to significantly decreased performance. (Van Erp & Padmos, 2003)

It also showed that the spatial reference aids in the test caused no performance improvements when it came to positioning, steering course and distance perception laterally, but that the participants preferred the presence of vehicle reference points (like for example the bonnet) (Van Erp & Padmos, 2003), which has been proved to impact the lateral positioning ability (Thomas, 1991, through Van Erp & Padmos, 2003).

Image Quality & Update Rate

The findings regarding the image update frequency showed that driving in sharp curves and lane changing tasks require a minimum update frequency of 5-10 Hz and a resolution of 64x60 pixels (at a 100 degrees FOV), and lower than that will lead to performance degradation. (Van Erp & Padmos, 2003)

External/Physical/Light & Weather Conditions

According to Schmidt et al. (2016) there are a lot of potential benefits regarding CMS, but also challenges. Regarding physical circumstances, CMS can be more resilient towards soil and rain drops than mirrors, and the small exterior camera and placing the displays inside the car also cause beneficial aerodynamic. There is also a risk for condensation and frost to occur on the CMS lens. In sunlight, CMS will not expose the driver to the same glare as in mirrors. Further, it offers the driver to adjust the brightness of the screen, depending on the ambient light conditions, which is necessary for driving in darkness. It is however a challenge to provide a good enough adaptability of the CMS. When light conditions suddenly change, the display needs to have a fast time of response, to adapt to the new light without any delays or glares that disturb the driving experience. Further, related to the image quality blooming or smears might appear in CMS screens, especially when displaying artificial light sources, which could result in the screens not depicting the real situation. Additionally, resolution close to mirror and good enough contrast and color reproduction is important, especially white for white colors as that can speed up the visual search and find ability. (Schmidt et al., 2016)

5.3 Reflection

In this subchapter, the reflection of phase I is presented. The reflection is categorized into distance perception and control and object detection, coherent with the structure of chapter 5.2.

5.3.1 Distance Perception

This part of the reflection chapter presents the reflection regarding parameters' impact on distance perception.

Estimations Near and Far Distances Using CMS Compared to Mirrors

The findings from previous literature regarding user performance for CMS to a mostly concern parameters affecting depth-, distance- and speed perception as well as the ability of detecting objects in the surrounding. Some of it also concern external conditions that affect the user performance and that are necessary to at least keep in mind when designing CMS.

Some findings concern simple comparisons between the distance perception when using CMS respectively sideview mirrors at different velocities. The findings from Schmidt et al. (2016) showed that estimations made with the respective system was not significantly different, but it

did show a significant decrease in distance estimation connected to increasing velocity for both systems. Even if there was not a significant difference in distance estimation caused by the interaction of the system type and velocity, it showed a trend of the differences in distance estimations converging at increasing velocities (up to 50 km/h). Since the estimations made with CMS were longer than those made with mirrors, this does not pose a safety threat (a larger gap is safer compared to a short), but the concern was that the difference between the two systems at some increasing velocity would diverge again and that the distance estimation of CMS would be lower (which would decrease road safety by obvious reasons).

The findings from Berberich et al. (2021) however tested the differences in distance estimations for CMS and mirrors for velocities up to 150 km/h, and the increasing velocities did not cause significant difference using the respective systems.

Even though the combination of the findings from Schmidt et al. (2016) and Berberich et al. (2021) showed that the velocity does not cause significant differences in distance estimation, it is difficult to draw any conclusions regarding if velocity never affects the distance perception and estimations. By speculation, there is a risk that the interaction between the velocity and another parameter might have impacts on the distance estimations. This is however not illustrated in the tests by Schmidt et al. (2016) and Berberich et al. (2021) since those tests did not vary any other parameters, but rather compared the perception using fixed systems. The conclusions that should be made based on these two sources should hence only be that the velocity did not impact the distance estimations significantly for those fixed systems, of which many parameters used are unknown, unfortunately.

Furthermore, the findings from Schmidt et al. (2016) of estimating distances to objects where both the subject and reference were standing still, showed that CMS led to underestimations of the distance while mirrors led to underestimations at close distances and overestimations at farther distances. One can however question the credibility of these results, as the participants had to estimate the distance verbally, which is proven to be difficult for distance longer than a few meters. The findings also showed that reverse driving towards a static object caused less overestimations using CMS compared to mirrors, and sometimes even underestimations. Since these two tests concerned distances of 4-20 meters, i.e. short-distances in the context of driving, overestimations of distances might be crucial since it could contribute to collisions that would not necessarily be dangerous but unnecessary and expensive (like scratching or bumping into a car, leaving marks). But at the same time, underestimations of distance could also become a problem since it would limit the driver in the context of driving in small spaces for maneuvers that require utilizing the available space. Since both underestimations and overestimation pose different difficulties and risks, one could still argue that the best thing when driving would be to perceive the distance accordingly to reality, since that would enable the user to make well informed decisions. Since the studies made in the context of estimating distances for reverse driving at low speeds, it is interesting to understand by what means the distance perception can be altered to correspond with the actual distance.

Longitudinal- & Vertical Placement of the Sideview Camera's / Viewpoint & Reference Point

The study by Bernard and Hecht (2020) investigated the sideview camera's longitudinal and vertical placement's effect on distance perception and the results showed that the lower vertical placement caused significant overestimations while the conventional and higher placements led to underestimations (the latter is more safe in driving). Since the low placement led to overestimations while the conventional led to underestimations, there is probably a placement in between that would cause accurate distance estimations. But the important take-away from this finding is that the vertical placement of the camera does affect the distance perception, which hence is a parameter that can be used to alter the distance perception according to preference.

However, when performing the tests of measuring a span of distances, the results showed that shorter distances are overestimated and larger distances are underestimated, but interestingly; when the presence of a vehicle reference was added, the estimated distances no longer differed significantly when using the different camera placements. This is useful information since this is a parameter that affects distance perception and that hence could be used for manipulating the perception according to a certain preference. It is especially useful if one would like to place the sideview camera far down.

The findings from Van Erp and Padmos (2003) showed that integrating spatial orientation aids that showing the exact distance from the bumper for a transverse line did not affect distance performance significantly, which is surprising. The authors suggest that the reasons might be that the number of runs did not give the participants time to start using the tool in the proper way, or that other cues for determining the perceptions were more dominating. The conclusion from these findings is therefore not that spatial orientation aids will never affect distance perception, but rather that more research and tests on concepts with other designs should - or at least could - be performed before determining the efficiency of this tool.

Lastly, the different longitudinal camera placements caused no significant difference in distance estimation, but one can however consider the placement in this axis anyway as this impacts the available vehicle reference in the image. Bernard and Hecht's recommendation was to place the sideview camera farther to the front than the back of the car due to this reason.

Magnification Level

The findings from Flannagan and Mefford (2005) showed that using CMS caused underestimations for both magnification levels (0.5 and 1.0) compared to using the mirror, which was positive seen from driving safety aspects (when testing the last safe gap at 40 km/h), but unit magnification caused longer distance measurements compared to 0.5 (indicating that distances were perceived as longer using magnification 0.5 compared to 1.0). The authors also suggested that zoom level 0.5 might be preferable for driving since this magnification led to the closest estimation compared to mirrors, but also that it conflicted with the findings from Roscoe (1984) who recommended somewhere around 1.25 for distance perception to be accurate with reality. To keep in mind regarding Roscoe's finding is however that it actually did not compare rearward vision but instead forward, and one can consider how that affects distance perception. Another thing to keep in mind is that Roscoe's tests were made at an open field where the stimuli object

was located 183 meters away, which by far is longer than the last safe gap estimation used for the highest velocity of which CMS has been tested on. (Berberich et al., 2021) In addition to that, Roscoe points out that one should not generalize too much regarding the optimal magnification factor, but rather perform tests for a specific situation in order to understand what works best in that context. Based on this reasoning, one would probably want to go for the Flannagan and Mefford (2005) findings, since his results are actually gathered from a rearview test in a car.

However, when comparing the Flannagan and Mefford (2005) findings to Van Erp and Padmos (2003) are actually coherent. The latter found that the display lead to overestimations of distance, that in addition became larger when using magnification 0.5 compared to 1.0 (meaning that the measured distances for level 0.5 were perceived as longer compared to 1.0, which was the case for the Flannagan and Mefford (2005) study too). The reason why one study led to overestimations while the other led to underestimations could be that the tests used were affected by other parameters dislocating the measurements. Since the Van Erp and Padmos (2003) results were performed using simulations, it is possible that this difference compared to Flannagan and Mefford's (2005) tests impacted the results this way. This information, combined with Roscoe (1984) suggesting that every single system should be evaluated to find the appropriate magnification level, is difficult to draw any conclusions of the magnification more than that it does affect the distance perception and also that lower magnification levels cause the user to perceive distances as longer.

The results from Van Erp and Padmos (2003) furthermore showed that the FOV has no impact on longitudinal distance perception, which is interpreted as if this parameter should not be taken into consideration to optimize this part of user performance when designing the system.

Distance to Display

Regarding the distance to the display, the findings from Flannagan et al., (2002) showed that the distances generally were underestimated and especially when using the CMS displays. In this case the longer distances to the screen led to longer distance estimations compared to the shorter placements. The differences in distance perception when using the screens as an effect of distance to the screen was however negligible. The distance to the display is therefore concluded not to be a parameter that affects the distance perception, which is useful to know when designing for CMS.

Depth Cues

Regarding the depth cues' impact on distance perception, only general findings were made in Röβing (2016). The message then was that the depth cues available in an image will be interpreted in order for the perceiver to get an image of the depth and distance in the image, and if some are missing or other are stronger, that will be compensated for. This finding tells us that there are multiple combinations of depth cues that could affect the user's distance perception, which makes it difficult to draw conclusions about how to prioritize among them. Instead, the message from this finding is brought further into the work that depth cues do affect distance perception, but exactly how much each one affects it could be investigated in future research. It is also worth mentioning that image resolution of the screen highly affects the depth cues perception, since it provides a basis for perceiving what is depicted in the screen.

Image Resolution & Update Rate

The findings concerning the image resolution and update rate are rather straight forward and show that the minimum resolution should be 256x242 pixels, with a minimum update rate of 3 Hz (Van Erp & Padmos, 2003). For lower image and update quality, the performance will be decreased when estimating distances, size and acuity mediating tasks. One can however question if those numbers are absolute, or if also they are depending on the other determined design parameters for CMS. On the other hand, the legal requirements already established that the resolution and update rate should be higher than what these sources provide, and it is perhaps more interesting to dig in what those constraints are based on.

5.3.2 Control & Object detection

This part of the reflection chapter presents the reflection of the parameters' impact on control and object detection.

Placement of Displays

Another parameter that according to the findings from Beck et al. (2017) affect the user performance when it comes to keeping track of the surrounding environment and objects in it is the placement of the screens, mainly covering aspects such as time-off-the-road and response time, as well as perceived safety, workload and preferences. The results from Beck et al. (2017) then showed that placing the screens horizontally closer to the driver (closer the steering wheel) generally led to better performance. It was also shown that all placements for the display in the test (see Figure 16) made the user perform better compared to using the mirrors. Also, placing the two sideview displays in the center stack display regarding performance causes as good performance as the other placements but provides the user with less feeling of safety and higher workload.

These findings go in line with the ones made by Berberich et al. (2021), which suggest that best performance in terms of perceived overview and stress level, was achieved when placing the two displays in the instrument cluster. Since the object detection time was the same as for mirrors for all set ups except from CMS 6, while the psychological aspects were rated higher than for mirrors for CMS 2, 3, 4 and 5 (Figure 17), the set ups closer to the viewpoint of the user should be prioritized. It does however say that placing the screens at the A-pillars cause increased object detection time, and that traditional placement of the middle rearview mirror is favored the least among the participants. If one can choose between these placements, placement 2, 3, 4 or 5 should therefore preferably be chosen. This result also say that placing the sideview images in one display does not affect the user performance negatively at these placements, but to point out is that the images were not merged in these tests, and there was a clear line separating them.

The findings from Schmidt et al. (2016) were in line with Beck et al. and Berberich et al. (2021), indicating that a placement closer to the users' viewpoint horizontally increased the object detection ability. It also contributed with knowledge of that lower placements of the displays compared to the users' forward viewpoint decreased the number of glances during the drive and hence the overview of the surrounding. This finding points towards that the screens should be placed farther up towards the line of sight (though, only evaluated up until where the dashboard ends) to increase the overview and hence the user performance when driving.

FOV

The findings from Van Erp and Padmos (2003) suggest that driving performance for taking sharp curves increases with wider FOV. Their study compared 100 with 50 degrees FOV and concluded that it did not affect the speed estimation. It would be interesting to further investigate those FOV in other scenarios than driving in a sharp curve, such as a straighter road or city driving. Could a wider FOV in some cases provide a too large FOV that it overloads the driver with unnecessary information about the rearview? For example, when driving in a city, where there are people and cars that will be displayed all over the screen. Perhaps it could be difficult to distinguish which car or object that it the most threatening object among the crowd. Furthermore, perhaps instead of having a very wide FOV that might trade-off with a deteriorated screen, it could be considered to use a dynamic FOV. To use a camera that shifts horizontal angle when turning in sharp corners could be beneficial as it provides the necessary FOV of the given time, such as modern cars' headlights following the road in curves.

Reference & Viewpoint

The findings from Van Erp and Padmos (2003) showed that the viewpoint's impact on lateral distance estimation depends on the FOV, and a higher placement leads to greater performance for a wider FOV, while the lower increases the performance if the FOV is smaller. The interaction of these two parameters are useful when designing CMS since it affects the driving performance and can be integrated directly when making design decisions regarding just that.

This source also showed that spatial reference aids did not impact the performance when it comes to lateral positioning, steering and distance perception, but that participants preferred vehicle reference points in the image and that this type of reference improves lateral position (Thomas, 1991, through Van Erp & Padmos, 2003), which also had positive impact on longitudinal distance estimation (Bernard & Hecht, 2020). Based on these findings, for improving the user performance when it comes to lateral positioning, a vehicle reference present in the images used for the sideview display is preferable. The spatial reference aids did not affect the lateral distance perception or position, but one should not draw the conclusions that it cannot affect longitudinal distance perception, and different concepts could be researched further in the future.

No findings were however made regarding how the presence of a vehicle reference point in the virtual inner rearview mirror (VIRM) will affect distance perception. It would hence be interesting to consider if it has the same impact as for the sideview displays, but to establish that further research would be necessary.

Image Resolution & Update Rate

When it comes to peripheral vision and being able to detect and distinguish objects (from chapter 5.2.2), the requirements for the performance to not decrease are higher compared to the ones for perceiving distance, demanding a resolution of 64x60 pixels and 5-10 Hz in image update rate (Van Erp & Padmos, 2003). Since both need to keep track of the surroundings as well as understanding distance and depth when driving, the interpretation is that the higher requirements should be prioritized if those are put against each other when using the same screen. However, these parameters are already covered by the legal requirements, where the update rate is stated to

be a minimum of 30 Hz (15 is allowed at low speeds and during dark lighting conditions) and the resolution takes in several different parameters such as images size in the requirements. One can however consider why the legal standards put higher demands on the image update rate than the conclusions drawn from this work.

External/Physical/Light & Weather Conditions

Regarding weather condition's effect on the CMS compared to mirrors, they are not design parameters, but still conditions important to think about in the design process of CMS, which is why they were included in these findings. The overall benefits are greater for CMS than for mirrors, since the small protected camera is located at the outside of the car and displayed inside on the screen. The displays will not get dirty and will be free from raindrops, snow and frost. Though, if a potential lens problem would occur, such as condensation on the lens, then it would be troublesome to remove it. On the other hand, the conventional mirrors will never fail in a way that the user is unable to fix, such as scrape frost of the mirrors. Regarding sunlight when driving with mirrors, it is possible to get temporarily blinded by the sun when reflected in the mirrors.

This would not be a problem when using CMS, since the brightest light that will reach the driver depends on the brightness of the screen, and a totally white image is the brightest that can be reached in a screen. However, the drawback could potentially be that the screens become unperceivable due to blooming and smear effects. The brightness would also be beneficial being dynamic, since it will not be beneficial having the same brightness of the screen driving in low light as when driving in daylight. The response time of adapting to new light conditions, such as driving through a tunnel, would preferably be as low as possible. The driving experience depends highly on the indirect vision which therefore must present the reality in the best way possible, and not as a white screen. The aspect of light and weather conditions is highly affecting the user experience of detecting and perceiving object in the screens but is difficult to draw conclusions regarding how to design the system to consider these aspects.

5.4 Conclusions

In phase I, the main activity was to perform a literature study which resulted in findings describing the impact design parameters have on different aspects of user performance when driving. As can be seen among the findings, many of them concern the user performance aspects "*Distance perception*" and "*Control & Object Detection*", which became the two subchapters. The presented findings create an overall view of what is known regarding parameters' impact on user performance as well as where additional research would be necessary.

The parameters that have proven effect on distance perception is longitudinal and vertical camera placement, presence of vehicle reference in the image, magnification level and image resolution and update rate. The parameters that have proven impact on the overall control and ability to detect objects when driving is the horizontal and vertical placements of the displays, interaction between vertical camera placement and FOV and the image resolution and update rate. One knowledge gap, amongst others, was discovered concerning how parameters affect the distance perception using the virtual inner rearview mirror (VIRM) since all previous findings have focused on the sideview displays. That is an area that could be further researched in the future to widen the knowledge of how to design CMS for good user performance.

6 PHASE II

IDENTIFYING SITUATIONS & PARAMETERS

In this phase, the definition of user performance when driving using, as well as driving situations and design parameters important when using indirect vision were identified, creating a basis for the further work in the project. In this chapter, the procedure, findings, reflection, summary of findings and conclusion of that is presented.

6.1 Procedure

The following procedure was used to identify driving situations and parameters for further investigation in the latter phases of the project. To gain input and investigate the experience of driving with a conventional rearview mirror car and more especially for using CMS, a benchmark was conducted. The benchmarking was performed by the two researchers rather unstructured since it was not known in beforehand what to look for. The cars that were investigated were Audi e-tron and Honda e since they are two of few cars available on the Swedish market with implemented CMS. A Tesla Model 3 was also benchmarked since it has an integrated function for reverse driving that works similarly to CMS. The benchmarking of these consisted of driving and experiencing different use cases, testing different set ups, comparing the FOV and assessing distance and velocity of objects behind. In the conventional mirror cars, the user experience of driving with different car models, sizes of mirrors and FOV was in focus.

Some of the methods that were used during this phase were conducted over a longer time and overlapped other methods. One such method was the expert interviews, which were conducted as a complement to the benchmarking. Several interviews were held to gain insights of CMS, with internal participants from the Ergonomics department and other departments of Volvo Cars. External interviews were also performed with interviewees from RISE (Research Institute of Sweden) and Volvo AB. The interviews that were held were mostly semi-structured but slightly less structured. Some of the interviews had well prepared questions, but some less, to enable a more open discussion. It could also be an informative meeting to let the interviewee share insights that were foreseen due to less experience in the concerned area.

Furthermore, mindmapping were performed to create a basis of what potentially could be relevant parameters affecting user performance in different driving scenarios. Literature research was conducted to gain knowledge of the field within user performance of CMS, and more specifically to understand what is important when it comes to driving and what parameters that could affect that. Through these methods, what user performance when driving really is was defined. This literature study was performed along the literature study in chapter 5, but the findings from the use cases from "*list of possible use cases applicable for CMS*" in SIS (2019) are presented here, since it is more relevant in the phase II context.

A P-Diagram was then performed with help from internal experts at Volvo Cars, extract all the possible parameters that potentially could affect the user experience of using a car with CMS. with the previous insight as a base. In preparation of the workshop, the large amount of control factors was distinguished from previous literature study and mindmapping. From that the majority of P-Diagram was performed by the researchers according to the P-Diagram regulations. Only few additions and changes were made compared to the factors that were stated from the previous work, since most the input, output, noise and control factors were covered by that.

The workshop started with the major part of P-Diagram already filled in by the researchers, to provide an understanding of what similar complementary aspects could be, and to have some input to trigger discussion. The workshop started with the 15-20 participants being introduced to the subject and situations by shortly presenting the master thesis and some background to what a

P-Diagram is and how to perform one. The participants were then presented with the already extracted parameters and were then allowed to discuss how to expand and/or correct the presented findings. The whole session was performed remotely using Microsoft Teams, due to the Covid-19 pandemic.

A hierarchical task analysis (HTA) was thereafter conducted for each of the chosen use cases to provide a structured way of assessing what steps that each driving scenario include. Some steps were reoccurring in the different driving scenarios, which is the reason for using building blocks in some steps of the HTA:s, since that enabled reusing them in other HTA:s. The HTA steps were later used to perform the FMEA.

Following up the HTA:s, the FMEA:s was performed for each of the eight driving scenarios by using the steps from the HTA:s. The steps that considered user performance of the visibility were used in FMEA, and some steps from the HTA were therefore excluded from the FMEA, i.e. to “*put in reverse gear*”. Some adjustments were also made to the FMEA to fit the aim of performing it better. The parameter “*detection mode*” and its accompanying numerical estimation was for example ill-fitting in the risk analysis of the driving situations and was not used. The risk product number (RPN) was therefore only a product of severity and occurrence of the errors happening. The definition of the severity was furthermore elaborated and determined as “*probability of serious consequence*” to include the aspect of probability of the risk into the RPN. The scales of severity and occurrence were also defined with words and rating to provide a sufficient comparison when evaluating the sub-tasks of each driving situation, see Table 1 and Table 2.

Table 1

Scale for determine the probability of serious consequence in FMEA.

Insignificant	Low	Very Low	Fairly Low	Moderate	Moderate	Fairly High	High	Very High	Inevitable
1	2	3	4	5	6	7	8	9	10

Table 2

Scale for determine occurrence of the risk happening in the FMEA.

Very Low	Very Low	Low	Low	Moderate	Moderate	High	High	Very High	Very High
1	2	3	4	5	6	7	8	9	10

6.2 Findings

The findings from phase II are presented in this subchapter, categorized on the method used.

6.2.1 Findings from Benchmarking

In this subchapter the findings from the benchmarking is presented. This includes Audi e-tron, Honda e, Tesla Model 3, Polestar 2 and Volvo V90CC, XC90, V60 and S60.

Audi e-tron

The Audi e-tron has displays as sideview vision but a regular middle mirror (class I). The screens

are located in the doors, rather low down, with a shape according to Figure 18. It provides a better direct sideways visibility, since the camera mounts on the outside are rather small and discrete (from the driver position). The image resolution is experienced as high (though depicted as more purple in Figure 18 than in reality). The screens are highly reflective which creates reflection lines on the screen from the dashboard, which partly disturbs the image recognition. The drawback of the placement is, especially for the left one, that it is placed unnaturally low which feels too far from the line of sight when driving. For the left display, the observing angle is not optimal, and it feels like it has been crammed into the door. The unnatural angle of the display also contributed to confusion regarding where the image is located in reality, probably due to the old habit of the mirrors being placed almost orthogonally from the door and not parallelly as they are in the Audi. Furthermore, there were some difficulties regarding accommodating and switching focus between the screens and road back and forth.



Figure 18 - Sideview displays of the Audi e-tron.

Regarding driving the Audi e-tron with CMS in low light conditions, some blooming and glare appear when approaching cars' headlights are shown in the display (Figure 19).



Figure 19 - Displays of Audi e-tron in dawn (left) and night (right) condition.

Honda e

The Honda e has implemented CMS for both side- and rearview, which differs from the Audi e-tron (the latter keeping the inner mirror). The middle display is located at the same position as a

regular inner rearview mirror and it is possible to change the display to mirror by a button press. The sideview displays are located in the dashboard (see Figure 20) with a more “normal” angle towards the driver compared to in Audi e-tron. The left-hand side display does however appear to get behind the driver’s arm or hand while having a certain grip on the steering wheel.

The most critical aspect of driving the Honda e was to estimate distance to objects rearwards through the displays. The distance perception in middle screen was not coherent with the distance perception in the sideview displays, which is confusing. Reverse maneuvering was therefore more difficult than driving forward, since the former relies more on the rearview display.

Regarding the brightness of the screen, it was found that the reflection caused by sunny weather and wet asphalt made the display image appear annoyingly bright. Driving in sunshine, the middle display was also considered too reflective (the reflectivity is due to the available mirror mode when being turned off) which was annoying and complicated the image recognition. When driving in daylight, flickering sometimes also appeared on the displays which was disturbing and directed attention towards the displays. One other thought that was triggered during the Honda e benchmarking was that a vehicle reference point available in the image made it seem easier to understand the images shown in the displays, which it was in the sideview displays but not the middle one. Without it, it felt more difficult to trust or understand the distance depicted in the screens



Figure 20 - Interior of Honda e.

The image in Honda e’s sideview displays can furthermore be changed into another mode, which has a wider horizontal FOV due to the outer part of the image being distorted in a similar way that many European cars have a distorted outer part of the mirror. This was experienced a bit

strange since it was difficult to understand where the distorted objects are located in the surroundings, even if one probably saw a wider FOV than using a conventional mirror.

Tesla Model 3

When benchmarking the Tesla Model 3, it was found that the car had a more extensive indirect rearview from three cameras during reverse driving (Figure 21), compared to the more common set-up of only having one reverse camera for parking. Since the two lower images of the rearview came from cameras that were located below the exterior mirror on each side of the car, it provided an image similar to what CMS could have on that car. If the images on the center stack display were to be used in the same way as CMS for Honda e or Audi e-tron, it would be difficult to use, partly because of the small height and small size, but also due to the viewpoint angle of the side displays that made it extremely difficult to map the image to the surrounding. To keep in mind is however that these images are only meant to be used for reverse driving in the Tesla, and the middle rearview camera display worked very well for that task which could be used for inspiration when improving the parking camera on other cars.

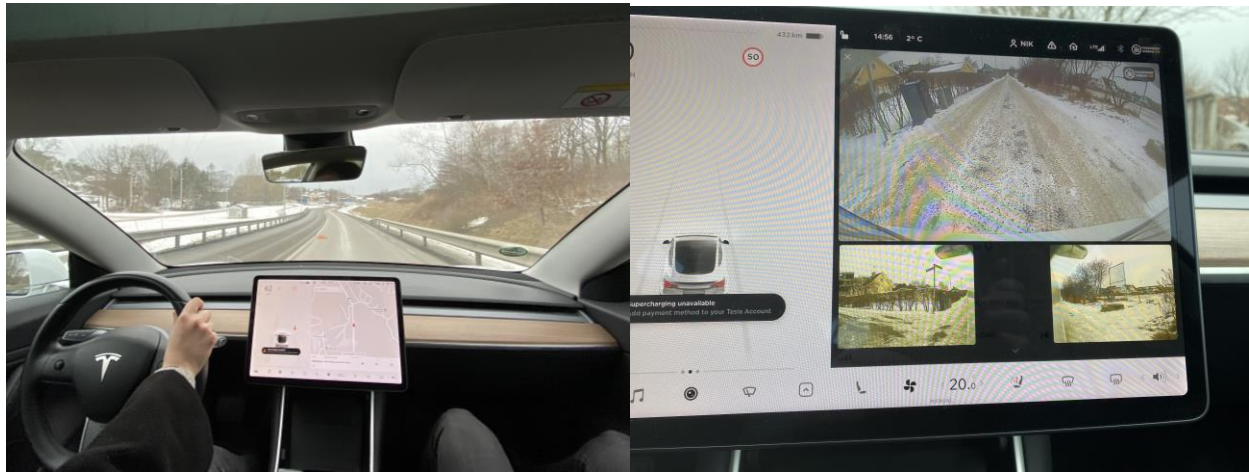


Figure 21 - Interior and parking cameras of Tesla Model 3 (2019).

Volvo & Polestar Models

None of the Volvo or Polestar models had CMS, but it was interesting to find out how the driving experience differed between the models and to understand the drawbacks and benefits of them. The Volvo models benchmarked were V90CC (2019, cross country), XC90 (2019), V60 (2020), S60 (2019) and Polestar 2 (2020). The direct vision towards the side were often a trade-off with the indirect view in exterior mirrors; seeing more in the side means seeing less in the rearview mirrors. As can be seen in Figure 22, the cowls and mirrors take up a rather large place and disturbs the direct sideview for the driver. The images are taken from the driver's ocular point. The large frame around the mirror also cause unnecessary obstruction of the direct FOV. Some of the models had automatic tilt down functions on the exterior mirror when reverse gear was selected, which was appreciated and worked smoothly to detect the parking lot lines and to control the placement of the wheels.



Figure 22 – Direct side views in Volvo V90 Cross Country (2019).

Furthermore, in many of the tested cars it was found that the inner rearview mirror obstructs the forward visibility, see Figure 23. The reason for that is partly because the WEM-cover (windscreen electronic module) behind the mirror, which contains sensors and other technology, is placed in the line of sight.



Figure 23 - Direct visibility from Volvo S60 (2019).

The benchmarked models all had significantly small frame or none at all around the inner rearview mirror. This was considered a positive feature since all of the surface that covered direct vision was used for providing a greater indirect FOV and simultaneously provide more aesthetic appearance. Polestar 2 however, has applied this feature to the exterior mirrors as well, as can be seen in Figure 24, providing a better side visibility to the sides when the cowl frame is removed.



Figure 24 - Exterior mirror of Polestar 2(2020).

6.2.2 Findings from Expert Interviews

In this subchapter, the findings from expert interviews are presented. This included findings from UX Design, display specialist, solution architect, validation engineer and visibility expert.

Interview with UX Design

The interview with two UX designers at Volvo Cars resulted in findings considering the visual ergonomics in CMS, based on their benchmarking of other car models with integrated CMS but also on customer input of current Volvo users as well as users with experience of CMS from other brands. The interview gave a better understanding of the driving situations that are extra important to take into consideration when designing CMS. It also highlighted the main pain points and preferences that users of current CMS cars have expressed, and furthermore some hesitations and expectations that Volvo users have considering integrating CMS into future Volvo models.

The driving and usage situations that the UX-designers pointed out were extra critical in the context of using CMS were:

- Motorway driving – especially when supporting the driver during lane changes, detecting vehicles located in the blind spot and determining the distance to vehicles behind
- City driving – providing the user with a seamless complement to the parking camera, with a wide angle and camera focus that is closer to the car
- Parking – adjustment of the camera angle and magnification
- Communication - between drivers in the front seat and passengers in the back

Common pain points were according to the UX-designers:

- Issues with distance assessment - especially in parking situations
- Poor image resolution and image quality - compared to mirrors

- Weather sensitivity – weather conditions affecting camera lens and disturbing the image; water droplets, condensation and direct sunlight affecting the image through the lens
- Uncomfortable placements of the displays

Common gain points for users of brands that currently have integrated CMS in cars were according to the UX-designers:

- Better image resolution and quality – compared to mirrors during some conditions; nighttime, during dusk and rain
- Greater FOV – wider angle possible compared to in mirrors
- Weather sensitivity – easy to keep camera lenses clean and protected from weather conditions; water and snow
- Comfortable placements of the displays

The UX-designers furthermore pointed out that common fears current Volvo users have of implementing CMS into future models are that it will lead to:

- Increased distraction from driving
- Problems with near and far-sight accommodation - especially if the user wears glasses and is using the VIRM
- Decreased perception of object size when using indirect vision

They also pointed down common expectations (of the minimum viable product) that current Volvo users expect that an implementation of CMS into future models will lead to:

- Safer driving
- Not having to turn head around as much as when using mirrors for indirect vision
- Elimination of blind spot
- Adjustable FOV, camera angle and zoom level - manually or automatically

Interview with a Technical Specialist for Displays

In the interview with the technical specialist for displays, the issue of accommodation in relation to indirect vision was discussed. More specifically, the reasons of why the accommodation is affected when replacing the mirror was discussed; the optical phenomenon that occurs when using a mirror for indirect vision cannot be separated from the reality and direct vision by the brain. The reason for this is that a flat mirror creates a virtual image of reality at the same length scale as that of the real world, and which appears to be behind the mirror; the perception of distance as experienced through the mirror thus coincides with that experienced in the real world (however, if the mirror is convex, the objects in the mirrors are minified which makes them appear as farther away). If a person for example is looking in a flat mirror, the eyes are focusing on a distance that is twice as far as the distance to the mirror. However, when looking at a display instead of a mirror, the binocular depth cues are removed. The accommodation depth cue is removed since the eyes will focus on the screen at the physical distance between the screen and the eyes, and the image itself will not give any binocular cues on how far away different things are located from the perceiver, which increases the difficulty of understanding the image compared to when using a mirror in terms of distance judgment.

The technical specialist for displays meant that this is related highly to the functions of the information provided by the indirect vision system, since they to a high extent are used for looking backwards and determining if it is safe to change the lane and perform an overtaking. The user then must be able to make distance estimations to the surroundings and objects in it, and the speeds at which they are travelling. The estimations do not have to be centimeter-specific, but it has to be possible to understand if one “can make it or not” by putting together the distance to the object and the relative speed of it in relation to the own car.

Other things that were discussed were that integrating displays for the indirect vision might lead to problems for drivers that are farsighted, which is a common visual impairment caused by age. This would cause a problem compared to using mirrors since it would require the drivers to be able to focus on near distances, while using mirrors only requires being able to focus far away.

This specialist also pointed out the following parameters as crucial since they most likely would affect the user performance in CMS; technical display parameters that would affect the effective contrast (i.e. the experienced contrast which is affected by the surrounding light: luminance, intensity, illuminance and luminous flux), display technology (several LED-based LCD technologies, or OLED technology, whose performance is more or less sensitive to temperature and ambient illumination), display surface texture and system latency.

One last note from this specialist was that integrating augmented reality and symbols into CMS would be ways to increase the user performance and experience of using CMS. The specialist also brought up that it might be interesting to investigate the possibilities of integrating CMS with a head up display (HUD) function, since HUD means projecting digital images farther away from the perceiver, making them also focus farther away to see the image sharply. Integrated in the right way, this could possibly reduce the accommodation issues that occur when replacing rearview mirrors with CMS.

Interview with a Solution Architect at Design

In the interview with the solution architect, the approach was discussed of the first step of integrating CMS as replacements of rearview mirror should be to aim for a minimum viable product at least as good as when using mirrors. The reason for that is that integrating CMS into cars already poses many challenges when it comes to the user performance and experience, and in order for it to become better than mirrors, one must start with filling the base requirements that the users have on it. This specialist also commented on the issues CMS causes concerning accommodating between the road and screen and that it reduces the binocular depth cues.

According to the solution architect, there is already knowledge concerning what the preferred placements of the screens would be, but that the optimal sizes and dimensions are rather unexplored (at least to this person’s knowledge). An interesting thing would be investigating the compromise between the FOV, display size and magnification level and their effect on the user experience and performance; should the FOV be cropped to not cause too big image distortions or is it better to have a more distorted image since that allows a greater FOV?

It was furthermore pointed out that the middle rearview mirror could benefit a lot from being a display instead of a mirror, since it in current cars can be difficult to see the rear environment

through it since the evolution of cars has gone towards – and keeps going towards – smaller and smaller rearview windows. It was also commented that there are already some thoughts regarding where the sideview display cameras should be positioned the following couple of years, but from practicality perspectives rather from user performance aspects.

Interview with a Validation Engineer

In the non-structured interview with the validation engineering at Volvo Cars many aspects regarding CMS were discussed. This person claimed that when driving the Audi e-tron, it takes up to 500 km to get used to driving using CMS, and that users easily checks for the old mirrors up until that time due to habit. In general, it takes longer time to check the displays and blind spots using CMS compared to conventional mirrors and blind spots, which can make it feel less safe for the user. With conventional mirrors, the step for checking blind spots becomes smaller when observing the mirrors on the outside compared to using CMS, since the blind spot is located farther away from the displays than the sideview mirrors. Integrating CMS in cars, one should furthermore aim for enabling observing and analyzing the image on the displays fast so that the user does not spend more time looking at the displays than on the forward road. An issue that this expert raised was that the sideview display position in the Audi e-tron was not optimal regarding this.

According to this expert, CMS makes it difficult to estimate distances due to lack of depth perception, mostly caused by the fact of CMS replacing the 3D image in the mirror with 2D images in the display. Further, it was expressed that it is difficult to observe and interpret the image in the display sometimes. The support systems such as parking or 360-view cameras and blind spot information system (BLIS) was according to this expert considered a must if CMS is implemented due to these reasons. Warnings could furthermore appear as support on the displays using different colors and symbols in the screens if something happens.

Lastly it was mentioned that CMS (at least the Audi e-tron version) cars are aimed for customers who are interested in the latest technology.

Interview with a Visibility Expert

From a non-structured interview with a visibility expert at Volvo Cars some interesting and relevant findings appeared. The Audi e-tron was often referred to when discussing CMS since it is one of the few cars available on the market with implemented CMS. The field of view that is shown in the displays of the e-tron is according to this expert too narrow, in relation to the conventional mirror. The screen sizes were also described as being too small, making it difficult to actually see what was depicted in them. The fish-eye effect is also to be considered when implementing CMS, since it provides a larger field of view, but on the expense of a distorted image that is more difficult to perceive. The placement of the screens is also an important aspect to consider in order to design a CMS that is user friendly.

Regarding the image of the displays, the screen cannot be too reflective as it disturbs the image perception. Filters to reduce reflection might be necessary on the screens, but it is important that they do not disturb something else regarding the user experience or image perception. Furthermore, the depth perception in CMS due is experienced as much worse in CMS due to the

flat image (two dimensional compared to three dimensional in mirrors). CMS could also be more sensitive regarding environmental conditions, such as rain, snow and moisture. Therefore, there are more challenges than only providing a good user experience and performance of the system.

This expert also pointed out that other things, like for example the type of glasses that the user uses should be considered when designing the screens, as the combination of some glasses (such as polaroid) and screen types could work less effective through them, cancelling some aspects in the image. More generally, it was also mentioned in the interview that it is important to design the system in a way that will not make the customer feel stupid nor ashamed when using the system in more complex and modern cars. It is preferable to design a CMS with intuitive adjustments and that the users understand what is being displayed in the screens.

According to the visibility expert, Cadillac among other brands has CMS integrated in the mirror and one can switch between them. By doing so, it can be possible to avoid some of the CMS regulations, which can be interesting to have in mind when designing the system.

6.2.3 Findings from Literature

The major part of the literature study is presented in phase I, though the presented scenarios in SIS (2019) were relevant to be presented here in phase II. The scenarios in SIS (2019) were categorized depending on each scenario's relevance regarding being a driving scenario or not. The following scenarios were found:

- Roundabout (monitoring traffic while image constantly changes)
- Merge lane (entering a freeway)
- Lane change (when objects in lane beside)
- Lane change (when approach object from behind)
- Reverse driving (detect relevant objects)
- Reverse driving (estimate distance to relevant objects)
- Turning (percept relevant objects)
- Exiting car (after temporary standstill)
- Exiting car (after longer period of resting in vehicle)
- Normal take-off and exit procedure
- Take-off after longer period of resting in vehicle

In the SIS (2019) literature, a definition of what the user should be able to do using the indirect vision system was stated, namely;

- View the FOV of the intended mirror class
- Observe relevant traffic situations
- Observe the near and far environment surrounding the vehicle
- Perceive objects (vehicles, cyclists, pedestrians, traffic lights & signs)
- Perceive location, distance and velocity of objects

6.2.4 Findings from Mindmapping

By performing the mindmapping, some driving situations and corresponding parameters affecting user performance in CMS were stated. The scenarios were parking, reverse driving (on a narrow road), reverse driving (on open field), slow down/breaking, performing an overtake in same direction (including changing lane), overtake in opposite direction (temporarily driving against traffic), stepping out of the car and turning (see Appendix A for a further description of the driving situations). The parameters that were stated were placements and viewing angle of displays, placement and angle cameras, screen size and dimensions, image magnification, resolution, distortion, contrast, light sensitivity and image update frequency of camera and display. The mentioned parameters were found relevant for all the previously stated driving situations.

Some other parameters that were found to be relevant for only some scenarios were presence of vehicle reference point, size of camera houses and A- and B-pillars. Furthermore, the aspect of accommodation when changing focus between the displays and the road, and also the coherence between the displays was found to be relevant when using CMS.

One general finding from this method was that it is highly appropriate to consider all the three direction of the car (front, sides and rearview) when implementing CMS for cars.

6.2.5 P-Diagram Workshop

The findings from the P-Diagram workshop are fully presented in Appendix B and summarized in this subchapter. They are categorized into inputs, noises, function, control factors, outputs and error states which follows the template of P-Diagram (see Figure 14). The function of using mirror respectively CMS was during the P-Diagram workshop uniformly decided to “*provide user with information about the surrounding (primarily rear and side) environment by using mirrors or CMS*”. Regarding the inputs for the CMS, it was decided to be mostly users driving and maneuvering the car, but also some technical less relevant aspects. The noises provided some interesting findings that are worth taking into consideration if implementing CMS, such as customers’ visual impairments, accommodation capabilities, dirty camera lens, customer being used to mirrors, weather (rain, snow, humidity, temperature, day and night), vibrations, exterior and interior design of car, support system integration and variation of driver position and sight angle and distance. The mentioned findings were however not something to further investigate in this work, since they are not adjustable design parameters and hence not something one should provide design guidelines for, as is the aim of this thesis.

The parameters that could be adjusted are the control factors, which for CMS respectively mirror was found to be the parameters in Table 3.

Table 3

The control factors according to the P-Diagram workshop.

Mirror	CMS
<ul style="list-style-type: none"> • Shape and size of: <ul style="list-style-type: none"> ○ Mirrors (height, width) ○ Cowl 	<ul style="list-style-type: none"> • Shape and size of: <ul style="list-style-type: none"> ○ Displays ○ Camera houses

<ul style="list-style-type: none"> • The relationship between FOV, magnification level and mirror size 	<ul style="list-style-type: none"> • The relationship between FOV, magnification level & display size
<ul style="list-style-type: none"> • Placement of: <ul style="list-style-type: none"> ○ Height ○ Width ○ Depth 	<ul style="list-style-type: none"> • Placement of: <ul style="list-style-type: none"> ○ Displays ○ Camera and camera houses (horizontal and longitudinal)
<ul style="list-style-type: none"> • Number of mirrors 	<ul style="list-style-type: none"> • Number of: <ul style="list-style-type: none"> ○ Displays ○ Cameras
<ul style="list-style-type: none"> • Adjustment range of: <ul style="list-style-type: none"> ○ Mirror angle ○ Seating position 	<ul style="list-style-type: none"> • Adjustment range of: <ul style="list-style-type: none"> ○ Camera angle ○ Seating position
<ul style="list-style-type: none"> • Reference point 	<ul style="list-style-type: none"> • Reference point
<ul style="list-style-type: none"> • Absorbent filter 	<ul style="list-style-type: none"> • Display angle
	<ul style="list-style-type: none"> • Latency of screen
	<ul style="list-style-type: none"> • Camera properties (dynamic range)
	<ul style="list-style-type: none"> • Display properties: <ul style="list-style-type: none"> ○ Contrast ○ Response time ○ Color reproduction ○ Luminance

The determined outputs in the P-Diagram workshop were that the user should be able to detect and perceive objects, estimate distance to objects, estimate the relative speed of objects and enable visual communication with people by using either system for indirect vision.

The error states that were found in the P-Diagram workshop were generally to not detect objects (or detect too late) and misjudging distance and speed of other objects in relation to oneself. The more specific error states are presented in Appendix B.

6.2.6 Findings from HTA & FMEA

The HTA created a base on which the FMEA was performed and is therefore highly relevant to mention it in the findings of this chapter. The scenarios that were evaluated was parking (forward, reverse and parallel), driving in an intersection, driving in a roundabout (one or more lanes), changing/merging lanes, performing an overtaking, turning, reverse driving and driving forward. See Appendix C for all the HTA:s that were produced from each scenario. From all eight driving situations, a total of 90 sub-tasks were analyzed regarding failure and error modes in the FMEA. Most of them (42/90) had to do with not being able to estimate distance to objects in the side or rear environment, which can be seen in Appendix D. Looking at the top ten most critical risks Appendix D, seven out of these ten actions are related to distance perception. As can be seen in the Appendix D, some of the most critical tasks belong to reverse driving, managing a roundabout, managing an intersection and overtakings. Estimating distance to objects behind, through indirect vision, while driving in reverse got the highest RPN value.

6.3 Summary of Findings

In this section, the findings from phase II regarding what user performance is when driving, designing CMS and what the findings originated from originate from are concluded in Table 4. The user performance aspects of driving related to the source they originated from Table 5 and Table 6. To read more about the origin of these aspects, parameters and driving scenarios, see chapter 6.2.

Table 4

The user performance aspects of driving related to the source they originated from.

User Performance Aspects in Driving:	Originated from:
<ul style="list-style-type: none"> • Detect objects in the FOV • Perceive objects (vehicles, cyclists, pedestrians, traffic lights & signs) • Estimate distance to objects • Estimate relative speed of objects 	<ul style="list-style-type: none"> • Benchmarking • Mindmapping • P-diagram workshop • Literature
<ul style="list-style-type: none"> • Observe relevant traffic situations • Observe the near and far environment surrounding the vehicle • Perceive location 	<ul style="list-style-type: none"> • Literature
<ul style="list-style-type: none"> • Communicate with other people using eye contact 	<ul style="list-style-type: none"> • Literature • P-diagram workshop

Table 5

Summary of the design parameters that affect user performance when using CMS.

Design Parameter:	Originated from:
<ul style="list-style-type: none"> • Shape and size of <ul style="list-style-type: none"> ○ Displays ○ Camera houses size and shape 	<ul style="list-style-type: none"> • Mindmapping • Expert interviews • P-Diagram
<ul style="list-style-type: none"> • Relationship between FOV, magnification level and display size 	<ul style="list-style-type: none"> • Mindmapping • Literature study • Expert interviews • P-Diagram
<ul style="list-style-type: none"> • Placement of: <ul style="list-style-type: none"> ○ Displays ○ Camera and camera houses (horizontal & longitudinal) • Number of: <ul style="list-style-type: none"> ○ Displays ○ Cameras 	<ul style="list-style-type: none"> • Mindmapping • Literature studies • P-Diagram workshop
<ul style="list-style-type: none"> • Adjustment range of: <ul style="list-style-type: none"> ○ Camera angle ○ Seating position 	<ul style="list-style-type: none"> • P-Diagram workshop
<ul style="list-style-type: none"> • Display angle • Camera angle/viewpoint 	<ul style="list-style-type: none"> • Literature studies

<ul style="list-style-type: none"> • Reference point • Depth cues in image 	
<ul style="list-style-type: none"> • System latency • Camera properties (dynamic range) • Display properties: <ul style="list-style-type: none"> ○ Contrast ○ Response time ○ Color reproduction ○ Luminance 	<ul style="list-style-type: none"> • Expert interview • Literature studies

Table 6
Summary of the most important driving scenarios when using CMS.

Driving Situation:	Originated from:
<ul style="list-style-type: none"> • Parking (forward, reverse & parallel) • Intersection • Roundabout • Change/merge lane • Overtaking • Turning • Reverse driving • Forward driving 	<ul style="list-style-type: none"> • Mindmapping • Literature studies • P-Diagram Workshop
<ul style="list-style-type: none"> • Exiting a car 	<ul style="list-style-type: none"> • Literature studies
<ul style="list-style-type: none"> • Communication with other people 	<ul style="list-style-type: none"> • P-Diagram workshop • Expert interviews

6.4 Reflection

In this chapter, the procedure and findings from phase II are discussed and analyzed.

The benchmarking session mainly provided personal insights and a feeling of what user related difficulties and benefits that could occur when using CMS in car where it had been integrated in different way. By also benchmarking rearview mirror cars with differently sized and positioned mirrors more insights were gained how the CMS integration contrast compared to using mirrors, and what became easier respectively more difficult when instead driving with CMS. This method was very useful and definitely necessary to perform prior to performing the HTA and FMEA, as they provided inspiration and an understanding of which scenarios one uses the indirect vision while driving, how one uses them and what situations are more critical or likely to happen.

The literature study in this phase, mainly consisted of the legal documents regulating the integration of CMS into cars. The reason for this is that it was surprisingly difficult to find information regarding how rearview mirrors are used more specifically. Sideview mirrors have the past 50 years been legally required for cars, and the usage of them are more or less obvious to users, which could be why this has not been analyzed and documented to a wide extent scientifically (at least not to our knowledge). These findings contributed to becoming aware of a few more driving situations that one must keep in mind when designing for CMS, but since the

findings corresponded highly with the situations determined by benchmarking and interviewing the experts, they were seen more as a confirmation that the previous work was headed in the right direction. The way that the legal regulations referred “*use cases*” were however not used accordingly to how use cases or driving scenarios are used in this thesis, which is why not all of the use cases stated in the legal requirements were implemented into this work.

The legal requirements were also used as a source to understand what parameters that affect the user performance and perception when driving using CMS. An interesting finding here was however that the legal requirements for replacing rearview mirrors with CMS to a high degree are focused on making the display images show the same images that would be present in a corresponding mirror. This is probably a first necessary step in the work of designing a CMS system that works at least as good as mirrors do, but the aspects of how the driver perceives the image and information, and designing the system with regard to that, seems to have been less of a priority considering that it is barely mentioned.

The interviews with the experts resulted in important input and understanding of what relevant parameters and use scenarios that could be of interest to investigate from the user perspective of designing CMS. Most interesting was the input from the UX-designers, who contributed with knowledge regarding what current CMS users though were critical with current solutions, and it also targeted what has to be improved for the user experience for CMS to become at least as good as when using mirrors. This information was not that new compared to the findings from the benchmarking and the literature study, but to get the confirmation that actual users agreed with the findings that had already been made, strengthened some use scenarios more and made it easier to prioritize among them.

Something that all expert interviews had in common was that they all brought up the issues of not understanding depth and distance perception when using CMS. Most of them had the same explanation to it; exchanging the three-dimensional image to a two-dimensional one takes away important depth cues; accommodation and convergence (these terms were not mentioned literally but indirectly), as well as the issues that reaccommodating between the near positioned display and the road bring. The interpretation was that depth and distance perception was an area where the experts seemed to know what the problem was, but not what the solution to it was (even if some had some speculations and suggestions regarding the solutions).

Other things that frequently were mentioned among the interviewees were the possibility of increasing the FOV that CMS opens up for, but doing that also posed other issues since the FOV is related to the display size and zoom level of the camera, which can affect the image to become distorted, and in turn affect the image perception. The screen size and placement were also commented recurringly, and that the placement of the displays in CMS could affect the user’s possibility of discovering objects if the screens are hard to reach by sight or if the object are portrayed small on the small screen. The interpretations of speaking to the experts concerning the trade-off between the FOV, screen size and image magnification as well as the screen placement and size was that they were aware that some constellations posed problems for perceiving the image, but also that knowledge was missing regarding how to solve the issues or if the proposed solutions would cause new unknown problems.

The mindmapping session was an efficient way of summarizing and categorizing the findings from the benchmarking, literature studies and expert interviews and understanding how different parameters had trade-off relationships considering the user performance.

The P-Diagram workshop verified that the experts had been interpreted correctly and that the parameters that were stated in the mindmapping were accurate, but also that the reasoning made from the benchmarking and literature studies made sense. It also contributed to better understand of which parameters are design parameters for CMS, and which ones that are external parameters that affect the user performance for CMS but that cannot be controlled in the design process, but that at least should be considered when designing CMS. The P-Diagram also contributed with an additional use situation of which mirrors fill a purpose; communicating with people in- and outside the car.

The HTA:s for the eight driving situations provided a structured way of understanding each situation with detailed steps of each part of the scenario. This was a rather time-consuming task, but it was necessary and provided a good basis for the progression of the project, as it provided input to the more extensive analysis of FMEA. As was mentioned in subchapter 6.2.6, among the top ten most critical actions from all HTA:s, seven out of them were related to distance perception. Furthermore, 42 of the total 90 actions in the whole table, which can be seen in Appendix D, are related to distance perception. It was therefore considered as highly relevant to focus further on distance perception, since that also is one of the things that defined good user performance when driving.

One reason for distance perception to be represented to such a high level in the FMEA, could be the effect of the structure of the HTA:s sub-steps. Most of the sub-steps were namely distance related, and it is likely that most errors therefore will be tied to those tasks. However, the HTA tasks were formulated in that way since distance estimation indeed was considered important when driving, and when performing any method of structuring the tasks it is inevitable to not take in any subjective influences of what is important. The result of the HTA:s and FMEA:s was also confirmed by other independent sources, such as the expert interviews, reading the SIS (2019) and performing the P-Diagram workshop which strengthened that the findings were relevant, and should be used for continuing the work. The ratings of severity and occurrence in the FMEA were however performed internally without any involvement of experts which could cause the distance estimations to reach an extra high RPN. But when considering the user performance when driving, most people would without any advanced analyses probably agree that distance perception is highly important when driving, in all scenarios, so the spontaneous thought corresponds with the FMEA results.

As described, distance perception was critical regarding the user performance of shifting from conventional mirror to CMS. It was therefore chosen to further investigate how one can achieve a distance estimation that is good in that transition. According to the findings of this chapter, there are several parameters that can affect the distance perception, such as the relationship between FOV, magnification level and display size, camera angle, placement of displays, size of displays, placement of camera, presence of reference point and a few more (see all potential causes in Appendix D).

The FMEA also showed that detecting objects received high RPN rating. Therefore, screen related parameters such as size and placement of screens would be interesting to investigate with aspect of object detection and distance perception. This was however not researched further since previous findings to a wide extent covered how display placement affected the ability of perceiving objects, and plus, the available prototype for further research already had fixed display layouts, preventing exploring those parameters further.

Perceiving velocity was another user performance aspect that received a high RPN value, which was not chosen for further investigation since it would be practically difficult to gain precise measurements during suitable driving situations to conduct a user test around it. A test performed around how velocity is perceived through the rearview displays, it would be cumbersome to perform with the subject driving, to create a realistic test environment, which was considered as too time and resource demanding for this project as it would also demand taking safety measurements to make sure that the driving would not pose risks for any participants or anyone else on the road.

The findings from phase II are very broad with different degrees of complexities concerning user performance of CMS, and some parameters' effect on user performance are more straight forward than others. From analyzing and comparing the findings, the scope for further research by conducting parameter user tests was converged to distance perception when using CMS. Within distance perception, zoom level and vertical camera placement (height) were the selected parameters to investigate deeply. According to the findings in phase II, the camera placement contributes to the user's experience of how to perceive the distance of an approaching object in the screens. Therefore, it is highly appropriate to converge into that parameter. Magnification (zoom level) was also an appeared parameter from the findings and contributes to how the user interprets distance.

Lastly, the scope for the continued research in parameter user tests was narrowed down further. According to phase I findings, there was already knowledge regarding the magnification level and placement of the cameras for the sideview displays, but there was a gap regarding those parameters' impact using the VIRM (enabling a larger range of the vertical camera placement than what had previously been researched) and researching it would hence fill those gaps. The expert interviews and FMEA also made it clear that current problems with estimating distance are related to the VIRM especially. Therefore, the VIRM was determined the focus in phase III when evaluating parameter's effect on distance perception of objects straight backwards. Since the prototype car made it possible to adjust the height of the camera and level zoom, those parameters were investigated.

6.5 Conclusion

The methods of performing benchmarking, expert interviews, mindmapping, P-Diagram workshop, HTA and FMEA resulted in greater knowledge regarding what user performance is when driving; namely a combination of detecting different type of objects in the side and rearview surroundings of the car, being able to estimate the location and distance to them, as well as understanding their relative distance and speed compared to oneself. It also resulted in understanding what driving situations and design parameters that are most important when it

comes to using CMS for indirect vision. The driving situations concluded were ten different ones, some also containing more specific versions of the situation, and twenty-one different design parameters. Any situation and parameters not included in the results of this work should not be considered as excluded from being important nor significant for the user performance using CMS. The ones concluded should be viewed as part of the initial work of stating the most important use scenarios and parameters to consider when designing for good user performance in CMS, and other aspects than the ones encountered in this work could be of importance.

The results of the FMEA showed that the most critical situations in driving occur due to lack of understanding the distance to objects in the side and rear surroundings when driving. The intention was therefore that it would be beneficial to further investigate how one can affect the distance perception using CMS. The parameters identified as possible causes of this in the FMEA was the relationship between the FOV, magnification factor and display size, presence of reference point, camera angle, degree of distortion, placement of displays, size of displays and a few more. The previous findings from literature covered how some of these parameters affect distance perception, but none of the encountered studies had investigated these parameters in the context of the VIRM. Since the findings from the expert interviews as well as the benchmarking had revealed that there are especially problems with understanding the image and distance using the VIRM, the scope was narrowed down even more to it. This, in combination with the limitations of testing many parameters due to lack of adjustability of the CMS prototype that was accessed, what was most interesting and possible to investigate was the zoom level as well as vertical placement of the middle rearview camera for the VIRM. The next phase (III) therefore investigate how these parameters affect distance estimation.

7 PHASE III

USER STUDIES

From Phase II it was concluded that the parameters affecting distance perception using the VIRM were rather unexplored, while this part of the user performance also posed many problems. The zoom level and the vertical placement of the VIRM camera's effect on distance perception were therefore chosen to investigate further in phase III. In this phase, two user tests were conducted. User test 1 was a parameter study investigating the impact that the zoom level and placement of the VIRM camera have on distance perception. User test 2 was an overall comparison between how users experience driving with a CMS prototype compared to driving an identical car with conventional rearview mirrors.

7.1 User test 1

User test 1 consisted of two main tests that here on after are referred to as “*short-distance test*” and “*long-distance test*”, where each one was divided into seven sub-tests, creating a total of 14 sub-tests combinations per participant. The short-distance test included slow reverse driving towards a parked car and investigated how well the participants could determine distance rearwards in this situation by only using the VIRM. The long-distance test included slow forward driving and estimating the distance rearwards to an approaching car by only using the VIRM.

7.1.1 Aim & Hypotheses for User Test 1

The aim with user test 1 was to understand if the middle display’s camera position in height affected the distance estimation to objects behind, and in that case how. It was also to investigate if the zoom level of the VIRM affected the distance estimation to objects behind and in that case how. An important aspect to clarify is that the zoom level referred to for these tests does not only alter the magnification level, but also the FOV. To meet this aim, eight hypotheses were developed, which are described below.

Hypotheses for the Short-Distance Test

- Hypothesis 1; the ratio between the estimated and measured distance will be lower for zoom level 2.5 and higher for zoom level 2.0
- Hypothesis 2; the ratio between the estimated and measured distance will be the lowest for the camera position on the roof, increase with the roof position on the glass and be the highest for the bumper position.
- Hypothesis 3; the ratio between the estimated and measured distance will be greater when using a mirror compared to using any of the display configurations
- Hypothesis 4; the settings with increasing ratios between the estimated and measured distances will correlate with the settings having increasing difficulty ratings

Hypotheses for the Long-Distance Test:

- Hypothesis 5; the measured distances will be shorter when using zoom level 2.5 and longer when using zoom level 2.0
- Hypothesis 6; the measured distance will be the shortest when using the camera position on the roof, increase with the position on the roof and be the longest on the bumper position.
- Hypothesis 7; the distance measurements will be smaller when using a mirror compared to using any of the display configurations
- Hypothesis 8; the settings where the distance estimation made using the display varied the least compared to the distance estimations made using the mirror, will correlate with the increasing estimated level of difficulty

Hypotheses 1 and 5 are for identifying if and how the camera magnification affect distance estimation, hypotheses 2 and 6 are for identifying if and how the camera position affect distance estimation. Hypotheses 3 and 7 are to identify if the mirror is superior to the display regardless or the magnification or camera position for estimating distances. Hypothesis 4 and 8 are for

understanding if the perceived difficulty to estimate the distance correlates to the actual difficulty of estimating the distance. Hypotheses 1-4 all concern the situation of slowly reverse driving towards a still standing car and is hence to estimate distances to static stimuli. Hypotheses 5-8 all concern estimating distances to a car behind when driving forward at 15 km/h and the car behind drives at 18 km/h, and hence to estimate distances to dynamic stimuli.

7.1.2 Preparations

Before performing user test 1, some preparations were required. The preparations concern the subject car, reference car and their equipment, but also location and test track as well as performing a pilot test and arranging with participants.

Subject Car, Reference Car & Equipment

In both the long- and short-distance tests, the zoom level as well as the position of the VIRM camera's effect on distance estimation were evaluated. Three different camera positions and two zoom levels for the camera were investigated in user test 1. Regarding the zoom level, zoom 2.0 and 2.5 were the settings used in both the long and short-distance test in user test 1. The setting of zoom level 2.0 had a FOV of approximately 50 degrees horizontally and 10 degrees vertically. The setting of zoom level 2.5 had a FOV of approximately 40 degrees horizontally and 8 degrees vertically (see Appendix F for full specification of the camera and display). The camera's positions were at the roof (A), glass (B) and bumper (C), see Figure 25. The displayed images from each combination of camera position and magnification can be seen in Figure 26 and Figure 27.

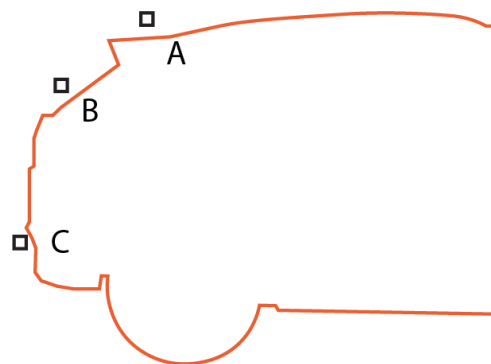


Figure 25 - Illustration of the camera positions on the rear end of a SUV.



Figure 26 - Images of the display view from the bumper, glass and roof positions at zoom level 2.0 (from left to right).



Figure 27 - Images of the display view from the bumper, glass and roof position at zoom level 2.5 (from left to right).

The camera was attached on a mount with a suction cup and adjustable arms (see Figure 28), making it possible to achieve the similar FOV for each placement even if the perspective was changed.



Figure 28 - The camera with mount and its suction cup.

For user test 1, all possible combinations of the parameters resulted in six sub-tests and one additional reference test with the conventional mirror to compare the distance estimations with the ones made using a mirror. In Table 7, the details of the combinations are available. To guarantee the same positions for the different placements between all participants, markings were made on the car using tape and a pencil.

The order of which the combinations were tested was randomized, making sure that all possible combinations were tested and that the results was not a result of the order of testing the different combinations. The mirror was however always tested last after the combinations.

Table 7

The test combinations used in user test 1, excluding the mirror since it had no specific settings.

	Bumper	Glass	Roof
Zoom 2.0	Bumper, Zoom 2.0	Glass, Zoom 2.0	Roof, Zoom 2.0
Zoom 2.5	Bumper, Zoom 2.5	Glass, Zoom 2.5	Roof, Zoom 2.5

The subject car used in the test was a white SUV. It was equipped with a dark plastic bag for covering the VIRM when the settings were changed between the sub-tests, folding rulers to measure distance in the short-distance test, sound recording device to record the conversations, and printed scales (see Table 8) supporting the user when rating the experience. The subject car’s exterior side cameras were furthermore covered to block the surroundings from appearing on the screen, see Figure 29. The VIRM display could be turned off and be used as a conventional mirror, having a reflective surface which was used when the mirror was to be tested.

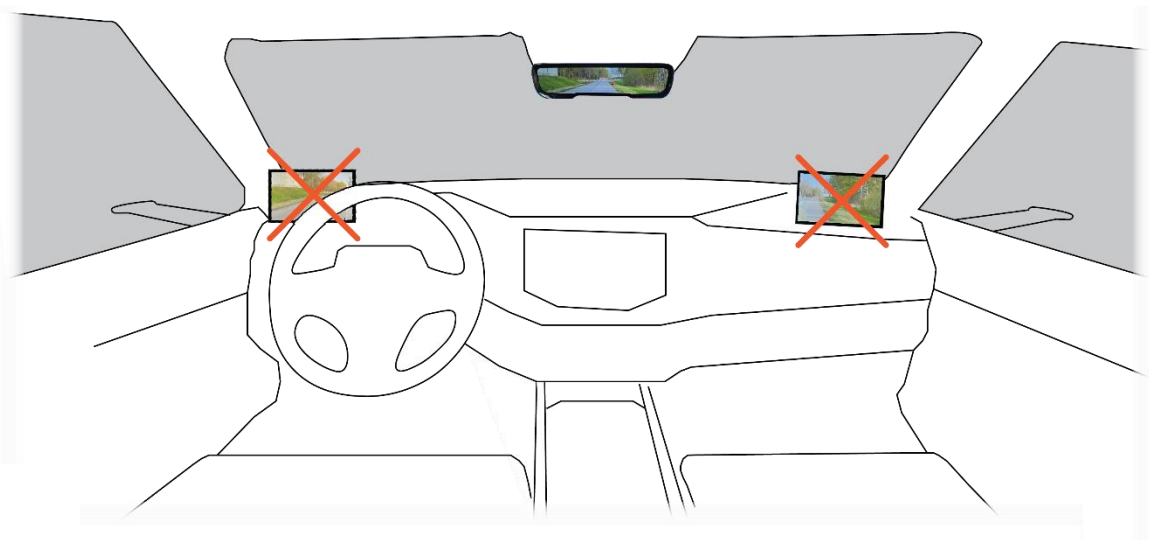


Figure 29 - Interior of subject car for user test 1.

Table 8*Scale of estimating difficulties in tasks.*

1	2	3	4	5	6
Very difficult	Difficult	Somewhat difficult	Somewhat easy	Easy	Very Easy

For the long-distance test, the reference car (a red SUV of the same model as subject car) was equipped with a laptop placed in a mount. The laptop was connected to the car's FlexRay network which made it possible to access signals from the car. The signals were logged using the software CANalyzer and stored for later interpretation. The signals logged in the long-distance test were “*RngOfTar*” (measuring the distance from own car's rear driveshaft to the rear end of the car in front, over time) and “*IndcrTypExtReq*” (logs the moment that the blinker signal lever is pushed). Logging both signals made it possible to determine the distance from the reference car to the subject car at a certain moment by creating a mark in the graph in the shape of a vertical line when the blinkers were turned on (see Figure 30).

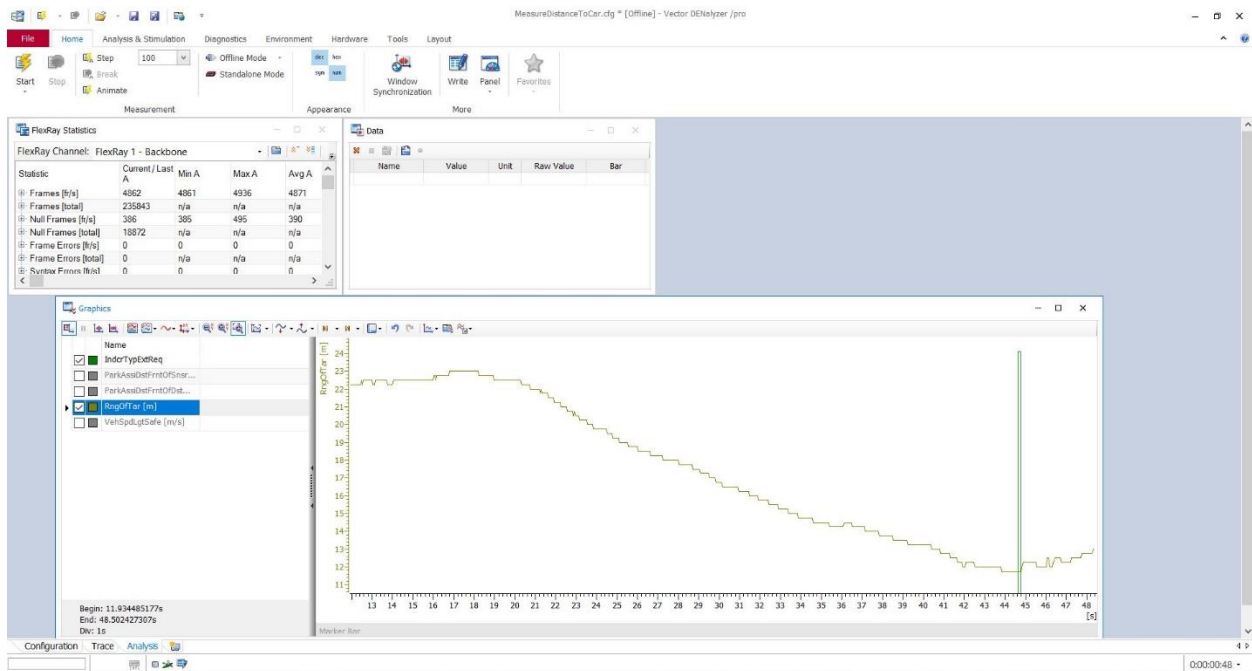


Figure 30 - Screen capture of an example log recording which demonstrates the layout of the analysis window in CANalyzer. The graph depicts *RngOfTar* over time. The green vertical line illustrates the blinker being turned on.

Location & Track Set Up

User test 1 was performed at Volvo Cars in Torslanda. Both the short- and long-distance test took place on a straight road, but on two different tracks (A & B, see Figure 31) were used since the preferred (least occupied) one was occasionally closed. The two tracks only differed slightly from each other; track A was a dedicated test track for cars only without pedestrians or vehicles. Other cars could however use the track simultaneously, but when they did, the sub-tests were put on hold letting through other vehicles before continuing. Track B was not a dedicated test track, but a normal straight street surrounded by parking lots. Cars, trucks and pedestrians could

interact with the test track even if this did not happen much during the tests at this track. The tracks were hence almost always free and convenient to use, even though some waiting time for objects to move away from the track occurred at rare occasions at both tracks.

The cones necessary for the short-distance test were cones B-I for track A respectively N-U for track B (see Figure 31), with randomized predetermined distances between each cone with the following distance between the cones: 10, 11, 17, 13, 12, 20 and 10 meters. The cones were equally placed using both tracks, but for track B some were placed on the opposite side of road for convenience to not block road exits. The short-distance test meant reverse driving towards the car behind, one time for each display configuration and one time using the mirror.

For the long-distance test the cones A, B, J and K were used for track A respectively L, M, U and V for track B (see Figure 31) and each pair of cones were placed at 25 m distance. The test meant driving straight forward from the starting position (cone J to K, respectively U to V) but also driving back to the start point (from cone A to B respectively L to M). Two measurements were hence registered for each configuration. The secondary starting placements for the cars are marked with dotted lines in Figure 31. The distances between cone B and J respectively M and U were approximately 250 m but differed with a few meters between the two tracks. Having the exact same distances on the two tracks in the long-distance test was however not important but using sufficiently long straight roads was. The tests were performed in mixed weather (wind, sun, rain, cloudy) on dry or wet asphalt.

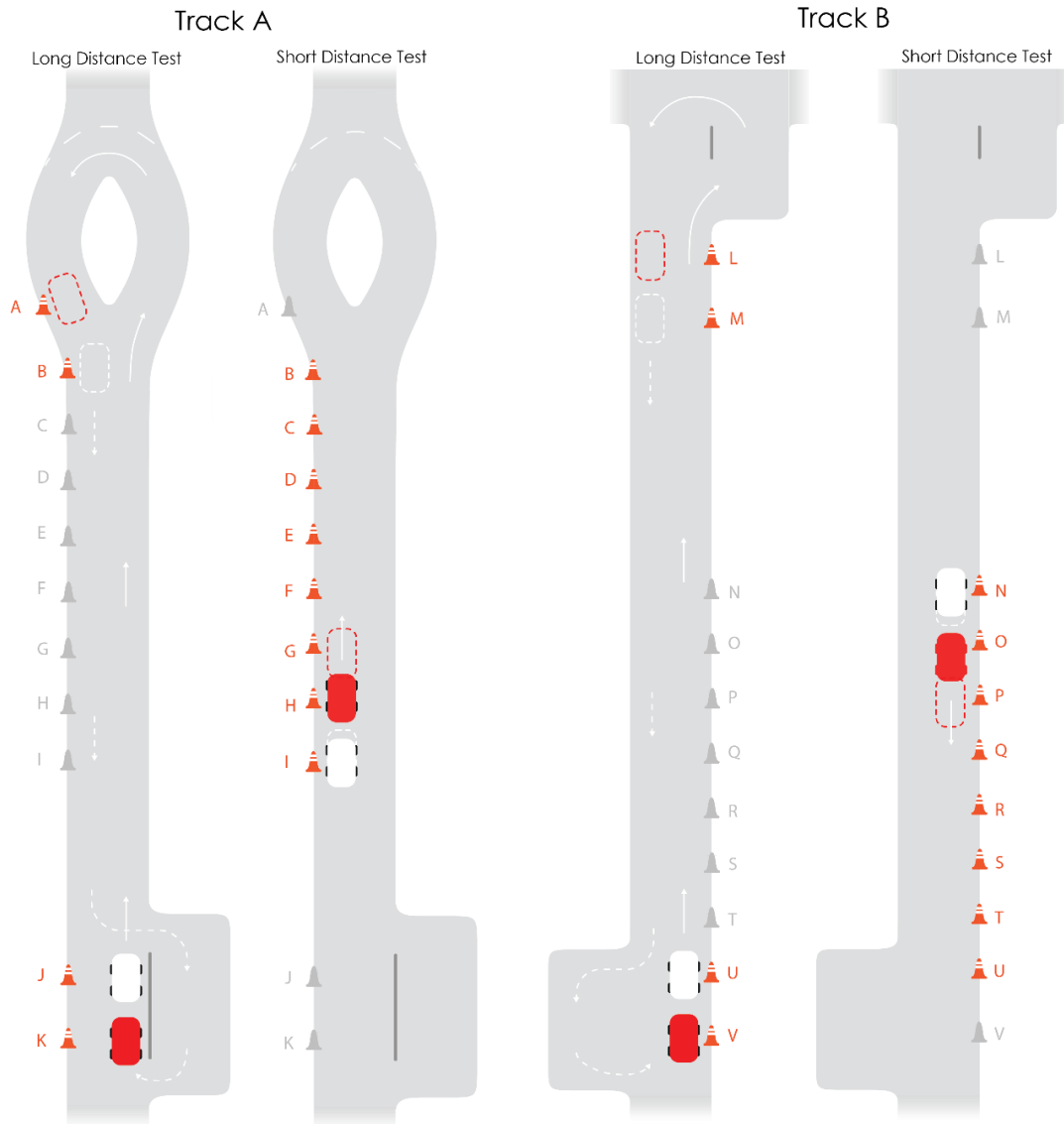


Figure 31 - Illustrations of Track A & B in both short- and long-distance test.

Pilot Test

A pilot test was conducted for user test 1 to try out the test procedure and find out where in the manuscript and test changes needed to be done or developed further. The pilot test consisted of performing the test through an early version of the manuscript. During the pilot test it was discussed whether the participants should let us know when the vehicle behind was getting enough close up behind that the test person started to feel unsafe *or* when the car behind was positioned what they thought was one car length away during the long-distance test. Finally, it resulted in the latter alternative since it was considered difficult to know what distance felt unsafe at such a low speed.

Participants

Due to the Covid-19 situation, only 16 participants took part in user test 1, all employed at Volvo Cars. The participants only received brief information of the project via the description of the

invitation; that the project researched the cognitive ergonomics aspect of replacing traditional rearview mirrors with CMS and the participants were not told what was evaluated in the tests. The participants further received no compensation for their participation. The participants' visual status as well as previous knowledge within the field of CMS are described in Appendix G.

7.1.3 Procedure of User Test 1

One test leader and one assistant performed the tests on the participants. User test 1 started with the test leader welcoming and providing the participants with information about the process in general, what was expected during the test and gave the participant the opportunity to ask questions. The person was then asked to fill in a consent form out of GDPR reasons, if the person had not done so earlier.

Short-Distance Test

The test started by letting the test person (TP) take place in the car that was located at the start position, see the white car (at cone I respectively N for track A respectively B) in Figure 31. While the VIRM was covered by the test leader, the assistant placed the reference car at its starting position (the red car at cone H or O in Figure 31) and then adjusted the camera position while the test leader adjusted the zoom level.

From here, the test leader asked the participant to estimate the distance it would usually aim for stopping at when reverse parking towards a car behind. After removing the cover from the VIRM, the test leader instructed the participant to slowly reverse drive straight towards the reference car behind by only using the VIRM and aim at stopping the car at the previously estimated distance. When the participant stopped the car and communicated to the test leader that the distance was reached, an estimation of the actual distance was made again by the participant, by showing the distance on a folding ruler inside the car. The assistant then measured the actual distance between the subject and reference car with a folding ruler outside the car. The test leader then asked the participant to rate the difficulty (scale in Table 8) of estimating the distance with the current setting before moving to the next sub-test. Between each sub-test, the zoom level and camera height were adjusted, and the reference car was reversing rearwards until next cone. This procedure was repeated for every sub-test, with the difference of using the conventional inner rearview mirror in the seventh sub-test. A more detailed version of how the test was carried out can be seen in the manuscript from user test 1 in Appendix E.

Long-Distance Test

The purpose of the long-distance test was to investigate how distance estimation using VIRM differs between the six settings and a conventional mirror when driving forward in 15 km/h. When letting the reference car (driven by the test assistant) approach from behind,

The long-distance test was performed by placing the subject car by cone J or U, depending on track (see Figure 31). The reference car's starting position was always 25 m behind the subject car, at cone K or V. See fully manuscript in Appendix E for the details of the test procedure. The assistant adjusted the camera position, while the test leader changed the zoom level according to manuscript for each the specific TP. When the TP, test leader and assistant were ready, the test

leader counted down and then let the test start. Just before starting, the assistant created a new file on the computer to log the signals for the test.

The TP then accelerated the subject car up to a speed of 15 km/h while the assistant accelerated until reaching 18 km/h, and both then drove in constant speed straight forward through the track. The TP's task was to say "now" loud and clear when he/she believed the car was at a car length distance behind the subject car. The reason for it to be loud and clear was that the assistant should hear it through the test leader's headphones. When the assistant heard the TP saying "now", the blinker signal was turned on in the reference car by the assistant, to be logged. After the test the log was turned off and both cars were driven to the second starting position which were at cone A and B (or L and M) in Figure 31.

From this position the same test was performed again, with the same settings but driving in opposite direction. The reason for that was to get a second measurement for each setting in case that experience significantly would affect the result. After performing the second measurement, the cars were repositioned at the first starting point again, and the settings (zoom level and camera placement) were changed to next combination while the TP was asked a few questions (see the manuscript in appendix E), e.g. rate the level of difficulty by using Table 8.

7.1.4 Analysis of User Test 1

To meet the aim of user test 1, the hypotheses presented in subchapter 7.1.1 were either confirmed or disputed by performing analyses of the results using ANOVA, T-testing or scatterplots. The data from test 1 was inserted into the Minitab-software, where the required ratios were calculated for the short- respectively long-distance test. The test results from TP 3 was excluded from the analysis since this person misinterpreted the assignment and based its decisions on other things than what the purpose was, which led to significant deviations compared to the test population's results.

For hypotheses 1-3, the ratios between the estimated and measured distances for all six combinations of the camera placements and zoom levels were compared for the participants using the ANOVA analysis to get an overview of the results. For the combinations that were at (or close to) significant distances from each other, two parameter T-tests were then performed to get more specific results regarding where the significant effects were located.

For hypothesis 4 and 8, regression analyses were performed in attempt of finding any correlation between the ratios and the estimated level of difficulty. This was done for each combination (placement and zoom).

For hypothesis 5-7, the measured distances for all six combinations were compared for the participants in the same way as for hypotheses 1-3 by first using the ANOVA and then the T-tests, with the exception of hypothesis 3, where the location of the significant effects were obvious by only using the ANOVA analysis and one T-test.

7.1.5 Findings from User Test 1

The findings from user test 1 are presented in this section.

Short-Distance Test

Hypothesis 1 - The ratio between the estimated and actual distance will be lower for zoom level 2.5 and higher for zoom level 2.0.

The ANOVA test did show differences when comparing the results from the three camera positions and two zoom levels, but they were only significant for the different zoom levels at the roof position (Figure 32). When performing the 2 sample T-test for the two zoom levels 2.0 and 2.5 on the roof positions, the results showed that the significance difference was with 98 % confidence ($P=0.02$). The results also show tendencies that the zoom levels do not cause variations for the bumper and glass placement, but also that the estimations are more accurate for the bumper placement since the ratios are the highest for the bumper. The first hypothesis is hence partly true; the zoom levels cause significant impact on the distance estimations and zoom level 2.0 cause more accurate estimations than 2.5 compared to the mirrors, but only when the camera is placed on the roof position.

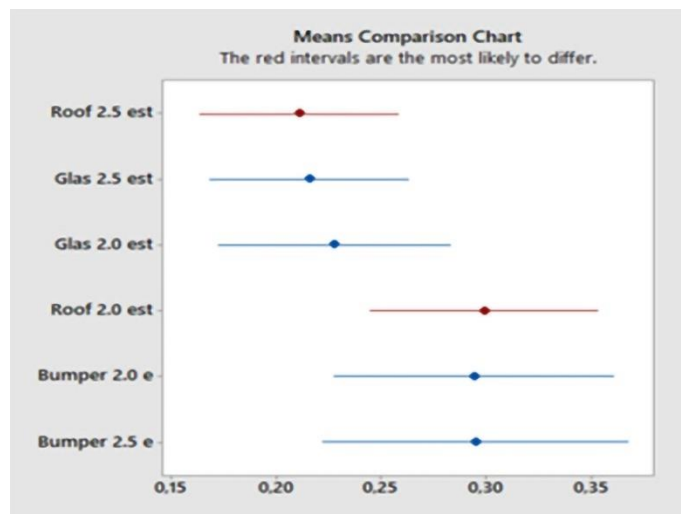


Figure 32 - ANOVA test results comparing the 2 zoom levels at the 3 camera positions for the short-distance test.

Hypothesis 2 - The ratio between the estimated and measured distance will be the lowest for the camera position on the roof, increase with the position on the roof and be the highest on the bumper position.

When it comes to the second hypothesis, the ANOVA test was divided and performed separately for the two zoom levels (Figure 33). The ANOVA test did not show any significant differences for the different positions for any of the two zoom level tests, but both indicated that there might be differences that would become visible if performing T-tests on some of them. For the 2.0 zoom level, T-tests were therefore performed between the glass and bumper position and between the glass and roof position separately. For the 2.5 zoom level, T-tests were performed comparing the bumper and glass position and the bumper and roof position separately.

The results then showed that at zoom level 2.0 there was a significant difference between the glass and roof position ($P=0.029$) and between the bumper and glass position ($P=0.027$) and but not between the glass and roof position. At the 2.5 zoom level, there was almost a significant difference between the bumper and glass position ($P=0.053$, which per definition does not make this difference significant) and between the bumper and roof position ($P=0.021$), but not between the glass and roof position.

Hypothesis 2 is not true; it cannot be concluded that the ratio between the estimated and measured value is greater for the roof position than the glass position, but it can be concluded that the bumper position causes the ratio to be significantly higher than the roof position at zoom level 2.0 and almost at zoom level 2.5.

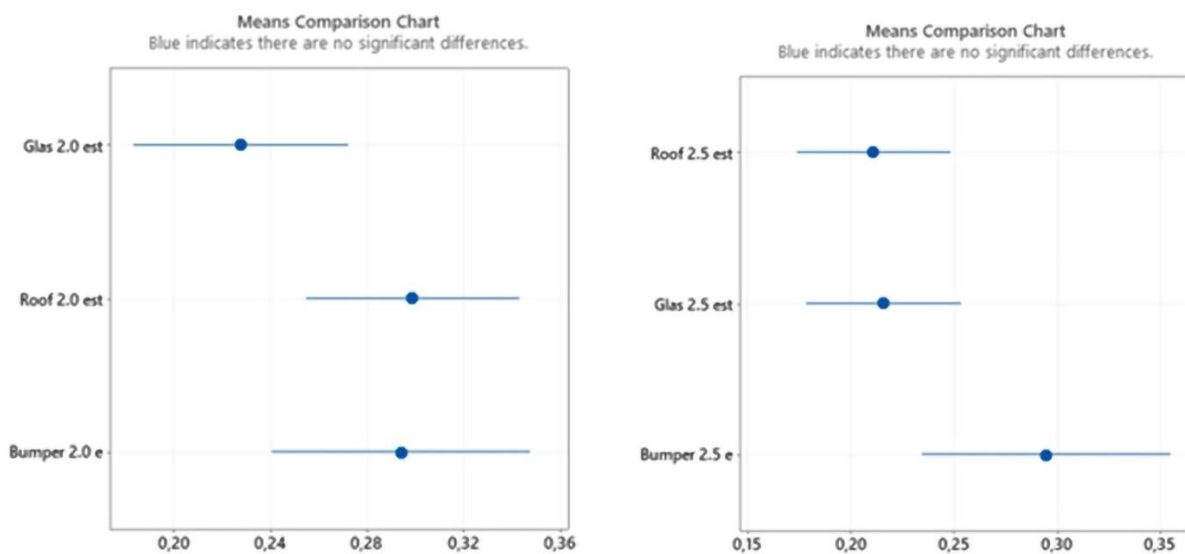


Figure 33 - ANOVA test results comparing the 2 zoom levels at the respective position for the short-distance test.

Hypothesis 3 - The ratio between the estimated and measured distance will be greater when using a mirror compared to when using the display.

The ANOVA test for hypothesis 3 (Figure 34) shows a tendency for a significant difference between both zoom levels at all three positions and the mirror, which was verified by doing a T-test between the mirror and the two bumper zoom levels since they showed the smallest difference between all configurations and the mirror. There is hence significant difference between all display settings and the mirror, by at least a confidence of ($P=0,002$). Hypothesis 3 is hence true; people do tend to estimate distances as shorter (and in this case more accurately to reality) when using the mirror compared to CMS in the rearward driving situation.

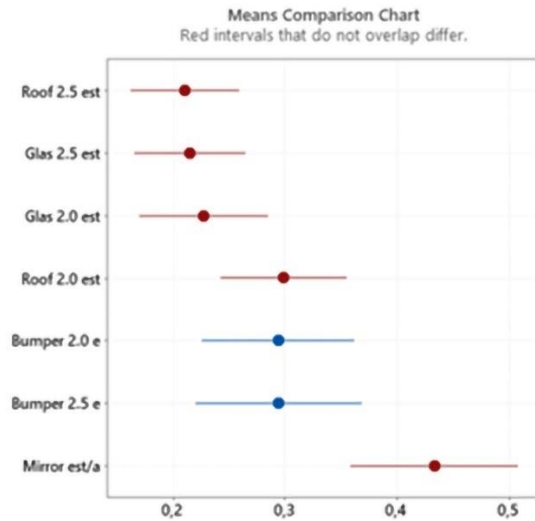


Figure 34 - ANOVA test results comparing the distance estimations using all display configurations compared to using the mirror.

Hypothesis 4 - The settings with increasing ratios between the estimated and measured distances will correlate with the settings having increasing difficulty ratings.

Regarding hypothesis 4, no relationship was found between the ratio of the estimated distance over the actual distance and the estimated level of difficulty for the scatterplot (Figure 35) performed for it. The results showed a low correlation and the R-square was not higher than 30%, meanwhile 80 % is needed to show a strong enough correlation between the means. Hypothesis 4 is hence not true.

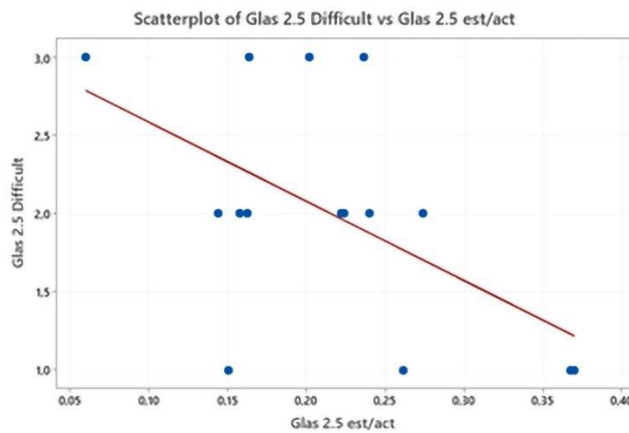


Figure 35 - The scatterplot for the correlation between the estimated and measured distance compared with the estimated level of difficulty.

The Long-Distance Test

Firstly, for the long-distance test, two measures were collected for each configuration. No significant difference was however found between measurement one and two in each of the test, and a mean value of the two was therefore used to compare the measurements for the different configurations and the mirror.

Hypothesis 5 - The measured distances will be shorter when using zoom level 2.5 and longer when using zoom level 2.0.

When it comes to hypothesis 5, the ANOVA (Figure 36) showed tendencies that the zoom levels caused significant difference for the measurements, and when performing the 2 sample T-tests between the different zoom levels for the respective positions, they showed that the zoom levels indeed did so at the bumper and glass position, and borderline significance for the roof position. However, when removing a few outlier TP:s that disturbed the results with both high and low results, the T-test also shows significant difference between the zoom levels for all three positions (this however causes some normality issues to the sample). The distance estimations for zoom level 2.0 are then lower compared to using zoom level 2.5. With this lastly mentioned modification, hypothesis 5 is true; the measured distances are significantly lower when using the 2.0 zoom level compared to the 2.5 one, but the differences are smaller with the roof position.

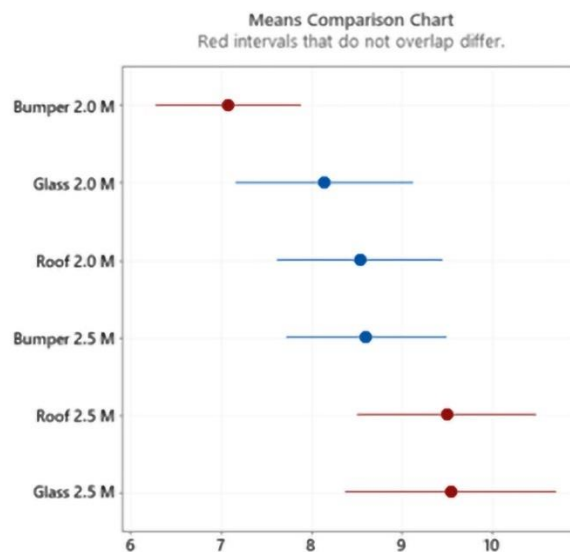


Figure 36 - ANOVA test results comparing the 2 zoom levels at the 3 camera positions for the long-distance test.

Hypothesis 6 - The measured distance will be the shortest when using the camera position on the roof, increase the roof position and be the longest on the bumper position.

For hypothesis 6, two separate ANOVA (Figure 37) were performed for the two zoom levels, and T-tests were performed to compare the roof and bumper positions at zoom level 2.0, and for bumper and roof at zoom level 2.5. The results then showed that the bumper camera position caused the lowest distance measurements, but they showed no significant difference compared to

the other positions (with the exception of the roof and bumper placement at zoom level 2.0, which did with $P=0,009$). Hypothesis 6 is therefore not true.

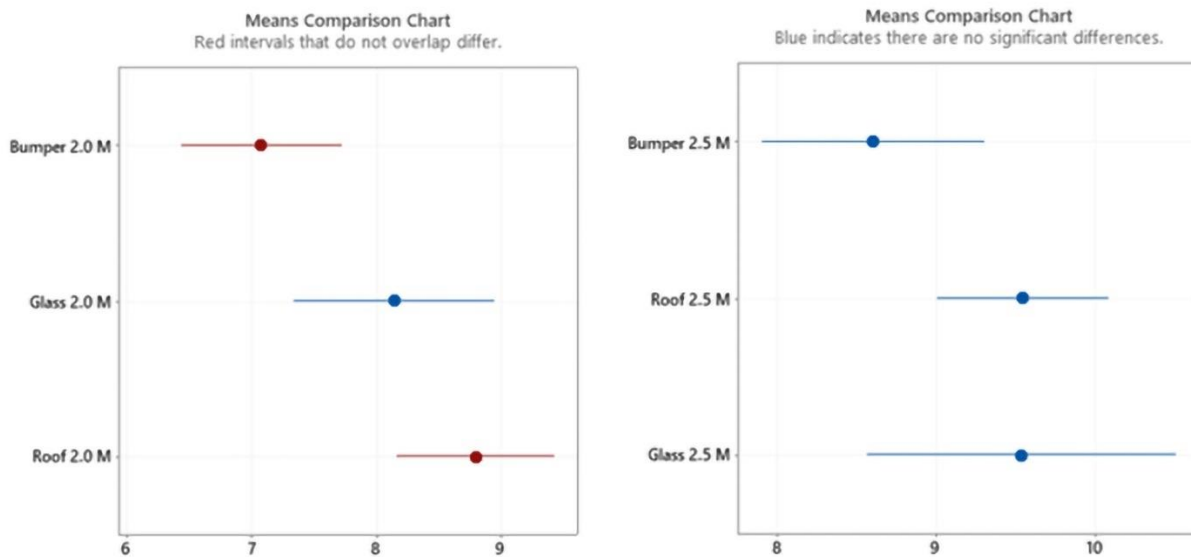


Figure 37 - ANOVA test results comparing the 2 zoom levels at the respective position for the long-distance test.

Hypothesis 7 - The distance measurements will be smaller when using a mirror compared to when using the display.

For hypothesis 7, the ANOVA tests (Figure 38) in combination with T-tests showed that there is a significant difference in distance estimations for all positions and zoom levels compared to the mirror, except from the bumper and glass placement at zoom level 2.0. To point out is also that the bumper position at zoom level 2.0 caused a smaller distance estimation compared to when using the mirror. Even though the means of the distance estimations made by using the mirror are among the lowest, the differences between the mirror and bumper (at 2.0) respectively the mirror and glass (2.0) are not being significant and the fact that the bumper placement caused lower distance estimations caused hypothesis 7 to be not true.

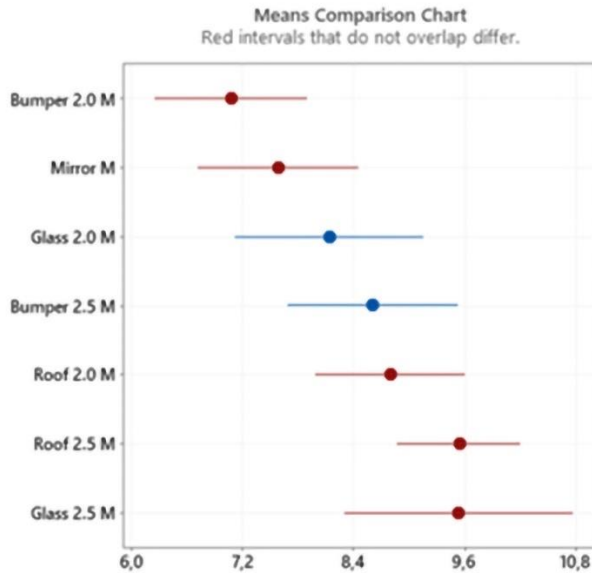


Figure 38 - ANOVA test results comparing the distance measurements made using all display settings with using the mirror in the long-distance test.

Hypothesis 8 - The settings where the distance estimation made using the display varied the least compared to the distance estimations made using the mirror, will correlate with the increasing estimated level of difficulty.

When performing a scatterplot (Figure 39) for hypothesis 8, to find out if there was a correlation between the different results in comparison to using the mirror and the estimated level of difficulty, the results showed a very low correlation between the two. The R-value was not higher than 5 % which can be compared to the value of 80 % which is the limit for showing a strong correlation. Hypothesis 8 is hence not true.

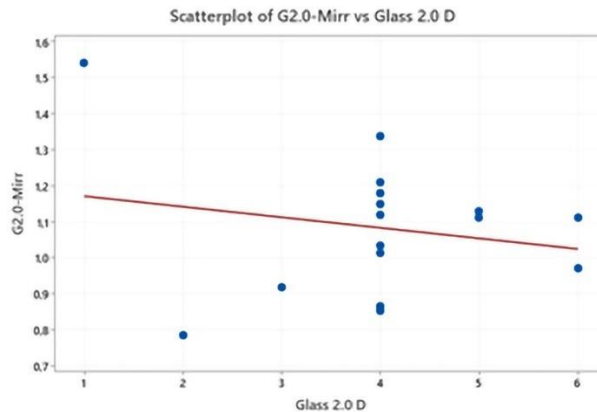


Figure 39- Scatterplot for comparing the measured distances when using a screen compared to the mirror with the estimated level of difficulty.

Comments During User Test 1

Other findings relevant from user test 1 originates from documented comments made by the users during the test. The most important issues to raise among them was that the majority of the people thought that it was difficult during both tests to estimate the distance, especially during the short-distance test. Most of the persons also commented that not being able to turn the head around and look back through the rearview window was the main reason why it was so difficult. They also pointed out that the lack of a reference to the own car was something that most likely increased the level of difficulty. The following quotes are made with aspect of these problem, and all by different people during user test 1:

“It feels tricky without reference. (...) Tricky to never have calibrated the brain for this task. It would be a lot easier being able to use the trunk window as a reference.”

“It is hard when one does not know where the camera is.(...) I have no reference to my own car.”

“I just see a small part of the hood [of the car behind]. Small fraction of the car behind and no reference.”

“I have no reference, I would like to go out and check for myself to get an estimation of how it feels.”

“I want to see the luggage door as reference.”

“I want to go out to check, then control the image, or turn around to look backwards.”

“I would like to practice and see how it looks outside”.

Two participants, both with hyperopia, also commented on that the inner rearview display became somewhat straining looking at after some time of usage and would have preferred a placement more to the front. It should however be mentioned that another user, that also had hyperopia, thought that there were no issues whatsoever focusing on the screen compared to the mirror.

7.1.6 Reflection of User Test 1

In the following part of the chapter, the reflection of user test 1 is presented. This includes reflections regarding the hypotheses, display configuration versus mirrors, magnification factors and camera position/viewpoint. Furthermore, it contains reflections about the accuracy of the correlation between the difficulty ratings and distance measurements and lastly potential sources of error that might have affected the collected data is presented.

The Hypotheses

The hypotheses used for analyzing the results of the short-distance test in user test 1 were formulated in a way that, when adding the results of them all together, would make it possible to understand which one of the camera position or zoom levels caused a distance estimation that was the most accurate to reality or at least the closest compared to the distance estimations made when using a mirror. The reason for that was that the approach of designing CMS (based on the findings from phase I), is to create a system that performs *at least* as good as mirrors, and if

possible – better! It was therefore interesting to compare the distance estimations when using the different CMS configurations to using the mirrors since the results would give a clue of which configuration is preferable when designing the system. If the mirror however turned out not to give accurate estimations, the next interesting thing would be to understand which configuration that led to the estimations being most accurate to the real distance, since that - needless to say - would be the most preferable configuration.

In the short-distance test, the ratio between the estimated distance and the actual distance was compared for the different configurations and the mirror. The reason behind that is that the driver's perception of how far the distance is compared to how far it actually is probably is a highly relevant matter in most driving situations, but perhaps especially when the margins are small, which they are in the context of reversing towards a vehicle behind the car. However, due to practical reasons (e.g. difficulties in verbalizing distances larger than a few meters to vehicles that are moving or accelerating) it is not always possible. In this context however, of estimating close distances for maneuvering tasks at low speed, it was possible since the estimation took part when both the subject and reference car were standing still, and it did not require the participants to verbalize the distances; they simply showed the estimates using a measuring rod.

In the long-distance test however, this was not possible since the test took place in ongoing speed, and also measured longer distances. That is the reason why the distances were measured and only compared to the measurements when using the mirror, as that would also be interesting reasoning as described in the first paragraph of this chapter, and the way possible to carry out in the context of user test 2.

Display Configurations Versus Mirrors

The test result proved hypothesis 3 to be true, and the mean ratio between the estimated and actual distance ratio was higher when using the mirror compared to using any of the display configurations in the context of estimating distances when reverse driving towards a still standing object. Since the mirror caused the most accurate distance estimations in this context, this means that trying to accomplish the most reality accurate estimations and the estimations closest to the mirror are the same things.

The results showed that hypothesis 7 was not true; the mirror caused significantly smaller measured distances compared to all configurations except compared to the glass and bumper position at zoom level 2.0, and the latter configuration actually resulted in lower distance measurements. Reasoning behind what that means, it is that the mirror causes users to perceive distances as longer compared to all configurations except from the glass and bumper position at zoom level 2.0. The only constraint these findings would bring regarding the recommended CMS configuration would hence be for the bumper position at zoom level 2.0 since one would probably not want to cause longer distance perception than the mirror due to safety reasons (perceiving distances as shorter compared to longer would lead to safer margins to vehicles behind). The difference is however not significant, meaning that it could have been caused by coincidence, and one should therefore not draw any conclusions based on that specific finding. Especially since the P-value for the difference between the mirror was as high as 0.823 which is very far from the limit of the maximum P-value for statistically significant differences (0.05).

Zoom Level

Hypothesis 1 was only partly true; the 2.0 zoom level cause more accurate distance estimations (longer) than using zoom level 2.5, but not for the glass or bumper position. This provides the information that when the camera is placed on the roof position, the 2.0 zoom level causes the user to perceive the distance as longer compared to at the higher zoom level at 2.5. Important to clarify is that the distances were always perceived as shorter than what they actually were, but when comparing the distances for configurations internally, the distance estimations using the 2.0 level at the roof position caused a longer distance estimation compared to at the 2.5 zoom level. The finding from this hypothesis therefore implies that a higher camera position causes longer distance estimations for zoom 2.0 compared to 2.5, but important to emphasize is that lower zoom levels for the VIRM have not been explored in this study.

One additional finding regarding the zoom level for the short-distance test of user test 1, is that there was a tendency present of the ratio being higher for the 2.0 zoom level than the 2.5 when comparing the positions internally, even if the differences are not significant for the glass and bumper position. One could interpret this as if the 2.0 zoom level always caused longer distance estimations than zoom 2.5 (since all configurations caused shorter estimations compared to the actual value).

Hypothesis 5 was true; zoom level 2.0 caused significantly shorter distance measurements compared to using zoom level 2.5, meaning that the distances by the user are perceived as longer for the 2.0 zoom compared to the 2.5, which coincides with the findings from hypothesis 1. The conclusion can therefore be drawn from these two hypotheses that zoom most likely affect distance perception and that lower zoom level leads to perceiving distances as longer compared to higher zoom levels. However, in order to understand which zoom level that is the optimal one, one would have to perform further testing in order to understand which level that causes the distance estimations closest to the one made using mirror, presupposed that the goal is to produce a perception corresponding with the mirror. Further considerations should however be done regarding if a performance corresponding to the mirror should be the goal, and the safest thing in one scenario could of course be a level that the user to uphold a longer and safer gap to the vehicles behind, while it in some could be the opposite way. To also clarify is that zoom level is also depending on more factors; magnification level and FOV, and during this test they are not separated but come as a combination through the different zoom levels. It can therefore not be concluded what causes the differences in distance perception of the two based on these tests, which is an insight that was reached rather late in the project.

Camera Position/Viewpoint

Hypothesis 2 was not true since no significant differences were shown between the placement of glass and roof position. It did however show significantly higher means for the bumper position compared to the glass respectively roof position (since the P-value for the roof position at zoom level 2.5 was 0.053, only 0.003 away from the significance level at 0,05, the difference will be interpreted as significant even if it per definition is not). Even though this hypothesis was not true, the results still provide meaningful information. In the context of perceiving distances when

reverse driving towards an object behind, the bumper position results in longer distance estimations compared to the higher ones.

Hypothesis 6 was not true; the bumper position caused significantly lower distance measurements compared to the glass and roof position, but it was not possible to tell by statistically significant difference what the internal order of the roof and glass position was. The conclusion can hence only be drawn that the bumper position causes longer interpretations of distances compared to the roof and glass position, which is in line with the findings from hypothesis 2 which said that lower vertical camera placement caused the user to perceive distances as longer compared to higher vertical placement. Which position is the optimal one based on distance perception for a given system must however be determined from case to case, as the same reasoning as before stands, and what the aimed distance perception should be first must be decided.

Accuracy's Correlation with Difficulty Ratings

Hypotheses 4 and 8 proved to be wrong when analyzing the results, and no correlations were found between the accuracy of the distance estimations nor measured distance and the estimated level of difficulty for determining the rearward distance. The hypotheses assumed that the participants would have a feeling regarding if they had interpreted the display image in accordance with reality. However, considering some of the comments made by the participants, it is not that surprising that no correlation was found. Many participants namely explicitly said that it was just as hard to estimate the distance regardless of the configuration used since they had no reference of where the camera was located when they were doing their estimations, nor were they allowed to turn around to get a reference of what the direct vision showed for a certain display image. It is debatable if the participants should have been provided information about the camera position or allowed to turn around, but the thought of not doing so was mainly that one of the benefits with integrating CMS is to be able to alter the rear of the car since the indirect vision then no longer is dependent of the vision through the rearview mirror.

This finding also provides information that it could be extra important to make informed decisions regarding how one wants the user to interpret distances, since it is difficult for the user itself to get a feeling of what it is interpreted correct or not.

Potential Sources of Error

There are several different sources of error that could have affected the collected data and interpretation of it in different ways. One potential source of error is that the angle of the camera for each configuration could have differed slightly between each participant, since it was difficult to achieve the exact same angle when switching the position of camera between the sub-tests. As mentioned in chapter 7.1.2 regarding the preparations, the camera mount was marked with a pen to indicate at what position each arm of the mount should be when positioned at the roof, glass and bumper. These indications were still creating a too wide marginal of FOV which led to differences between each set up. Though it was not a major difference, it could slightly contribute since less visibly ground between the cars could be displayed in the VIRM for the very same setting.

The mirror was always tested after the combinations of the VIRM display. In the long-distance test, this caused the participants not being able to practice the test route with a “normal” settings (i.e. using the mirror), and just adapting to driving on the test route could have affected the results of driving with CMS for this test, as it was the first thing the participants got to do. This could also be applicable to the short-distance test, since the participants could have gotten a different feeling of distance in the tasks if the mirror had been tested first. Though, the relevant aspect was to create the same experience for each participant, which was done.

According to Budiu (2017) the required number of participants should be at least 30 persons. In the tests however, there were only 16 participants since the user tests had to follow certain company safety regulations due to the pandemic of Covid-19, which restricted this. This made it more difficult to get hold of participants, and also increased the difficulty of carrying out the tests, simultaneously trying to minimize the physically contact with other people. The test sample is also not normal distributed because of this. Being aware of this, one should not blindly follow the findings of these tests, as statistically they are not sufficient. One can however see them as indications to use in the meantime until it is possible to carry out the tests in a larger scale.

Potential Sources of Error in Short-Distance Test

A potential source of error in the short-distance test was that some participants mentioned the tactics of circumventing the test by analyzing where the cones or other surrounding artefacts on or outside the test track were located, which was mostly applicable for track B (being surrounded by more objects and buildings). It was then possible to use the object as a reference point when reversing towards the car behind. It was mentioned by one participant during the test that the strategy was applied to perform well in the tests, even though it was communicated that the system was the one being tested and not the TP. As mentioned in the chapter 7.1.5, the outliers' measures that were too deviating were not used in the result (and this person was one of them) since the data had not been collected in the same way as the others. It is however not possible to know that other TP:s did not also use this tactic.

During the tests, some participants expressed concerns regarding the test design. It was mentioned that they would have liked to exit the car to review the actual distance one time in advance to get a reference of what the VIRM showed in reality, since they would have done so in a real driving situation. It was understandable that they had this opinion, but the test was still equally performed between the participants, and because of this it could not be changed when users started expressing this. By not having any reference at either of the sub-tests, they are still comparable, and it was interesting to understand what the lack of reference and direct rearview vision causes, since the rear shape of the car is often discussed.

Potential Sources of Error in Long-Distance Test

There are some aspects that potentially could affect the data from the long-distance test too. For example, it was noticed that some participants had difficulties in keeping the velocity of 14-15 km/h simultaneously as focusing on the test and keeping track of the approaching reference car in the VIRM/mirror. The velocity mainly was 14-15 km/h but was sometimes exceeded to 17-18 km/h or lowered to 13-14 km/h. This is not a tremendous error since it should not affect the

distance estimation at such low velocities. The opposite thing did occur, and some participants focused more on keeping the velocity at 15 km/h than checking the VIRM/mirror for the rear vehicle, which perhaps led to fast, spontaneous decisions when observing the car closing up.

Further, the actual velocity differed from 15 respectively 18 km/h, which were the intended velocities of the subject car respectively reference car. The reason is that the cars use a safety margin when it comes to velocities, and the speedometer show somewhat higher velocity compared to the actual one when driving. A control check was performed through displaying the FlexRay signal of the reference car's own speed in CANalyzer while logging and driving in 15 respectively 18 km/h (according to speedometer). According to the FlexRay signal of own speed, they were 13.68 respectively 16.52 km/h. It affects the test in regard of testing the distance perception of object in VIRM (and mirror) when driving in around 13.68 km/h and not 15 km/h.

The distance between the cars when the participant said “*now*” was marked with the blinker signal. Because of this, the marquee in the graph was always slightly delayed since the assistant had to listen for the signal through headphones, react and then press the blinker. This should however not be a significant source of error, mainly since it can be assumed to be somewhat the same for each test, making them comparable. Even if it would differ between the tests, the distance did not change significantly much during those extra fractions of seconds at the low speed. The radar's precision was 0.25 m, which would not result in a change of distance if the delay was a bit short or longer during a test. The precision is of course a drawback of the test, but in regard of measuring distances of 5-15 m, 0.25 m in precision was considered good enough for the test. It was also the best option available.

Some participants mentioned during the test that it did not correspond well to a real driving situation to estimate when a car is at a car length behind one's own car. It could not be argued against, but the aim of estimating this was to gain an overall understanding of how distance to objects behind was perceived, and the point was merely to have the users aim for the same distance for all tests. Another idea of the design of the test was to let the participants say “*now*” when they thought the approaching reference car was uncomfortably close. This idea was however discarded since it at such low speeds would have been difficult to know when the car behind was becoming too close, which was found in the pilot test. There is also acclimatization of feeling uncomfortable, which could have caused different result depending of the order of which a combination was tested.

Another aspect that could have affected the collected data was the fact that the tests took place at two tracks. Track A was optimal for the test, but was occasionally booked which complicated the plan, and therefore track B was used quite a lot. Test track B meant that some regular traffic could occur, which might have caused the participants to be stressed due to potential obstacles appearing. This driving situation therefore demanded a somewhat higher degree of attention towards the surroundings, and therefore it could have affected the participants' attention towards the actual test.

The long-distance test was conducted by collecting two measurements, since habit could possibly affect how the user performed in the test. This was only done in the long-distance test

and not the short-distance test since participants in the latter had to the possibility of adjusting the distance until feeling done, which is not possible in the long-distance test. As mentioned in the findings, there was however no significant difference between measurement one and two, implying that there was no degree of learning affecting the distance perception in the long-distance test.

7.1.7 Conclusions from User Test 1

User test 1 was performed to investigate the impact that the zoom level as well as the vertical camera placement had on distance estimation, both when reverse driving towards a still standing vehicle (the short-distance test), but also when driving forward at 14-15 km/h with a car approaching from behind at 17-18 km/h (the long-distance test). ANOVA and T-test analyses as well as scatterplots were used to answer eight different hypotheses, with the aim of understanding the impact the two parameters had on distance estimation during each sub-test.

Concluding the results of the hypotheses from the short-distance test, they showed that people perceive distance as shorter than what they really are when using either system, but using the mirror causes the user to perceive distances as longer compared to when using any of the display configurations. The zoom level that was varied between level 2.0 and 2.5 alone had no significant impact on distance estimation in the short-distance test. The results moreover showed that lower vertical placement of the VIRM camera led to significantly longer distance estimations compared to the higher ones in the short-distance test. The interaction of the two parameters showed that zoom level 2.0 caused longer distance estimations than 2.5, but only at the higher vertical camera placements.

In the long-distance test, the results showed that the mirror caused shorter distance measurements than most of the display configurations, but not all, indicating that the mirror causes the users to perceive the distance as longer when using the mirror compared to any configuration. Furthermore, the results showed that zoom level 2.0 led to perceiving distance as longer compared to using the 2.5 level. It also showed that the vertical camera placement caused no significant impact on distance estimation in the long-distance test. The interaction of the two parameters did however show that using the lower zoom level caused the user to perceive distance as longer compared to the higher placement.

The results from the short- and long-distance test are hence coinciding. These results could also be interpreted as agreeing with the previous findings regarding the vertical camera placement for the sideview displays, which also concluded that lower camera placements led to perceiving distance as longer compared to higher placements. Since the varied zoom level included varying two factors in these tests; both magnification and FOV, it is difficult to know which one of them that caused the differences in distance perception that was found based on the zoom level. The results should therefore be applied for their specific use cases, and furthermore it is recommended to perform more extensive testing covering isolation of the two parameters present in zoom, a wider zoom range as well as in more relevant driving situations.

The results did show that there was no correlation between the estimated level of difficulty for estimating distance using the different configurations, and the accuracy of the or proximity to the

measured distance using mirrors. This was most likely because the participants had no vehicle reference present in the VIRM image, and additionally had no chance of seeing how the displayed images related to reality by using direct vision in the rear, which indicates that just that could be preferable when learning how to drive using CMS as provider of the indirect vision.

7.2 User test 2

In this part of phase III, the aim, preparations, procedure, analysis, findings, reflections and conclusions regarding user test 2 are presented.

7.2.1 Aim for User Test 2

The aim of user test 2 was to evaluate the overall user performance and experience of a CMS prototype compared to using a regular car equipped with mirrors for the indirect vision. Furthermore, the aim was to gain an understanding of whether the user performance and experience changed for the two types of cars in any specific use situation, and in that case to understand how and why.

7.2.2 Preparations

To perform user test 2, some preparations had to be done in advance. The preparations concerned the location and set up, subject and reference car, but also performing a pilot test and selecting participants. These things will be described in this subchapter.

Location & Set Up

User test 2 was performed on a predetermined route in Torslanda. The route took approximately 20 minutes to drive and included the driving situations of driving in a parking garage (during dark lighting conditions), entering a highway, performing an overtaking, driving in a roundabout (both single and double laned), exiting the car, reverse parking (between two cars on a larger parking lot), managing intersection (both a small one with one lane and a larger one with traffic lights) and driving straight at the 80 km/h highway. The route can be seen in Figure 40 and the area where the roundabouts, intersection and parking were located can be viewed more zoomed in looking at Figure 41.

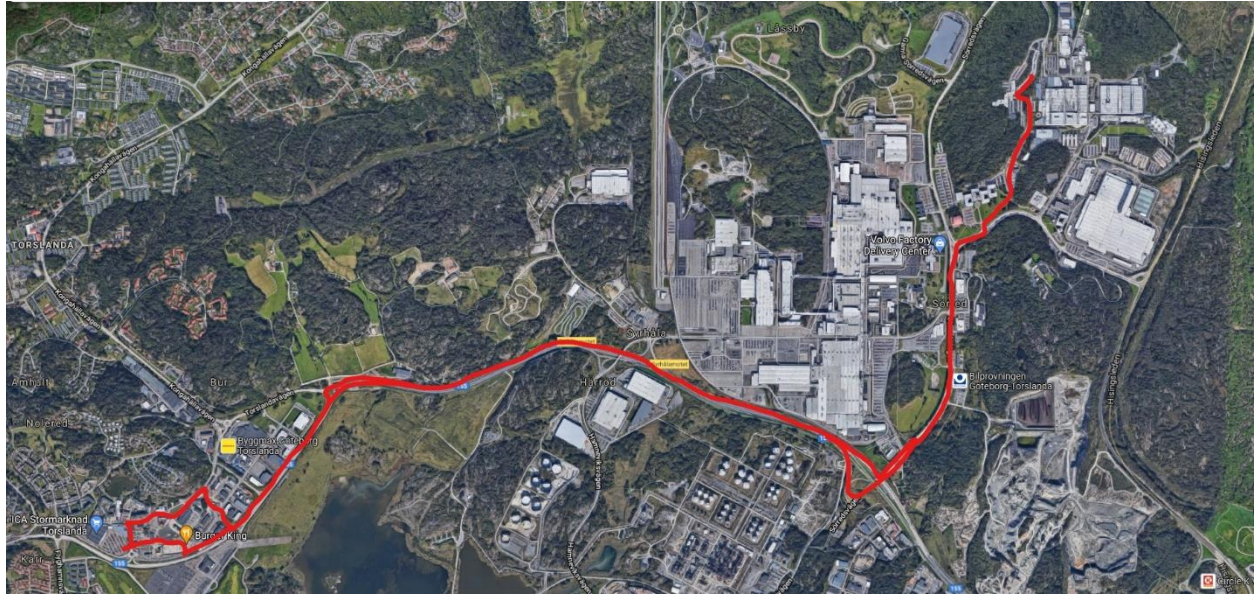


Figure 40- Overall map of the test route. (Google, 2021)



Figure 41 - A zoomed in map illustrating the more complex area of the route. (Google, 2021)

Subject Car, Reference Car & Equipment

The subject and reference car used for user test 2 were two identical SUVs. The reference car had traditional inner- and sideview mirrors (see Figure 42 and Figure 43 for the mirror images) placed at the traditional mirror layout in the car.



Figure 42 – Left and right mirror images in the reference car.



Figure 43 – Middle rearview mirror image in the reference car.

In the subject car (CMS prototype), the VIRM was positioned in the center of the dashboard and the two sideview displays were positioned close to the traditional placement of the sideview mirrors (see Figure 44).

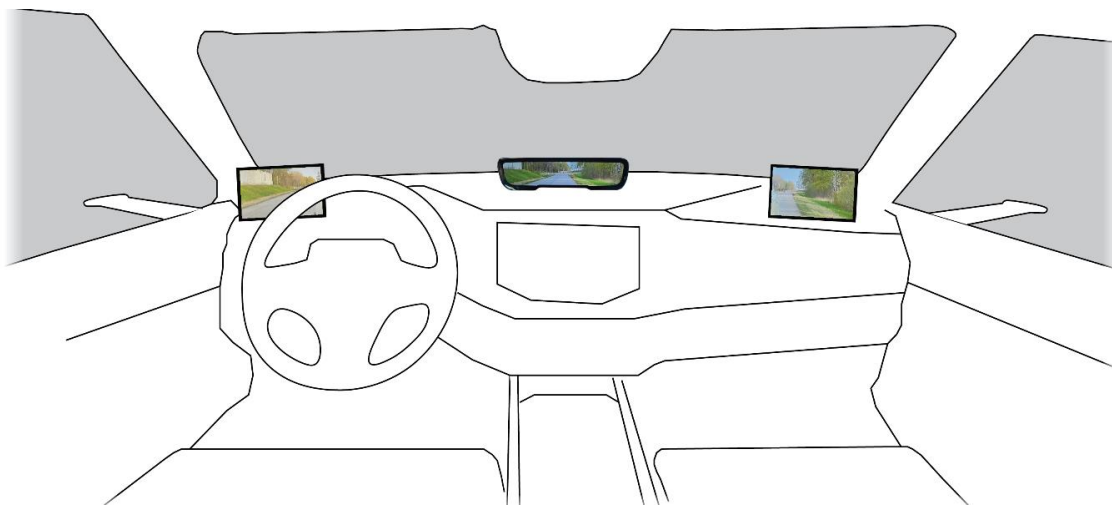


Figure 44 - Interior of the subject car with CMS.

In the CMS prototype, the cameras for the sideview displays were positioned where the sideview mirror are traditionally placed, and the VIRM camera was placed above the rearview window. The zoom levels used for the sideview displays were unknown, but 2.0 for the VIRM. The images and viewpoints seen through the respective displays during user test 2 can be seen in Figure 45 and Figure 46 (note that the display images in the figures however are photographed and appear to be of less quality than looking at them with the naked eye). In Figure 47, it is possible to see the FOV of both for the subject- and reference car (measured with an arbitrary angle of the sideview cameras/mirrors, showing a bit of the own car as seen in Figure 42 and Figure 46).



Figure 45 - FOV in the VIRM.



Figure 46 - FOV in the sideview displays.

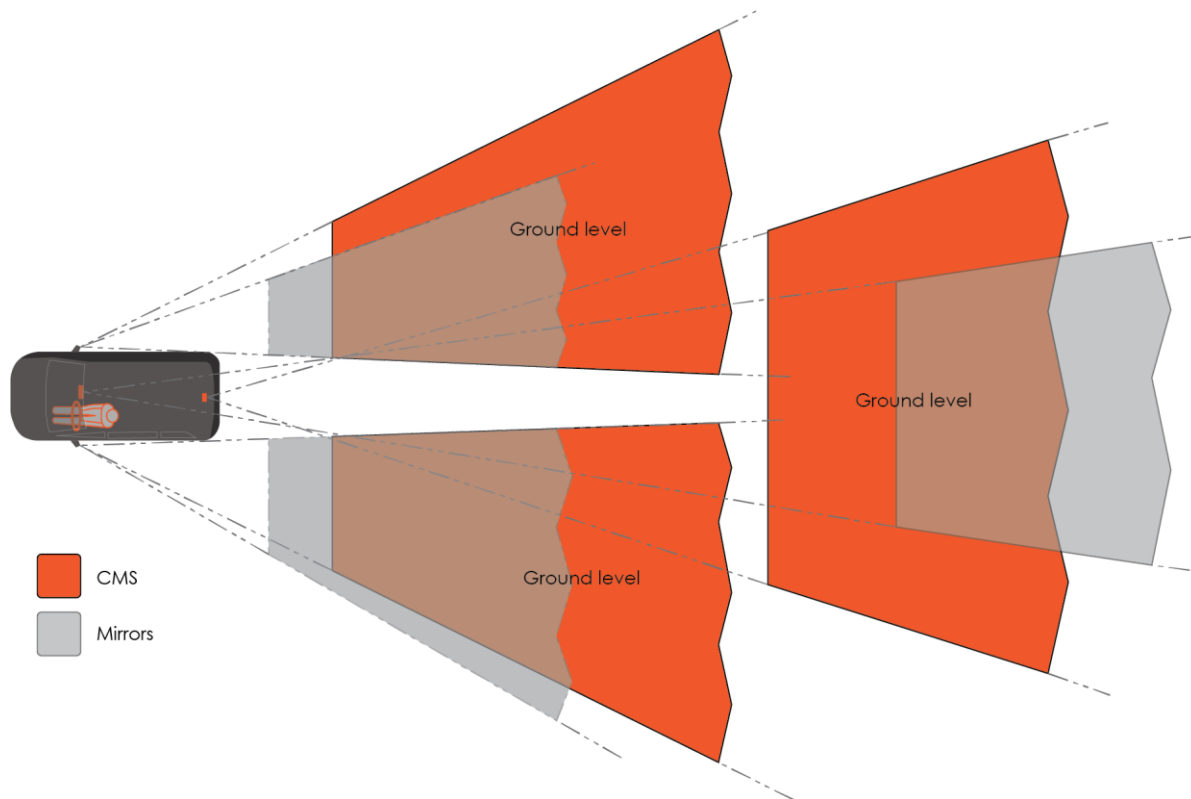


Figure 47 - Approximately FOV in CMS respectively mirrors.

A sound recording device was used in both rounds during the tests. Additionally, the rearview window was totally covered with a dark non-transparent plastic sheet in the CMS subject car.

Participants

User test 2 included five participants who all were employees at Volvo Cars. To view details about the participants' visual status and previous experience within CMS, see Appendix G. The participants were invited by e-mail, and received no previous information about the project other than that it explores the cognitive ergonomics aspect of replacing traditional rearview mirrors with camera monitoring systems (CMS), and that it would take place on public roads.

Pilot Test

A pilot test was held for user test 2 to try out the test procedure and find out if anything needed changes and consisted of performing the test through an early version of the manuscript.

7.2.3 Procedure of User Test 2

Before letting the TP drive, the test leader introduced the procedure and the driving route. The TP was asked to think aloud during the drive, which means describing actions and thoughts in words for the test leader throughout the whole test. The test leader asked complementary questions during the driving and while the car was standing still, for example after the participant

had parked the car according to one of the tasks. The whole test was audio recorded to enable transcription and further analysis after the test.

As can be seen in Figure 41, user test 2 included driving through roundabouts, intersections, performing reverse parking and driving through stressful areas with pedestrians and cars present in an urban environment.

In the first round the participants drove a regular SUV and the usage of the mirrors was investigated regarding what worked well and worse using them. When returning to the starting position, the TP was asked general questions regarding the experience of driving the car with conventional mirrors. The participants also filled in a questionnaire after this. The questionnaire consisted of scales with nine steps where the test persons was to score the different driving situations regarding how easy, safe and practical it felt using the mirror in general but also during each driving situation (see Appendix H).

After finishing the questionnaire, a short introduction to the prototype car was held by the test leader, and the cameras' and displays' functions were demonstrated. When the TP felt comfortable with the CMS prototype, the exact same route was driven again by the participant. The participant was again asked to think aloud, and the test leader asked complementary questions. After finishing the route, the test leader asked some additional questions and the TP filled in a new identical questionnaire as after the first time, but now concerning the driving experience of using the CMS prototype. Also this manuscript is available in Appendix H.

7.2.4 Analysis of User Test 2

When user test 2 had been performed with the participants, the audio recordings from them were transcribed. Four of the tests/interviews were transcribed manually and one was transcribed automatically by the help of the application Dovetail.

The transcripts were analyzed using a modified version of the method KJ-analysis, also using the Dovetail application. The transcripts were read through and tagged with relevant themes/codes that summarized what a quote or paragraph was about. Each transcript was read and tagged two times by two different people to enable different interpretations and finding more patterns between the tests. The analysis resulted in a total of about 25 different themes concerning driving with mirrors and 25 concerning driving using CMS, see Table 9. The categories from driving with mirrors then formed four main categories and the ones from driving with CMS formed four additional main categories. The total of eight main categories were then summarized by reading through the quotes from each category and extracting the main findings from them.

Table 9

The tags in the KJ-analysis from Dovetail.

CMS – support systems & improvements	CMS – System dimension & specifications	CMS – Attitudes, perception & usage	CMS - Scenarios
Demanding situations	Size	Distrust	Reverse parking
Support system	Aesthetics	Attitude	Exiting car
Improvements	Placements	Habits	Highway

	Image	Attention	Changing lane
	Lightning conditions	Change of focus	Roundabout
	FOV	Image perception	Overtaking
		Distance perception	Intersection
			Easier situations
Mirrors – support systems & improvements	Mirrors – System dimension & specifications	Mirrors – Attitudes, perception & usage	Mirrors - Scenarios
Support system	Placement of mirror	Attitude	Exiting car
Improvements	Size	Habit	Overtaking
	Aesthetics	Change of focus	Reverse parking
	Lightning conditions	Image perception	Intersection
	FOV	Distance perception	Highway
			Change lane
			Roundabout
			Easier situations
			Demanding situations

The ratings collected from the overall experience and the specific driving situations in the questionnaire were also analyzed and interpreted through comparing the data when putting them into graphs.

7.2.5 Findings from User Test 2

The result from user test 2 is described in this subchapter. The results from the questionnaires are demonstrated through the charts while the interviews can be read about in text form.

Findings from Interviews & Observations

The following findings were exhibited from the semi-structured interviews and observations that were performed during user test 2. This section will describe findings related to each driving situation investigated, what support systems and general improvements proposed for the CMS prototype, more findings related to system dimensions and specifications and at last describe the findings concerning the usage and attitudes for the CMS prototype.

Scenarios

In this section, findings regarding each specific driving scenario is available, namely from reverse parking, highway driving, exiting the car, changing lane, driving in a roundabout, performing overtakings and driving in an intersection.

Reverse Parking

When it comes to parking in reverse while using rearview mirrors, most users pointed out that this task is something they usually use the 360 degree camera or parking camera for, and that rearview mirrors are not used for reverse parking if those tools are available. In this task the users all glanced at those aids somewhat but tried to perform the parking maneuver without looking at the camera display. The users let us know that the sideview mirrors during this task mainly were used to understand where the car was in relation to the surrounding. The middle

rearview mirror was not used for that as much since less information is provided through it when working with short-distances, and it was used at rare occasions for checking that no object appeared right behind the car. The general interpretation is that most users think that the reverse parking task is not that easy to perform by the help of mirrors and that it is especially difficult to understand if something is close behind the car and understanding where the car was located in relation to the parking lines when they were not visible through any of the mirrors.

Performing the reverse parking instead using CMS, one user though was generally at the same level of difficulty compared to the mirrors. This person did however point out that the person felt like having to concentrate more on the task when performing it using CMS to make sure that no person appeared in the zone behind the car all of the sudden. Others however seemed to think that the task in total was easier compared to using the mirror, and some even said that it was the easiest of all tasks to perform. Additionally other participants commented that the distance estimation rearwards during the reverse parking using the VIRM was much more difficult compared to the middle rearview mirror, and that the reason behind it might specifically have been that the camera was angled so far up, making it impossible to see the area closest to the rear of the car.

Highway Driving

Driving straight on the highway, the middle rearview mirror seemed to be used most among the mirrors for indirect vision. In this driving situation, the middle rearview mirror was mostly used for regularly checking if a car appear behind and in that cast the approximate distance to it. One user described it as a vehicle appearing in the rearview mirror was what alerted him/her to start paying attention to also the sideview mirrors, since that is when the user needs to pay closer attention to the own or others' relative location through the sideview mirrors. One user did however claim to look primarily in the sideview mirrors instead of the middle rearview mirror when driving straight on the highway.

Regarding using CMS for driving forward on the highway, the findings from the test showed a somewhat decreased experience compared to driving with the mirrors. Someone furthermore expressed issues with understanding if the system covered all necessary views, another experienced a heavy blind spot in the horizontal FOV and someone else also said that distance assessment to cars approaching from behind was remarkably more difficult. One person did however think that there was not any difference compared to driving with the rearview mirrors and said that the FOV and image in the middle display were really good for this driving situation. The participants thus had somewhat different opinions regarding this situation.

Exiting the car

It should first be mentioned that the situation of exiting the car refers to exiting the car towards a road with ongoing traffic. When exiting the car, the majority of the users looked through the rearview mirror first, some then looked at the blind spot, and all of them then looked outside on the road meanwhile opening the door in order to see if a person or vehicle appeared outside. All persons seemed to be aware of the importance of keeping track of the road while opening the door.

When instead using the CMS car and exiting the road, most people just looked at the left-hand side screen instead of on the mirror which no one seemed to have issues with. One person even explicitly said that it felt like he/she did not have to check the blind spot since the FOV seemed to cover more than the mirror did in this situation. The users did however have issues with the fact of the sideview displays being turned off immediately as the car was and pointed out that it could not be the case in a real car due to safety reasons. One user also pointed out that it was pleasant that one could keep looking at the sideview screen while slowly opening the door with the effect of scanning the surrounding slowly, and that this expanded the FOV before stepping out of the car in a positive way.

Changing lane

When performing lane changes when using the mirror, the sideview mirrors are used the most. The left-hand side rearview mirror is used before the user pulls out to the left and the right-hand side rearview mirror is used before pulling to the right. The middle rearview mirror is used now and then to check if there is a vehicle behind and to understand the approximate distance to it. A few users expressed that *“I do not look in the rearview mirror unless there is anyone behind me”*, which indicates that they do in fact use it for information since it helps them keep track of if there is anyone behind them subconsciously, but that they only focus on it further if they have in fact noticed something being there. One participant expressed that it many times is necessary to check the mirrors multiple times as the image evolves when changing the lane, making new things and parts of the scene visible. This, according to the users, becomes extra important when changing between multiple lanes at the same time, or at roads with more than two lanes.

When changing lanes using CMS, some users felt more uncomfortable compared to using the mirrors in the same situation. The participants looked at the displays for longer periods of time than they did using the mirrors and expressed feeling slightly insecure having to *“rely only on an image on a display”* and they wanted to check the blind spots more frequently to complement that feeling. They did however point out that this might be a question of habit, and some of the users expressed that the FOV in the side displays felt larger and better compared to the sideview mirrors. They further said that the sideview displays felt natural to use and that judging distance to cars in other lanes was not difficult compared to using the sideview mirrors.

Roundabout

The usage of the mirrors when driving in roundabouts differed a lot from person to person in the tests. Some claimed that they never use the mirrors in this situation and others that it is very important to keep supervision of the traffic flow behind oneself. Generally however, people said that changing lane within the roundabout demanded a glance in the exterior sideview mirrors, but that it was not as important to check the inner mirror. For the TP:s that actually used the mirrors in the roundabout, it was mentioned that it takes time and effort to turn the head in different directions and changing focus, primarily when using the right exterior mirror which is located at a larger distance and angle from the drivers forward line of sight compared with the left and middle one. It was further mentioned that the situation of maneuvering in a roundabout is simple if the participant was an experienced driver, especially since the traffic situation was not very intense during the test.

The findings from the interviews and observations regarding driving through the roundabouts using CMS was that the users generally liked it more compared to using the mirrors in this situation, but that it was more difficult retrieving information using CMS compared to mirrors. Also at this scenario there were some mixed opinions among the participants. The most critical aspect of the roundabout driving was that one participant claimed to have driven into another car when changing lane in the roundabout, if it would not have been for him/her carefully observing the cars in the roundabout *before* entering the roundabout. Therefore, the impression was that the situation demands a better control of the rear and side surroundings than what the CMS prototype provides. The VIRM was described as too small and useless in the situation. Though, CMS was better regarding the placement of the screens compared to the mirrors, causing a decreased need for turning around and checking the blind spots. Overall, the participants did not describe CMS as better than the conventional mirrors in the aspect of driving through a roundabout.

Overtaking

Performing an overtaking with mirrors was according to the TP:s rather simple, mostly due to the fact of being used to the mirrors. Furthermore, mirrors show a distorted image of the surroundings, which could make it difficult to perceive velocity and distance of the cars being passed in the right lane. Through observation it was noticed that the exterior sideview mirrors were used when looking for cars in another lane and the interior mirror was used for keeping supervision of the car after performing the overtaking to control the situation.

When driving the CMS car there were some differences from driving the car with mirrors when performing an overtaking. The users expressed that the sideview cameras had a better field of view compared to the mirrors which helped when doing the overtaking. Less usage of the VIRM compared to using the mirrors was also noticed from the test leader's observations. Participants said that the screens "*felt natural*" and "*easy for determining distances*". Though, some expressed that it was way more difficult to perform an overtaking using CMS, since the car behind "*vanished*" in the rearview display and because the participants were not used to the system. It takes a while to learn that it is not possible to bend slightly forward to gain a better view when using CMS.

Intersection

The usage and experience of mirrors in the situation of driving in an intersection was generally not very interesting since many participants did not use them at all. They explained that it felt more important to keep control of what was happening in front of oneself and on the right- and left-hand side of the crossing instead of looking rearwards. A few participants said that a short glance at the mirrors was made right before starting to drive after standing still in the intersection to evaluate the traffic situation behind. Further, one's peripheral vision catches potential movements in the mirrors but is mostly not something regularly used in this situation.

Regarding the usage of CMS in an intersection, the findings were also scarce due to the same reasons as for the mirrors. As for the mirrors, participants said that it is more essential to focus on the intersection and the traffic in front of the car instead of the rearview. It was difficult to get a detailed statement about what worked well, but the general impression was that the TP:s

experienced no problems related to CMS in this situation. Though, one participant mentioned the aspect of the VIRM placement during this situation, but that will be described in findings about placement of displays and cameras.

Support Systems & Improvements

Every car driver is used to conventional mirrors, but when it comes to enhancing the user performance, some support system and other improvements might be helpful. From the interviews in user test 2 it was shown that all TP:s regularly use support systems such as 360-degree view in the center stack display or blind spot indicator which warns the driver about objects in the blind spots, both are common tool in modern cars. To further enhance the system of conventional mirrors it was suggested to implement automatic tilt down of the exterior mirrors while reversing (which already is available in some cars) and adding other functions to the mirrors such as showing latitude for easier navigation. It was mentioned that the reference car had too large cowl frames around its exterior mirrors which made the image perceived as smaller.

Potential improvements for the CMS system was integrating BLIS, lane mitigation, automatically adjusted cameras, objects being marked in the display or other functions that warns the driver when a collision might be close in it. Even though CMS sometimes performed better than conventional mirrors, users still thought that it is relevant to implement these standard support systems to make it even better.

Continuing, a larger VIRM display was clearly preferred for increasing the rearview. Participants furthermore suggested implementing the VIRM behind the steering wheel and integrated a map function in it. Furthermore, it was obvious that the displays should have non-reflective surfaces since several users were bothered by the image on the VIRM being cancelled out completely during certain lighting conditions. Also, the suggestion came up of having an extremely wide VIRM display integrated with the dashboard and discarding the sideview displays and corresponding cameras completely, but how that would be received in practice is debatable. A hybrid of CMS and mirrors through replacing the sideview mirrors while keeping the middle rearview mirror was also suggested. Further, the aspect of placing all displays within a small area close to the driver's forward visual viewpoint was also discussed with some participants, thinking that it might prevent them from looking away as much from the road.

System Dimensions & Specifications

Here it is possible to read about the findings regarding system dimensions and specifications, including placement of displays and cameras, size and FOV, display resolution, quality and lighting conditions.

Placement of Displays & Cameras

The TP:s understood that the placement of the conventional rearview mirrors is a question of function rather than design and see it as more or less the only possible solution having them where they are. Participants did however comment that it might have been nicer if they were located somewhat farther to the front of the car since that would increase the field of view and meanwhile also decrease the extent of which the user needs to twist its head to use them.

Regarding the placement of the displays that CMS consist of, the users have more opinions. Generally, the users accept it and point out that they are not in the way and having them as far to the front of the car decreased the need for the user to turn the head in varying positions to see the information on them. Almost all users do point out that they initially turned to look at the traditional mirrors' placements for the indirect vision, but also that it most likely feels like an old habit that one will readjust from.

When asking the users about what they would like to adjust regarding the display position, the speculations are quite inconsistent between the users; one TP thinks that it is more difficult to look at the left-hand side compared to the right-hand side, and also that the middle display feels too far away considering its small size and would prefer to have one display on each side of the steering wheel and the middle display behind the steering wheel. Another user thinks that the displays complement each other well by covering different FOV, while others prefer only having one larger display in the middle of the dashboard, substituting all three.

The TP:s did however seem to think that one should use the opportunity better when implementing CMS to decrease the attention off the road by choosing a placement that is more optimized with regard of that and hence is less spread out. One user did however express that he/she did see a point with having a slower evolution of developing CMS; older users would have a chance to adapt to and accept the new system.

One TP also expressed skepticism regarding the aesthetics of placing the sideview cameras on arms in the traditional place of the rearview mirrors, and wondered why they just had not been placed on the handles of the doors or another more discrete location where they blend more into the general shape of the car.

Size & FOV

The size of the mirrors was left rather uncommented during the route with the regular car, except for one user who thought that the sideview mirror images are too small considering driving an SUV.

The CMS display sizes were not very commented either, even if users expressed that the middle display felt too small and furthermore that it would be beneficial for it to have other dimensions. Also that the side and middle displays should harmonize more in terms of size and dimensions. One user explicitly said "*it feels like the middle one is short and wide while the others are high. It should be somewhere in between*".

Many users mentioned that a critical task regarding the FOV when using the mirrors is to keep track of the blind spot and turning the head around in order to see it, but also that it is a habit that everyone is used to. Participants also considered it easy to expand the view when necessary by turning the head slightly.

Users thought that the FOV felt wider in the sideview displays compared to the mirrors, and that the FOV of CMS in general works well. They however said that the blind spot issues present in the mirror car could be addressed more in the CMS prototype; "*I don't have the feeling that the blind spot is gone*". Some users expressed that they sometimes felt that they did not have to

bother checking the blind spot at all now though; *“If I look at the left display then I don’t have to check the blind spot”*. In the parking situation, the fact that the sideview displays covered a lower FOV made the task easier of reverse driving.

In the VIRM, the horizontal FOV was also experienced as increased compared to the mirrors. In the parking situations however, the experience of the VIRM is decreased since it is angled too far up, resulting in only seeing the top of the cars behind, making it difficult to understand what is happening right behind the car and estimating distance to the back. One user also commented the same thing when driving straight on the highway; it did not feel as easy to discover cars approaching from the back as when using mirrors. Some people commented that the reduced rear direct vision caused by the covered rearview window made it difficult to verify the interpretation of the distance made using the VIRM.

Display Resolution & Quality

Regarding the image resolution and quality of the displays used in the CMS prototype, users thought that the middle display was superior to the screens on the sides and perceived it as really good: *“Sharp as a knife”, “The contrast is regulated well automatically and the middle one does a great job. It is really always crisp and has a good contrast. Nice image quality”*. They also expressed that the sideview displays are of lower quality and sometimes feel a bit yellow compared to the direct vision. Further, that it would be better if the side and middle displays harmonized in this concern (and aim for the middle display). One user however thought that the quality of the middle display was even *too* good and discussed the risk of if capturing too many details could be distracting in the context. The TP:s also agreed on that the reflective surface of the prototype middle display was bothering and prevented them from using the display in the intended way. Some users also said that flickering effects sometimes appeared in the screens, decreasing the experience of them.

Lighting Conditions

Some participants said that the image in the mirrors is dark when driving in darkness but seemed to see it as completely normal and did not appear to have any specific issues with that. In the same dark situations when instead using CMS, they expressed it being easier to see the surroundings since the screens were lit up compared to the mirrors. Some users also expressed that the middle display adjusted the lighting automatically which was considered good, but someone thought that the light intensity should be lower in dark environments and an additional another user thought that the contrast needs improvements to adapt faster to changes in light.

Attitudes, Perception & Usage

In this part, findings regarding attitudes, habits, change of focus and attention, image- and distance perception are presented.

Attitudes

The attitudes towards driving with conventional mirror were that one is used to the mirrors and thereby have accepted them as a normal and necessary parts of driving a car. The mirrors have always been there, and it provides a natural and trustful indirect vision, *“what you see is what you get”*. Even though the participants all have years of experience of the mirrors, they think that

the mirrors have some flaws and the experience of driving with them is far from perfect. The driver needs to turn its head quite a lot using them, especially for the right exterior mirror. The FOV was also perceived as insufficient; even if the driver knows what can be seen and not through the mirrors, it still covered far from the FOV that the user would like to see.

From having different amounts of previous knowledge about CMS, still most participants had a positive mind regarding implementing CMS after driving with them. Further, they mentioned that CMS might provide better direct sideways FOV when the huge cowls covering the mirrors are removed. The system is believed to be able to eliminate blind spots in a more effective way than conventional mirrors. Though it has positive benefits, there were also dissatisfaction since the expectations on CMS were higher than what the prototype performed. The users thought that the CMS prototype was too similar to regular mirrors, and that one all opportunities that one would expect using CMS had not been used. That could be integrating support system with CMS, such as BLIS, lane mitigation etc. or other tools enabling adjusting to the traffic better.

The users however expressed that they believed that CMS would be the next step of cars' evolution. They also expressed believing that it requires some driving time to build trust for the system, since it is a rather revolutionary system and transitioning from looking at mirrors to screens for indirect vision inevitably would feel odd at start. Many participants described the problem of driving with screens instead of mirrors as not trusting the system completely, since it provides a vision through a technology that one is not used to. Being unsecure and not knowing what CMS will contribute with completely leads to actions such as turning around and looking through windows more than what might be necessary. Not being fully aware of the cameras' blind spots also created an uncertainty regarding trusting of the system. The aspect of looking at virtual reality in screen and at the reality through a mirror is crucial to consider, since it explicitly decreased the level of experienced control, making it more difficult interpreting what one sees.

Habits

Obviously, there is the aspect of the TP:s' habits regarding driving with conventional mirrors, which they do on regularly basis. This was also exhibited in the interviews. All the participants were used to driving with conventional mirrors and were aware of and had acceptance the mirrors' drawbacks. The main problem of the mirrors was to constantly having to observe the rearview through the mirrors when they were placed far away from each other. This results in many head turnings, but simultaneously, it is a part of the driving routine that the TP:s were used to.

The participants had no previous experience of driving the CMS prototype, except for a few who had only been sitting a CMS car once. When driving it, some expressed that it was rather similar compared to driving with conventional mirrors, but most thought that it felt different. The changed placement of the displays caused the participants to glance at the old location of the mirrors' multiple times during the tests, which was considered annoying. Not being used to driving with CMS implied a longer time for interpreting the image, which made the TP:s look away from the road for a longer time than usual. Overall, the users thought it felt different and difficult in the beginning to drive using CMS, but that time was needed to get used to it. There is

then also the aspect of changing cars in the everyday life, and some concerns were raised concerning switching between using CMS cars and regular mirror on a weekly basis.

Change of Focus & Attention

As mentioned in previous paragraph regarding habits, a major drawback with the mirror is to constantly shift focus between the exterior sideview mirrors, the road in front and the inner mirror. Even though this was expressed as a problem, it was not a big deal since all participants were experienced drivers and used to turning their heads to observe the mirrors.

Regarding the change of focus when driving the car with CMS, the general opinion was that it felt better having the screens located towards the front of the car since it lead to less turning to check the rearview and also to faster focus shifts. Some participants though did express that they wanted the screens to be even closer towards the forward line of sight, preferably having all screens around the steering wheel or similar, and that the right-hand sided one especially should be closer.

Other users pointed out that it would be *“a tough accommodation shift for elderly if a screen would be placed too close to the eyes”*. Additionally, the alternative of having only one display with all three images integrated together would be interesting to investigate, since it might reduce the accommodation time and head turnings. Though, it was stated that the aspect of using screens compared to mirrors generated a longer accommodation time, since it was *“a bit trickier to perceive the image than on mirrors”*.

Regarding the image quality, some thought that it was good enough to quickly perceive the image and therefore smoothly shifting between the display images. Others thought that the sideview displays lacking image quality contributed to longer time and decreased experience regarding shifting focus between the screens and road.

Regarding the displays' properties, the VIRM display's high resolution, contrast and brightness, made the participants pay more attention to the screens than what was necessary. It was experienced as *“very annoying, since it happens a lot in the screen”* which shifts the attention from the road to the screens, even in situations when it is not critical to check the displays.

Image Perception

When discussing what the users looked for in each mirror and perceived from them, it was clear that they use a combination of the three to get an overview of what happens around the car, and the middle rearview mirror was primarily used for noticing whether a car appeared in the surrounding. Not many of the users said so, but some thought that the images provided in the side respectively middle mirror sometimes do not cohere completely. They meant that the images provided different information regarding objects' location, size and velocity, making it difficult to make decisions based on the information. Those users did however point out that this is more obvious and noticeable when driving a car that one is not used to.

When discussing the perception of the image when using CMS, some of the users raised the issue of feeling that *“I'm looking at a screen. I'm not looking at reality”*, which indicated that the screen replacing the mirror affects the perception in some way. One person raised the issue of

not understanding how zoomed in the image displayed on the screens are. Some also talked about issues with the middle display; it is difficult to understand where an object is located when using the middle display, and it sometimes feels as if a car appears right behind oneself all the sudden. No user said that there were any problems with the sideview displays in terms of the latter issue.

Distance Perception

The users expressed that it can be difficult to understand the distance to vehicles behind using the mirrors, and that they are sometimes hesitant in taking some decisions because of that, and it might require several checks before being comfortable doing so. The users however seem to think that the mirrors serve the user with a distance perception that is good enough even if it is not flawless, and do not see it as a major problem.

TP:s think that it becomes more difficult to assess distance to objects and vehicles behind using CMS compared to using the mirrors. It is however easier to understand the distance when using the sideview displays compared to using the VIRM, and users explicitly said that they did not rely on the VIRM for assessing distance. They furthermore expressed that the difficulties understanding the distance rearwards most likely was increased by not being able to turn around and get a reference to the direct vision since the rearview window was covered. One user said that understand the distance to cars approaching from behind was especially difficult when deciding to performing an overtaking or not, while someone else stressed that it was difficult to estimate distance to the sides in the parking situations.

Findings from Questionnaires

In Figure 48, Figure 49, Figure 50 and Figure 51 the charts follow the same theme and structure for all graphs. The result is clustered by the category researched in the specific diagram. Each TP is color coded as can be seen below each graph. Each person has two staples, one colored and one in grey scale, to demonstrate the mirror- respectively CMS-value.

In Figure 48, the results of the general experience of driving in a car with mirrors respectively CMS are demonstrated. Overall, the results were rather mixed. Generally though, comparing experienced security of the test persons' in a car with mirrors and CMS, the assessments are lower for the latter. Test person 22 evaluated that driving with CMS felt safer but otherwise the CMS scores were lower or equal compared to mirrors regarding the experienced level of safety driving with either system. The perceived level of easiness was also mixed. Furthermore, CMS is experienced as slightly less safe than using mirrors. The experienced practicality also varies between the participants, and the general attitude towards CMS is somewhat higher than for using mirrors.

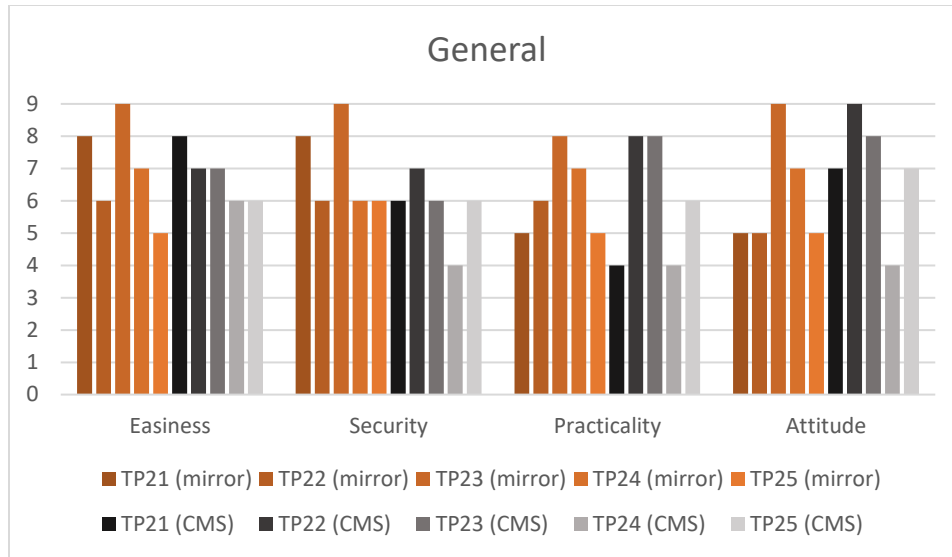


Figure 48 - The participants' general attitude towards driving with mirrors respectively CMS.

In Figure 49, the results from the estimated easiness regarding driving a car with mirrors respectively CMS is demonstrated for each driving situation. The graph shows that driving with CMS tends to be easier in darkness (in the parking garage). Reverse parking was also experienced as easier when using CMS compared to conventional mirrors. It is also shown that CMS is considered somewhat easier for driving straight on a highway, performing overtakings and driving in an intersection.

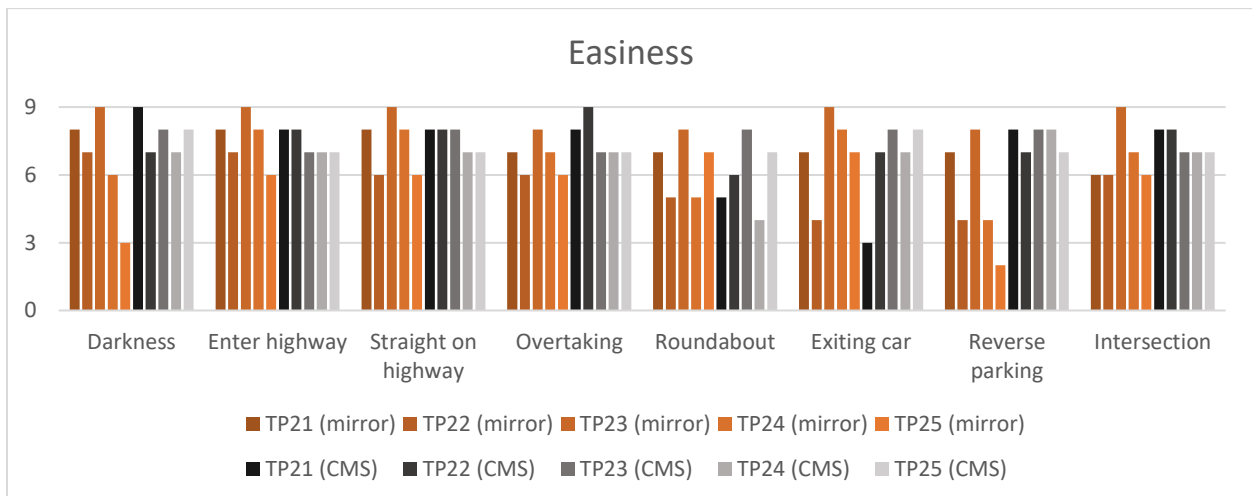


Figure 49 - The participants' estimated easiness of driving with mirrors respectively CMS.

In Figure 50, the result of the experienced security when driving a car with mirrors respectively CMS is demonstrated. Regarding the security level the results also vary within the scenarios comparing CMS with conventional mirrors. The participants tend to feel less secure when using CMS when driving in a roundabout and while performing an overtaking. They do however feel more secure when using CMS for reverse parking.



Figure 50 - The participants' estimated security of driving with mirrors respectively CMS.

In Figure 51, the result of the experienced practicality for driving a car with mirrors respectively CMS is shown. Similarly to the results regarding the experienced easiness and security, the results were inconsistent between the participants. Though, darkness (driving in a parking garage), performing an overtaking as well as reverse parking tend to be considered as easier when using CMS compared to mirrors. There is also a major difference from TP 21 regarding driving in a roundabout and exiting the car, who experienced CMS as less practical.

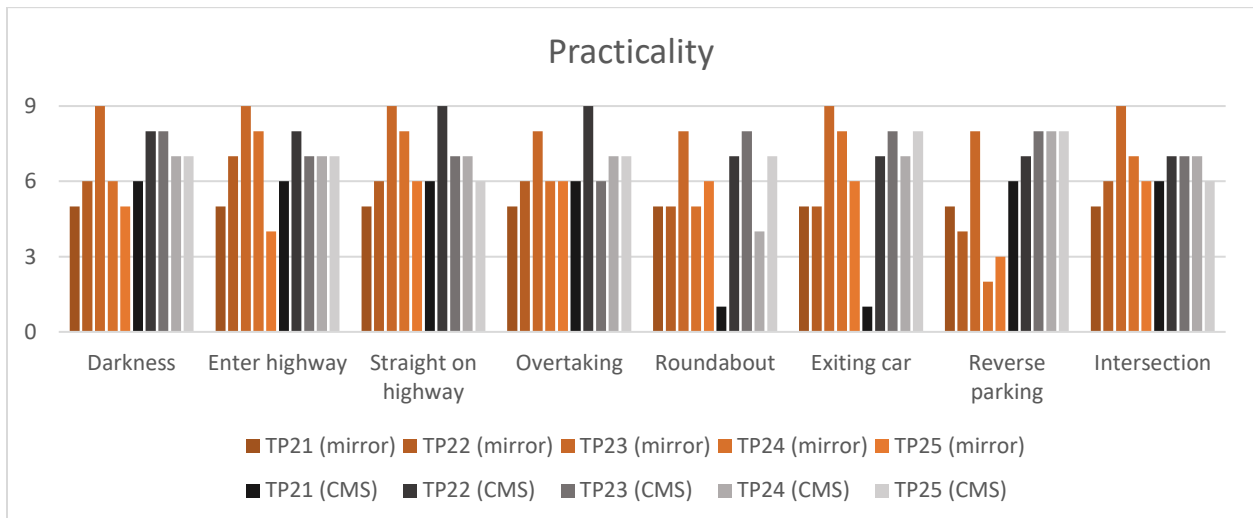


Figure 51 - The participants' estimated practicality of driving with mirrors respectively CMS.

7.2.6 Reflections from User Test 2

In the following part of the chapter, the reflection of user test 2 is presented. This includes reflections regarding difficult and easy driving situations, support systems and improvements, system dimension and specifications, attitudes, perception and usage.

Difficult Situations

When analyzing the findings from the interviews and observations, the most difficult situations that were found were changing lane, performing overtakings, driving in roundabouts and exiting the car. This result is validated from the ratings in the questionnaires, where overtaking and roundabout made the users feel less secure. However, when looking at the easiness graph (Figure 49) no situation is distinguishably less easy when it comes to using CMS. When taking a closer look at Figure 51 regarding the practicality, it is shown that overtaking was considered as more practical when using CMS. This is contradicting since the opposite was expressed in the interviews.

The situations of changing lanes, performing overtakings and driving in roundabouts are all performed in relatively high velocities or contain rather complex traffic situations. The first three situations all include the actions of detecting objects and estimating distances to object simultaneously as controlling the position to other cars at relatively high speeds. The driving situation in the roundabout was performed in a slightly lower speed than the other two situations but required more attention and control of the situation in the front compared to changing lane or performing an overtaking on a highway or straight road.

The reason why the participants did not feel safe during these situations might be an effect of them not being used to driving with CMS while being so driving with mirrors, making users extra uncomfortable in these demanding situations. Another reason for them not feeling safe using the system could be that they received no explanation regarding what the FOV covered, of course leaving some people uncertain of what coverage could really expect. In other driving situations such as reverse parking, the TP at any given time could stop the car and analyze the surroundings when feeling unsafe or uncertain in the situation. In the situations of performing a lane change, overtaking or driving in a roundabout, the same thing is of course not possible. The driver is constantly in a demanding situation and has no other choice than continuing to drive and making decisions, which of course can feel unsafe if one does not understand if all important information is provided for making the decision. One user did express that a vehicle “*disappeared*” in the rearview through VIRM during an overtaking, which strengthens this reasoning.

The fourth difficult situation was exiting the car. However, it was mainly considered as a critical situation since the sideview displays turn off when the car was. This was disturbing since the screens then cannot be used, making the situation more difficult and potentially dangerous, especially if one is used to look through the mirrors before opening the door. The low ratings for this driving situation are visualized in Figure 51. However, according to the regulations of UNECE Regulation 46 (UNECE, 2016) this is not allowed to happen when using a car shortly after standing still, and this factor is most likely only a prototype error that should not be expected in a real CMS implementation. When exiting the car, it is furthermore important that the users not completely trust the displays for all kinds of traffic outside the car. For example, it would be a problem if the user would rely only on looking at the display, as it might not cover all directions necessary before exiting the car.

Easy Scenarios

The driving situations of reverse parking, driving in darker light conditions and driving straight on a highway were considered easier when using CMS. Managing an intersection was also considered an easy situation but it was not highly as relevant in this analysis since the users barely used CMS during that situation, but paid attention to traffic in front. To point out was however that no larger intersection was used during this test, and the intersections had traffic lights and a very controlled traffic flow, demanding little of the driver in terms of keeping control of the rear surrounding.

Reverse parking and driving in darker lighting conditions were also considered easier when using CMS compared to mirrors regarding easiness, security as well as level of practicality. Regarding the dark lighting conditions, CMS apparently performs better which mostly can be explained by the brightness of the display and camera properties. It should be considered that the camera and display properties are rather specific for this precise prototype. The same result regarding driving in darkness might not appear when driving other CMS cars like Audi e-tron or Honda e. In the benchmarking study it was found that driving the e-tron at night made the screen too dark and blooming effects also appeared when road lights and headlights were displayed. Though, when looking at this specific prototype car, it provided a bright screen compared to the darker mirrors and made it easier to observe the surroundings according to the participants. Since some participants however considered the light as too bright, one can consider the alternative of not making it just that bright, only almost. It would further be interesting to investigate the prototype car's performance during even darker light conditions than in the parking garage, like during nighttime as that might cause other reactions among the test persons.

Reverse parking was surprisingly easy, secure and practical according to the ratings made in the questionnaires, which cohered with the interview findings. The main reason for that was interpreted as that the sideview mirrors covered a larger FOV both height and width wise. The FOV covering a larger height especially made it easier to understand where the car was in relation to the ground during this situation; sometimes it was even possible to see the parking lines. The VIRM was mostly not used during the reverse parking since it did not provide much information about fitting the car in between two others. It did however provide information about if other cars or people appeared behind while reversing. It should be mentioned that the 360 degrees view was available while performed the task, since it most likely would be in a car that CMS is integrated in. This could have contributed to why the participants trusted the system in this driving situation and reversing while still feeling safe. These support systems were however also available for the same driving situation using mirrors. Further, the participants usually reverse drive by the help of the 360 degrees view or parking sensors, so it might not be necessary to design the rearview displays with aspect of performing reverse parking by the help of CMS.

To point out here is however that the parking lot where the reverse driving took place contained a lot of space. The users therefore almost always reversed with a 45-degree angle, causing both sides of the car to be free. One can consider how difficult it would be making a 90 degree turn where the sides of the car are not free at start. Based on own observations during these tests, this is much more difficult, even when using a combination of the displays, 360 *and* parking camera.

The users did however need to concentrate more when reverse parking with CMS compared to mirrors. The reason for that could be lack of experience of using the CMS. Having used regular mirrors for many years makes it rather different to view almost the same view from a two-dimensional display with no possibility to lean your head forward to extend the FOV in the display. The reason of needing to concentrate more could perhaps also be the aspect of worse mapping of the surrounding, since the FOV is changed and in addition also overlaps to a greater extent than the mirrors do, making it more difficult to understand where the overlapping areas actually belong. Regarding the side view displays, the user could perhaps need more time to understand where in the surroundings the images displayed in the screens are located, since they do not have the intuitive mapping to reality as mirrors do.

The general interpretation of driving on highway was that the users felt less comfortable using CMS compared to driving with the rearview mirrors, but also pointed out that it probably was because of lack of experience in using CMS. It was difficult to be aware of how much of the FOV and blind spot that it covered, even if users got the impression that it covered more than mirrors did.

Support Systems

Regarding the potential improvements of CMS it was found in the interviews that integrating BLIS, lane mitigation, automatically adjusted cameras depending on situation, objects being marked in display or other functions that warns the driver when a collision might be close is highly relevant and these are things that the users expect. When implementing CMS, it opens the opportunities for digital enhancements that would not be implementable in mirrors the same way.

System Dimensions & Specifications

In this part of the reflection, placement of the displays and cameras, the display size and FOV, resolution, quality and lighting conditions are discussed.

Placement of Displays & Cameras

Regarding the placements of the displays in the prototype car, some participants expressed that the VIRM could be placed closer to the steering wheel, since that probably would lead to less head turnings than where they are located in the CMS prototype, the screens being closer to the driver's forward line of sight. Though, changing the placement of the VIRM could lead to increased accommodation problems since it would end up closer to the driver's ocular point. A hybrid of mirror and CMS (having sideview displays and a middle rearview mirror, as in the Audi e-tron) was also mentioned. Compared to the prototype car, this could perhaps have been advantageous, mostly since the VIRM made it problematic to estimate distances and maintain control the surroundings. That type of set up would however put constraints on the rear shape of the car, which would compromise important benefits of CMS.

The comments regarding the placement of the displays only are opinions or suggestions made by the participants, that in no way have been tested or validated. There are therefore no findings regarding how the driving would be experienced with the suggested placements. That means that the summary of results regarding placement of the screens can be used as interesting ideas or suggestions for potentially further investigation only.

One interesting aspect of aiming for less head turnings while driving, by placing the screens closer to the driver's forward line of sight, is that it perhaps makes the user less alert for objects appearing from the sides. If the system provides screens that depict the whole necessary FOV, the users might become lazy and only care about the image provided in displays. The system would probably not immediately become 100 % perfect, and the user would still have to maintain control of the situation by also looking at other angles. If it does, it is preferable that the user feels the need for doing so now and then, instead of falsely thinking that CMS is covering all relevant FOV. The system could of course provide a FOV that covers a great area immediately, but since mirrors currently do not, a big change could be bad if one aspires to accustom more users to CMS since an image that is very different from what users are used to might cause unnecessary confusion.

Size & FOV

It is highly relevant for the CMS to communicate what FOV it is displaying and whether there are blind spots or not. Users that shift from mirrors to CMS might have the preconception of CMS covering an all-round view without blind spots, since it consists of cameras providing the image. Shifting to a more advanced system could potentially cover the whole necessary view but doing so could make the image distorted. However, if the user is aware of the system having blind spots, they might have the habit of being more alert, as is the case with the mirrors.

Regarding the size of the displays, the middle one was described as short and wide, while the sideview displays were described as unnecessary high. Something in between the two types of displays was described as preferable when it comes to shape, making them feel uncoherent. Screens that match each other better would be preferred among the participants, as that would let the user know that they are a part of the same system and complement each other.

Display Resolution, Quality & Lighting Conditions

As discussed in the previous paragraph, the screens should harmonize better with each other regarding size and form, but also regarding the image quality. It was mentioned among the participants that the screens had different sharpness when comparing sideview displays and VIRM. In the test, a prototype CMS car was used, which is probably the reason why the image quality differed between the displays. In future versions coherence regarding the resolution between the display types should be aimed for. It was however also mentioned that the VIRM had the preferable screen quality and sharpness, and if adjusting any of the displays to better harmonize with the other, the sideview displays should be adapted to fit the VIRM quality.

Furthermore, the VIRM had a highly reflective surface, causing trouble in the context of bright ambient light. This is also highly related to the test being performed on an early prototype, but similar findings were made in the benchmarking of Audi e-tron's sideview displays. The aspect of reflection in screens should therefore be considered carefully when designing CMS, since it was mentioned in user test 2 that some TP:s stopped using the VIRM because they only saw the passenger's reflection in it.

The lightning conditions should also be taken into consideration. It was interesting that some participants expressed that the VIRM automatically adjusted the brightness depending on the

given situation, since it was not a function of the displays. The reason for that could be that the users expect more feature from the high-tech CMS compared to the mirrors, which at least tells us that this is something that should be considered in future design of CMS. Having automatic adjustment of the screens would indeed be preferable so that users are not blinded by the light in dark environments.

Attitudes, Perception & Usage

In this part of the reflection, the attitudes, habits, change of focus and attention, image- and distance perception are discussed.

Attitudes

The attitude among the test persons were in general that implementing CMS in cars should maintain or achieve better performance than using mirrors, otherwise there would be no point of changing the system according to them. The users are – not very surprisingly – looking at CMS mainly from the user perspective. People have driven cars with mirrors for many years and in the huge change of transitioning into CMS from that, there will be opposition and people that initially feel skepticism towards the system. Therefore, it is relevant to meet and overcome the expectations of the users. The prototype car with CMS did not cause many benefits from a user perspective compared to using a car with conventional mirrors, which was expressed as somewhat disappointing. Furthermore, to clearly present the system boundaries and the advantages of the CMS it would be preferable to not create false expectation of what the system will do for the users and be transparent with that towards the customers.

Habits

When using CMS for the first time, all the test persons were used to driving with mirrors but not with screens. It is rather intuitive to use the screens if they display the surrounding in a familiar way. Though, when using the screens, the participants said that it took longer time and more effort to perceive the image, which by speculation would increase the eye-off-road-time. The fact that the test persons constantly looked at the locations of where the mirrors usually sit out of habitual behavior caused some annoyance among the users. The tests with CMS were conducted during 20-25 min on road which is not a long time for getting used to CMS, compared to years of driving with mirrors. This is most likely one of the reasons why it was experienced as difficult and more demanding driving with CMS among the participants. It would however be interesting to investigate further if these the old habits disappear with time or not when using CMS, since that not only would be good to know out of driving safety reasons, but also as a sales argument for CMS cars. What would the behavior be like after a month of using CMS? The real benefits or drawbacks of the system might appear after a longer period of usage and it would be interesting to compare the experiences of using CMS at that point.

Change of Focus & Attention

There are several aspects of having a screen that might affect the eyes-off-road-time, such as the image quality, distance to screen and placement of them. It was mentioned among the test participants that the accommodation between the road and displays probably could become a problem if the screens are located too close to the eyes of the driver. This could be especially troublesome for elderly people which generally demand a longer time of changing focus from a

far to a short distance (and vice versa). The image quality also affects the time to perceive the image, and therefore it is important to have a high enough image quality for fast perception and interpretation of image. Though, it was mentioned that the VIRM with its sharper detailed image was pulling attention slightly more than necessary, which should be considered in future development of CMS. It could of course be problematic if the driver looks too often at the screen.

Image Perception

The conventional mirrors provide different images of reality, and users perceiving the same object as being at different distances and of different sizes depending on what mirror they are looking at. Every driver is however used to this, and they might therefore expect the same thing using CMS which could explain why the users did not react much on the images provided by display types being slightly different.

CMS was believed to change the image perception compared to using mirrors since it delivers a digital image of reality which differs from much from observing reality through a mirror. Most comments related image perception was directed towards the VIRM, and users pointed out that it was difficult to understand how zoomed in the image in it was based on the information it provided. Problem formulations were also directed to users not being able to understand where the displayed images were located, and that it sometimes felt like cars appeared out of nowhere from the behind. This makes the VIRM rather unreliable and not very useful, and these matters are therefore things that should be considered during future development of CMS. The lack of comments directed towards the sideview screens might imply that there was less problems with perceiving the image in them and that they depicted the real surroundings in a trustworthy way.

Distance Perception

Perceiving distance to objects when using CMS was generally more difficult compared to using mirrors. The VIRM the most difficult one since it displays a zoomed in image. The opinions regarding the reasons behind perceiving the distances less when using the displays compared to mirrors were divided. It would have been interesting to let the participants turn around and perceive the distance by themselves to get an understanding about the distances, which would have been possible if the cover of the rear window was removed. It is more challenging to enter a new system in a car and not having a reference of how it relates to the surroundings. It would therefore perhaps be preferable to get a feeling of the CMS related to the surroundings first and then trying to estimate distances using the displays. The perception of distances would then probably be improved after gaining some experience and testing the limits of the system. Using this reasoning, it might be preferable to give users an opportunity of seeing the rear environment in the first implementations of CMS in cars, by offering direct vision through a rearview window.

Potential Sources of Error

For the results of user test 2, there are some potential sources of errors that need to be raised. To start, the results of the interviews, observations and questionnaires are based on the number of participants that performed the test. As was seen in Figure 48, Figure 49, Figure 50 and Figure 51 the result was rather mixed and the participants often had different opinions about the driving

experience when comparing CMS with conventional mirrors. The study of user test 2 was qualitative and not quantitative, which makes it highly relevant to use few participants, but only five is considered rather low. This was however the only possible way of carrying out the test due to the Covid-19 pandemic, but it still becomes difficult to draw conclusion with high significance based on these findings, even if they capture trends.

The tests were performed on employees at Volvo Cars, which potentially could have affected their answers in the interviews and questionnaires. However, the aspect of the participants being Volvo Cars employees could be biased in two ways. They might be more positive or negative towards the new features of CMS because of professional industry insights, and therefore they can be considered as just as biased as any other external TP would be. This applies for user test 1 as well since also they were Volvo employees. The aspect of having all male participants could potentially affect the findings based on the lengths of the participants. The generally tall participants (mean value 185.2 cm) of the test might sit farther away from the displays than a shorter person would when adjusting the seating to a normal driving situation to reach the pedals while receiving good visual field forward. The screens are all in a fixed position which thereby means that the distance to the screens might differ between shorter and taller persons.

The route was mainly chosen since it covered many interesting driving situations. As can be seen in Figure 40, the route was back and forth to Torslanda, which meant driving on public roads with non-controllable traffic of cars and pedestrians, making each driving experience unique. Different amounts of traffic were present on the roads during each test, which provided a more or less stressful situation for different participants. This parameter must be accepted but considered since it can be a reason for getting different answers among the participants. In this test it was appropriate with small or medium amount of traffic to not put the participants in a too stressful situation, since it was the first time of them trying out CMS. In the future, it would however be interesting to perform a similar test but in heavy traffic to test how the system is experienced in a more stressful environment.

7.2.7 Conclusions from User Test 2

User test 2 was performed comparing the CMS prototype to an equivalent rearview mirror car in different use situations. The findings were that the participants thought that the CMS prototype was surprisingly easy to use in the driving situations of reverse parking, driving in darker light conditions and driving on highway. Changing lane, performing overtakings and driving in a roundabout were more difficult compared to driving with mirrors.

The tests also showed that the display types (VIRM and sideview screens) were experienced as uncoherent regarding size and shape. The different display FOV also overlapped too much which reduced the mapping between the different displayed images and reality. The displays did not either harmonizing regarding image resolution and were slightly too bright in dark conditions. More issues regarded not being able to use direct rear vision to understand how the images related to the surrounding. Continuing, the reflective surfaces of the screens prevented the user from seeing the image and the displays turning off immediately when turning the car off was also problematic. These are aspects that should be taken into consideration when iterating the CMS prototype, and issues that will be raised in the guidelines for the CMS prototype in phase IV.

8 PHASE IV

GUIDELINES & RECOMMENDATIONS

In this chapter, the findings from phase I, II and III are first summarized. The general guidelines are then presented for how to design CMS for maintained user performance. Following, the guidelines for how to increase the user performance and experience in the evaluated CMS prototype are presented. At last, these guidelines are discussed and concluded.

8.1 Procedure

In this phase of the project, two types of guidelines were developed: general guidelines and specific guidelines for improving the CMS prototype in regard of user performance. The general guidelines are primarily based on the knowledge presented in phase I, that describes the impact that researched design parameters have on different aspects of user performance and experience when driving, but also from phase III. The procedure for developing guidelines was to read through the subchapters of chapter 5.2, 5.3, 7.1.5 and 7.1.6 one by one, analyzing and interpreting those as well as concluding those in a table. After the knowledge had been summarized, it was categorized into different categories, depending on the similarity between them and how they related to each other.

The categories were then arranged in the order of which it made most sense to make decisions when developing CMS, which depended on how the parameters related to each other, but also somewhat on how the development of the system most likely will be carried out. The findings were then translated into guidelines and recommendations of how the process of making decisions regarding the parameters based on their relation to each other. When it was necessary, the original sources were used to clarify any hesitations regarding the findings and what they would mean for the design process of CMS. One guideline was based on one or several findings from one or several sources. What guidelines that originated from which finding and source can be tracked in Appendix I. The guidelines were then iterated, both regarding the order of which they are to be carried out as well as the formulations of them, to polish the recommended design process as well as clarifying the messages of the guidelines.

The process of developing the specific guidelines for improving the CMS prototype with regard of user performance was performed in a similar way as the general guidelines. The subchapters 7.2.5 and 7.2.6 were read through one by one, and guidelines were then formulated based on the findings and reasoning there. The guidelines were documented along with what findings they originated from, which can be found in Appendix J. The guidelines were then categorized according to their content to interpret them more easily.

8.2 Findings

The findings from phase IV are presented in this subchapter. It includes a short summary of previous findings from phase I-III, followed by the general guidelines for designing CMS and then the specific guidelines for improving the CMS prototype car.

8.2.1 Summary of Findings from Phase I, II & III

In this subchapter, the findings from phase I, II and III are summarized in tables, along with the origins they are derived from. Table 10 summarizes the most important driving situations and Table 11 summarizes the parameters that can affect the user performance when designing CMS for cars. Table 12 summarizes the findings that are of importance when designing CMS with regard to user performance in cars as well as their origins, and Table 13 concludes the findings of how to improve the user performance in the CMS prototype and where they came from.

Table 10*Summary of the most important driving scenarios when using CMS.*

Most Important Driving Situations for Indirect Vision:	Originated From:
<ul style="list-style-type: none"> • Parking (forward, reverse & parallel) • Intersection • Roundabout • Change/merge lane • Overtaking • Turning • Reverse driving • Forward driving 	<ul style="list-style-type: none"> • Mindmapping • Literature studies • P-Diagram Workshop
<ul style="list-style-type: none"> • Exiting a car 	<ul style="list-style-type: none"> • Literature studies
<ul style="list-style-type: none"> • Communication with other people 	<ul style="list-style-type: none"> • P-Diagram workshop • Expert interviews

Table 11*Summary of the design parameters that affect the user performance of CMS.*

Design Parameter:	Originated From:
<ul style="list-style-type: none"> • Shape and size of <ul style="list-style-type: none"> • Displays • Camera houses 	<ul style="list-style-type: none"> • Mindmapping • Expert interviews • P-Diagram
<ul style="list-style-type: none"> • Distortion (relationship between FOV and display size) 	<ul style="list-style-type: none"> • Mindmapping • Literature study • Expert interviews • P-Diagram
<ul style="list-style-type: none"> • Placement of: <ul style="list-style-type: none"> ○ Displays ○ Camera and camera houses (horizontal & longitudinal) • Number of: <ul style="list-style-type: none"> ○ Displays ○ Cameras 	<ul style="list-style-type: none"> • Mindmapping • Literature studies • P-Diagram workshop
<ul style="list-style-type: none"> • Adjustment range of: <ul style="list-style-type: none"> ○ Camera angle ○ Seating position 	<ul style="list-style-type: none"> • P-Diagram workshop
<ul style="list-style-type: none"> • Display angle • Camera angle/viewpoint • Reference point • Depth cues in image 	<ul style="list-style-type: none"> • Literature studies
<ul style="list-style-type: none"> • System latency • Camera properties (dynamic range) • Display properties: 	<ul style="list-style-type: none"> • Expert interview • Literature studies

<ul style="list-style-type: none"> ○ Contrast ○ Response time ○ Color reproduction ○ Luminance 	
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Table 12

Summary of the findings for designing CMS regarding user performance, along with their origins.

Summary of Findings for Designing CMS with Regard of User Performance	Originated From:
What is considered good/safe user performance is situation dependent	Phase I: Literature study, Schmidt et al. (2016) & Berberich (2021)
Lower vertical placement of the sideview camera leads to longer distance estimations compared to higher camera placements	Phase I: Literature study, Bernard & Hecht (2020) Phase 3: User test 1, long & short-distance test
Distance estimation is not affected by the longitudinal placement of the sideview camera	Phase I: Literature study, Bernard & Hecht (2020)
Adding a vehicle reference in the sideview images eliminates the vertical camera placement parameter's impact on distance estimation	Phase I: Literature study, Bernard & Hecht (2020)
The magnification factor impacts the distance estimation	Phase I: Literature study, Flannagan & Mefford (2005), Roscoe (1984) & Van Erp & Padmos (2003) Phase 3: User test 1, long & short-distance test
The horizontal FOV has no impact on longitudinal distance perception for the sideview displays	Van Erp & Padmos (2003)
The distance to the display does not affect distance perception	Phase I: Literature study, Flannagan et al. (2002)
Pictorial depth cues can be used to alter distance perception: <ul style="list-style-type: none"> • Larger objects will appear as closer than smaller ones • Objects that are located on either of two converging lines will appear to be closer if they are further away from the converging point • Brighter objects will appear to be closer compared to darker objects in the same image • Objects overlapping other objects will appear to be closer compared to the overlapped one • Sharper objects will appear to be closer compared to more blurred ones • Objects with clear textures will appear to be closer compared to the ones with more undefined texture 	Phase I: Literature study, Rößing (2016), Teittinen (1993), Braunstein & Ozkan (2010), Levitin (2002), Pinna (2012), Durand et al. (2002) & Cherry (2021)

Higher image resolution will lead to shorter distance estimations compared to lower resolution	Phase I: Literature study, Van Erp & Padmos (2003)
Higher image update rate will lead to shorter distance estimations compared to lower update rates	Phase I: Literature study, Van Erp & Padmos (2003)
The closer to the driver's forward line of sight the sideview displays are placed, the more it decreases detection time, time-off-the-road, perceived workload and will over time increase the perceived safety and preferences	Phase I: Literature study, Beck et al. (2017), Berberich et al. (2021) & Schmidt et al. (2016)
Integrating the two sideview displays into one monitor will not increase detection time or perceived stress level nor decrease the perceived overview	Phase I: Literature study, Berberich et al. (2021)
Placing the sideview displays farther up towards the driver's line of sight vertically will decrease the number of glances	Phase I: Literature study, Schmidt et al. (2016)
A larger horizontal FOV increases the lateral lane keeping ability and general peripheral control	Phase I: Literature study, Van Erp & Padmos (2003)
A vehicle reference present in the sideview displays increases the lateral positioning ability	Phase I: Literature Study, Thomas (1991), through Van Erp & Padmos (2003)
The interaction of the vertical placement of the sideview camera and the horizontal size of the FOV impacts the lateral distance estimation	Phase I: Literature Study, Van Erp & Padmos (2003)
Higher image resolution will increase the ability to detect and distinguish objects compared to lower resolution	Phase I: Literature Study, Van Erp & Padmos (2003)
Higher image update rate will increase the ability to detect and distinguish objects compared to lower update rate	Phase I: Literature Study, Van Erp & Padmos (2003)
The interaction of the vertical camera placement (of the VIRM) and FOV/magnification factor impacts the longitudinal distance estimation at higher positions. When it does, a larger FOV and smaller magnification factor leads to longer distance estimations.	Phase III: User test 1, short-distance test
Decreased distance between the driver and the display increases the effort of accommodating between the direct and indirect vision	Phase III: User test 1, long and short-distance tests

Table 13
Summary of the findings relevant for improving user performance in the CMS prototype, along with their origins.

Findings Relevant for Improving User Performance in the CMS Prototype	Originated from:
The driving situations of changing lane, performing overtakings and driving in a roundabout were considered difficult among the participants, partly because the FOV was perceived as limited	Phase III: Reflections from user test 2, difficult scenarios
The users thought that different FOV and camera viewpoints suited better during different driving situations	Phase III: Reflection from user test 2

The driving situations of reverse parking, driving in darker light conditions and highway driving were considered easy	Phase III: Reflections from user test 2, difficult scenarios
The displays were turned off immediately as the car was, preventing the user from seeing the rear surroundings when exiting the car	Phase III: Reflections from user test 2, difficult scenarios
Some users thought that the displays lit up too much during dark conditions, causing strain and distraction from the road	Phase III: Reflections from user test 2, display resolution, quality and lighting conditions
The highly reflective surface of the middle display caused significant difficulties in focusing on the displayed image instead of the reflected image, reducing the ability of seeing important rearward information	Phase III: Reflections from user test 2, display resolution, quality and lighting conditions
The users thought it was difficult to get a reference of how the image related to the real world when the direct vision through the rearview window was removed	Phase III: Reflection from user test 1 and 2
The participants expectations were that CMS would cover also the blind spots (- it does not), but at the same time felt unsafe trusting that it would	Phase III: Reflections from user test 2, support systems and improvements
Reverse driving at straight or small angles worked well for the participants, but doing so at wider angles was extremely difficult only using CMS	Phase III: Reflections from user test 2, support systems and improvements Own observations
The distance to the displays did not cause strain on the users testing the CMS prototype in user test 2, but it however did when testing it in user test 1	Phase III: Reflection from user test 1 and 2
The users pointed out that the two types of displays varied greatly from each other considering shape and height, causing concerns regarding if the displays belonged to the same system or were different	Phase III: Reflections from user test 2, size & FOV
The users had strong difficulties understanding distances using the middle rearview display	Phase III: Reflections from user test 2, Distance perception
The users found it difficult to understand where the images shown on the displays were located in reality	Phase III: Reflections from user test 2, easier scenarios, Image perception
The images in the displays overlapped to a high extent, causing confusion in where the image was located in the real world	Phase III: Reflections from user test 2, size & FOV
The images in the two types of displays did not cohere regarding magnification and perceived object size, making it difficult to know which one to base decisions on	Phase III: Reflections from user test 2, Image perception

The middle rearview display image was too zoomed in considering its size, making it difficult to get a perspective of where objects were located in the surroundings	Phase III: Reflections from user test 2, Distance perception
The participants experienced the resolution of the two display types as different, and thought that it was too low in the sideview displays while somewhat too high in the middle display	Phase III: Reflections from user test 2, display resolution, quality and lighting conditions

8.2.2 General Guidelines for Designing CMS with regard of User Performance

The General Guidelines (GG) for designing CMS regarding user performance are found in the section below. The origin of each guideline can be traced by using Appendix I. The following guidelines (GG1-12) are presented in a recommended sequence of which to make decisions about the design parameters, starting with GG1.

General

GG1: Identify and determine what should be achieved regarding user performance when using CMS. Decide what the aimed time-off-the-road, number of glances, detection-time, distance estimation and possibly other aspects should be.

Display Layouts

GG2: The displays should be placed close to the driver's forward line of sight on the dashboard. The closer to this position the displays will be horizontally, the shorter/lower the detection time, time-off-the-road and perceived workload will be, and the higher the perceived safety and preferences will be. The farther up the displays will be vertically on the dashboard will increase the number of glances.

GG3: The distance to the display should however be considered so it is placed far enough away from the user's ocular points to not to cause strain. The distance to the display does namely affect how straining it is to accommodate between the direct and indirect vision.

GG4: Integrating the two sideview images into one or two displays can be chosen according to preference. The number of displays will not increase detection time or perceived stress level nor decrease the perceived overview.

Magnification & FOV

GG5: The FOV, magnification factor and screen size should be considered in relation to each other.

- *FOV should be determined first* since the horizontal FOV affects the ability of maintaining control of the surroundings and lane keeping and lateral distance estimation, even if it does not affect the longitudinal distance perception.
- *The magnification factor should be determined second* since it will affect the longitudinal distance estimations made using the system.
- *Screen size should be determined third* since it has no documented impact on user performance while driving.

Viewpoint/Camera Placement

GG6: The longitudinal placement of the sideview cameras can be determined according to preference. This placement does not affect distance estimation.

GG7: A vehicle reference should be present in the sideview images. A vehicle reference present in the images increases the lateral positioning ability and eliminates the effect that the vertical placement has on distance estimation.

GG8: If a vehicle reference however is not present in the sideview images, the vertical placement of the sideview cameras should be chosen more carefully. Without a vertical reference point, a lower placement then leads to longer distance estimations compared to higher camera placements. This decision should also consider that the interaction of the vertical placement and chosen FOV will affect the lateral distance estimation.

GG9: Choosing the vertical placement of the VIRM camera should consider that the longitudinal distance estimations at higher placement will be affected by the zoom level. This impact decreases with lower positions. At the higher positions, a larger FOV and smaller magnification factor leads to longer distance estimations.

Image Quality

GG10: The image resolution should be high enough for the user be able to take in all necessary details and distinguish objects and depth cues that are necessary for interpreting distance. Higher resolution will lead to shorter distance estimations compared to lower.

GG11: The image update rate should be high enough for the user to be able to detect and distinguish objects as well as estimating distances to objects. Higher image update rates will lead to increasing those abilities and shorten the estimated distances.

GG12: Pictorial depth cues should be used to modify the user perception of the image. This should be done if there is a need to further increase the user performance of using the system after altering the previously mentioned designed parameters.

8.2.3 Guidelines for Improving the CMS Prototype with regard of User Performance

The Specific Guidelines (SG) for improving the user performance of the CMS prototype are based on the findings and reflections from user test 2. The more specific origin of each guideline can be found in Appendix J. The guidelines do not follow any specific order, hence can be applied independently from each other and individually cause improvements. The recommendation is however to consider and apply all guidelines when improving the CMS prototype since they are based on findings from that specific prototype.

Situation Related Guidelines

SG1: The user performance and experience should primarily be improved in the driving situations of changing lane, performing overtakings and driving in roundabouts. These situations are experienced as the most difficult ones, and the reasons for that should be evaluated more in detail.

SG2: The sideview FOV should preferably be dynamically changed between the different driving situations.

- Slightly wider when changing lane, performing overtakings and driving in roundabouts
- The sideview displays should continue to cover a vertical FOV farther down vertically than a mirror as they do in the prototype during parking situation

SG3: Changes that are made to optimize the user performance for changing lane, performing overtakings and driving in roundabouts should consider and not compromise the user performance when driving in other scenarios. This is important to keep in mind since different scenarios could benefit from settings that are contradictory towards each other.

Technical System Improvements

SG4: The CMS displays should remain turned on some time after the car is turned off. Shutting the displays off immediately reduces the user's ability of perceiving the surrounding when exiting the car which could reduce safety.

SG5: The CMS displays should light up less during dark conditions, and preferably adjust to changes in lighting automatically. The current light intensity in the CMS prototype causes distractions from the direct vision for the user, which is straining for the user and could decrease safety.

SG6: The surface of the displays should not be reflective. Reflective display screens provide two images to focus on; the displayed image and a reflected image, and during certain exterior lighting condition this can prevent the user from perceiving the displayed image at all, which decreases safety. Perceiving the reflected image instead of the displayed image is furthermore frustrating from a user perspective.

SG7: The user should access direct vision through the rearview window. The user is adjusting to CMS and needs direct vision accessible initially to better understand how reality is translated into the displayed images.

Integration with Support Systems

SG8: BLIS warnings should be integrated into the CMS system. There are still uncertainties regarding if the indirect vision in the CMS prototype covers all blind spots, and users want the assurance of detecting objects by maintaining BLIS warnings in the system.

SG9: A visual support system (preferably 360 or parking camera) should be mandatory when choosing CMS in the car. The current solutions in the CMS prototype are not providing enough information to maintain the user performance in parking situations only using the information displayed on the CMS screens.

Display Size & Placement

SG10: The distance between the closest display (the left hand sideview) and user's eyes should remain the same or at least not be significantly smaller in the prototype car. Reducing the distance significantly will increase strain on the user for accommodating between the direct and indirect vision.

SG11: The size and shape of the sideview and middle display should cohere greater. Preferable ways of improving this is to:

- *Increase the overall size of the middle display.* Users perceived the current VIRM size as too small.
- *Decrease the height of the sideview displays and/or increase the height of the VIRM*

Displayed Images

SG12: The distance perception should be increased for the middle rearview display, suggestibly by using the parameters described in Table 11. The difficulties are experiences as very much decreased in the prototype car compared to mirrors.

SG13: The system should provide the user with a greater mapping between the surrounding and the images provided in the screens. In the current prototype the mapping is not sufficient to understand where the images are located in the real world, especially not for the middle rearview image.

- *The horizontal FOV for the middle display should be decreased.* There is no need for it to overlap the sideview mirrors to the high extent as it currently does. The fact that it does decreases the mapping ability between the images and where they are located in the real world.

SG14: The images provided through the sideview respectively middle display should provide images that harmonize better regarding level of magnification and object size. Lack of harmony decreases the user's ability of knowing what provided info should be prioritized.

- The image in the middle rearview display should be less zoomed in, in relation to its current size.

SG15: The quality and resolution of the sideview respectively middle displays should harmonize better. The sideview display resolution should preferably be adjusted towards the quality and resolution of the middle display since it was favored among the users.

8.3 Reflection

In this subchapter, the aim of summarizing the findings from phase I, II and III are discussed as well as the guidelines, both in more general and specific terms.

8.3.1 Summarizing the Findings from Phase I, II & III

The summary of the findings from phase I, II and III was made to provide and an overview of what design parameters that could affect the user performance in CMS and how the researched ones affect it. As mentioned in the introduction, lots of knowledge regarding some parameters' impact were known, but it was difficult to put the findings in relation to each other, making it difficult to implement them when designing a new system. By summarizing the findings and expressing them in the same format and by not using project-internal references, the findings have become more accessible for designers or anyone who would benefit from understanding the overall impact on user performance by adjusting one or several parameters.

This summary was also a necessary part of the process of developing the guidelines since an overall view of the findings and their relation to each other was the first step of developing them.

8.3.2 General Guidelines

One important thing to keep in mind is that the general guidelines for designing CMS should not be seen as the optimal way of designing the system, nor as the only way of doing it. The general guidelines are suggestions for how to work within the rather unexplored area of implementing CMS in cars, that are based on the information currently available regarding the subject. When working with and researching more parameters that impact the user performance of CMS, people within the car industry will have increased knowledge regarding them and how they relate and work in relation to each other. When more knowledge is present, it might hence be preferable to work in another process than described in these guidelines when developing and designing the CMS system.

The order of the guidelines is recommended to follow, as previously mentioned. If one chooses to not apply all the guidelines in the list, they would still be applicable one by one. Preferably, all guidelines should be used together, but for different reasons it could be necessary to skip one or another in some applications. It is easier to use all of them, as they are designed to fit together, for increasing user performance. Many of the guidelines includes decision that inevitably must be taken when designing CMS, and one might as well apply the knowledge provides in the guidelines then. In those cases, it is difficult to see why one would choose to take an uninformed decision over an informed one.

The first general guideline (GG1) could be interpreted in different ways. To decide what is the most optimal user performance is a rather specific issue. For some it could be to reduce the number of glances to the displays simultaneously as others might find that reduced detection time is the definition of enhanced user performance. This difference in aiming for different user performance is therefore important to consider, and thereby follow the GG1 to create an understanding of what to strive for in each specific case. It is relevant to make a conscious choice about what to strive for and from that consider the other guidelines.

Regarding the guidelines concerning the displays (GG2-GG4) it is relevant to distinguish what to strive for. It could be interpreted as the displays are to be placed as close as possible to the line of sight, though it might not be as effective in all use situations. There are other aspects to consider when deciding screen placement, such as letting the user get used to the placement and CMS in general, before making radical changes of the display placement. Furthermore, the optimal placements could be interesting to have in mind when planning for the future, and to incorporate changes when the time is right as users become more familiar to the system. Another aspect to consider would be to understand what would happen if the displays are placed too far from the line of sight. If this makes the placement worse, then worse than what? A worse display placement could still enhance the user performance compared to the conventional mirrors. Therefore, it is appropriate to keep in mind what the aim of the placement's impact is.

Regarding GG5, the relationship between screen size, magnification level and FOV is rather complex. The proposed order to decide them are based on the literature study and user test 1. The

benefits of choosing the proposed order are to put the user performance in focus. Seeing enough FOV is highly relevant since, otherwise it would not be possible to have a basis for analysis of what is detected. In second, it is relevant to decide the level of magnification of the displayed images to be able to make longitudinal distance estimations in a preferred way. Lastly, the screen size will be decided, to fit the interior of the car and mostly to match the predefined FOV and magnification. If one were to decide the screen size, magnification and FOV in other sequences than the recommended, it could potentially lead to worse user performance. When propitiating to achieve a preferred placement of the screen, it could trade-off the FOV, which would not be beneficial at all.

In GG6 it does not matter in what order the longitudinal placement of the sideview cameras are placed. Though, it might be relevant to take the car as a reference point into account. Regarding the manufacturing point of view, it would perhaps be beneficial to decide the longitudinal placement of the sideview screen a bit early anyways, to let the car body integrate the features. Therefore, it might be necessary to be flexible to adjust it after some other parameters have been chosen. The GG6 was placed in the order due to that it was considered necessary to decide vertical and longitudinal placement of the camera together.

In GG7, a reference point in form of seeing a part of the own car, is considered as beneficial. It is not completely necessary but recommended. The FOV and other aspects might not be changed in a positive way by having a vehicle reference, but it would provide advantages and a higher degree of freedom when deciding other parameters' settings, which could be beneficial. GG8 is the opposite to GG7, since it concerns the situation of not choosing to have a reference point. One aspect of this is that it might be beneficial in some cases to have a reference point and some not. Not having a vehicle reference in the screen would imply that there are several parameters that are adjustable, which might be beneficial in some cases.

When discussing GG9, it is not known whether the sideview display findings can be implemented on the VIRM. When comparing these two cameras, there are different angles and vertical placements of them, which might lead to differences in perception even though other settings are set to be the same. This makes it unknown whether it is possible to draw the same conclusions about them both, when just investigating one camera type. Therefore, it would be beneficial to differentiate the two camera types at this point and draw conclusions for each of them separately.

GG10 and GG11 discuss the image quality and update rate, and state that increasing those parameters will increase user performance. It is possible to interpret it as the user performance will increase linearly to these parameters, but most likely it will only have a significant effect within a certain range. The message of these guidelines are therefore not that the image resolution and update rate should always be as high as possible, but rather that a minimum level will be required and necessary to reach a certain level of user performance, and that these parameters will affect it.

Regarding GG12, it is difficult to distinguish exactly how pictorial depth cues works, though the important information from it is that it is possible to direct the drivers' attention by using the

cues. These cues are suggested to be used last in order according to the list of guidelines, mostly because it can be an add-on functions to enhance some aspects in the displayed image. Therefore, it is highly relevant to use these pictorial depth cues in this stage to compensate the perception caused by the previously decided parameters, to enhance the user performance.

8.3.3 Guidelines for Improving User Performance in the CMS Prototype

The guidelines that were developed for improving the user performance in the CMS prototype are based on user test 2. The test provided guidelines for improving the user performance based on the specific prototype, and all guidelines should be considered to increase the user performance as much as possible, even if the guidelines can be used successfully individually as well. It is however important to clarify that these guidelines are developed from insights of only five test participants, and it should therefore be considered that it might not correspond to most the people's preferences.

These guidelines should furthermore not be applied directly by any other developers of CMS than the ones that developed this specific prototype, since they are the only ones with control and knowledge of the whole layout and design. It can and should however be used as inspiration by anyone regarding what works better and worse in the context.

Many of the guidelines for improving the user performance in the CMS prototype are very specific and straight forward, and it is easy to understand what they derived from by using Table 19 in Appendix J. There are however some that could use some clarifications. One of them is SG4, stating that the displays should remain turned on some time after the car is turned off. This function is however already regulated in UNECE Regulation No.46 (UNECE, 2016), so this should not be a problem in a legal CMS integration. Even if this would not be an issue when following the regulations, it is still interesting to clarify that this did in fact affect the user performance, since this connection is not obvious when reading the legal regulation.

Continuing, the reason why SG7 suggests that the user should access direct vision though the rearview window is simply because that there most likely will be a transition for the user switching from mirrors to CMS cars. The need of being able to look out rearward through the window was also strengthened from findings in user test 1. This guideline does not oppose closing the rear sight of the CMS cars in the future but rather suggests what the initial step of that evolution should be, taking user performance and experience into consideration. This reasoning is also part of the background of SG8 and SG9, since integrating the support systems might be a necessary transition into CMS since the users tend to distrust the system more than when using mirrors. Integrating the support systems could decrease that feeling by also providing information in a way that the user is used to and knows how to use to a higher extent.

Finally, guideline SG10 and SG11 regard the size and placements of the displays, which is highly interesting since the CMS affects the interior design of the car to a high extent. Since the user performance and experience when driving is affected by those design decisions as well, it is important to keep in mind which concepts work better or worse from a user performance perspective when making them.

8.4 Conclusions

Phase IV consisted of first summarizing all findings about the parameters into tables from phase I-III, which were presented and easily compared. From the summary in the tables, guidelines were created to further enhance the user performance of CMS. They were created through analyzing the parameters' effect on the user performance, and then iterated and expressed in the shape of guidelines. The guidelines are divided into general guidelines, which concern CMS overall and provides input in how car manufacturers should prioritize and work with the parameters to enhance the user performance of using CMS. The second type of guidelines were the specific guidelines, which are directed towards improving the existing prototype car. Though, they are relevant for other cases as well, apart from the prototype car since it includes useful information about enhancing user performance.

It can be concluded that the designed guidelines are to be considered when designing CMS in cars with user performance as focus. The general guidelines are meant to be used as a coherent collection in the presented prioritization order but would still be applicable by using some chosen ones as well, but to a lower degree. The specific guidelines for the prototype are also meant to be used all together, though still possible one by one. There is however no prioritization order for the specific guidelines. The sources of each guideline are structurally shown in the tables in chapter 8.2.1. This provides a clear overview of the origins of each guideline if deeper knowledge is needed.

9 OVERALL DISCUSSION

In this chapter, an overall discussion of the project is presented. The concerned areas of the project are the fulfillment of the aim and deliverables, the thesis process, consequences of the project and recommendations for future work.

9.1 Fulfillment of Aim & Deliverables

The aim of the thesis was to identify the parameters that play a role for the user performance when using CMS for rear- and sideview indirect vision, define how they can be altered to increase the user performance and to deliver guidelines of how to apply that knowledge in further development of CMS. The parameters have been identified as well as the impact researched ones have on user performance, hence fulfilling the first deliverable. User tests have also been conducted to evaluate the impact two VIRM parameters have on user performance, as well as for evaluating and understanding what should be improved in the CMS prototype to increase the experience using it. The second and third deliverable have hence been fulfilled. Guidelines for how to approach the design process of CMS as well as for improving the CMS prototype have also been delivered, hence fulfilling the fourth deliverable and in total also reaching the aim.

9.2 Process

This thesis work has included several ways of collecting knowledge. Knowledge that covers both an overall view of what is important to consider when designing CMS and how the user can be affected by using different means, but that also have deep dived into more specific areas to contribute with further knowledge that is meaningful to the car industry. The area of designing CMS with regard of user performance turned out to be rather unknown, even if some professional research sure has deep dived into some highly relevant aspects of it throughout the years. To find that documented work while navigating through a so far poorly recognize field was demanding, but very lucrative when those findings were made. That knowledge was often very described on a very high level, making it difficult for novices to perceive the implications of them, which strengthens the cause of this work.

Initially, the idea was to also use literature to define what good user performance is when driving and what is important in different driving situations. Surprisingly, this was a rather undocumented subject (most likely since driving is such an old sport that hence is obvious to the general person), which is why these subjects ended up being explored using other methods. The process of performing interviews with experts at Volvo Cars filled this purpose well, and eventually these findings were also supplemented by documentation from legal regulations for CMS.

The interviews worked well for exploring what parameters could affect the user performance when using CMS. This approach was used since the project had not yet come across any documented compilations of that in the early stage. Later in the project, similar findings were encountered, but they were not as elaborated as the ones that were found by the help of the experts and a compilation was still necessary to summarize them with findings from other sources. One thing to point out regarding the overview of the parameters and driving situations is that it is possible that the findings in this thesis did not generate exactly all parameters that are relevant to consider when designing CMS with this angle. Discovering or realizing others should therefore be seen as additional parameters and driving situations, as this work does not exclude that other ones are definitely insignificant. The findings in this thesis should hence be seen as the initial start of providing an overview of how to design CMS with regard of user performance, but

that preferably could be explored and iterated further for greater and a more extensive understanding.

Looking back at the process, it is easy to say what should have been done differently to improve the project. One of these things would have been to document the literature findings encountered at an early stage since that would have facilitated the later part of the project by not having to go back as much and interpret and make the same realizations all over again. But on the other hand, the angle and more specific aim of the project were determined rather late in the project, and back then the prioritization was to get the overall picture to understand what was important for the following work.

The HTA:s and FMEA were important parts of the project to understand where further work was needed, and hence necessary methods for progressing with the work. The most important thing from this part is to keep in mind that the prioritizations made from them are mainly based on our personal experiences and estimations, why someone else might judge some situations differently, but this has already been discussed in chapter 6.4.

User test 1 was performed to fill in knowledge gaps lacking in previous literature. Unfortunately, these findings were not completely univocal, and as more previous work was discovered, it also turned out that not all findings agreed with each other and that lots of research had been performed in different contexts. This made it difficult to draw conclusions regarding some parameter's impact on distance perception. In the future, it might be preferable to clarify earlier on what the specific context of which the user test should take place in to contribute more to the overall findings. In user test 1, the realization was also made that the explored context of testing the parameters might not have been the most critical ones. For example, the short-distance test explored distance estimations during reverse driving, but in a real situation support systems such as parking- and 360-view camera would probably be integrated in a car with CMS system, making this situation less useful for the context of CMS. These findings are however still interesting considering if CMS could also replace those systems. The process so far was hence relevant and necessary to provide general level information regarding CMS for the industry.

To continue the work with improving CMS from a user perspective compared to where Volvo Cars currently are, it was also meaningful to perform user test 2, as it provided insights of what worked well and not for their prototype. One thing that could have improved the outcome of the study would be if the tests had contained more participants since that could have increased the reliability as well as the ability of seeing patterns in their opinions. Due to the Covid-19 pandemic however, the number of people able to attend the tests was limited, and the tests were designed considering that, which in the context provided valuable information.

Developing design guidelines on a general level that should be applicable for anyone independent from the system was challenging. Perhaps primarily since the purpose of them was rather unspecified for at least half of the project, but also since many of the parameters involved in the user performance in CMS depend on each other and therefore must be determined in relation to each other. The guidelines however did come together nicely, and even if they could be more specific, this was the most relevant way of describing the general process of which that

the design process should be carried out considering the user performance. The guidelines will hopefully facilitate the work within car industry by helping people navigate and provide them with a roadmap that hopefully gives them an understanding of how the parameters fit together. That, in combination with the summary of adjustments the parameters cause regarding user performance, will hopefully decrease the take-off distance for designing CMS and enable making well informed decisions.

9.3 Consequences of the Project

The exact impact of the project is difficult to say, but some assumptions can be made. Regarding Volvo Cars' usage of the project, the report and project will provide a wide basis for further investigation of CMS. A broad area within CMS are covered in the report, even the parts are explored on different levels. Some guidelines are specifically pointing to areas for further research, such as the ones in Appendix K. The report therefore points towards where knowledge gaps in the area are located. If the user experience of the prototype car is to be enhanced, there are some clear guidelines that are rather specific regarding what would lead to improvements in the future versions. From the enhanced prototype car, a more realistic car is provided to perform tests on for further analyses.

The report can further be used by Volvo Cars as a short cut to the most necessary aspects regarding user performance of CMS and be guided in how to design CMS and in what order parameters should be considered. Therefore, time and effort are saved which leads to faster decision making. The focus of the project has been distance estimation, control and object detection of the indirect sight using CMS. This implies that there are a few more findings to collect concerning that area, which are highly relevant to consider in a future.

The car industry in general might benefit from this project in the same way as Volvo Cars does, except from the specific guidelines concerning the prototype, which might not be relevant for others to consider. The report could be used to enhance user performance when using CMS for every existing car manufacturer. The findings and guidelines that are presented can make a difference for the industry to a relatively high degree since it explored features that are rather new on cars. Some car manufacturers may have investigated the concept of CMS for a longer time, while some others might not. This project might however provide input to the car manufacturers regardless of at what stage of the development process the manufacturers currently are at. In a further future, this work could hence potentially have contributed to a more user friendly design of CMS.

Lastly, a few ethical, sustainable and societal consequences of the project should be addressed. One of the driving forces for replacing rearview mirrors with CMS is to reduce energy consumption by making the car more aerodynamical. This aspect is however contradicted by the aspect of simultaneously using more electrical components when implementing CMS. The traditional rearview mirror consists of glass with a surrounding cowl which is rather simple and offers passive functionalities. Because of the big cowls and the area that it takes up along with the cowls' placement, replacing the rearview mirrors with CMS will lead to less aerodynamical resistance. CMS however relies on displays, cameras, wires and processing units, creating a higher demand of electrical equipment. The environmental benefits of

replacing mirrors with CMS hence is tradeoff between material increase and fuel consumption decrease, which is important to remember when debating environmental impacts of replacing mirrors with CMS.

One can also consider the economic and societal aspect of developing a car with more complex and expensive components, since it could raise the prices for owning cars and hence decrease the number of people being able to afford owning one. This could however also lead to more people sharing cars and using mobility services and utilizing the available cars to a higher extent would of course be good from an environmental perspective. But the reason for changing people's driving behaviors should perhaps preferably be the effect of them wanting to do so, and not because of being left with no other alternative.

Another aspect is the increasing usage of screens in people's everyday life. Replacing traditional mirrors with screens increasingly exposes the user to harmful blue light which in turn could lead to retinal cell death and age-related macular degeneration. (Boothe, 2016). It is also important to consider the higher level of complexity with more high-tech products, that might not be suitable for all users, making it more difficult for some people to use the cars. Another aspect should be considered is that replacing mirrors with CMS could cause a change of safety when replacing the tool that has been used for indirect vision for decades with something very different. The car industry is however very aware of some of the problems this might pose on safety, and this thesis could arguably be seen as a receipt of that since companies are eager to find out what affects the user performance when using CMS. Since this thesis sorts out just that as well as explains where there are knowledge gaps are that need to be covered by future research, this work will help to design CMS that enables at least as safe cars as when using rearview mirrors, and possibly – even safer!

9.4 Future Work & Recommendations

The project could impossibly concern all aspects to a sufficient extent that it covered everything regarding the area of CMS. Therefore, there are several aspects that are worth investigating further, that were not explored in this project. The following described future work can be derived from different parts in the project, see Appendix K for the exact origin.

One interesting area would be to evaluate what impact spatial orientation aids could have on distance estimation, for different concepts and over longer periods of time. In the study conducted by Van Erp and Padmos (2003) they found that using spatial orientation aids, in form of indicating the exact distance from the bumper to the transverse line, did not have any significant impact on the ability of estimating distances. According to the authors, the test participants might have needed to try the system for a longer time for it to have an impact, or that other cues could have dominated this tool in the image. This implies that there are more to investigate within this area.

Another interesting aspect found from the literature study and user test 1 was that magnification levels' effect on user performance are still not completely certain. Some studies investigated different magnification levels but ended up with different results. What is missing so far is to evaluate the impact magnification has on distance estimation, for the magnification range between 0 and 2.0 and in the most critical use situations, such as reverse driving, roundabouts,

intersections and performing overtakings. Many reports exploring the magnification level's impact on distance estimation mention different optimal levels, because they have tested them in different contexts. Some authors of the literature mention that one must look at each case since the optimal level will differ from case to case. When performing the user tests in this thesis, only zoom level 2.0 and 2.5 were investigated, because of test equipment limitations. In that regard, it would have been interesting to perform similar tests, but for a larger span of magnification levels, such as below 1.0. Furthermore, to investigate how different levels of magnifications do affect the user performance in different driving situations, such as the critical mentioned ones, but also in others would be relevant.

To conduct further research and evaluate what parameters or functions can be used to optimize the object detection ability, using CMS in all types of weather and light conditions would also be interesting. This has not been selected as a scope in this project but was found to be a knowledge gap worth filling. It was not selected as a focus in this thesis since it is demanding and difficult to perform user tests in a real environment with constant weather and light conditions for each of the participants. Though, for future research it is still a field that needs to be considered to make CMS perform as well as mirrors in that regard.

When performing user test 2, it was found that it would have been interesting to investigate the impact of CMS on the user performance after a longer time of using the system. The participants were all novices to driving the prototype car and to CMS in general, which might have affected the user experience and performance of the participants when performing user test 2. To investigate the participants performance after learning to drive with the system would therefore contribute with other findings, which could be explored further. To perform tests on people not used to driving with either systems, such as beginner drivers, could also be an idea of better comparing the user performance of mirrors and CMS.

Another guideline for future work is to investigate at what distances between the users' eyes and screens that accommodation problems occur. It was not structurally tested in any user tests, but some participants experienced issues focusing on distances closer to the eyes compared to mirrors. This would have been interesting to investigate further, since difficulties already after only half an hour of usage in the tests. What would the effect be using screens that are too close to the eyes during a longer time period? Does it affect the user performance or the human health perhaps?

A last future work recommendation regards the FOV. During the project the discussion was brought up regarding how large the FOV should be to optimize the user performance with focus on distance estimation. Though, is it possible that a wider FOV in some cases provides FOV large enough to overload the driver with unnecessary information about the rearview? This is an aspect that was not investigated in this project but that would be highly interesting to gain knowledge about before implementing a wider FOV, since that is one of the benefits with implementing CMS.

10 OVERALL CONCLUSIONS

In this chapter, the overall conclusions of the project are presented.

This master thesis explored how to design CMS in cars to enhance the user performance, by investigating design parameters and driving situations that might affect it. The deliverables were to present a list of parameters that affect the user performance of the indirect vision when using CMS, a list of how known parameters impact user performance and to also deliver design guidelines of how to design CMS to enhance the user performance on both a general level and a CMS prototype specific level.

Twenty-one different design parameters were established that affect user performance when driving using CMS. Furthermore, 10 different driving scenarios were identified that are important when designing CMS in cars, namely parking, driving through intersections, roundabouts, changing/merging lane, performing overtakings, turning, reverse driving, forward driving, exiting the car and communicating with other people. The FMEA and expert interviews showed that among these scenarios, the most critical ones were reverse driving and driving when a vehicle approached from behind, which is why the parameter user test examined those scenarios.

The literature findings led to insights regarding different parameter's impact on the two user performance aspects perceiving distance as well as detecting object and maintaining overall control of the driving situation. The longitudinal distance perception is affected by the vertical camera placement, the presence or lack of a vehicle reference in the image, magnification factor, resolution and image update rate, the interaction between the vertical camera placement and FOV/magnification level and the available depth cues in the image. The interaction of the vertical placement of the sideview camera and the horizontal size of the FOV does however impact the lateral distance estimation. Design parameters that do not affect longitudinal distance estimation is the longitudinal placement of the sideview camera, the horizontal FOV and the distance between the driver and the displays.

The design parameters that affect the ability to detect objects and maintain control in the driving situations are the vertical and horizontal placements of the displays, the horizontal FOV, the presence or lack of a vehicle reference in the image, the resolution and update rate as well as the distance between the driver and the displays. This user performance aspect is however not affected by decreasing the number of displays on which the CMS images are portrayed.

A combination of what was the most interesting and feasible to carry out using the available CMS prototype narrowed the scope down more regarding what to explore further. A parameter study exploring the impact that the vertical camera placement and zoom level, as well as the interaction of the two parameters had on distance perception for the two most critical driving scenarios was conducted. The results showed that higher vertical camera placements for the VIRM makes the user perceive distances as shorter compared to at lower placements. It also showed that higher zoom level at higher vertical camera placements caused shorter distance estimations compared to the lower zoom levels. An overall user test was also performed to understand how the CMS prototype should be developed to increase the user experience driving with it, covering all encountered user performance aspects of CMS.

The thesis resulted in twelve general guidelines aimed for car manufacturers about to design CMS to enhance user performance. These general guidelines are presented in a prioritization order to optimize the design process and are arranged on the five categories *defining the aimed user performance, display layout, magnification level and FOV, camera placements and image quality*. It also resulted in 15 specific guidelines for how to improve the user experience of the CMS prototype, arranged in the five categories *situation related guidelines, technical system improvements, integration with support systems, display size & placement and displayed images*. The aims and deliverables of the thesis were thus fulfilled.

Lastly, the report suggests areas for future work based on findings made along the project. There is a need of performing a more comprehensive research covering the magnification factor, FOV and screen size's separate impact on distance perception. It is also recommended to evaluate these parameters for a wider range than what has previously been, as well as in dynamic driving contexts. Another interesting area to research is the FOV's effect on other user performance aspects than distance estimations, since increasing more and more it potentially will cause problems detecting or distinguishing objects in the image. Finally, the impact that other concepts of spatial orientation aids (than what previously have been researched) could have on distance estimation and object detection should be explored further.

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APPENDICES

Appendix A – Mindmapping

In this appendix, the results from the mindmapping session is presented. Each driving situation has a unique color and the bullet points below the heading answers the question: “What is important for the vision in the different driving situations using either mirrors or CMS?”.

Parking

- Distance to surrounding objects
 - Mirrors
 - Dimensions of side- and rearview mirror
 - Distortion
 - Placement of side mirrors (dept)
 - Placement of rearview mirror (height)
 - CMS
 - Most general parameters but mainly:
 - Placement of cameras
 - Zoom
 - Distortion
 - Coherence between different displays
- How you approach other objects
 - Mirrors
 - Distortion
 - CMS
 - Most general parameters but mainly:
 - Placement of cameras
 - Zoom
 - Distortion
 - Coherence between different displays
- Where are the car's corners, wheels and most outer points (dragkrok, bumpers)
 - Mirrors
 - Placement of sidemirrors
 - Dimensions of side mirror
 - Distortion
 - Reference point (corners, wheels & outer points)
 - CMS
 - Placement of camera
 - Reference point (corners, wheels & outer points)
 - Dimensions of the displays
 - Distortion

For all scenarios

- What is behind
- What is in front
- What is on the sides

General parameters:

Inte precis liknande men en generell

- Switching between forward and backward view
 - Mirrors
 - Varying between forward and backward accomodation (basically no difference)

CMS

- Accommodating between near and far sight

- Swithing between side and front view

Overturns in opposite direction

- Detect object in front of you moving towards you
 - Mirrors
 - Size of mirror cowls and A- & B- pillars
 - CMS
 - Size of camera houses and A- & B- pillars
- + The rest of overturns in same direction/switching lanes

Stepping out the car

- Object detection in side/rear
 - Mirrors:
 - Dimension
 - Distortion (important to detect, but not what it is)
 - CMS:
 - Reference point (car)
 - All general but especially:
 - Fps
 - Distortion
 - Dimension
- Estimate moving cars' speed towards you
 - Mirrors:
 - Distortion
 - Placement (height)
 - CMS
 - Placement of cameras (height)
 - distortion
 - Shifting focus from display to rear
 - All general

Turning (and driving across a pedestrian walk or bike lane)

- Detect objects (pedestrians and bikers) on side and side/rear
 - Mirrors:
 - distortion
 - Dim. (width)
 - Clear view when turning your head
 - CMS:
 - All general but most:
 - Distortion
 - Display dim. (width)
 - Placement of cameras (preferably more in front)
- Detect object front/side (behind mirror and a-pole)
 - Mirrors:
 - Dimension of mirror and cowls (height and width)
 - CMS:
 - Dimensions of camera housing
- Estimate shorter distances
 - Mirrors:
 - Dimensions of mirrors
 - Placement of mirrors (dept, height)
 - Distortion
 - Reference point
 - CMS:
 - Most general parameters but mainly:
 - Zoom
 - Placement of cameras
 - Distortion
 - Reference point
- Estimate lower speeds of objects
 - Mirrors
 - Dimensions of mirrors
 - Placement of mirrors
 - Distortion
 - Reference point
 - CMS:
 - Most general parameters but mainly:
 - Zoom
 - Placement of cameras
 - Distortion
 - Reference point

If left turn:

- Estimate longer distances and speed to objects in front
See breaking section n

Driving in reverse (faster)(open field)

- Detect objects from the side
 - Mirrors**
 - Dimensions (height & width)
 - Form
 - Angle adjustments
 - Distortion (which relates to field of view)
 - Placement (height and depth)
 - CMS**
- See backwards further away
 - Mirrors**
 - Dimensions (primarily height)
 - Placement (height)
 - Shape and size of rear window
 - Transparency of rear glass (dirt, shading)
 - Angle adjustment
 - Distortion
 - Headrest, passengers' heads and luggage
 - CMS**
 - See general parameters
- Determine distance to objects further away backward
 - Mirrors**
 - Distortion
 - Reference point (car)
 - CMS**
 - Reference point (car)
 - And general parameters, especially zoom and distortion.
- Determine velocity to objects further away backward
 - Mirrors**
 - Distortion
 - Reference point (car)
 - CMS**
 - Reference point (car)
 - And general parameters, especially zoom, distortion and fps.
- See the ground behind the car further away backward
 - Mirrors**
 - Height placement
 - Height of mirror
 - The car's rear design (how low is the window)
 - CMS**
 - General parameters

In this scenario it is especially important that the FOV is large.

Driving in reverse (faster)narrow

- Object detection in behind
 - Mirrors**
 - Placement (height) of rearview mirror
 - Dimensions (with and height) of mirror
 - Headrest, passengers' heads and luggage
 - Rearview design
 - CMS**
 - All general but mainly:
 - Dimensions of display
 - Distortion
- See the ground behind (further away)
 - Mirrors**
 - Placement (height) of rearview mirror
 - Rearview design
 - CMS**
 - does not demand much from cms
- Identifying where the wheels are compared to the edge of ground (lane)
 - Mirrors**
 - Placement of mirrors (distance from car, dept)
 - Dimensions (primarily width)
 - Distortion
 - CMS**
 - Placement of camera
 - Dimensions of display
 - Zoom
 - distortion
 - Reference point (the wheels)

Slow down/breaking

- Moving object detection straight backwards, cars detection (middle distance)
 - Mirrors:**
 - Visaility (size) through rear window
 - Dimensions of mirror (height, width)
 - Headrest, passengers' heads and luggage
 - CMS:**
 - All general parameters
- Object detection in other lanes (back half of your car)
 - Mirrors**
 - Dimensions (especially width since it covers blind spot)
 - Placement of mirrors
 - Distortion
 - CMS**
 - All general but especially:
 - Placement of camera
 - Dimensions of display
 - Distortion (related to FOV)
 - Zoom (related to FOV)
- Estimation of distance and velocity on objects behind and other lanes
 - Mirrors:**
 - Distortion
 - Placement of mirrors (especially height)
 - CMS:**
 - All general parameters but especially:
 - Placement of cameras (height)
 - Zoom
 - Fps
 - Distortion

Overturns in same direction/ Switching lanes

- Moving object detection
 - Behind
 - Sides
 - 1-2 lanes away (including blind spot)
- Mirrors:
 - Distortion
 - View angle
 - Dimensions
 - Headrest, passengers' heads and luggage
 - Car rear design (dim window back)
 -
- CMS:**
 - All general but most:
 - Dimension of displays (especially width)
 - Distortion
 -
- Distance estimations to objects
 - Mirrors:**
 - Distortion
 - Dimensions
 - Placement of mirrors (height)
 - CMS:**
 - All general but most:
 - Placement od camera (height)
 - Zoom
 - Fps
 - distortion
- Velocity estimation of objects
 - Mirrors:**
 - Distortion
 - Dimensions
 - Placement of mirrors (height)
 - CMS:**
 - All general but most:
 - Placement of cameras (height)
 - Distortion
 - Zoom
 - Dim of display

Appendix B – P-Diagram Workshop

The findings from the P-Diagram workshop are categorized according to the template in Figure 14, by inputs, noises, function, control factors, outputs and error states.

Function

The function of the system providing indirect vision in cars was during the P-Diagram workshop uniformly determined to:

“Provide user with information about the surrounding (primarily rear and side) environment by using mirrors or CMS”.

Inputs

The inputs of the situation were determined to be the following ones:

- Users driving and maneuvering the car
- Electrical energy
- Data (from other systems)
- Light from environment

Though, it should be mentioned that the first input; *“users driving and maneuvering the car”*, was the most relevant and used through the workshop.

Noises

The noises are categorized according to the method in chapter 2.4.6 on *piece to piece variation, changes over time, external environment, system interaction and customer usage*, and therefore the findings follow the same structure in the following paragraphs.

Piece to Piece Variation:

- Users’ body dimensions
- Users’ visual impairments and corrections when driving
- Users’ accommodation capabilities

Changes over Time:

- Wear out, fatigue
- Dirty mirrors
- Dirty camera lenses
- Driving experience
- Habit of using the system

External Environment:

- Weather (rain, snow, sunlight, humidity, temperature)
- Time of the day (affecting light conditions)
- Road condition (smooth or uneven ground)
- Vibrations

System Interaction:

- Support systems (reverse- and parking assistance, 360-degree bird view)
- Exterior- and interior shape and design of the car
- Luggage usage (sight hindering)
- Other maneuvering and interaction devices inside car

Customer Usage:

- Adjustment of mirror angle
- Variation in sight angle and distance
- Variation in driving position

Control Factors

The found control factors from the P-Diagram workshop can be seen in Table 14 below and are categorized in “*mirror*” and “*CMS*” depending on which system the parameters are relevant for.

Table 14

The control factors according to the P-Diagram workshop.

Mirror	CMS
Shape and size of: <ul style="list-style-type: none"> • Mirrors (height, width) • Cowls 	Shape and size of: <ul style="list-style-type: none"> • Displays • Camera houses
Distortion (relationship between FOV, magnification level & mirror size)	Distortion (relationship between FOV, magnification level & display size)
Placement of mirror: <ul style="list-style-type: none"> • Horizontal • Longitudinal • Vertical 	Placement of displays and cameras: <ul style="list-style-type: none"> • Horizontal • Longitudinal • Vertical
Number of mirrors	Number of: <ul style="list-style-type: none"> • Displays • Cameras
Adjusting range of: <ul style="list-style-type: none"> • Mirror angle • Seating position 	Adjusting range of: <ul style="list-style-type: none"> • Camera angle • Seating position
Reference point	Reference point
Absorbent filter	Display angle
	Latency of screen
	Camera properties (dynamic range)
	Display properties: <ul style="list-style-type: none"> • Contrast • Response time • Color reproduction • Luminance

Outputs

The outputs established in the P-Diagram workshop was that the driver should be able to:

- Detect and perceive objects
 - moving
 - standing still
- Estimate the distance to:
 - approaching objects
 - objects that are approached
- Estimate the speed of which
 - an object is approaching
 - the car is approaching objects
- Communicate (using eye contact)
 - with passengers
 - other drivers (to predict their next move)

Error States

The result of error states in the P-Diagram workshop was divided into *general error states* and *specific error states* to present the findings in a structured way.

General Error States

- Not detecting (at all or too late)
 - object approaching
 - object being approached
- Misjudging
 - the distance to other objects (judging distance as farther than what it is)
 - the speed of approaching objects (judging speed as slower/faster than what it is)
 - the own speed while approaching objects

Specific Error States

Specific error states for using the mirror:

- Disturbance of sight caused by cowls/mirrors
- Blind spot becomes too big and causes danger
- Fog on exterior mirrors

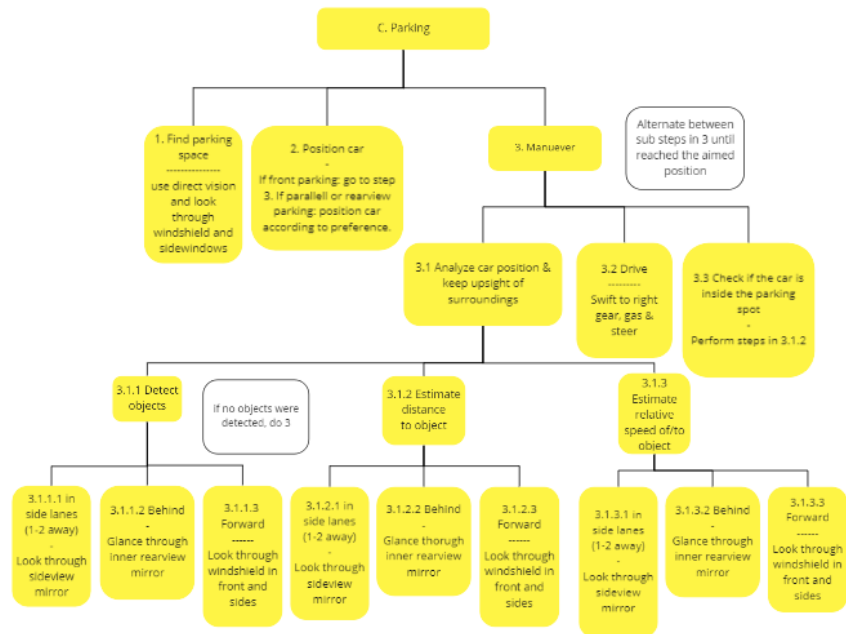
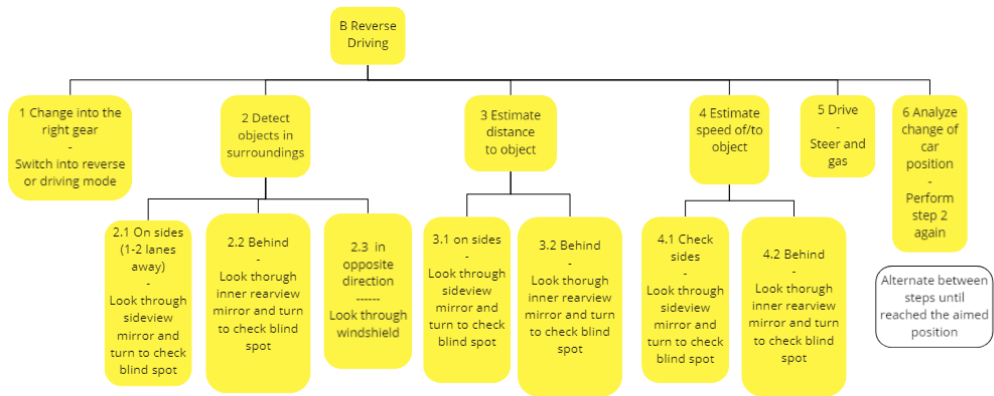
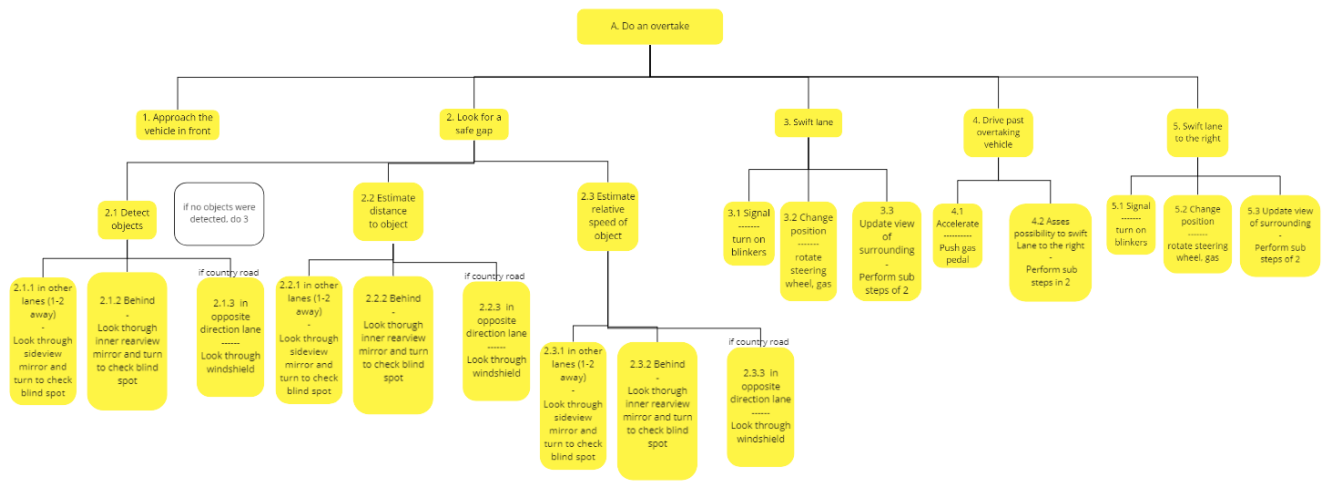
Specific error states for using CMS:

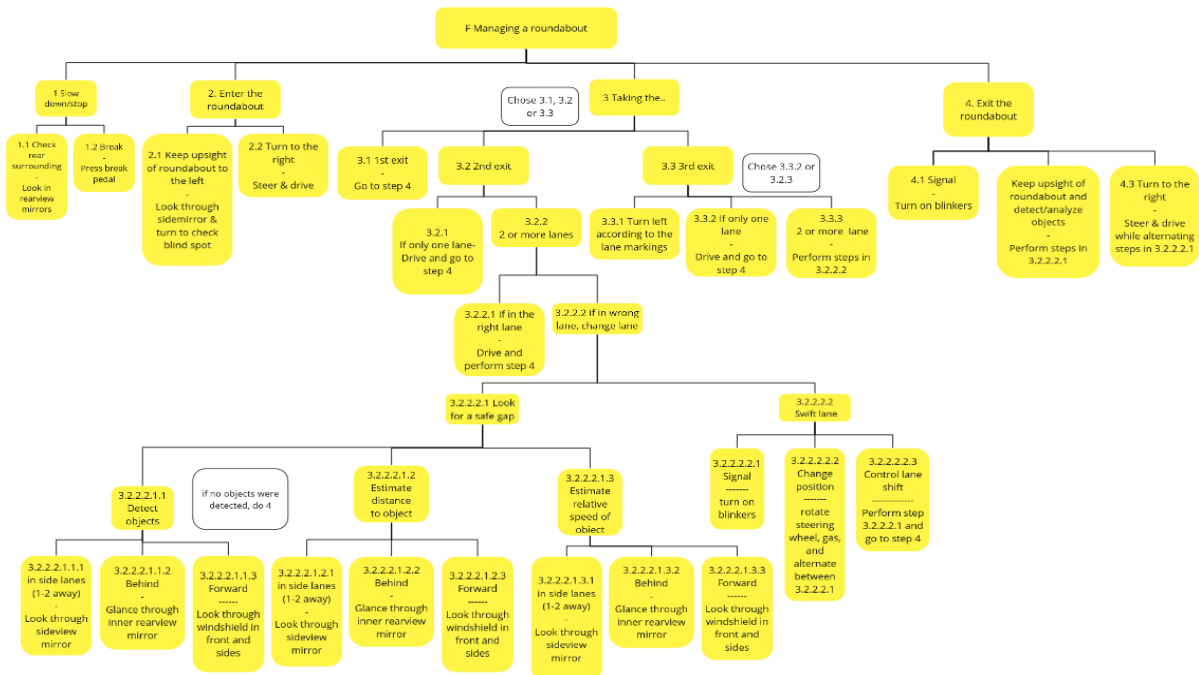
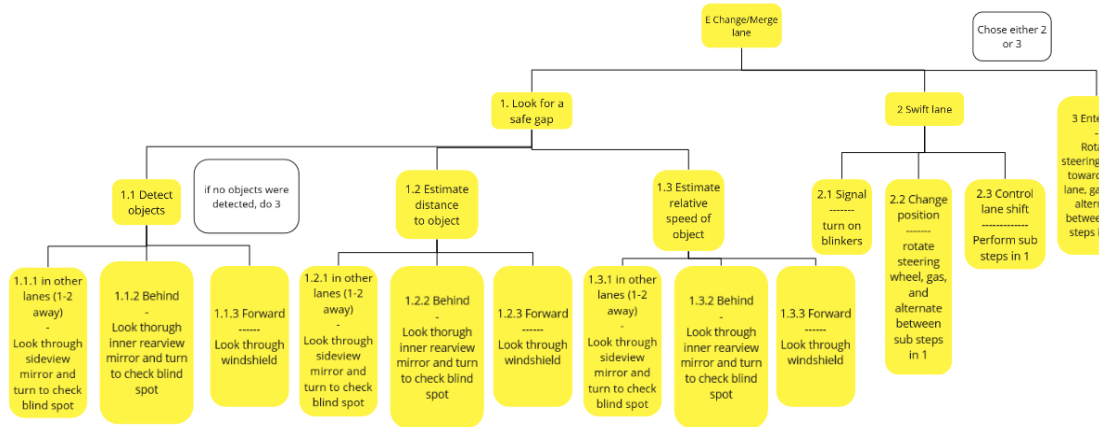
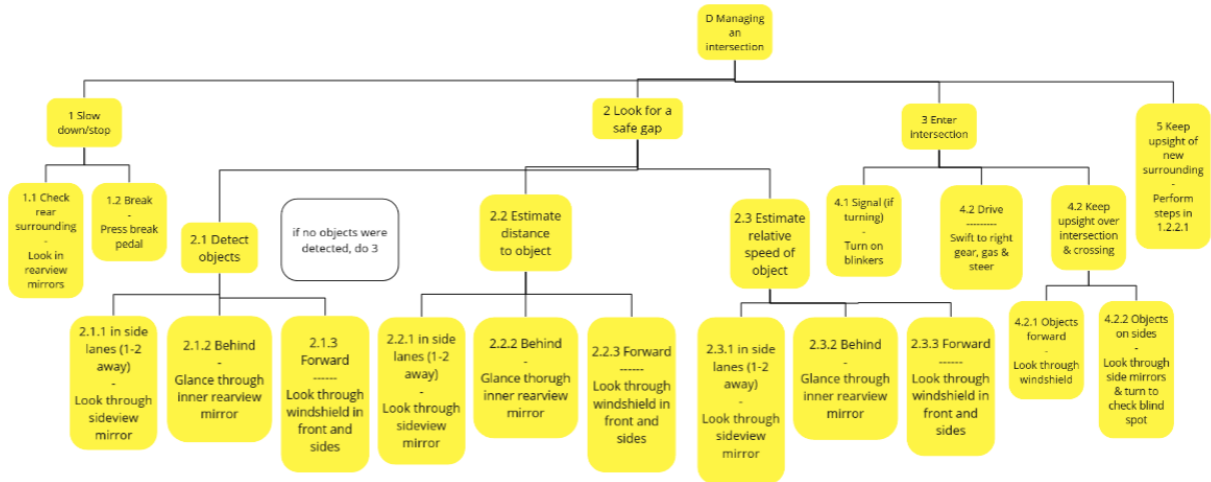
- Blind spot becomes too big and causes danger
- Eyes off road time increases
- Less or no depth estimation
- Decreased depth perception in combination with distortion
 - Decrease of speed perception
 - Decrease of distance perception

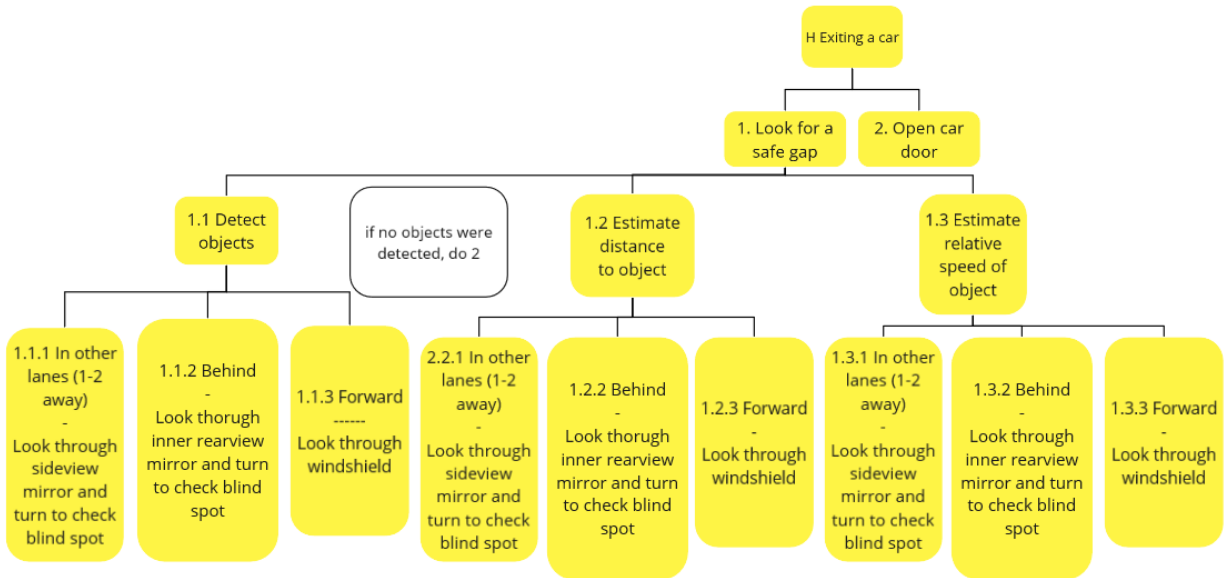
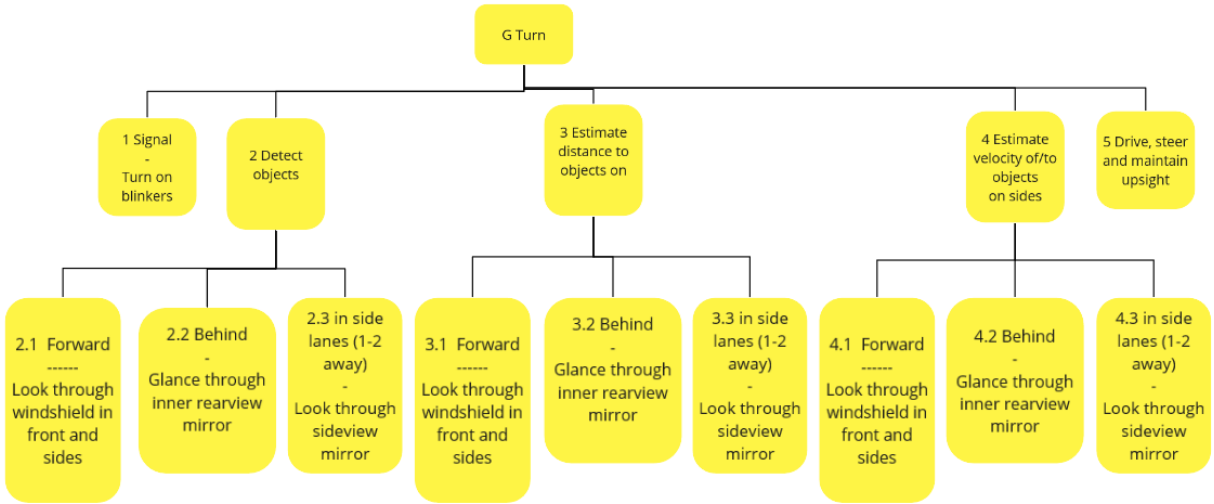
- Thinking objects are approaching faster/slower than what they really are
- Sunlight luminating the screen, making the driver unable to see
- Camera glare affects the display
- LED lights flickering in display (strobe effect)
- Low screen contrast making it hard to view details and see appearing objects
- Not being able to move the head to get better FOV (no eye box), less flexible FOV
- Non-homogenic luminance of screen (luminance non-uniformity)
- Fog on camera
- Difficulties in perceiving image due to vibrations
- Reflection of screens disturbing the direct vision through the windscreen

Appendix C – HTA

In this appendix, the eight produced HTA:s are presented.







Appendix D – FMEA

In this appendix all the steps from the FMEA:s are summarized and presented in the order of the risk priority number (RPN) (Table 15), with the highest score at the top. The colors in Figure 52 are used for coding what driving situation the failure mode belongs to.

	Overtaking		Parking
	Change/merge lane		Managing a roundabout
	Managing an intersection		Entering a new road
	Reverse driving		Exiting a car

Figure 52 – Colors' meaning in the FMEA.

Table 15

The full FMEA.

Process step	Failure Type	Potential Impact	SEV	Potential Causes	OCC	RPN
3.2 Estimate distance to objects behind	Not being able to estimate distance	<ul style="list-style-type: none"> - Distrusting system - Frustration - Need of using a complementary help tool 	5	<ul style="list-style-type: none"> -No depth perception caused by accommodation - Difficult to perceive change of vehicle image from straight angle - No reference point - Magnification - Camera angle 	9	45
3.2.2.1.2.2 Estimate distance to objects behind	Not managing to estimate distance/estimate as closer	<ul style="list-style-type: none"> - Being incapacitated - Being more careful than necessary, causing loss of time - Disturbing traffic - Making dangerous movements 	4	<ul style="list-style-type: none"> - FOV (magnification, distortion, camera angle) - No reference point of difficult to understand it 	9	36
3.1 Estimate distance to objects on sides	Estimating distance as farther than what it is	<ul style="list-style-type: none"> - Bumping into or running over object - Distrusting system - driving off road (crossing lane lines) 	5	<ul style="list-style-type: none"> - Distortion - Magnification - Reference point -No depth perception caused by accommodation 	7	35
3.2.2.2 Change lane	Not being able to keep up sight in all directions while driving in roundabout	<ul style="list-style-type: none"> - being stressed out - being incapacitated - decreased feeling of control - Not being able to detect objects in all directions - Not being able to detect distance and velocity in all directions 	5	<ul style="list-style-type: none"> - Placements of displays - Size of displays - Displays providing contradictory information (different magnification and distortion and camera angles) 	7	35
2.2.2 Estimating distance to objects behind	Not being able to determine distance	<ul style="list-style-type: none"> - Becoming stressed out - Extra careful, resulting in loss of time - Disturbance of traffic flow - Frustration 	4	<ul style="list-style-type: none"> - No reference point, or difficult to understand it - Difficult to perceive change of vehicle image from camera angle straight back - Camera angle -No depth perception caused by accommodation 	8	32

2.2.1 Estimation of distance to objects in other lanes	Estimating distance as farther away than what it is	Changing lane at an unsafe moment	5	- Too much distortion - screen size - Magnification - Reference point -No depth perception caused by accommodation	6	30
3.2.2.2.1.1 Detect objects (alternating between sub-steps)	Not managing to alternate between sub-steps efficiently enough	- Being stressed out - Not managing to detect objects in various directions	5	- placement of displays - Accommodation shift - display size/form	6	30
2.1.1 Detect objects in other lanes (also 5.3)	Not detecting objects	- Changing lane eventhough a vehicle is there, clashing into another car - Changing lane eventhough a vehicle is there, but nothing happens - user becomes frightened - Disturbance in traffic flow	5	- Screen parameters (image resolution, distortion), - - Placement - FOV(how much coverage of field of view, size, magnification, distortion) - camera being blind from dirt or weather. - Distraction caused by information devices competing for attention - Tiredness caused by increased screen time - Vigilance	6	30
2.3 Detect object in side lanes	Not managing to detect objects	- Driving into/over objects - Being startled - Disturbing traffic - Decreased feeling of control	6	- FOV (display size, magnification, distortion, camera angle, interior design, B-pillar design) - display & camera parameters (resolution, contrast, luminance)	5	30
2.2.2 Estimation of distance to object behind	Estimating distance as closer than what it is/not managing to determine distance at all	User misses opportunity to switch lane and loses time	4	- Too much distortion - Magnification - Reference point - difficult to perceive change of vehicle image from straight angle -No depth perception caused by accommodation	7	28
2.3.2 Estimation of relative speed of objects behind	Estimating speed as higher than what it is/ not managing to estimate the speed	Missing out on opportunities to change lane, causing loss of time and irritation	4	-No depth perception caused by accommodation - no reference -difficult to perceive change of vehicle image from straight angle	7	28
1.2.2 Estimate distance to object behind	Not being able to estimate distance	- Being incapacitated - Being stressed out - Frustration	4	- FOV (especially magnification) - Difficult to perceive change of vehicle image from camera angle straight back - No reference point	7	28
4.2 Estimate speed of/to object behind	Not being able to estimate velocity	- Having to use a complementary tool to the display to make estimation - Frustration - Being more careful than necessary, resulting in loss of time	4	- Difficult to perceive change of vehicle image from straight angle - No reference point - Magnification - Camera angle - Distortion - No depth perception caused by accommodation	7	28

3.1.2.2 Estimate distance to object behind	Not understanding where the car back bumper is in relation to object	<ul style="list-style-type: none"> - Backing into an object - Leaving more safety marginal than necessary, causing loss of time - Parking outside the lines or closer to one side 	4	<ul style="list-style-type: none"> - No reference point, or difficult to understand it - Magnification - Camera angle -No depth perception caused by accommodation 	7	28
1.2.2 Estimate distance to object behind	Determine distance as shorter than what it is	<ul style="list-style-type: none"> - Distrust to system - More careful driving than necessary, causing loss of time - Vehicle behind crashing into rear 	3	<ul style="list-style-type: none"> - FOV (especially magnification) - Difficult to perceive change of vehicle image from camera angle straight back - No reference point - No depth perception caused by accommodation 	9	27
3.2 Estimate distance to objects behind	Estimating distance as shorter than what it is	<ul style="list-style-type: none"> - Being more careful than necessary, resulting in loss of time - Irritation 	3	<ul style="list-style-type: none"> - Magnification - Camera angle -No depth perception caused by accommodation 	9	27
3.2.2.1.1.1 detect object in side lane	Not detecting object	<ul style="list-style-type: none"> - Driving into vehicle on the side - Being startled - Decreased feeling of control - disturbing traffic 	5	<ul style="list-style-type: none"> - FOV (interior design, camera angle) -display (resolution, contrast, magnification) - display size, form 	5	25
2.2.1 Estimating distance to objects in side lanes (1-2 lanes away)	Determining distance as farther away than what it is	<ul style="list-style-type: none"> - Driving into vehicle - Negatively surprised - Decreased feeling of control - distrust to system 	5	<ul style="list-style-type: none"> - Distortion - Magnification - no reference point -No depth perception caused by accommodation 	5	25
4.2 Assess possibility to swift lane to the right	User does not manage to determine distance on the right hand side	<ul style="list-style-type: none"> - Changing lane at an unsafe moment (too early) - driving too long in opposite lane (in country road) - needs more margin of safety space to feel secure 	4	<ul style="list-style-type: none"> - Difficulty to perceive image on right display (screen parameters) -Compromised FOV (blind spot) on right hand side 	6	24
1.1.1 Detect objects on sides	Not detecting objects	<ul style="list-style-type: none"> - Colliding with objects - Being startled - Decreased feeling of control 	4	<ul style="list-style-type: none"> - FOV (magnification, camera angle, distortion) - display form and size - Display parameters (resolution, contrast, luminance) - Display placement 	6	24
2.1 Detect objects (alternating between 2.1.1, 2.1.2, 2.1.3)	Not being able to take in information from all 3 directions as fast as required	<ul style="list-style-type: none"> - driving into/over object - decreased feeling of control - being stressed out 	4	<ul style="list-style-type: none"> - Ackommodation problem - mental capacity 	6	24
3.1.2.3 Estimate distance to object forward	Not understanding where the car front bumper is in relation to object	<ul style="list-style-type: none"> - Parking outside the lines or closer to one side - driving into/over an object 	3	<ul style="list-style-type: none"> - Not being able to see the corners of the car - Exterior shape of the car - Interior covering sight forward (but most likely not that much) 	7	21
4.2.2 Keep upsight over intersection to detect objects on side	Not detecting object	<ul style="list-style-type: none"> - driving into/over object - decreased feeling of control - being stressed out 	7	<ul style="list-style-type: none"> - FOV 	3	21
2.2 Detect objects in surrounding behind	Not detecting object	<ul style="list-style-type: none"> - Driving into/over object - Embarrassment - Stopping car 	5	<ul style="list-style-type: none"> - FOV (width, height, zoom, camera angle) - Distortion (if any) - Camera & display quality - Display size 	4	20

2 Detect objects in surrounding (combination of 2.1 & 2.2)	Not managing to keep track of all directions at the same time	<ul style="list-style-type: none"> - Not detecting objects - Decreased feeling of control - Increased stress level 	4	<ul style="list-style-type: none"> - Too many directions to keep in mind at the same time - quick changes of accommodation and adjustment - number and placement of screens 	5	20
2.1 Keep upsight of the roundabout to the left	Not detecting object	<ul style="list-style-type: none"> - disturbing traffic in roundabout - collision with vehicle in roundabout 	5	<ul style="list-style-type: none"> - Disturbed FOV (A-pillar, interior design) - camera house size 	4	20
3.2.2.2.1.2.1 Estimate distance to object in side lane	Not managing to estimate distance	<ul style="list-style-type: none"> - Being incapacitated - Being stressed out - Frustration 	4	<ul style="list-style-type: none"> - Magnification - Distortion - No depth perception caused by accommodation problems 	5	20
2.1.3 Detect object forward	Detecting object late	<ul style="list-style-type: none"> - Becoming frightened - traffic disturbance - stressful situation 	4	<ul style="list-style-type: none"> - FOV (a-pillar) - Accommodation problem 	5	20
4.2.2 Keep upsight over intersection to detect objects on side	Detecting object late	<ul style="list-style-type: none"> - decreased feeling of control - being stressed out 	5	<ul style="list-style-type: none"> - FOV 	4	20
4.2.2 Keep upsight over intersection to detect objects on side	Not understanding distance to object	<ul style="list-style-type: none"> - Driving into/over object - being stressed out - decreased feeling of control -distrust to system 	4	<ul style="list-style-type: none"> - Magnification - Distortion - No reference point or difficult to understand it 	5	20
1.1.1 Estimate distance to objects in other lanes	Estimating distance as farther than what it is	<ul style="list-style-type: none"> - Opening door even though it is not safe yet - Resulting in accident - Being startled 	4	<ul style="list-style-type: none"> - FOV (especially distortion) - No reference point or difficult to understand it - No depth perception caused by accommodation 	5	20
3.2.2.2.1.2 Estimate distance to object (alternating between 3.2.2.2.1.2.1 & 3.2.2.2.1.2.2)	Not being able to estimate distance since information from different sources are contradicting	<ul style="list-style-type: none"> - Distrust to system - being stressed out - being incapacitated - Frustration 	3	<ul style="list-style-type: none"> - different camera angles, magnification, distortion on the respective displays 	6	18
3.2 Estimate distance to objects behind	Not being able to determine distance/closer than what it is	<ul style="list-style-type: none"> - Frustration - Decreased feeling of control 	2	<ul style="list-style-type: none"> - FOV (especially magnification, camera angle) straight back - No reference point - No depth perception caused by accommodation 	9	18
1.1.1 Detect objects in other lanes	Not detecting objects	<ul style="list-style-type: none"> - Objects colliding with opened door, causing accident - Very frightening - Disturbing traffic 	3	<ul style="list-style-type: none"> - FOV (a-pillar, interior design, camera angle, magnification) - Accommodation shift - display parameters (resolution, contrast, luminance, placement, size, form) 	6	18
1.2.1 Estimate distance to object on sides	Determine distance as farther than what it is	<ul style="list-style-type: none"> - Changing lane at a dangerous moment, resulting in collision - Driver is negatively surprised - Distrust to system 	4	<ul style="list-style-type: none"> - Distortion - magnification - size of Display - No depth perception caused by accommodation - No reference point 	4	16

2.1 Detect objects in surroundings on sides (1-2 lanes away)	Not detecting object	- Driving into/over object - Decreased feeling of control	4	-FOV (width & height, camera angle) -Distortion - Camera & display quality - Display size	4	16
3.1 Estimate distance to objects on sides	Not being able to estimate distance	- Distrusting system - Frustration - Need of using a complementary help tool	4	- Distortion - Reference point -No depth perception caused by accommodation	4	16
3.1.1.2 Detect objects behind	Not detecting objects	- Driving into/over an object - Disturbing traffic situation	4	- FOV (width, height, magnification, camera angle, distortion) - accommodation problem - display position	4	16
3.1.2.1 Estimate distance to object on sides	Not knowing where the car tires are in relation to markings on ground	- Parking outside the lines or closer to one side - scratching rims against sidewalk	2	- FOV (width, height, magnification, CAMERA ANGLE, distortion) - no reference point -No depth perception caused by accommodation	8	16
3.1.2.2 Estimate distance to object behind	Not knowing where the car tires are in relation to markings on ground	- Parking outside the lines or closer to one side	2	- No reference point, or difficult to understand it - Magnification - Camera angle - No depth perception caused by accommodation	8	16
3.1.2.2 Estimate speed of/ to object behind	Not understanding the speed of which the vehicle is approaching the object behind	- Frustration - Being more careful than necessary, causing loss of time - Bumping into and damaging objects behind	4	- Magnification - Difficult to perceive change of vehicle image from camera angle straight back - Distortion - No depth perception caused by accommodation	4	16
1.1 Check rear surrounding	Not detecting object	- Object bumping into rear - being startled	4	- FOV (interior design, camera angle) -display (resolution, contrast, magnification)	4	16
3.2.2.1.3.1 Estimate relative speed of/to objects in side	Not being able to estimate speed	- frustration - Colliding with vehicle - being incapacitated - Disturbing traffic	4	- FOV (Magnification, distortion, camera angle)	4	16
	Estimating velocity as slower than what it is	- Decreased feeling of control - Disturbing traffic - Drive into objects - Being startled/surprised	4	- Magnification - Distortion - No depth perception caused by accommodation problems	4	16
2.2.2 Estimation of distance to object behind	Estimating distance as farther away than what it is	User swifts to other lane at the same time as vehicle behind does	5	- too much distortion - Magnification - Reference point - difficult to perceive change of vehicle image from straight angle -No depth perception caused by accommodation	3	15

2.3.1 Estimation of relative speed of object in other lanes	Estimating velocity as slower than what it is	Changing lane at an unsafe moment	5	- Too much distortion - Magnification - Screen resolution - Field of view (including screen size) - No depth perception caused by accommodation	3	15
1.2 Estimate distance to objects	Being confused by taking in contradicting information from different views	- Being stressed out - Not understanding/being able to assess distance	3	- Different magnification, distortion and camera angle on different screens - No depth perception caused by accommodation	5	15
3.1.2.1 Estimate distance to object on sides	Not understanding where the car side body is in relation to surrounding objects	- Scratching/damaging objects - Parking outside the lines or closer to one side	3	- FOV (width, height, magnification, camera angle, distortion) -No depth perception caused by accommodation	5	15
3.2.2.1.2.1 Estimate distance to object in side lane	Estimating distance as farther than what it is	- Distrust to system - making dangerous movements -vehicles behind drive into rear	5	- Magnification (too much) - Distortion - No depth perception caused by accommodation problems	3	15
3.2.2.1.2.1.1 Estimate distance to object in side lane	Estimating distance as closer than what it is	- Being surprised/startled - Being more careful than necessary, causing loss of time - Disturbing traffic	3	- Magnification (negative) - Distortion - No depth perception caused by accommodation problems	5	15
2.1.1 Detect objects in side lanes (1-2 lanes away)	Detecting object late	- Decreased feeling of control - Becoming frightened	3	- FOV (camera angle, distortion) - Display parameters (bad resolution)	5	15
3.3 Estimate distance to objects to the side	Not being able to determine distance	- Frustration - Decreased feeling of control	3	- FOV (Distortion, magnification, size of display) - No depth perception caused by accommodation - No reference point	5	15
4.3 Estimate speed of/to object in side lanes	Not being able to estimate velocity	- Frustration - Decreased feeling of control - Drive into object	3	- Magnification - Distortion - No depth perception caused by accommodation problems	5	15
2.1.3 Detect objects in opposite lane	Not detecting objects	- Switching lane at wrong moment, resulting in frontal crash - Nothing happens - User switches lane at dangerous moment and manages to steer away but becomes becomes afraid, upset - Disturbance in traffic flow	4	- Decreased FOV forward (A pillar design and display size) - Distraction caused by information devices competing for attention - Tiredness caused by increased screen time - Vigilance	3	12

2.2.1 Estimation of distance to objects in other lanes	Estimating distance as closer than what it is	Missing out on opportunities to change lane, causing loss of time	3	- Too much distortion - FOV (including screen size) - Magnification - Reference point - No depth perception caused by accommodation	4	12
1.1 Detect objects	Not being able to alternate between views	- Being stressed out - Not detecting objects	3	- Accommodation problem - number and placement of displays - Mental capacity	4	12
3 Estimate distance to object (combination of 3.1 & 3.2)	Not understanding the distance to object since different information sources provide contradicting information	- Having to use a complementary tool to the display to make estimation - Frustration - Being more careful than necessary, resulting in loss of time	4	The different display tools provide contradicting information (distortion & magnification)	3	12
4.1 Estimate velocity of/to object on sides	Estimating velocity as higher than what it is	- Being more careful than necessary, resulting in loss of time - Frustration - Distrusting system	3	- Distortion - Magnification (negative) - No depth perception caused by accommodation	4	12
3.1.1.1 Detect objects on the sides	Not detecting objects	- turn into an object - Disturbing traffic situation	4	- accommodation problem - FOV (width, height, distortion, camera angle) - display position (longer time to find screen)	3	12
2.1.1 Detect objects in side lanes (1-2 lanes away)	Not detecting object	- Driving into/over object	4	- FOV (camera angle, distortion) - Display parameters (bad resolution)	3	12
2.1.2 Detect object behind	Detecting object late	- Decreased feeling of control - Disturbance of traffic flow	3	- FOV (camera angle, distortion) - Display parameters (bad resolution)	4	12
2.2.1 Estimating distance to objects in side lanes (1-2 lanes away)	Not being able to determine distance	- Becoming stressed out - Driving into vehicle - Extra careful, resulting in loss of time - Disturbance of traffic flow	4	- Distortion - Magnification - no reference point - No depth perception caused by accommodation	3	12
2.2 Estimating distance to objects (alternating between 2.1.1, 2.1.2, 2.1.3)	Not managing to assess distance when alternate between the 3 directions	- Not being able to take action - Becoming stressed out - Frustration - Distrust system	4	Receiving contradicting information from different displays	3	12
3.3 Estimate distance to objects to the side	Estimating distance to object as farther away than what it is	- Driving into object - Being startled	4	- FOV (Distortion, magnification, size of display) - No depth perception caused by accommodation - No reference point	3	12
1.1.1 Estimate distance to objects in other lanes	Not being able to estimate distance	- Being incapacitated - Having to be more careful than necessary, causing loss of time - Frustration	3	- FOV (especially distortion) - No reference point or difficult to understand it - No depth perception caused by accommodation	4	12

1.3.1 Estimate velocity of/to objects on sides	Not being able to estimate velocity	<ul style="list-style-type: none"> - Being incapacitated - Having to be more careful than necessary, causing loss of time - Frustration 	3	<ul style="list-style-type: none"> - FOV (especially distortion) - No reference point or difficult to understand it - No depth perception caused by accommodation 	4	12
2.1.1 Detect objects in other lanes (also 5.3)	Detect object that does not exist	<ul style="list-style-type: none"> - confusion - Missing out on opportunities to change lane, causing loss of time 	2	<ul style="list-style-type: none"> - Screen parameters (image resolution, distortion) - Tiredness caused by increased screen time 	5	10
2.3.1 Estimation of relative speed of object in other lanes	Estimating speed as higher than what it is	Missing out on opportunities to change lane, causing loss of time and irritation	3	<ul style="list-style-type: none"> - Too much distortion - Magnification - Screen resolution - Field of view (including screen size) - No depth perception caused by accommodation 	3	9
1.1.2 Detect objects behind	Not detecting objects	<ul style="list-style-type: none"> - Vehicle behind crashing into rear - changing lane simultaneously which might result in collision 	3	<ul style="list-style-type: none"> - FOV (magnification, camera angle, distortion) - display form and size - Display parameters (resolution, contrast, luminance) - Display placement 	3	9
1.3.2 Estimate velocity of/to objects behind	Not being able to assess velocity	<ul style="list-style-type: none"> - Being incapacitated - Being stressed out - Frustration - More careful driving, causing loss of time 	3	<ul style="list-style-type: none"> - FOV (especially magnification) - Difficult to perceive change of vehicle image from camera angle straight back - No reference point - No depth perception caused by accommodation 	3	9
1.3 Estimate velocity of objects	Being confused by taking in contradicting information from different views	<ul style="list-style-type: none"> - Being incapacitated - Being stressed out - Frustration - More careful driving, causing loss of time 	3	<ul style="list-style-type: none"> - Different magnification, distortion and camera angle on different screens - No depth perception caused by accommodation 	3	9
2.2.2 Estimating distance to objects behind	Determining distance as closer than what it is	<ul style="list-style-type: none"> - Becoming stressed out - Extra careful, resulting in loss of time - Disturbance of traffic flow - Frustration - Distrust to system 	3	<ul style="list-style-type: none"> - No reference point, or difficult to understand it - Difficult to perceive change of vehicle image from camera angle straight back - Camera angle -No depth perception caused by accommodation 	3	9
2.2 Detect object behind	Not managing to detect objects	<ul style="list-style-type: none"> - Driving into/over objects - Being startled - Disturbing traffic 	3	<ul style="list-style-type: none"> - FOV (a-pillar, interior design, camera angle, magnification) - Accommodation shift - display parameters (resolution, contrast, luminance, placement, size, form) 	3	9
1.3.1 Estimate velocity of/to objects on sides	Estimating velocity as lower than what it is	<ul style="list-style-type: none"> - Opening door even though it is not safe yet - Resulting in accident - Being startled 	3	<ul style="list-style-type: none"> - FOV (especially distortion) - No depth perception caused by accommodation 	3	9

2.1.2 Detect objects behind	Not detecting the objects	Decreased control of surrounding and the initial point of the overtaking	2	<ul style="list-style-type: none"> - Screen parameters (image resolution, distortion) - Placement - FOV(how much coverage of field of view, size, magnification, distortion) - camera being blind from dirt or weather. - Distraction caused by information devices competing for attention - Tiredness caused by increased screen time - Vigilance 	4	8
1.1.3 Detect objects forward	Not detecting objects	<ul style="list-style-type: none"> - colliding with objects in front - being startled 	4	<ul style="list-style-type: none"> - FOV (a-pillar size) - Placements of display and size - Focus on other things - Accomodation problem (shifting from looking at display to road) 	2	8
1.2.1 Estimate distance to object on sides	Determine distance as shorter than what it is	<ul style="list-style-type: none"> - Distrust to system - More careful driving, causing loss of time 	4	<ul style="list-style-type: none"> - Distortion - No reference point or difficult to understand reference point - Size of display 	2	8
1.3.1 Estimate velocity of /to object on sides	Not being able to assess velocity	<ul style="list-style-type: none"> - Being incapacitated - Being stressed out - Frustration - More careful driving, causing loss of time 	2	<ul style="list-style-type: none"> - Distortion - Magnification - Reference point - No depth perception caused by accomodation 	4	8
2.1 Detect objects forward	Not managing to detect objects	<ul style="list-style-type: none"> - Driving into/over objects - Being startled 	4	<ul style="list-style-type: none"> - FOV (a-pillar, interior design, camera angle, magnification) - Accommodation shift - display parameters (resolution, contrast, luminance, placement, size, form) 	2	8
4.2 Estimate velocity of/to objects behind	Not being able to estimate velocity	<ul style="list-style-type: none"> - Frustration - Distrusting the system 	2	<ul style="list-style-type: none"> - FOV (especially magnification) - Difficult to perceive change of vehicle image from camera angle straight back - No reference point - No depth perception caused by accomodation 	4	8
2.3.2 Estimation of relative speed of objects behind	Estimating velocity as slower than what it is	- Changing lane at an unsafe moment (too early)	3	<ul style="list-style-type: none"> -No depth perception caused by accomodation - no reference -difficult to perceive change of vehicle image from straight angle 	2	6
1.2.1 Estimate distance to object on sides	Not being able to estimate distance	<ul style="list-style-type: none"> - Being incapacitated - Being stressed out 	3	<ul style="list-style-type: none"> - Distortion - magnification - size of Display - No depth perception caused by accomodation - No reference point 	2	6

1.3.1 Estimate velocity of /to object on sides	Estimating velocity as higher than what it is	<ul style="list-style-type: none"> - Being stressed out - Driver is negatively surprised - More careful driving, causing loss of time 	2	<ul style="list-style-type: none"> - Distortion - No depth perception caused by accomodation 	3	6
3.1 Estimate distance to objects on sides	Estimating distance as shorter than what it is	<ul style="list-style-type: none"> - Being more careful than necessary, resulting in loss of time - Irritation 	3	<ul style="list-style-type: none"> - Distortion - Magnification - Reference point -No depth perception caused by accomodation 	2	6
3.1.1.3 Detect objects in front	Not detecting objects	<ul style="list-style-type: none"> - Driving into/over an object - Disturbing traffic situation 	3	<ul style="list-style-type: none"> - Display size - Display placement - FOV (size of a-pillar, camera house) 	2	6
3.2.2.2.1.1.2 detect object behind	Not detecting object	<ul style="list-style-type: none"> - Being surprised/startled - making unpredictable movements - disturbing traffic - vehicle driving into rear/side 	3	<ul style="list-style-type: none"> - FOV (interior design, camera angle,) -display (resolution, contrast, magnification) - placement of display -size of display 	2	6
1.1.3 Detect objects in forward	Not detecting objects	<ul style="list-style-type: none"> - Objects colliding with opened door, causing accident - Very frightening - Disturbing traffic 	2	<ul style="list-style-type: none"> - FOV (a-pillar, interior design) - Accommodation shift 	3	6
4.2 Assess possibility to swift lane to the right	User does not manage to detect object on the right hand side	<ul style="list-style-type: none"> - User pulls out to the right too early - Unsure regarding when to move back to right lane - dangerous if driving too long in opposite lane 	2	<ul style="list-style-type: none"> - lack of FOV (B-pillar design, magnification, distortion) 	2	4
3.2.2.2.1.1.3 detect object forward	Not detecting object	<ul style="list-style-type: none"> - Driving into rear on object forward 	2	<ul style="list-style-type: none"> - FOV (a-pillar design, interior design) 	2	4
2.3.1 Estimate velocity to objects on sides	Estimating velocity as higher than what it is	<ul style="list-style-type: none"> - Extra careful, resulting in loss of time - Frustration 	2	<ul style="list-style-type: none"> - Distortion - Magnification - No reference or difficult to understand it - No depth perception caused by accomodation 	2	4
2.3.2 Estimate velocity to objects behind	Not being able to determine velocity	<ul style="list-style-type: none"> - Extra careful, resulting in loss of time - Frustration - Distrust to system - Distrubance of traffic flow 	2	<ul style="list-style-type: none"> - Distortion - Magnification - No reference or difficult to understand it - Difficult to perceive change of vehicle image from camera angle straight back - No depth perception caused by accomodation 	2	4

Appendix E – Manuscript & Test Instruction for User Test 1

The manuscript and test instructions in this appendix were used for one test person. The order the of settings thus varied between each test person, even if that cannot be distinguished in these documentations.

Test Instructions TPX

Preparations:

The prototype car should be equipped with:

- Black plastic bag for covering VIRM
- 2 gloves to cover the exterior sideview cameras.

Procedure

1. Drive and welcome the TP. Park the prototype car according to cone I or N in Figure 31, in the middle part of test track with covered side cameras, support system OFF, tape camera for rain. Red SUV should also have support system OFF. Cover center stack display with the A4 scales.
2. Short meeting outside the car to present the test.
3. **Let TP know the following info:**
We are Pontus and Sara and today I am the test leader and XX is the assistant who will drive the other car. We study Industrial Design Engineering at Chalmers and are doing our master thesis here at Volvo Cars during this spring. In the project, we are investigating Camera Monitoring Systems (CMS), as mentioned in the email. CMS is used instead of traditional rearview mirrors by placing cameras on the car which generate the images in displays inside the car, which already is available in a few car models today. You are soon going to see and perform tests in this prototype car which is equipped with CMS. You are going to do two main tests, which both are divided into seven sub-tests. Totally, it will take 1 h to perform everything. You do not have to think about that no, only follow the instructions provided to you before each sub-test. We can already now warn you about that we are going to be rather unpersonal and read a lot straight from the document, but is to not miss any information and to be efficient so all tasks are performed within the time. There will be time for small talk a bit after the tests. Does it sound OK? Then we are going to start by entering the car and then we will ask some questions, and make some administrative stuff, then you will get the first instructions.
4. Step into the car and provide info about the prototype car:
 - *Instead of sideview mirrors, there are cameras outside connected to the screens inside. There is also a camera at the rear end of the car which is connected to the VIRM.*
 - *Our focus is the VIRM, therefore the sideview cameras are covered, and will remain so during all tests.*
5. Walkthrough the questions:
 - *Have you signed the consent form before? If not, you need to sign it now.*
 - *Is it ok if we record the sound during the session? It is mostly to remember what was said, in case of we want to go back and check something specific later.*
 - *Do you have any visual impairments? **Take notes:***
 - *How familiar are you with CMS? **Take notes:***
 - *What are your thoughts regarding CMS? **Take notes:***
6. Inform TP:

- The test will be performed here at the test track (A or B)
 - We will begin by performing a test that involves very slow reverse driving.
 - In the second test, you are going to drive a bit faster here at the straight lanes.
 - We are going to ask you some questions after each test
 - We would like you to think aloud in this first test, so you are welcome to tell us exactly what you are thinking during the test
 - You will get more questions after time
 - Do you have any questions before we start?
7. Start sound recording and call each other on phone.

Short-Distance test

Short	Camera position	Zoom-level	TP's estimation of distance (cm)	Measured distance (cm)
CMS1.1	Roof	2.0		
Step	Test Leader (TL)			Assistant (A)
1	Tell TP to adjust seating position and VIRM according to preference. While TP adjust; set zoom-level as above			Set camera position according to above
2	Inform TP about task <ul style="list-style-type: none"> • What is the closest distance you approach a car behind you, i.e. reverse parking towards another car. Show with hands! • Your task now is to slow reverse drive towards the car behind, only using the VIRM. You can absolutely not use the sideview displays (therefore covered) nor turn around and see. • We want you to reverse drive towards the car and aim for stopping at the distance you just showed up with your hands. Stop and tell me when you have reached that position. • Do you have any questions? Remember to think aloud. See that the support system is turned OFF.			
3	Start the test!			
4	TP says stop: <ul style="list-style-type: none"> • How far behind is the car now do you think? Show on the folding ruler. Take note: Put on bag over VIRM and tell A to measure <ul style="list-style-type: none"> • How certain are you on your answer? Show on the scale. Take note here. Comments? <ul style="list-style-type: none"> • How was it to estimate distance with these settings? Take note here: Now you can relax for a while when we make some changes for next test.			

5		Wait for signal from TL and go out and measure distance between the cars, use 2 folding rulers. Take note: Notify TL when it is done
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Short	Camera position	Zoom-level	TP's estimation of distance (cm)	Measured distance (cm)
CMS1.2	Glas	2.5		
Step	Test Leader (TL)			Assistant (A)
6	Set zoom-level as above and cover VIRM			Set camera position as above
7	Instruct the next test: <ul style="list-style-type: none"> • <i>Slow reverse driving</i> • <i>Aim for same distance as you aimed for before (the distance you usually aim for)</i> <i>Do not turn around, only use VIRM</i>			Position reference car farther back and notify TL when it is done
8	Uncover display Start the test!			
9	TP says stop: <ul style="list-style-type: none"> • <i>How far behind is the car now do you think? Show on the folding ruler. Take note:</i> Put on bag over VIRM and tell A to measure <ul style="list-style-type: none"> • <i>How certain are you on your answer? Show on the scale. Take note here. Comments?</i> • <i>How was it to estimate distance with these settings? Take note here:</i> <i>Now you can relax for a while when we make some changes for next test.</i>			
10				Wait for signal from TL and go out and measure distance between the cars, use 2 folding rulers. Take note: Notify TL when it is done

Short	Camera position	Zoom-level	TP's estimation of distance (cm)	Measured distance (cm)
CMS1.3	Bumper	2.0		
Step	Test Leader (TL)			Assistant (A)
11	Set zoom-level as above and cover VIRM			Set camera position according to above

12	Instruct the next test: <ul style="list-style-type: none"> • <i>Slow reverse driving</i> • <i>Aim for same distance as you aimed for before (the distance you usually aim for)</i> <p><i>Do not turn around, only use VIRM</i></p>	Position reference car farther back and notify TL when it is done
13	Uncover display Start the test!	
14	TP says stop: <ul style="list-style-type: none"> • <i>How far behind is the car now do you think? Show on the folding ruler. Take note:</i> <p>Put on bag over VIRM and tell A to measure</p> <ul style="list-style-type: none"> • <i>How certain are you on your answer? Show on the scale. Take note here. Comments?</i> • <i>How was it to estimate distance with these settings? Take note here:</i> <p><i>Now you can relax for a while when we make some changes for next test.</i></p>	
15		Wait for signal from TL and go out and measure distance between the cars, use 2 folding rulers. Take note: Notify TL when it is done

Short	Camera position	Zoom-level	TP's estimation of distance (cm)	Measured distance (cm)
CMS1.4	Roof	2.5		
Step	Test Leader (TL)			Assistant (A)
16	Set zoom-level as above and cover VIRM			Set camera position as above
17	Instruct the next test: <ul style="list-style-type: none"> • <i>Slow reverse driving</i> • <i>Aim for same distance as you aimed for before (the distance you usually aim for)</i> <p><i>Do not turn around, only use VIRM</i></p>			Position reference car farther back and notify TL when it is done
18	Uncover display Start the test!			
19	TP says stop: <ul style="list-style-type: none"> • <i>How far behind is the car now do you think? Show on the folding ruler. Take note:</i> <p>Put on bag over VIRM and tell A to measure</p> <ul style="list-style-type: none"> • <i>How certain are you on your answer? Show on the scale. Take note here. Comments?</i> 			

	<ul style="list-style-type: none"> • <i>How was it to estimate distance with these settings? Take note here:</i> <p><i>Now you can relax for a while when we make some changes for next test.</i></p>	
20		<p>Wait for signal from TL and go out and measure distance between the cars, use 2 folding rulers. Take note:</p> <p>Notify TL when it is done</p>

Short	Camera position	Zoom-level	TP's estimation of distance (cm)	Measured distance (cm)
CMS1.5	Glas	2.0		
Step	Test Leader (TL)			Assistant (A)
21	Set zoom-level as above and cover VIRM			Set camera position according to above
22	Instruct the next test: <ul style="list-style-type: none"> • <i>Slow reverse driving</i> • <i>Aim for same distance as you aimed for before (the distance you usually aim for)</i> <p><i>Do not turn around, only use VIRM</i></p>			Position reference car farther back and notify TL when it is done
23	Uncover display Start the test!			
24	TP says stop: <ul style="list-style-type: none"> • <i>How far behind is the car now do you think? Show on the folding ruler. Take note:</i> Put on bag over VIRM and tell A to measure <ul style="list-style-type: none"> • <i>How certain are you on your answer? Show on the scale. Take note here. Comments?</i> • <i>How was it to estimate distance with these settings? Take note here:</i> <p><i>Now you can relax for a while when we make some changes for next test.</i></p>			
25				<p>Wait for signal from TL and go out and measure distance between the cars, use 2 folding rulers. Take note:</p> <p>Notify TL when it is done</p>

Short	Camera position	Zoom-level	TP's estimation of distance (cm)	Measured distance (cm)
CMS1.6	Bumper	2.5		
Step	Test Leader (TL)			Assistant (A)
26	Set zoom-level as above and cover VIRM			Set camera position as above
27	Instruct the next test: <ul style="list-style-type: none"> • <i>Slow reverse driving</i> • <i>Aim for same distance as you aimed for before (the distance you usually aim for)</i> <p><i>Do not turn around, only use VIRM</i></p>			Position reference car farther back and notify TL when it is done
28	Uncover display Start the test!			
29	TP says stop: <ul style="list-style-type: none"> • <i>How far behind is the car now do you think? Show on the folding ruler. Take note:</i> <p>Put on bag over VIRM and tell A to measure</p> <ul style="list-style-type: none"> • <i>How certain are you on your answer? Show on the scale. Take note here. Comments?</i> • <i>How was it to estimate distance with these settings? Take note here:</i> <p><i>Now you can relax for a while when we make some changes for next test.</i></p>			
30				Wait for signal from TL and go out and measure distance between the cars, use 2 folding rulers. Take note: Notify TL when it is done

Short	Camera position	Zoom-level	TP's estimation of distance (cm)	Measured distance (cm)
Mirror1	-	-		
Step	Test Leader (TL)			Assistant (A)
31	Change to mirror mode Cover mirror			Put camera in trunk
32	Instruct TP to adjust mirror angle			Position reference car farther back and notify TL when it is done
33	Instruct the next test: <ul style="list-style-type: none"> • <i>Slow reverse driving</i> • <i>Aim for same distance as you aimed for before (the distance you usually aim for)</i> <i>Do not turn around, only use mirror</i>			
34	Uncover mirror and let TP start			
35	TP says stop: <ul style="list-style-type: none"> • <i>How far behind is the car now do you think? Show on the folding ruler. Take note:</i> Put on bag over VIRM and tell A to measure <ul style="list-style-type: none"> • <i>How certain are you on your answer? Show on the scale. Take note here. Comments?</i> • <i>How was it to estimate distance with these settings? Take note here:</i> • <i>Now you can relax for a while when we make some changes for next test.</i> 			
36				Wait for signal from TL and go out and measure distance between the cars, use 2 folding rulers. Take note: Notify TL when it is done

Long-Distance Test

1. Inform TP how the test will proceed:
 - *This test will be performed as, you will accelerate and drive on this straight lane in 15 km/h (no cruise control, not possible under 30 km/h)*
 - *You will drive first and then the assistant in the other car will start a bit behind you and will come closer and closer since it drives faster.*
 - *Your task is to say "NOW" (loud) when you estimate the reference car being positioned one car length behind. You can only use VIRM, not turning around.*
 - *After you have said "NOW", the test is ended and you can drive the rest of the track and stop when TL says so.*
2. Drive cars to starting positions. (beginning of track by the cones)
3. Ask TP if he/she wants to test drive the track first.

Long	Camera position	Zoom-level
CMS2.1	Roof	2.0
Step	Test Leader (TL)	Assistant (A)
1	Instruct TP to place car by the cone (in front of the reference car). You should have the tape between you and the cone.	Place reference car by the cone
2	Set zoom level according to above and cover VIRM	Adjust camera position according to above
3		Start log Note log# here: Let TL know when you are ready
4	Uncover display. Wait for signal from A. Make sure TP is ready to start	
5	Count down from 3,2,1 DRIVE for both TP and A.	
6	<i>Perform test round 1</i>	Turn ON blinkers when TP says "NOW" Let TP know that it was heard. Turn OFF blinkers
7		End log
8	Instruct TP to place beside the cone	Place car by the cone
9		Start log Note log# here: Let TL know when you are ready
10	Wait for signal from A. Make sure TP is ready to start	
11	Count down from 3,2,1 DRIVE for both TP and A.	
12	<i>Perform test round 2</i>	Turn ON blinkers when TP says "NOW" Let TP know that it was heard. Turn OFF blinkers
13		End log
14	Instruct TP to place beside the cone	Place car by the cone...and change position of camera according to next test
15	<i>How did the test feel? Take note:</i> <i>How was it to estimate distance with these settings? Show on the scale. Take note:</i>	

Long	Camera position	Zoom-level
CMS2.2	Glas	2.5
Step	Test Leader (TL)	Assistant (A)
16	Set zoom level according to above and cover VIRM	Adjust camera position according to above
17	Instruct TP about next test <ul style="list-style-type: none"> • We are now going to do the same thing again • Say "NOW" loud and clearly when you estimate the car behind behind being a car length away. • Do not turn around, only use VIRM 	
18		Start log Note log# here: Let TL know when you are ready
19	Uncover display. Wait for signal from A. Make sure TP is ready to start	
20	Count down from 3,2,1 DRIVE for both TP and A.	
21	<i>Perform test round 1</i>	Turn ON blinkers when TP says "NOW" Let TP know that it was heard. Turn OFF blinkers
22		End log
23	Instruct TP to place beside the cone	Place car by the cone
24		Start log Note log# here: Let TL know when you are ready
25	Wait for signal from A. Make sure TP is ready to start	
26	Count down from 3,2,1 DRIVE for both TP and A.	
27	<i>Perform test round 2</i>	Turn ON blinkers when TP says "NOW" Let TP know that it was heard.

		Turn OFF blinkers
28		End log
29	Instruct TP to place beside the cone	Place car by the cone...and change position of camera according to next test
30	<i>How did the test feel? Take note:</i> <i>How was it to estimate distance with these settings? Show on the scale. Take note:</i>	

Long	Camera position	Zoom-level
CMS2.3	Bumper	2.0

Step	Test Leader (TL)	Assistant (A)
31	Set zoom level according to above and cover VIRM	Adjust camera position according to above
32	Instruct TP about next test <ul style="list-style-type: none"> We are now going to do the same thing again Say "NOW" loud and clearly when you estimate the car behind behind being a car length away. Do not turn around, only use VIRM 	
33		Start log Note log# here: Let TL know when you are ready
34	Uncover display. Wait for signal from A. Make sure TP is ready to start	
35	Count down from 3,2,1 DRIVE for both TP and A.	
36	<i>Perform test round 1</i>	Turn ON blinkers when TP says "NOW" Let TP know that it was heard. Turn OFF blinkers
37		End log
38	Instruct TP to place beside the cone	Place car by the cone
39		Start log Note log# here: Let TL know when you are ready
40	Wait for signal from A. Make sure TP is ready to start	
41	Count down from 3,2,1 DRIVE for both TP and A.	

42	<i>Perform test round 2</i>	Turn ON blinkers when TP says "NOW" Let TP know that it was heard. Turn OFF blinkers
43		End log
44	Instruct TP to place beside the cone	Place car by the cone...and change position of camera according to next test
45	<i>How did the test feel? Take note:</i> <i>How was it to estimate distance with these settings? Show on the scale. Take note:</i>	

Long	Camera position	Zoom-level
CMS2.4	Roof	2.5

Step	Test Leader (TL)	Assistant (A)
46	Set zoom level according to above and cover VIRM	Adjust camera position according to above
47	Instruct TP about next test <ul style="list-style-type: none"> We are now going to do the same thing again Say "NOW" loud and clearly when you estimate the car behind behind being a car length away. Do not turn around, only use VIRM 	
48		Start log Note log# here: Let TL know when you are ready
49	Uncover display. Wait for signal from A. Make sure TP is ready to start	
50	Count down from 3,2,1 DRIVE for both TP and A.	
51	<i>Perform test round 1</i>	Turn ON blinkers when TP says "NOW" Let TP know that it was heard. Turn OFF blinkers
52		End log
53	Instruct TP to place beside the cone	Place car by the cone
54		Start log

		Note log# here: Let TL know when you are ready
55	Wait for signal from A. Make sure TP is ready to start	
56	Count down from 3,2,1 DRIVE for both TP and A.	
57	<i>Perform test round 2</i>	Turn ON blinkers when TP says "NOW" Let TP know that it was heard. Turn OFF blinkers
58		End log
59	Instruct TP to place beside the cone	Place car by the cone...and change position of camera according to next test
60	<i>How did the test feel? Take note:</i> <i>How was it to estimate distance with these settings? Show on the scale. Take note:</i>	

Long	Camera position	Zoom-level
CMS2.5	Glas	2.0

Step	Test Leader (TL)	Assistant (A)
61	Set zoom level according to above and cover VIRM	Adjust camera position according to above
62	Instruct TP about next test <ul style="list-style-type: none"> We are now going to do the same thing again Say "NOW" loud and clearly when you estimate the car behind behind being a car length away. Do not turn around, only use VIRM 	
63		Start log Note log# here: Let TL know when you are ready
64	Uncover display. Wait for signal from A. Make sure TP is ready to start	
65	Count down from 3,2,1 DRIVE for both TP and A.	
66	<i>Perform test round 1</i>	Turn ON blinkers when TP says "NOW" Let TP know that it was heard. Turn OFF blinkers

67		End log
68	Instruct TP to place beside the cone	Place car by the cone
69		Start log Note log# here: Let TL know when you are ready
70	Wait for signal from A. Make sure TP is ready to start	
71	Count down from 3,2,1 DRIVE for both TP and A.	
72	<i>Perform test round 2</i>	Turn ON blinkers when TP says "NOW" Let TP know that it was heard. Turn OFF blinkers
73		End log
74	Instruct TP to place beside the cone	Place car by the cone...and change position of camera according to next test
75	<i>How did the test feel? Take note:</i> <i>How was it to estimate distance with these settings? Show on the scale. Take note:</i>	

Long	Camera position	Zoom-level
CMS2.6	Bumper	2.5
Step	Test Leader (TL)	Assistant (A)
76	Set zoom level according to above and cover VIRM	Adjust camera position according to above
77	Instruct TP about next test <ul style="list-style-type: none"> We are now going to do the same thing again Say "NOW" loud and clearly when you estimate the car behind behind being a car length away. Do not turn around, only use VIRM 	
78		Start log Note log# here: Let TL know when you are ready
79	Uncover display. Wait for signal from A. Make sure TP is ready to start	
80	Count down from 3,2,1 DRIVE for both TP and A.	
81	<i>Perform test round 1</i>	Turn ON blinkers when TP says "NOW"

		Let TP know that it was heard. Turn OFF blinkers
82		End log
83	Instruct TP to place beside the cone	Place car by the cone
84		Start log Note log# here: Let TL know when you are ready
85	Wait for signal from A. Make sure TP is ready to start	
86	Count down from 3,2,1 DRIVE for both TP and A.	
87	<i>Perform test round 2</i>	Turn ON blinkers when TP says "NOW" Let TP know that it was heard. Turn OFF blinkers
88		End log
89	Instruct TP to place beside the cone	Place car by the cone...and change position of camera according to next test
90	<i>How did the test feel? Take note:</i> <i>How was it to estimate distance with these settings? Show on the scale. Take note:</i>	

Long	Camera position	Zoom-level
Mirror2	-	-
Step	Test Leader (TL)	Assistant (A)
91	Change to mirror mode and cover mirror	Place camera in trunk
92	Instruct TP about next test <ul style="list-style-type: none"> We are now going to do the same thing again Say "NOW" loud and clearly when you estimate the car behind behind being a car length away. Do not turn around, only use VIRM 	
93		Start log Note log# here: Let TL know when you are ready
94	Uncover mirror. Wait for signal from A. Make sure TP is ready to start	

95	Count down from 3,2,1 DRIVE for both TP and A.	
96	<i>Perform test round 1</i>	Turn ON blinkers when TP says "NOW" Let TP know that it was heard. Turn OFF blinkers
97		End log
98	Instruct TP to place beside the cone	Place car by the cone
99		Start log Note log# here: Let TL know when you are ready
100	Wait for signal from A. Make sure TP is ready to start	
101	Count down from 3,2,1 DRIVE for both TP and A.	
102	<i>Perform test round 2</i>	Turn ON blinkers when TP says "NOW" Let TP know that it was heard. Turn OFF blinkers
103		End log
104	Instruct TP to place beside the cone	Place car by the cone...and change position of camera according to next test
105	<i>How did the test feel? Take note:</i> <i>How was it to estimate distance with the mirror? Show on the scale. Take note:</i>	

Questions:

What is your general impression of CMS now after the test? **Take note:**

What settings did you prefer for the distance estimation? More zoomed in? Position in height?
Take note:

Was there something that worked well when you used CMS in the test? **Take note:**

Was there something that worked bad when you used CMS in the test? **Take note:**

What do you think about the placement of the VIRM? **Take note:**

Appendix F – Specifications of VIRM (Camera and Display)

In this appendix the properties of the VIRM camera and display are described in a more technical approach.

Gen 1.0 Mid – Camera Design

- CMS camera
 - 10640 Imager
 - 1.3 Mpix HDR
 - Raw output format
 - Supports 60fps output
 - Split pixel technology with 4.2 μ m pixel pitch
 - Target sensitivity = 6-7V / lux*sec
 - High conversion gain on floating diffusion
 - 20% - 30% sensitivity improvement

- Approx 60 degree high performance lens

- OV10640 Megapixel Based Camera Module
 - 1.3 Megapixel (1280 x 1080); YUV422;

Gen 1.0 Mid – Display Specification

Properties	Description
Active Screen Size	7.0 inches diagonal
Active Area	152.40 mm (H) × 91.44 mm (V) (Typ.)
Aspect ratio	15:9
Outline Dimension	168.19 mm (H) × 107.94 mm (V) X 8.10 mm (D) (Typ.)
Dot Pitch	0.1905 mm x 0.1905 mm
Pixel Configuration	800 horiz. by 480 vert. Pixels, BGR stripe arrangement
Input Video Signal	LVDS 8bit(D), 16.7M colors
Luminance, White	530 cd/m2 (Perpendicular, Min.)
White color chromaticity	W(x)=0.315 and W(y)=0.338 (±0.03)
Luminance uniformity	80% (min)
Contrast ratio	800:1(Perpendicular, Min)
Viewing Angle (CR>10)	Viewing angle (R/L 178 (Min.), U/D 178 (Min.)
Light source	White LED
Power Consumption	Total 4.46W (Typ.)
Weight	180g (Typ.)
Display Mode	AH-IPS, Transmissive

Appendix G – Participants in User Test 1 & 2

This appendix presents the characteristics of the participants for the respective user tests. In Table 16, the participants that performed user test 1 are described by their previous experience of CMS, height and visual status. In Table 17 the same is described for the participants of user test 2.

Table 16

Participants of user test 1.

	Height (cm)	Previous experience of CMS	Eyesight
TP 1	184.8	A bit out in the traffic with Audi e-tron.	Astigmatist, but normal corrected vision.
TP 2	175.5	Has driven Audi e-tron for a few days	Nearsighted
TP 3	179.6	Tried it for a few days.	Good
TP 4	187.5	Worked with it	Nearsighted, but perfect vision with glasses
TP 5	189.9	Tried Audi e-tron on public road (1h)	Good
TP 6	203.0	No	Good with glasses
TP 7	192.7	Pretty well, works with packaging of the door, benchmarking of a Jaguar, have driven a bit within the Volvo -area	Good
TP 8	163.0	Have not seen or tested	bad vision on close distances
TP 9	146.0	No	Good
TP 10	170.0	No	Astigmatism on both eyes, oversight on left eye, a bit nearsight on right eye. Perfect with glasses.
TP 11	189.5	Seen concept, tried Audi e-tron for five days (250 km)	Good
TP 12	184.3	In the Audi e-tron	Farsighted, age related.
TP 13	198.0	Seen the Audi e-tron	Farsighted, but uses progressive glasses.
TP 14	158.0	Not at all, maybe read about it	Nearsighted on right, farsighted on left. But left vision is very bad.
TP 15	190.0	Only among other car models, never driven a CMS car	Glasses, nearsighted
TP 16	195.0	Known for a while, seen cars with it. Know that it is upcoming.	Reading glasses. Bad at close distances.

Table 17

Participants of user test 2.

	Height (cm)	Eyesight	Previous experience of CMS
TP 21	185	Have normal vision using glasses, without them darker and less contrast.	None
TP 22	182	Normal vision using glasses, without bad vision on large distances.	None
TP 23	188	Age related decreased vision. When driving: 1.0 in spectacle reinforcement	Heard of CMS
TP 24	179	Farsighted, good with glasses.	None
TP 25	192	Astigmatism and nearsighted. Good with glasses.	Very inserted through work, have tested it

Appendix H – Manuscript of User Test 2

This appendix is a copy of the manuscript for user test 2, which includes task instructions and the manuscript for the tests.

- In the cars:
 - Sanitizer
 - Mouth cover
 - Paper napkins
 - Garbage bin
- Clean the reference and prototype car with the sanitizer on all interaction surfaces before the test person arrives.
- Prototype car and reference car is ready. Parking camera and warning signals are ON. BLIS OFF.
- Meet the test person in parking garage
- Short meeting outside the car. **Let the TP know the following info:**
We are Pontus and Sara, and today you are going to perform a test together with me as a test leader. I can begin by saying that we are going to be rather unpersonal and read direct from the paper to get all information and to keep the test efficient. We are studying Industrial Design Engineering at Chalmers and this user test is a part of our master thesis, where we are investigating the Camera Monitoring Systems (CMS), as mentioned in the email. CMS is used instead of traditional rearview mirrors (inner and exterior) by placing cameras on the car. The image the cameras generate are displayed on screens inside the car and this technology is already used on a few car models today.

The today's test will be performed by driving a predetermined route (two laps) to Torslanda, but more specific information will be provided to you when we are entering the car. The first lap will be with a regular car. The second lap will be driven with a prototype car with CMS implemented. I will also talk to you a lot during the test and ask many questions, and ask you to "think aloud" during driving.

Before we enter the car, I want to be sure that you have signed the consent form for GDPR. We would also like to point out that you whenever have possibility to abort the test without having a reason for it.

- *TP eventually signs consent form*
Then, we would like to ask you if it is OK to sound record our conversation? It is only because it is easier for us to go back afterwards to check on details if necessary.
Now you can enter the driver's seat and adjust it and the mirrors (exterior and inner) according to your preferences. Then I will ask you some questions and walkthrough the map of the route.
- Begin record sound.
- Show map:
We are going to drive this route to Torslanda, and I will guide you if you eventually need to change lane, turn or take a specific road. On this road I will ask you to accelerate and then will want you to perform an overtake somewhere on the road. Then we will drive through some roundabouts, entering a smaller city center, and eventually end up on a parking lot where you will park the car, then drive back this way (show on map). It will take approximately 20 min and then we will come back here, and you will answer some questions. Then you will drive the next round.

We would like you to ask you once again to "think aloud" during the test when you are driving. You can have in mind that no thoughts are too small or unimportant to share, we would rather know TOO MUCH than too little. And I will remind you of this if you forget.

Do you have any questions?

When you are feeling ready, we can start and drive out of the parking garage too the left. And you can begin thinking aloud already now.

- *Tell TP that the BLIS is off.*

DRIVE LAP 1 – ask simultaneously the question if there is room for it for every scenario

- Do you have any visual impairment?*
- How tall are you?*
- How familiar are you with CMS?*
- What are your thoughts regarding CMS?*

Drive through darkness/parking garage

- How did it feel?
- Was it easy/difficult?

Entering a highway:

- How was it to change lane?
- How did it feel?
- Do you use the rearview mirrors when entering the highway? In what way?
- What was difficult?
- What was easy?

Driving straight on an 80 km/h-road

- Placement of mirrors? What would have been optimally?
- How is it to shift focus from the road to the mirrors?
- How did it feel to keep control of the cars behind?

Overtaking:

- How was it to change lane?
- How did it feel?
- What was difficult?
- What was easy?
- How was it to estimate distance to the car behind?
- How do you use the mirrors when making an overtake? How did it go?

Roundabout:

- How did it feel to drive in a roundabout?
- What was difficult?
- What was easy?
- How was it to change lane within the roundabout?
- How was it to keep track at many directions at the same time?
- How did it work to keep track to the sides/rearwards?

Exiting the car:

- How did it feel?
- What was difficult?
- What was easy?

Reverse parking:

- How did it feel?
- How was it to reverse drive with the mirrors?
- What was difficult?
- What was easy?

Intersection:

- How did it feel to drive in an intersection with the mirrors?
- Was something good? Did something feel difficult?

• **Question time 1** (*in parking garage*)

- How was it to drive with the mirrors?
- Is it something that is missing or excessive when you are using the mirrors? Information? In a specific direction? Feeling?
- Was there any driving situation that felt extra easy or difficult when using the mirrors? Which situations? Why?
- Ask complementary questions from the list above.

• **Ratings 1** – Ask the test person to fill in the ratings papers for round 1.

Now I would like to ask you to fill in this form for the round (hand over document)

• Change to CMS-car.

Here is the cameras (rear) to respectively screen. Here you can see that there are two screens, one to the right and one to the left, also one in the middle. Adjust the seat and FOV of the side screens if you want (show how). We are now going to drive the same route again. This time, I will once again ask you to think aloud, and you are welcome to compare the thoughts with the mirrors if you like. If anything feels better, worse or just different, we would like to know about it. But once again: the most important is to remember that no thoughts are too small or unimportant, but would rather know TOO MUCH than too little. When you feel ready, we can start and drive the same route as before. And you are welcome to start thinking already now!

• DRIVE LAP 2 (CMS) – ask simultaneously the question if there is room for it for every scenario

Drive through darkness/parking garage

- How did it feel?
- Was it easy/difficult?

Entering a highway:

- How was it to change lane?
- How did it feel?
- Do you use the screens when entering the highway? In what way?
- What was difficult?
- What was easy?

Driving straight on an 80 km/h-road

- Placement of screens? What would have been optimally?
- How is it to shift focus from the road to the screens?
- How did it feel to keep control of the cars behind?

Overtaking:

- How was it to change lane?
- How did it feel?
- What was difficult?
- What was easy?
- How was it to estimate distance to the car behind?
- How do you use the screens when making an overtake? How did it go?

Roundabout:

- How did it feel to drive in a roundabout?
- What was difficult?
- What was easy?
- How was it to change lane within the roundabout?
- How was it to keep track at many directions at the same time?
- How did it work to keep track to the sides/rearwards?

Exiting the car:

- How did it feel?
- What was difficult?
- What was easy?

Reverse parking:

- How did it feel?
- How was it to reverse drive with the mirrors?
- What was difficult?
- What was easy?

Intersection:

- How did it feel to drive in an intersection with the mirrors?
- Was something good? Did something feel difficult?

• Question time 2

- How was it to drive with CMS?
- Were there any differences between driving with mirrors and CMS? What? Why?
- Is it something that is missing or excessive with CMS? Information? In a specific direction? Feeling?
- Was there any driving situation that felt extra easy or difficult when using the CMS compared to mirrors? Which situations? Why?
- Ask complementary questions from the list above.
- What is your experience of CMS now after trying the prototype?
- What would make you use CMS?

- **Ratings 2** – Ask the test person to fill in the ratings papers for round 2.

Now I would like to ask you to fill in this form for the round (hand over document)

- *Now we are getting close to the end of this test. Do you have any other thoughts that you would like to share or is there anything else that you think that we would like to know regarding the test?*

The following rating tables have been comprised due to same design of most of them. The ratings are used for both experience of driving a regular car *and* the CMS prototype.

RATINGS:

General experience:

How easy was it to drive with the mirrors?

Difficult		Somewhat difficult		Neither	Somewhat easy		Easy	
1	2	3	4	5	6	7	8	9

How safe did it feel to take decisions with the mirrors?

Unsafe		Somewhat unsafe		Neither	Somewhat safe		Safe	
1	2	3	4	5	6	7	8	9

How practical was it to drive with the mirrors?

Impractical		Somewhat impractical		Neither	Somewhat practical		Practical	
1	2	3	4	5	6	7	8	9

What is your general attitude towards driving with mirrors?

Negative		Somewhat negative		Neither	Somewhat positive		Positive	
1	2	3	4	5	6	7	8	9

For the all following situations:

- **Drive through darkness/parking garage**
- **Entering a larger road**
- **Drive straight on an 80 km/h road**
- **Overtaking**
- **Drive in roundabout**
- **Exiting the car**
- **Reverse parking**
- **Drive through an intersection**

...these three ratings were made for respectively situation:

How easy was it to drive with the mirrors?

Difficult		Somewhat difficult		Neither	Somewhat easy		Easy	
1	2	3	4	5	6	7	8	9

How safe did it feel to take decisions with the mirrors?

Unsafe		Somewhat unsafe		Neither	Somewhat safe		Safe	
1	2	3	4	5	6	7	8	9

How practical was it to drive with the mirrors?

Impractical		Somewhat impractical		Neither	Somewhat practical		Practical	
1	2	3	4	5	6	7	8	9

After rating each situation for regular car respectively CMS car, the questionnaire ended with asking for “*other comments*”.

Appendix I – Origin of General Guidelines for designing CMS

In this appendix the general guidelines are structured in a way making it possible to follow what findings, phases and sources they derived from.

Table 18

General guidelines, the findings they are derived from as well as what source the findings originated from.

Guideline	Finding	Origin
GG1: Identify and determine what should be achieved regarding user performance when using CMS. Decide what the aimed time-off-the-road, number of glances, detection-time and distance estimation and possibly other aspects should be.	What is considered good/safe user performance is situation dependent	Phase I: Reflection of Literature study, Schmidt et al. (2016) & Berberich (2021)
GG2: The displays should be placed close to the driver's forward line of sight on the dashboard. The closer to this position the displays will be horizontally, the shorter/lower the detection time, time-off-the-road and perceived workload will be, and the higher the perceived safety and preferences will be. The farther up the displays will be vertically on the dashboard will increase the number of glances.	The distance to the display does not affect distance perception	Phase I: Literature study, Flannagan et al. (2002)
	The closer to the driver's forward line of sight the sideview displays are placed, the more it decreases detection time, time-off-the-road, perceived workload and will over time increase the perceived safety and preferences	Phase I: Literature study, Beck et al. (2017), Berberich et al. (2021) & Schmidt et al. (2016)
	Placing the sideview displays farther up towards the driver's line of sight vertically will decrease the number of glances	Phase I: Literature study, Schmidt et al. (2016)
GG3: The distance to the display should however be considered so it is placed far enough away from the user's ocular points to not to cause strain. The distance to the display does namely affect how straining it is to accommodate between the direct and indirect vision.	Decreased distance between the driver and the display increases the effort of switching accommodating between the direct and indirect vision	Phase III: User test 1, long and short-distance tests
GG4: Integrating the two sideview images into one or two displays can be chosen according to preference. The number of displays will not increase detection	Integrating the two sideview displays into one monitor will not increase detection time or perceived stress level nor decrease the perceived overview	Phase I: Literature study, Berberich et al. (2021)

time or perceived stress level nor decrease the perceived overview.		
<p>GG5: The FOV, magnification factor and screen size should be considered in relation to each other.</p> <ul style="list-style-type: none"> • FOV should be determined first since the horizontal FOV affects the ability of maintaining control of the surroundings and lane keeping and lateral distance estimation, even if it does not affect the longitudinal distance perception. • The magnification factor should be determined second since it will affect the longitudinal distance estimations made using the system. • Screen size should be determined third since it has no documented impact in on user performance in driving. 	The magnification factor impacts the distance estimation	Phase I: Literature study, Flannagan & Mefford (2005), Roscoe (1984) & Van Erp & Padmos (2003) Phase 3: User test 1, long & short-distance test
	A larger horizontal FOV increases the lateral lane keeping ability and general peripheral control	Phase I: Literature study, Van Erp & Padmos (2003)
	The horizontal FOV has no impact on longitudinal distance perception for the sideview displays	Phase I: Literature study, Van Erp & Padmos (2003)
GG6: The longitudinal placement of the sideview cameras can be determined according to preference. This placement does not affect distance estimation.	Distance estimation is not affected by the longitudinal placement of the sideview camera	Phase I: Literature study, Bernard & Hecht (2020)
<p>GG7: A vehicle reference should be present in the sideview images. A vehicle reference present in the images increases the lateral positioning ability and eliminates the effect that the vertical placement has on distance estimation.</p>	Adding a vehicle reference in the sideview images eliminates the vertical camera placement parameter's impact on distance estimation	Phase I: Literature study, Bernard & Hecht (2020)
	A vehicle reference present in the sideview displays increases the lateral positioning ability	Phase I: Literature Study, Thomas (1991), through Van Erp & Padmos (2003)

<p>GG8: If a vehicle reference however is not present in the sideview images, the vertical placement of the sideview cameras should be chosen more carefully. Without a vertical reference point, a lower placement then leads to longer distance estimations compared to higher camera placements. This decision should also consider that the interaction of the vertical placement and chosen FOV will affect the lateral distance estimation.</p>	<p>Lower vertical placement of the sideview camera leads to longer distance estimations compared to higher camera placements Phase I: Literature study, Bernard & Hecht (2020)</p>	<p>Phase 3: User test 1, long & short-distance test</p>
	<p>The interaction of the vertical placement of the sideview camera and the horizontal size of the FOV impacts the lateral distance estimation</p>	<p>Phase I: Literature Study, Van Erp & Padmos (2003)</p>
<p>GG9: Choosing the vertical placement of the VIRM camera should consider that the longitudinal distance estimations at higher placement will be affected by the zoom level. This impact decreases with lower positions. At the higher positions, a larger FOV and smaller magnification factor leads to longer distance estimations.</p>	<p>The interaction of the vertical camera placement (of the VIRM) and FOV/magnification factor impacts the longitudinal distance estimation at higher positions. When it does, a larger FOV and smaller magnification factor leads to longer distance estimations.</p>	<p>Phase III: User test 1, short-distance test</p>
<p>GG10: The image resolution should be high enough for the user be able to take in all necessary details and distinguish objects and depth cues that are necessary for interpreting distance. Higher resolution will lead to shorter distance estimations compared to lower.</p>	<p>Higher image resolution will lead to shorter distance estimations compared to lower resolution</p>	<p>Phase I: Literature study, Van Erp & Padmos (2003)</p>
	<p>Higher image resolution will increase the ability to detect and distinguish objects compared to lower resolution</p>	<p>Phase I: Literature Study, Van Erp & Padmos (2003)</p>
<p>GG11: The image update rate should be high enough for the user to be able to detect and distinguish objects as well as estimating distances to objects. Higher image update rates will lead to increasing those abilities and shorten the estimated distances.</p>	<p>Higher image update rate will lead to shorter distance estimations compared to lower update rates</p>	<p>Phase I: Literature study, Van Erp & Padmos (2003)</p>
	<p>Higher image update rate will increase the ability to detect and distinguish objects compared to lower update rate</p>	<p>Phase I: Literature Study, Van Erp & Padmos (2003)</p>

<p>GG12: Pictorial depth cues should be used to modify the user perception of the image. This should be done if there is a need to further increase the user performance of using the system after altering the previously mentioned designed parameters.</p>	<p>Pictorial depth cues can be used to alter distance perception:</p> <ul style="list-style-type: none"> • Larger objects will appear as closer than smaller ones • Objects that are located on either of two converging lines will appear to be closer if they are further away from the converging point • Brighter objects will appear to be closer compared to darker objects in the same image • Objects overlapping other objects will appear to be closer compared to the overlapped one • Sharper objects will appear to be closer compared to more blurred ones • Objects with clear textures will appear to be closer compared to the ones with more undefined 	<p>Phase I: Literature study, Rößing (2016), Teittinen (1993), Braunstein & Ozkan (2010), Levitin (2002), Pinna (2012), Durand et al. (2002) & Cherry (2021)</p>
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Appendix J – Origin of Guidelines for Improving the CMS Prototype Considering User Performance

In this appendix the CMS prototype guidelines are structured in Table 19 making it possible to follow what findings, phases and sources they derived from.

Table 19

Specific guidelines for improving the CMS prototype, the findings they derived from as well as the finding's source origin.

Guidelines for improving the CMS prototype car	Finding	Origin
<p>SG1: The user performance and experience should primarily be improved in the driving situations of changing lane, performing overtakings and driving in roundabouts. These scenarios are experienced as the most difficult ones, and the reasons for that should be evaluated more in detail.</p>	<p>The driving situations of changing lane, performing overtakings and driving in a roundabout was considered difficult among the participants, partly because the field of view was perceived as limited</p>	<p>Phase III: Reflections from user test 2, difficult scenarios</p>
<p>SG2: The sideview FOV should preferably be dynamically changed between the different driving situations.</p> <ul style="list-style-type: none"> • Slightly wider when changing lane, performing overtakings and driving in roundabouts • The sideview displays should continue to cover a vertical FOV farther down vertically than a mirror as they do in the prototype during parking situation 	<p>The users thought that different FOV and camera viewpoints suited better during different driving situations</p>	<p>Phase III: Reflection from user test 2</p>
<p>SG3: Changes that are made to optimize the user performance for changing lane, performing overtakings and driving in roundabouts should consider and not compromise the user performance when driving in other scenarios. This is important to keep in mind since different scenarios could benefit from settings that are contradictory towards each other.</p>	<p>The driving situations of reverse parking, driving in darker light conditions and highway driving were considered easy</p>	<p>Phase III: Reflections from user test 2, difficult scenarios</p>

<p>SG4: The CMS displays should remain turned on some time after the car is turned off. Shutting the displays off immediately reduces the user's ability of perceiving the surrounding when exiting the car which could reduce safety.</p>	<p>The displays were turned off immediately as the car was, preventing the user from seeing the rear surroundings when exiting the car</p>	<p>Phase III: Reflections from user test 2, difficult scenarios</p>
<p>SG5: The CMS displays should light up less during dark conditions, and preferably adjust to changes in lighting automatically. The current light intensity in the CMS prototype causes distractions from the direct vision for the user, which is straining for the user and could decrease safety.</p>	<p>Some users thought that the displays lit up too much during dark conditions, causing strain and distraction from the road</p>	<p>Phase III: Reflections from user test 2, display resolution, quality and lighting conditions</p>
<p>SG6: The surface of the displays should not be reflective. Reflective display screens provide two images to focus on; the displayed image and a reflected image, and during certain exterior lighting condition this can prevent the user from perceiving the displayed image at all, which decreases safety. Perceiving the reflected image instead of the displayed imaged is furthermore frustrating from a user perspective.</p>	<p>The highly reflective surface of the middle display caused significant difficulties in focusing on the displayed image instead of the reflected image, reducing the ability of seeing important rearward information</p>	<p>Phase III: Reflections from user test 2, display resolution, quality and lighting conditions</p>
<p>SG7: The user should access direct vision through the rearview window. The user is adjusting to using CMS and needs direct vision accessible initially to better understand how reality is translated into the displayed images.</p>	<p>The users thought it was difficult to get a reference of how the image related to the real world when the direct vision through the rearview window was removed</p>	<p>Phase III: Reflection from user test 1 and 2</p>

<p>SG8: BLIS warnings should be integrated into the CMS system. There are still uncertainties regarding if the indirect vision in the CMS prototype covers all blind spots, and users want the assurance of detecting objects by maintaining BLIS warnings in the system.</p>	<p>The participants expectations were that CMS would cover also the blind spots (- it does not), but at the same time felt unsafe trusting that it would</p>	<p>Phase III: Reflections from user test 2, support systems and improvements</p>
<p>SG9: 360 view/parking camera should be mandatory when choosing CMS in the car. The current solutions in the CMS prototype are not providing enough information to maintain the user performance in parking situations only using the information displayed on the CMS screens.</p>	<p>Reverse driving at straight or small angles worked well for the participants, but doing so at wider angles was extremely difficult only using CMS</p>	<p>Phase III: Reflections from user test 2, support systems and improvements</p> <p>Own observations</p>
<p>SG10: The distance between the closest display (the left hand sideview) and user's eyes should remain the same or at least not be significantly smaller. Reducing the distance significantly will increase strain on the user for accommodating between the direct and indirect vision.</p>	<p>The distance to the displays did not cause strain on the users testing the CMS prototype in user test 2, but it however did when testing it in user test 1</p>	<p>Phase III: Reflection from user test 1 and 2</p>
<p>SG11: The size and shape of the sideview and middle display should cohere greater. Preferable ways of improving this is to:</p> <ul style="list-style-type: none"> • Increase the overall size of the middle display. Users perceived the current VIRM size as too small. <p>Decrease the height of the sideview displays and/or</p>	<p>The users pointed out that the two types of displays varied greatly from each other considering shape and height, causing concerns regarding if the displays belonged to the same system or were different</p>	<p>Phase III: Reflections from user test 2, size & FOV</p>

<p>increase the height of the VIRM</p>		
<p>SG12: The distance perception should be increased for the middle rearview display, suggestibly by using the parameters described in Table 11. The difficulties are experiences as very much decreased in the prototype car compared to mirrors.</p>	<p>The users had strong difficulties understanding distances using the middle rearview display</p>	<p>Phase III: Reflections from user test 2, Distance perception</p>
<p>SG13: The system should provide the user with a greater mapping between the surrounding and the images provided in the screens. In the current prototype the mapping is not sufficient to understand where the images are located in the real world, especially not for the middle rearview image. The horizontal FOV for the middle display should be decreased. There is no need for it to overlap the sideview mirrors to the high extent as it currently does. The fact that it does decreases the mapping ability between the images and where they are located in the real world.</p>	<p>The users found it difficult to understand where the images shown on the displays were located in reality</p>	<p>Phase III: Reflections from user test 2, easier scenarios, Image perception</p>
	<p>The images in the displays overlapped to a high extent, causing confusion in where the image was located in the real world</p>	<p>Phase III: Reflections from user test 2, size & FOV</p>
<p>SG14: The images provided through the sideview respectively middle display should provide images that harmonize better regarding level of magnification and object size. Not harmonizing</p>	<p>The images in the two types of displays did not cohere regarding magnification and perceived object size, making it difficult to know which one to base decisions on</p>	<p>Phase III: Reflections from user test 2, Image perception</p>

<p>decreases the user’s ability of knowing what provided info should be prioritized. The image in the middle rearview display should be less zoomed in, in relation to its current size.</p>		
	<p>The middle rearview display image was too zoomed in considering its size, making it difficult to get a perspective of where objects were located in the surroundings</p>	<p>Phase III: Reflections from user test 2, Distance perception</p>
<p>SG15: The quality and resolution of the sideview respectively middle displays should harmonize better. The sideview display resolution should preferably be adjusted towards the quality and resolution of the middle display since it was favored among the users.</p>	<p>The participants experienced the resolution of the two display types as different, and thought that it was too low in the sideview displays while somewhat too high in the middle display</p>	<p>Phase III: Reflections from user test 2, display resolution, quality and lighting conditions</p>

Appendix K – Origin of Guidelines for Future Work

This appendix contains guidelines for future work, structured in Table 20 making it possible to find the origin of each guideline.

Table 20

Guidelines for future work related to the source the originated from.

Guidelines for future work	Origin:
Evaluate what impact spatial orientation aids could have on distance estimation, for different concepts and over longer periods of time	Phase I: Literature study, Van Erp & Padmos (2003)
Evaluate the impact magnification has on distance estimation, for the magnification range between 0 and 2.0 and in the most critical use scenarios; <ul style="list-style-type: none"> • Reverse driving • Driving in roundabout • Driving in intersections • Performing overtakings 	Phase I: Literature study, Flannagan & Mefford (2005), Roscoe (1984) & Van Erp & Padmos (2003) Phase III: User tests, user test 1 Phase II: FMEA
Research and evaluate what parameters or functions can be used to optimize the object detection ability using CMS in all types weather and light conditions	Phase I: Literature study, Schmidt et al. (2016) Phase III: User tests, user test 2
Generally, perform CMS studies during longer time periods	Phase III: Reflection from user test 2
Investigate at what distance to the screen that the accommodation starts to bring problems.	Phase II: Expert interviews Phase III: User test 1 & 2
Investigate if a too large FOV would overload the driver with information.	Phase I: Reflection of Van Erp & Padmos (2003)

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