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COLLISION WARNING DESIGN IN AUTOMOTIVE HEAD-UP DISPLAYS

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ABSTRACT

In the last few years, the automotive industry has experienced a large growth in the hardware and the underlying electronics. The industry benefits from both Human Machine Interface (HMI) research and modern technology. There are many applications of the Advanced Driver Assistant System (ADAS) and their positive impact on drivers is even more. Forward Collision Warning (FCW) is one of many applications of ADAS. In the last decades, different approaches and tools are used to implement FCW systems. Current Augmented Reality (AR) applications are feasible to integrate in modern cars. In this thesis work, we introduce three different FCW designs: static, animated and 3D animated warnings. We test the proposed designs in three different environments: day, night and rain. The designs static and animated achieve a minimum response time 0.486 s whereas the 3D animated warning achieves 1.153 s.

Keywords: Automotive, AR, HUD, FCW design, collision.

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FOREWORD

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Hamza Zair

ABBREVIATIONS

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistant System
AEB	Autonomous Emergency Braking
AMTTC	Adjusted Minimum Time-to-Collision
API	Application Programming Interface
AR	Augmented Reality
AUTOSAR	AUTomotive Open System ARchitecture
CAVE	Cave Automatic Virtual Environment
CMBS	Collision Mitigation Braking System
CNN	Convolutional Neural Network
CRT	Cathode Ray Tube
DLP	Digital Light Processing
ECU	Electronic Control Unit
DoF	Degree of Freedom
FCW	Forward Collision Warning
FCM	Forward Collision Mitigation
FoV	Field Of View
FPS	Frames Per Second
GPS	Global Positioning System
GPU	Graphics Processing Unit
HDD	Head-Down Display
HMD	Head Mounted Display
HMI	Human Machine Interface
HMPD	Head-Mounted Projection Display
HOG	Histogram of Oriented Gradients
HUD	Head-Up Display
ISMAR	International Symposium on Mixed and Augmented Reality
LIDAR	Light Detection And Ranging
MAR	Mobile Augmented Reality
NFT	Natural Feature Tracking
OCR	Object Character Recognition
OEM	Original Equipment Manufacturer
OLED	Organic Light-Emitting Diode
ORD	Objective Rating of Drowsiness
OST	Optical See-Through
PDA	Personal Digital Assistant
PC	Personal Computer
RFID	Radio Frequency Identification
SIFT	Scale Invariant Feature Transform
SURF	Speeded-Up Robust Features
SUV	Sport Utility Vehicle
RSSI	Received Signal Strength Indicator
TOA	Time Of Arrival
TTC	Time To Collision

UMPC	Ultra-Mobile PC
UX	User Experience
VE	Virtual Environment
VFD	Vacuum Florescent Display
VR	Virtual Reality
VST	Video See-Through
WIFI	Wireless Fidelity

1. INTRODUCTION

1.1. Background

The automotive industry is a recent term which refers to the group of organizations and companies that contribute to the vehicle industry. It can be manufacturing, software development, marketing, and many other areas that involve vehicles in general. This industry contributes largely to economic growth today. Different car companies may manufacture their own car components or parts that will be used in other cars. These companies are referred to as Original Equipment Manufacturer (OEMs). The fact that OEMs have a common specification and performance criteria makes it easier to integrate the components in new cars design even from outside the company or organization. Different car manufacturers have their own products but agree on many standards and specifications for lean development and manufacturing.

Figure 1. Automotive Head-Up Display
https://i.ebayimg.com/images/i/332312984183-0-1/s-l1000.jpg

1.2. The HUD History

Car displays are one of the highly important instruments in cars. They are one of the main interaction interfaces between drivers and their cars. The first appearance of a display instrument was in the form of CRT displays. They were first prototyped in 1897 and became available commercially in 1922. Twenty-four years later, another revolutionary idea was introduced to enhance the user experience even further. In 1946 Paul Fitts [1] proposed the idea of overlaying different images on the same display instrument to give the user an augmented reality experience, but the first implementation of the idea was on a military aircraft as a Head-Up Display. After 1985 the HUD gained more attention in the automotive industry [1].

The Head-Up Display (HUD) is an instrument that displays data on the screen without distracting the user or keeping the driver from losing focus on the main viewpoint [2][3]. The origin of the term is related to the pilot and how he/she can view data on the main display [4] that is usually on the upward position. The pilot is usually required to act and respond quickly, by displaying data on the transparent screen makes it easier to act quickly [3] without extra thought processing.

One of the most important reasons for selecting the automotive head-up display (HUD) over the traditional head-down display (HDD) is reducing the driver's distraction or what is known as eye-off-the-road time [5]. The HUD provides the driver with a minimum information access cost and improves driving performance and safety [6].

The year 1988 marks the first appearance of the commercial automotive HUDs by General Motors and many car companies adopted it afterwards. The use of automotive HUD is expected to be increasing in the upcoming years. It is expected that by 2024, around one-third of the cars will be equipped with a HUD [6].

The HUD research has been beneficial because of the current ADAS and its improvement on the driver's safety [2]. Because of ADAS, there exists a large number of HUD applications [5]. The applications can vary from different warnings such as lane departure and forward collision [7] to other types of static visualization such as speed and adaptive cruise control.

1.3. Contribution

The main objective of this research work is to enhance the driving experience by designing and implementing an FCW in the HUD and make use of the design concepts from HMI research [8]. The User Experience (UX) has a huge impact on the driver's safety. It is the most important factor when discussing the introduction of a new technology to the car cockpit. It compromises between safety and the amount of information that can be processed by drivers [9].

After the design and the implementation of the FCW, the evaluation will be conducted on different people who have driven an actual car before. There will be many test cases where the participants will have different driving scenarios. Different aspects of the design have to be considered and here is the list of the most important ones:

- **The size:** It should be suitable for the HUD size. The size should compromise between the notification visibility and the HUD blind spot.
- **The color:** The colors should be clear but not too distracting.
- **The animation:** The behaviour of the notification during its life time should keep the driver noticed and responsive to the warning.

- **The topography (3D or 2D):** The augmented image of the notification on the HUD should not affect the driver's perception of the surrounding 3D space.
- **The weather effect:** The driver's cognition is heavily influenced by the environment change [10],e.g., weather, so only necessary information should be displayed.
- **The frequency:** How often the notification appears (flickers) on the HUD after and during the danger zone.
- **The lifetime:** There are three time periods that should be considered:
  - T1: The period that the warning will be alive in the memory when the car enters the collision zone.
  - T2: The period that the warning will be alive in the memory when the car is in the collision zone.
  - T3: The period that the warning will be alive in the memory after the car leaves the collision zone.

1.4. Related Work

Many research has been conducted to build and assess the efficiency of the FCW system. We will discuss related research but before that we need to clarify some terminologies.

- **Brake Response Time** is the elapsed time since the FCW first appears until braking [10].
- **Adjusted Minimum Time-To-Collision (AMTTC [11])** is the remaining time for the driver before a crash. The positive values refer to the remaining time before collision. The negative values are used as a severity measure. The larger the negative values, the more severe the collision is [12].
- **Threat period** refers to the period that the driver has a risk of colliding with another car. It is correlated with the driver's speed.

A research study [13] introduces a natural driving study that focuses on the driver's performance by analyzing the eye movement and the response to brake-capacity FCW. The study considers the scenarios where drivers respond to both predicted and unpredicted events. The data collection is performed during and after the threat periods.

Another study [14] performs an analysis of the FCW modality and its timing. Different sets of parameters are considered in this study. Some of these parameters will be used for evaluation as safety and performance measures when designing and implementing the FCW notification. Another study [15] analyzes the crash warning systems using head-up interfaces. The experiments are conducted in four different scenarios. The participants in this experiments perform the tasks and report back verbally whenever a threat is present.

1.5. Thesis Structure

This thesis is structured as follows: Chapter 1 is an introduction to this research, which contains a literature review concerning the automotive industry and the HUDs history. It also states the objectives and the scope of this research. It contains a section that represents the terminology used in automotive for both industry and research. In Chapter 2, we present the theory behind AR and the different key concepts in both machine vision and AR. We also discuss the AR applications and limitations in general and in automotive in particular. Chapter 3 discusses the automotive HUD, ADAS applications and the HDD. Chapter 4 discusses the related works in more details. In chapter 5, we present the software and hardware used in our implementation and the different test cases and scenarios. Chapter 6 discusses the evaluation of our implementation. It contains the collected data from the different driving scenarios followed by discussions. In Chapter 7, we conclude our work and provide some insights for future work.

2. AUGMENTED REALITY

2.1. Introduction

This chapter discusses the Augmented Reality (AR) in more details and presents AR concepts that are necessary for chapter 3. It discusses the general AR framework and how it is mapped to the real world. It contains the most important AR concepts with some background.

Augmented Reality (AR) refers to the real world with superimposed synthesized objects. It allows for the coexistence of both virtual and real objects in the same mixed space. It lies in the middle of the Virtual-Real perception as shown in Figure 2. It can also refer to the application where a Head Mounted Display (HMD) is needed [16]. In a more concise form, AR applications will have these three features [16]:

1. A combination of the real and the virtual world.
2. A real time interactive process.
3. A three dimensional registration.

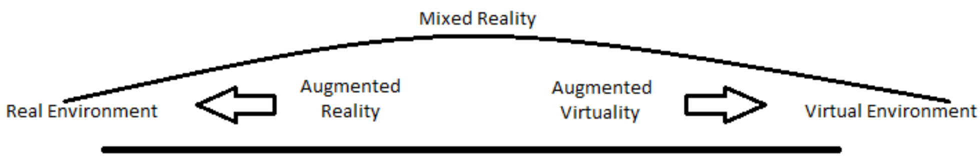

Figure 2. Mixed reality consortium

2.2. Image Registration

The image registration is the first and most important step of any AR application and it is usually performed after calibrating the camera. The registration refers to the process of mapping the virtual image to the real world image in an AR application. The mapping is performed using mathematical tools and state-of-the-art algorithms. The AR registration is performed in real time, so the computational complexity and the optimized hardware are highly correlated. AR affects the human senses, so it is not like Virtual Reality (VR) where the user is exposed to a synthesized 3D image and the interaction is based on the behaviour of the user inside the virtual world. Both AR and VR use virtual images and provide the user with interactive tools and methods depending on the applications. One of the most important differences is that AR mostly maps a virtual world to the real world. On the other hand, VR takes the user entity and maps it to the virtual world where a new set of physical laws are applied.

2.3. Displaying Techniques

Any AR system is built around the user, so the interaction layer constitutes a major role. This layer can have different channels, which can be a single or a combination of different human senses. There are five types of displays which can be aural, olfactory for smell, haptic for touch, gustatory for taste, and visual displays [17]. Throughout this report, the term display will be used to refer only to the visual display, which will be discussed with more details in the upcoming subsections.

2.3.1. See-through HMD

The Head-Mounted Displays (HMDs) are devices used for VR and AR applications. For VR applications the user is disconnected from the physical world by interacting only with the virtual world; whereas, for AR applications, the user can see the physical world with superimposed objects by either optical or video technologies [18]. They can be either Optical See-Through (OST) or Video See-Through (VST) displays [18].

- **Optical See-Through (OST):** OST displays allow the user to naturally see the physical world with their eyes through holographic optical elements, half-silvered mirror, or a similar technology [18]. The main advantages of OST are simple and lightweight structure, real-time view of the physical scene and zero-parallax between the real and the augmented views [18].
- **Video See-Through (VST):** VST displays provide a video view of the physical world with super imposed objects on it. Because of the advances in computer vision [19], the VST displays can overcome occlusion problems more efficiently than OST displays [18]. They provide consistency between real and augmented views because of the available image processing techniques for image projection and manipulation like intensity correction, tint correction, and blending ratio control [18].

2.3.2. Projection-Based Displays

Projection-based displays are suitable for applications that do not require users to use any extra AR instruments. These displays use many techniques to project graphical information on real objects or other usual surfaces. They require a compromise between the lighting requirements for both the camera and the projector. This makes it challenging to implement systems based on such displays [18]. Projector illumination techniques presented by Bimber and Fröhlich [18] used view-dependent OST displays to correct the occlusion effects. In another work, Bimber et al. used an ordinary surface for view-dependent stereoscopic visualization that uses four basic components: geometric warping, radiometric compensation, multi-focal projection, and multi-projector contributions [18]. They became the main focus of the display technology. They became the main focus of the display technology. The main advantage of these displays is collaborative viewing, which can improve the user experience. It makes it possible for multiple users to use the same application without extra settings.

Another aspect of these displays is the resolution they have. According to [20], there are many high-resolution virtual environment projection techniques and technologies used. One of these technologies is the Cave Automatic Virtual Environment (CAVE) which is composed of square back projected displays that can vary from three to six displays. The reason for the back projection is to remove any distraction that can happen because of the user shadows [21].

2.3.3. Handheld

Handheld displays can be a good alternative for the HMD and HMPD displays because of the high mobility, availability and social acceptance [18]. The AR applications became more popular because of the availability and the mobility of the recent handheld devices like smartphones, Ultra-Mobile PCs (UMPCs), Personal Digital Assistant (PDAs) [18], and many more. The first mobile AR system is introduced by Möhring et al. [18]. The system integrates the 2D and 3D graphics into a live video stream with a low resolution. Another contribution was made by Wagner et al. where they implemented the first portable PDA AR application. They developed another computer graphics library Klimt [18] which targets PDAs and mobile phones. The Klimt library implementation wraps OpenGL ES.

2.4. Tracking Techniques

Tracking refers to the evaluation of the current pose information [22]. The information is assumed to be a varying quantity such as speed, translation, rotation, acceleration, and different motion configurations. There are techniques and tools to calculate and measure these quantities for different AR applications. The collected pose information is used to align the virtual objects with the physical ones in the physical world [22]. There are mainly three AR tracking techniques, sensor-based, vision-based, and hybrid tracking techniques. A general overview of the different tracking techniques is shown in figure 3.

2.4.1. Sensor Based

Based on the types of the sensors used [22], these techniques can be divided into inertial, ultrasonic, magnetic, and electromagnetic techniques. The sensors used

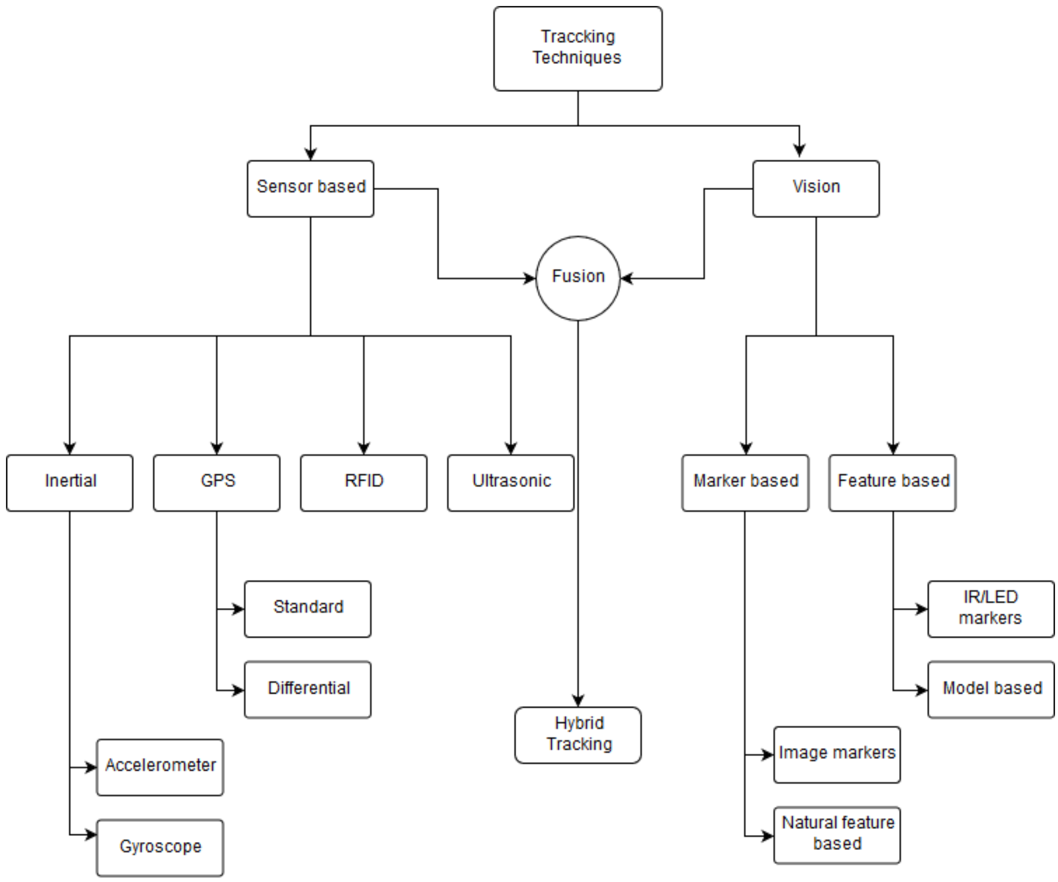

Figure 3. Tracking techniques in AR [23]

include inertial, acoustic, optical, mechanical, magnetic, and ultrasonic sensors [22][18].

- **Inertial-based techniques:** These techniques depend heavily on the acceleration that the sensors measure. The reason for focusing mainly on acceleration is the fact that both the velocity (hence the speed), position, and angle can be calculated using the acceleration value [22]. These techniques prove useful in many situations and even today these sensors are heavily dependant upon on almost all AR and VR applications. Recently, these techniques became more popular because of IMUs (Inertial Measurement Units) which are devices with accelerometers and gyroscopes. The acceleration and the rotation measurements are performed by the IMUs at 100 fps which makes them suitable for hybrid applications as well. The IMUs are prone to error because of drift and the measurements must be updated at high frequency, 100 FPS [24]. The IMUs are portable because of their size, they are very common in the smartphones.

- **Ultrasonic-based techniques:** The ultrasonic sensors are used in these techniques for estimating the target's position and velocity with high accuracy in a controlled environment. These sensors are not very common in MAR (Mobile Augmented Reality) and they are sensitive to ambient noise, temperature, and occlusion so they have been replaced by other techniques [22].

- **Magnetic-based techniques:** These techniques use the earth's magnetic field to obtain the target's spatial information. They use other tracking techniques and have six degrees of freedom. The sensors used in these techniques are suitable for indoor applications because these sensors are highly sensitive to ambient electromagnetic fields [22].

- **Electromagnetic-based techniques:** The basis of these techniques can be Time Of Arrival (TOA), Received Signal Strength Indicator (RSSI), or the phase shift of the received signal. These techniques can include GPS, WIFI, RFID. The GPS system is widely used for outdoor applications but also has limitations because it can not be used for indoor applications and even for outdoor applications where high accuracy is needed. Many contributions were made to overcome these challenges but they used base station locations for high accuracy. Some of these works include differential GPS and real-time kinematic GPS (RTK GPS). The WIFI is used for nearby applications and it has the problem of connectivity loss when mapping the environment. Another one is the RFID which uses tags for tracking and it requires high proximity. The RFID is not suitable for new environments and large targets [22].

These techniques use mostly one type of sensors, but there are many applications where different sensors are used and data is fused to obtain the highest accuracy possible.

2.4.2. Vision Based

These techniques depend on the feature similarity for estimating the pose. These techniques are classified into two categories, marker-based and markerless (feature-based) techniques [25] depending on the tracked features.

Marker-based techniques: These techniques use fiducials as features [22]. The fiducial has predefined geometry and texture. One type of the fiducial marker is the planar fiducial due to its robustness under light changing conditions. It can be used for systems that require minimum computational power. Markers with binary images, similar to Figure 4, are commonly used. Usually, the marker detection techniques are simple limited. The marker identification process follows this pipeline [25]: (1) Grayscale conversion of the input image. (2) Binary thresholding. (3) Contour detection. (4) Marker matching. (5) Marker detection and encoding. (6) 3D Pose estimation. Markers can be categorized as follows [26]:

1. Markers with black boundaries: They are rectangular images surrounded by a thick black boundary that is used to track the marker. The tracking is based on tracking the thick border surrounding the marker after using suitable thresholding. In order to use this technique in an AR system, these

markers have to be stored in a database beforehand to be compared with the detected markers from the physical world. After detecting the marker the AR application context will display the relevant object accordingly [26].

Figure 4. Black boundary marker

2. NFT(Natural Feature Tracking) markers: These markers differ from the previous markers in the borders. They detect the image as it is from the physical world (Figure 5) and process it by extracting its features. The extracted features are not as accurate as the previous ones because they contain more visual information. These markers use many feature extraction algorithms for these markers (for example, SIFT, HOG, SURF, Wavelet-based techniques, or deep feature using CNN for more complicated features). Finally, the extracted and the stored markers are compared [26].

Figure 5. Natural feature tracking marker
https://cdn.wikitude.com/static-website/2015/03/17101458/SDK-7-SLAM-PAGE-truck.png

3. GPS based markers: They are based on GPS for locating the objects in the real world. The location can include other objects that need to be tracked in the AR application. These objects can include buildings or any other objects that can be located using GPS. The accuracy of the position obtained from the GPS can be off up to a few meters, so the accuracy of such markers is lower than the previously mentioned markers [26].

Despite being cheap and robust to light changes, the marker-based techniques have many disadvantages that need to be eliminated in certain applications.

These techniques have the following limitations such as the occlusion, which affects heavily the detection; the color constraint (black and white) which is expected since the technique is computationally cheaper with only two colors; the marker shape is mostly rectangular. The design of such markers is not related to real objects, so algorithms used to detect such markers have high performance [25].

Marker-less based techniques: These techniques use object recognition as an underlying basis. Generally, any object containing enough discriminative information in the scene can be targeted in this approach. There are many applications where these techniques can be used such as company logos and magazines [25]. The main advantages of using such techniques are:

1. Detecting real-world objects without referring to extra markers.
2. Tracking the object in the real world even in the presence of partial occlusion.
3. Any texture can be used except the ones that are solid or gradually smooth [25].

The camera is projected in the 3D space by combining object detection and image recognition algorithms. Because there is no constraint on the complexity of real object structure, pose estimation algorithms are required for 3D projection [25]. To detect an arbitrary image in a video, feature descriptors are used. The reason is that image pixels cannot be compared directly with the reference image due to the fact perspective transformation may affect the patterns in an image. The feature extraction is performed using appropriate feature detection algorithms to search for geometric properties such as blobs or corners which are based on the gradient and the feature-point calculations. It is very common to use feature invariance algorithms such as rotation or scale invariant feature representation. The next step is removing outliers by performing cross-checks or ratio tests. After that the homography transformation is obtained by multiplying both the rough and the refined homography then the resulting pattern is transformed into the image coordinate system to match the pattern on the input image [25].

2.4.3. Hybrid Tracking

Tracking in AR can be implemented by combining both vision and sensor techniques. In the early International Symposium on Mixed and Augmented Reality (ISMAR), markers were the basis of hybrid methods. Later applications combined both inertial and vision-based techniques in order to remove outliers and compensate the slow vision-based by the robustness of the inertial techniques and benefit low jitter and absence of drift of the vision-based techniques. The object pose can be estimated and the movement information can be extracted by measuring the acceleration and the rotational speed [18]. The 2D feature-motion is obtained from the inertial data and the vision feature corrects the measurements. Alternatively, the search space for the vision-based tracker is reduced to account for more interruptions [27]. Even though the focus is on a 3 Degree of Freedom (DoF), it is possible to extend it to a 6DoF systems that include gyros in addition to other sensors such as accelerometers, compass and pedometer measurements [27]. A hybrid multi-sensor approach [28] is implemented by combining markers and inertial sensors for measuring the head's position. The work used a 3D marker set in order to obtain a precise 6DoFs.

2.5. 3D Vision

A machine vision system contains processing hardware to simulate the human vision that includes the 3D realization and identification of an object [29]. The human brain can perceive the 3D world effortlessly, but the digital machines require more processing and effective algorithms to do so. There are various machine vision applications such as object recognition, machine navigation, photogrammetry (3D model building), automotive safety, OCR, exposure bracketing, ...etc [30]. The following subsections discuss the most relevant aspects of machine vision in AR.

2.5.1. Depth Perception

The images registered by the camera are in the form of 2D images. The physical world contains real 3D objects. It is crucial for any AR system to calculate the correct distance between the camera and the objects in order to augment the virtual object in the correct location. The depth information can be obtained using different techniques. The most known one is applied to intensity images captured by two cameras that are separated from each other by a known distance [31]. Another technique is to use a moving camera to capture and compare the range images which are widely used in triangulation [31]. In addition, there are other techniques for extracting 3D information of an object. These techniques use cues such as texture and shading [31]. The brightness application is well known and applied even in art. For objects with the same size, the brighter one appears closer [32].

In a related work on AR depth perception design [33], six factors are considered: aerial perspective, shadows, shading, billboarding, dimensionality, and surface texture. The first three are used to describe the virtual object and the last three are used for its simulation in the environment [33]. These factors are defined as follows:

1. **Aerial perspective:** It is also known as the atmospheric attenuation . It is a result of the distance increase between the observer and the object. As the distance changes, the contrast between the object and the environment changes [33]. This technique is commonly used in computer graphics for estimating object positions at short and long distances [33].

2. **Shadows:** Shadows from the physical world are simulated as **cast shadows**. They are implemented using several techniques such as shadow mapping and baked lightening [33]. Some studies show that cast shadows can have a limited effect in stereo scenes [33] whereas others show that they can be useful in obtaining the object's position using monocular [33] and stereoscopic displays [34, 35]. Because there is no virtual supporting ground for rendering shadows, one approach to overcome the issue is rendering a semi-transparent plane with the same shadow shape and size then aligning it with the physical plane [33].

3. **Shading:** Virtual objects are defined by the material and the reflectance properties by their surface shading models. The non-dependency of real and virtual lightning on each other results misalignment between the virtual highlights and the physical world [33].

4. **Billboarding:** When a two-dimensional virtual object's rotation changes such that it continuously faces the camera at a constant angle. It can be useful in AR applications such as interacting with the user through holographic menus. Alternatively, it can reduce the volumetric visual cues such as the fixed angle that the user sees the virtual object which limits the depth information [33].

5. **Dimensionality:** The virtual object's dimensionality can improve the depth perception by providing extra pictorial depth cues such as curvature or linear perspective [33].

6. **Surface texture:** The importance of this pictorial cue lies in the fact that the texture density is proportional to the distance between the user and the augmented highlight. There are different arguments about the importance of a texture as a depth cue. It is shown that depth estimation can be improved by adding a separately measured texture to objects [33]. However, other studies [36] showed that texture has less depth perception effect compared to other cues.

2.5.2. Depth of Field

The depth of field is defined as the distance between the closest object and the objects that are seen by the user. It also refers to the distance to the plane containing the object of interest. The plane that contains the object is called the focal plane [37]. Objects lying on the focal plane appear sharper. Alternatively, objects lying outside the focal length i.e, at different planes will be blurred [37]. The camera lens is used to control the amount of light [38] by compromising between its aperture size and the depth of field. The larger aperture size, the more light is captured and the smaller the depth of field is [31]. Conversely, the smaller the aperture size, the less amount of light is received and the larger the depth of field [31]. The object is calculated from different aperture points to obtain the correct depth of field [37].

3. AUTOMOTIVE HEAD-UP DISPLAY

3.1. Introduction

The Head-Up Display (HUD) is one of the latest automotive technologies used by cars today. It relies heavily on the Advanced Driver Assistance System (ADAS). ADAS has various applications that aim for the driver's safety and comfort. For these reasons, the current HUDs focus on providing vital navigation information for drivers with minimum distraction. The HUDs were first dominant in the early 70s and they were used in fighter jets and later for military helicopters flying at low altitude [39].

The main topic of this chapter is the automotive HUD, but more related concepts and UX aspects will be discussed as well. First, ADAS is discussed for it is very important for the HUD. Next, the HUD design is discussed in more details. After that, HMI is discussed from driver's viewpoint. Finally, alertness and depth perception research is presented.

3.2. The Advanced Driver Assistance System (ADAS)

The advances in the automotive industry are accompanied by new strategies for making the driving experience more secure and reliable. The main three crucial parts that power modern cars are (1) software (AUTOSAR) which car manufacturers refer to when they design their own electronics,(2) electronics (ECUs) which rely on AUTOSAR but each manufacturer has his own hardware implementation, and (3) other safety measures that are provided by safety performance programs such as Euro NCAP (The European New Car Assessment Program).

The Advanced Driver Assistance System (ADAS) is part of the car electronics system and it is designed mainly to improve the driving experience [40]. The classic DAS (Driver Assistance System) relied on **proprioceptive sensors** that were used for assessing and measuring the internal values of the different vehicle sensors and parameters such as the rotational velocity and the acceleration of the vehicle. One of the systems based on these sensors was the ABS (Anti-lock Braking System) from Bosch and started production from 1978 [41]. There are a number of ADAS applications such as Lane Departure Warning (LDW) and Lane Change Assistance (LCA). The steering and lane data are collected to analyze the lane of both the current vehicle and the neighboring vehicles and prevent possible risks. If the driver makes a quick maneuver, then the system will set up a warning that lives until the driver leaves the risky lane and location. Ignoring the warning for a certain period of time makes the system intervene by trying to get back to the safe lane. In the next subsections, we discuss the ADAS applications that are mostly relevant to our research scope.

3.2.1. Adaptive Cruise Control (ACC)

ADAS tasks can range from displaying information for drivers to intervening in critical situations and taking control over the car to save the driver from bad scenarios. The automatic intervention required some time to be included as a feature in the automotive industry [40]. The current ADAS makes use of **exteroceptive sensors** such as video and LIDAR. The ACC is improved since 1999 when 30km/h was a minimum speed. Currently, systems with automatic transmission are able to cope well in challenging driving situations such as jam where the vehicle can automatically follow other vehicles [40]. The forward collision prevention systems rely on low-range and low-resolution versions of LIDAR sensors. Both Ford systems: "City Safety" [42] and "City Stop" [40] appeared in 2014.

3.2.2. Autonomous Emergency Braking (AEB)

It is known that car accidents do not only occur for vehicles moving at high speeds, but they can also occur at low speeds such as in a jam or when parking. The AEB uses different sensors to monitor the road in the vicinity of 6-8 m. A common road monitoring technology for the AEB is LIDAR which is commonly mounted on the top of the windscreen to make it easier to determine whether there is an object in the front and if so then the AEB system will efficiently assist the braking by recharging the brakes. To avoid collisions, the car will automatically brake in case of no response from the driver. If the driver intervenes by either braking or steering the vehicle away from the object, then the system will hand the system control to the driver [40]. The "City Safety" AEB system is mainly designed for protection in rear-end crash protection in urban areas [40]. The "City Safety" AEB system first appeared in XC60 Volvo around 2009. The AEB support speeds up to 30 km/h or 50 km/h [42]. The system is implemented with different characteristics and considerations under the name FCM.

3.2.3. Forward Collision Mitigation (FCM)

This system is designed for frontal collision prevention based on collecting information about the vehicle and its surroundings. The environment perception can be achieved using vision sensors, radar, ultrasonic sensors [43]. It has more strict requirements because it has to compromise between a collision risk and the driver's response time. The braking will not be launched until it has a high probability of a crash. The probability has to be close to 100% for the system to take over the braking process. The system first warns the driver through audible or tactile alerts [40], but if the driver does not respond quickly enough the system pretensions the seat belt while applying maximum braking. The Mitsubishi FCM [44] specification is shown in Table 1 and the notification is shown in Figure 6.

The Mitsubishi AEB can detect objects at distances up to 200m. When a crash risk arises, the system warns the driver using audible and visual warnings and the

Sensing technology	Radar
Frequency	77 GHz
Range	200 m
Max speed	180 km/h
Maximum deceleration	8 ms^{-2} ,if the speed is less than 30 km/h. 6 ms^{-2} ,if the speed is more than 30 km/h

Table 1. Mitsubish FCM specification [44]

AEB is activated. In case there is no response from the driver the system applies smooth braking while a warning is being triggered. If the system expects a high probability of collision, then high pressure is applied on the brakes with different deceleration values. The vehicle will decelerate at $8ms^{-2}$ if the speed is less than 30 km/h; otherwise, it will decelerate at $6ms^{-2}$ keeping in mind that the system remains active until the speed reaches 180km/h [44]. Achieving a 100% FCM implementation for all cars will reduce the fatalities to 1%, severe injuries to 3%, and small injuries to 12% according to statistical studies in Germany [44].

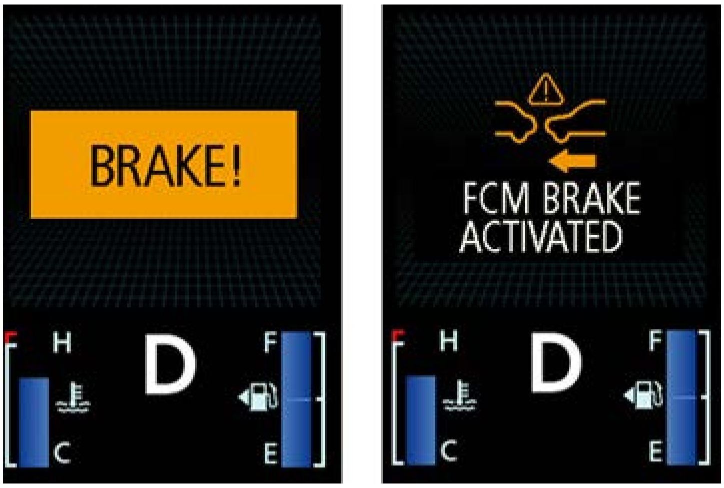

Figure 6. Mitsubishi FCM Notification[44]

It is noticeable that the notification is shown on the dashboard of the vehicle which causes even more risk of collision if the driver is not fast enough to quickly recognize it and act accordingly.

3.3. The Head-Up Display (HUD) Design

The automotive HUD is a display used for projecting the vehicle or driving information on the driver's field of view. The information displayed on the HUD is projected from another source onto the windshield [45], as shown in Figure 7. It is shown that the driver's response time to emergencies is 75% - 80% faster compared to cars without HUDs. It becomes a major parameter of the vehicle's safety [46]. The cost and the HUD size play a major role in the automotive industry. Because of the advances in the microsystem technology, the micromirrors coped with that advance and it became more feasible to consider them in modern HUDs because of their high level of integrity into the vehicles [46]. The micromirror based HUDs being integrated more in the industry, so they will be discussed in the upcoming subsection.

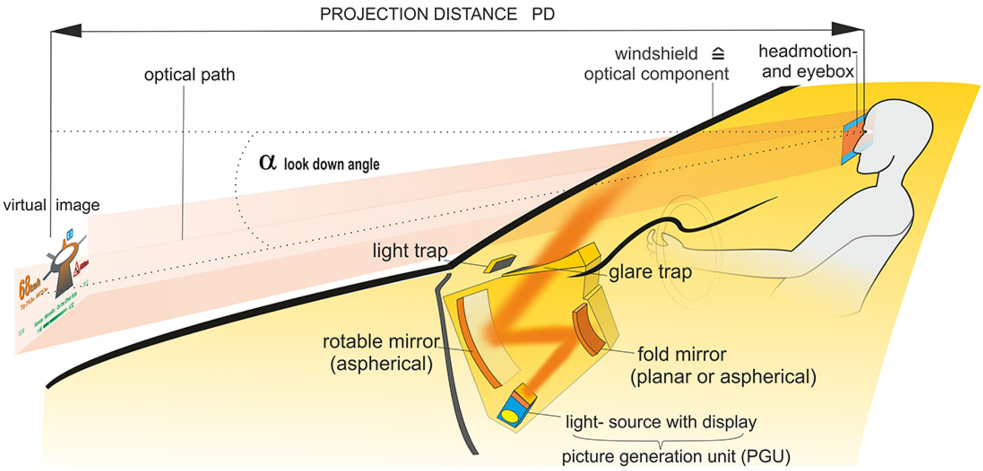

Figure 7. Continental Head-up Display http://continental-head-up-display.com/wp-content/uploads/2014/08/HUD$_{T}echnology_{S}afety,jpg$

3.3.1. The Micromirror-Based HUD

There are many HUD types that are classified according to the technology used. The manufacturing can be based on emissive displays such as OLED, VFD and backlit LCD. The latter is the most common one in the market. In addition, there are digital micromirror devices such as DLP and micromirror based laser displays. The commonly used display modules in the market today are LCDs and a custom windshield as a combiner for reflecting the virtual image [46]. The hardware consideration is moving towards the micromirror HUD because of its low cost, high contrast, and small size. A high-level view of the such HUDs is shown in Figure 8.

3.3.2. Display Module Design

The display module consists of a micromirror (CQFP44 package), a laser diode module and a double concave lens. A green, modulation capable laser diode is used operating at power < 5mW with a beam diameter <1.2 mm. The laser beam is reduced for fitting the 1 mm micromirror diameter. The CQFP44 chip contains the micromirror and it is pre-adjusted in order to align with the incident beam.

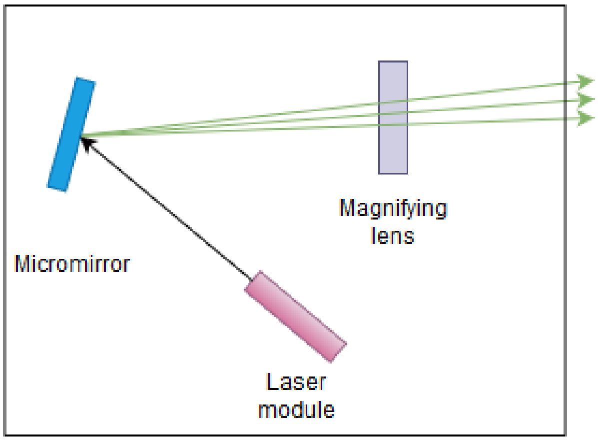

Figure 8. Micromirror display module [47]

The double concave lens is positioned such that the laser beam is intercepted. They are used for increasing the scanning angle and reducing the beam divergence caused by the micromirror curvature. The desired pattern is generated by the micromirror rotation and the laser digital modulation (ON/OFF). The laser power at the leaving the display module is < 0.8 mW. For higher visibility compared to conventional HUDs, the laser power can be increased by replacing the pinhole with a focusing lens in order to focus the whole laser beam onto the micromirror surface [46].

3.3.3. Micromirror Design

The micromirror is positioned in the center of four identical actuators. Each actuator is independently driven by a voltage and it is used to rotate the mirror plate around two axes. Every two opposite actuators rotate the plate around one axis, as shown in Figure 9. The display module should be calibrated by applying different bias voltages and recording the laser beam position using a position sensing detector [46]. Using two bias voltages, it is possible to tune each actuator and then the mirror can move around the two axes. The bias voltage used in this design is 62.5V [46].

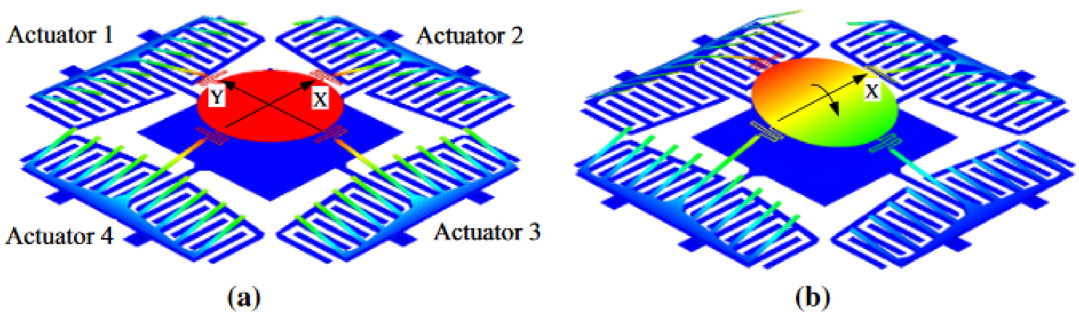

Figure 9. The micromirror package [46]

3.3.4. Current HUDs

Big car companies such as Audi, BMW and Marcedes Benz already have HUDs installed on their cars. Each company has its custom HUD. Continental is a large supplier for automotive HUDs and the previously mentioned companies are some of its customers. Many recent BMW cars have a full-color HUD and it is capable of displaying information such as directions, speed limit, warnings and BMW Nigh Vision. Corvette HUD displays more information such as tachometer, compass, the temperature outside the vehicle, selected gear and vehicle messages. Other car manufacturers that have the HUD already installed on their cars include Jaguar XE, Hyundai Genesis, Toyota Prius, General Motor SUVs and many more [48].

Because of the rapid growth of applications on smartphones, there are HUD applications such as "Navier HUD" and "Sygic" that are used to display the relevant driving information as a reverse image brightly on the windshield, as shown in Figure 10.

Figure 10. Application based Head-up Display

Current HUDs from Continental are shown in Figure 11 where (a) is for Audi A6/A7 and A8 series, (b) for BMW 3 Series, and (c) for Mercedes-Benz C-Class [49].

Figure 11. Continental Head-up Displays for Audi, BMW and Mercedes-Benz

3.4. The Importance Of HMI

HMI has been noticeably improving. LCDs were the main HMI, but nowadays there are more advanced HMIs such as touch screens, RFIDs. It plays a major role in vehicles and it has to be intuitive so that the driver should be able to interact unconsciously. When driving, HMI is crucial for timing and quick response. The design should account for dangerous and probably fatal scenarios such as foggy weather and slippery. In such situations, drivers should have quick and full access to all controls in order to assess the vehicle status properly.

A good design should be able to support and guide the user to improve the user interventions such as maneuverability, senses such as collision and lane departure symbols, and decision making such as lane detection. Consequently, all relevant driving information is delivered in a graphical way which enables the driver to process it quickly that's why the driver's cognition and perception are expected to enhance when using the HUD [8].

Text detection and reading experiment is conducted by Tsimmhoni et al. [50]. The participants were asked to detect and read names in 8 positions on the HUD. It shows that detecting and reading text on the central location of the HUD with a tolerance of 5 degrees is more preferred and it results in the best overall performance. The the second most preferred locations are the bottom row locations.

The driver-vehicle interaction can be categorized into three paradigms: (1) Interface paradigm which is a collection of integrated HMI systems that provide services to the driver, (2) Interaction paradigm which is about providing interaction channels between the driver and the car such as vocal and haptic and (3) communicative paradigm that is a continuous and real dialog that connects the driver to the vehicle [51]. The communicative paradigm is heavily integrated into modern cars in a form of different applications and services such as the notifications and warnings in the HUDs, and many ADAS applications that have been discussed in the previous sections.

Prioritization plays a major role in the driver's attention on the road. The distinction between the primary task and the secondary tasks should be done carefully such as reducing the external light intensity during a turn at night vs turning with the same light intensity. Although the HMI design makes reaching the light control easier, the decision can heavily affect the driver and the other cars on the road. This can result in an accident if the timing is not suitable.

Different driving tasks have different mental workload on the driver. These tasks can be classified into three classes: primary, secondary and tertiary tasks [45] as follows:

1. **Primary tasks:** They are mainly the car control tasks that are involved in driving: (1) steering which can be lane change for example, (2) navigation which decides the departure and destination route, (3) stabilization which is one of the most important tasks for driving safety and it is performed using different control parts and mechanisms such as steering wheel and brake pedals.

2. **Secondary tasks:** They are driving interactions such as turning the headlights up. These tasks are less important, but they are part of any driving experience.

3. **Tertiary tasks:** These are the tasks that include communication and entertainment. They are not necessarily related to the driving task directly.

Liu and Wen [52] performed a comparison between the HUD and the HDD using STI driving simulator. The participants were asked to perform four different tasks: commercial food delivery, navigation, speed detection and urgent event response. The delivery task showed no significant difference but the performance was high in the other tasks. The driver's performance is inversely proportional to the driving workload. Speed control and reaction time to urgent events and speed limit signs were positively affected using the HUD than using the HDD. The driver's awareness and caution increases when using the HUD. The mental stress was less when using the HUD and it was easier for users to get familiar in the first time they tried it [52]. When comparing both the HUD and the HDD [48], it has been found that having the HUD in the car can have either positive or negative effects on the driver.

Having the HUD installed in the car can improve the driving experience in many ways. The response time to urgent events is higher [52, 48] and there is less stress on the driver. The driver's awareness of the car speed helps driving within the speed limits (within 120 km/h). HUDs are becoming more responsive to light changes in order to reduce the effect of these changes during the night or on weather changes. Distraction can be reduced by connecting the HUD to different devices and services such as mobile phone interaction, navigation and traffic information and most importantly reducing the time that the driver has to look away from the road which can increase the risk significantly if it is longer than 2s.

On the other hand, having an HDD on the car can be better than the HUD in some situations. The HUD can have a negative effect on the driver in situations when the displayed information is irrelevant. Another important challenge is cognition where the driver has to cognitively switch between the HUD and the traffic which requires a processing time and may cause to cognitive tunneling. The latter occurs when the driver's attention is consumed by processing the information while neglecting the surrounding environment [53]. A pilot is an example of such case.

3.5. Alertness And Distance Perception

The HUD design research today is advanced enough to focus more on the driver's interaction with it. Extensive research has been done for identifying the optimum HUD position. Determining such position is achieved by measuring a secondary task performance during a constant primary task [54].

Haeuslschmid et al. [54] proposed taking advantage of the entire windshield display and allocating different areas for specific information, as shown in Figure 12. These areas are: (1) the notification area which includes primary and potentially secondary task warnings, (2) the vehicular area which contains the car information such as fuel consumption, (3) the personal area which displays driver's related information such as messages, (4) the ambient area which contains low priority information such as weather and date and (5) the reading area which displays continuous texts such as emails.

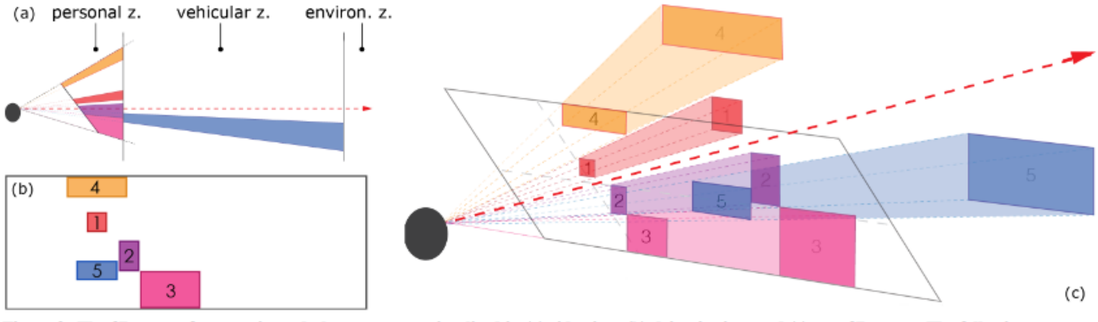

Figure 12. Windshield display areas used [54]

4. FORWARD COLLISION WARNING

This chapter is a literature review of the forward collision warning systems. The first section introduces the FCW algorithms developed over the years. The next section discusses related works on FCW using the HUD.

4.1. FCW Algorithms

Collisions are one of the key concerns in traffic. Both rear and forward collisions can cause damage not only to the driver but to the other car as well. Many forward collision algorithms [55] have been developed to increase driving safety. Wang et al. [56] proposed an FCW algorithm that adapts with the driver's behaviour by changing different warning thresholds in real time. The algorithm uses an online risk identification model behavioural braking data for adaptation. Nakaoka et al. [57] introduced a stopping distance calculation and the tire-road friction coefficient. Compared to fixed TTC (Time to Collision) algorithm, the algorithm [57] increased the TTC value in wet conditions compared to dry conditions.

The collision warning algorithms are mainly based on two approaches [58]: perceptual and kinematic. Some of the main algorithms will be discussed in this section.

- Perceptual approach: This approach is based on the TTC thresholds which is one of the most important safety measures. The critical value ranges between 2 and 5 seconds.

  Different algorithms have different critical values. The TTC threshold for the Honda algorithm is 2.2 seconds while it is set to 3 seconds for both Honda's CMBS and Hirst&Graham algorithm.

- Kinematic approach: It is a combination of vehicle motion with the reaction time in order to determine the minimum distance for stopping safely. Both the Mazda and the PATH(Berkely) algorithms set this value to 5 meters.

4.2. Practical Studies Of FCW System

An FCW research [59] proposed a design shown in Figure 13. The arrow's color in Figure 13 (b) changes to yellow in case of violating the safety distance, and it changes to red if the collision becomes imminent. The arrows are displayed in the form of animation so that they have more attention when there is a collision risk. The implementation was done using driving game simulation for the study. Metaphor M1 is triggered with an audible warning but when entering the imminent danger area both notifications start blinking synchronously with an audible warning at 4 Hz. Equation 1 is used for calculating the stop distance (d_p) and Equation 2 is used for calculating the safe distance (minimum distance necessary to avoid collision). The warning will be triggered when $d_{min} < 0$. The distance d_{actual} corresponds to the relative distance between the test car and the reference car. The speed is measured in km/h and the distance is measured in meters. Different driving scenarios were simulated that include random reference car stop. The study included questionnaires before and after the experiment. The second design was less perceptible before the simulation but while driving, the second design was easier to perceive as a safe distance warning in the car's HUD. In general, participants preferred the second warning design with audio. All participants who are 42 years or older preferred as well.

$$d_p = 0{,}0717v^{1{,}5274} \tag{1}$$

$$d_{min} = d_{actual} - d_p \tag{2}$$

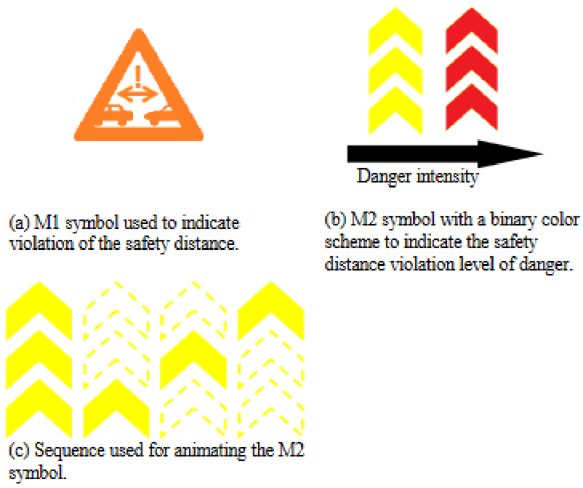

Figure 13. Safety distance violation symbols [59]

Charissis et al. [60] performed a case study on early notification in traffic congestion and sharp notification warning as shown in Figure 14 under different weather conditions. The driving route can have many sharp edges such as intersections. The crash risk can increase even more in some weather conditions such as low visibility and slippery ground. Their study presented a sharp turn notification and traffic warning cues in addition to the driver's performance with a HUD and with an HDD. The simulation scenario is shown in Figure 15.

The study is conducted on 40 users holding driving licences. During the sharp turn, the users strongly perceived the color change. The congestion traffic and the turn symbols allowed to small and constant deceleration. Using the HUD, the user did not collide with any of the other vehicles. In the congestion traffic scenario, the collision rate was 37.5 % using the HDD compared to 5 % using the HUD which is more than 7 times better. The avoided collision rate was 62.5 % using the HDD compared to 95 % using the HUD. Displaying warnings on the HUD did help avoiding collisions.

A study of drowsiness on drivers in the presence of FCWs [12] where the driver's drowsiness is based on the Objective Rating of Drowsiness (ORD) scale. The

Figure 14. Notification design for congestion traffic and sharp turn [60]

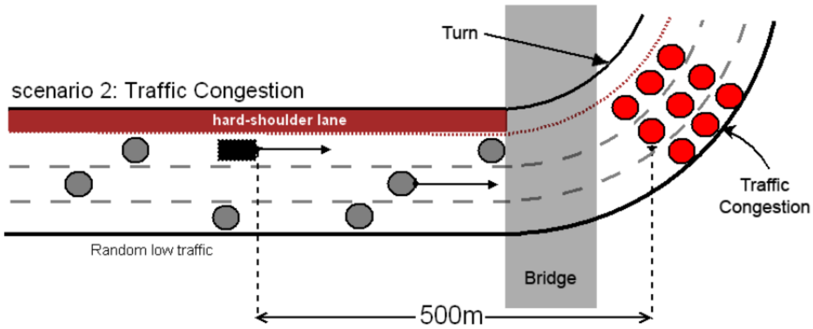

Figure 15. Congestion traffic scenario [60]

participants had three different and consecutive nighttime segments. The start was an urban part then went through an interstate part and finally they went through a rural path. The driving was conducted for two driving rounds. One was between 10pm and the other one was between 2am and 6am and only drivers with ORD level 3,4 or 5 were considered as reliable.

The FCWs is not effective for drowsy drivers. Neither crashes are reduced nor the response time is increased. These results concern both auditory or haptic warnings. The study concluded that detecting the threat was on average the same for both drowsy and non drowsy drivers but the braking response took a longer time from drowsy drivers.

A possible explanation is that drowsy drivers despite their fatigue and high ORD level, they kept looking at the road and can spot the event.

Another HUD and collision work was conducted by Kim et al. [15]. The study had four driver vehicle interfaces with different driving scenario for each interface. The drivers were required to perform four different tasks: lane change, turning, following a vehicle, and passing a broken down through verbal instructions. The participants reported back the risky situations verbally by indicating which side that causes that risk "front, left or right" for each driving scenario. The simulation had crash warning system, traffic and mirrors. It was performed using **InstantReality** [61] as shown in Figure 16.

The study had three different measures: the performance, the mental workload and the subjective preference for both the HUD and the conventional driver-

Figure 16. The driving simulator from the virtual driver's seat [15]

vehicle interface. The performance measure consisted of two parameters: the driver's reaction time and the error which is measured based on the total number of crashes. The visual warnings varied in transparency as the car gets closer to a crash scenario.

Compared to conventional driver-vehicle interfaces, the participants perceived the hazards quickly using the HUDs. In addition, more than 50 % of the participants ignored the console texts or the side mirrors' blind-spot detection icons. The HUD is a better stimulator than the conventional HMI in presenting visual front threat warnings.

Bella and Russo [58] conducted a driving study using a driving simulator. Their study is performed on 32 drivers in an environment that consisted of a double lane rural road with four traffic scenarios. The driving task had different familiarity training before starting the actual experiment. After performing the task, the driver is given about five minutes to recover from the experiment workload. The last step of the experiment is requesting the drivers to answer a questionnaire about the discomfort perceived during the four driving tasks. The study introduced a new collision warning model that is used to obtain a distance threshold that can be used for ADAS.

There are many driving scenarios and factors that affect the driver's response time to different hazard situations. A common case is easily recognized in transportation where the driver acquires more experience on the road which makes it easier than a driver who is not familiar with the same road. Aust et al. [62] investigated the driver's braking response time when exposed to a repeated event (a lead vehicle braking) and an FCW. The study shows that the measured FCW effect from experiments is heavily dependent on the experimental environment such as the visual distraction, the time chosen for displaying the warning, and event repetition. The latter almost eliminates the surprise factor so the response time can be affected.

5. IMPLEMENTATION

5.1. Introduction

This chapter introduces the project implementation. In the first section discuss the development environment in which we present the hardware used and the development platforms. In the next section, we present the implementation structure. Following that, the different design parameters are introduced with more details. The last part contains the different visualizations for the designed FCW scenarios.

5.2. Simulation PC

We implemented a 3D car driving simulation using Unity3D running on Windows operating system. For the control part, we integrated an external steering wheel to obtain more realistic driving experience. We used a laptop equipped with a dedicated GPU and external screen with the specifications listed in Table 2. The rendering is good enough for the simulation. The car movement is smooth and natural.

Operating System	Windows 8.1 x64
RAM	8GB
CPU	i7
GPU	NVIDIA
Screen size	15.6"

Table 2. The PC hardware specification

5.3. Unity3D

Unity3D is a cross-platform engine that was first launched in 2005 by Unity Technologies and it supported only Mac OS X at first but over more than a decade it can now support more than 24 platforms. It supports the common platforms such as Windows, Linux, Mac OS, VR and AR headsets, game consoles, mobile platforms and wearables. It comes with two plans: free and commercial. It is possible also to use the free version if the annual gross revenue does not exceed $100K [63]. The engine supports several graphics APIs such as Direct3D, OpenGL, ESWebGL and many more. The engine uses both C# and JavaScript as scripting languages but C# is the most commonly used.

The engine offers native C++ performance and it leverages the use of multicore processors for its multithreaded system. Although the engine is mainly used for 2D and 3D game development, it can be used also to build applications such as animations and simulations as well. It renders real-time visualizations based on physics and real-time global illumination because of its native graphics APIs such as iOS Metal, nVidia VRWork and AMD LiquidVR. Different 3D models can be imported from different modeling software such as Blender [64] to Unity3D projects. The modeling and logic can be performed separately by different developers but it is also possible to perform both in unity3D. It is possible to develop instant games because the engine offers rich assets and materials. The engine includes 3D physics engine so handling physics is usually the least worries in 3D games and it saves time to focus only on the design for the most part. There are many interesting VR and mobile games and applications that are developed using Unity3D that gained popularity because of their easy-to-grasp concepts and their good design. The engine has a large community so it is easy to find support and speed up the development process. In our study, we use external hardware which is the racing wheel to control our driving simulation by only downloading and configuring the set of inputs as we have discussed earlier. More details about the FCW implementation will be discussed in the next sections.

5.4. PC Steering Wheel

There are many racing wheel products to choose but in our study, we chose one that is suitable for the experiment. We used a racing wheel (Black bolt racing wheel) for our study. It includes a steering wheel, control buttons, clickers, and two pedals. The steering wheel automatically returns back to its position after the driver releases it. The wheel can be fixed easily on a smooth surface. Although the steering wheel has many buttons, we did not use all of them because they are not relevant to our study. The kit is shown in Figure 17.

We only integrate the wheel and the two pedals in Unity3D. The Kit is designed for games but it requires setup. We download the steering wheel package from the Unity3D asset store then we include it in the project. The gas and the brake pedals are configured according to their corresponding functionalities to match the ones in real cars.

The wheel is included in the project as a dependency package. The package is a collection of components that include physics, camera, input, scripts, ..etc. It is intuitive to locate the relevant parts and edit their script components. Each object in Unity3D has components, such as transform, camera components. A script component is a component containing a script that is used to simulate the object's behaviour inside the game. The kit is connected to the PC using a USB cable. The hardware driver can be downloaded and installed from the provider website [65]. The kit does not have to be configured from within a Unity3D project only, but it is possible to configure it externally for specific games using the guidelines provided by the website for more details as well.

The kit is compatible with all Windows games using either XInput or DInput. It has 8 buttons similar to the ones found in joysticks, 10 buttons located on the wheel center and 2 side handles. In addition, the steering wheel has a 180 degrees [66] which is needed in the experiments. The wheel is sensitive enough to simulate a real one in order to provide the participant with realistic driving experience, especially at high speeds. The participants have a rehearsal before starting the experiment. The car controls are intuitive so the rehearsal is mostly for testing the entire kit sensitivity and for demonstrating possible scenarios.

Figure 17. Black bolt racing wheel [65]

5.5. FCW

We designed three different FCW notifications. All designs are tested and evaluated based on the criteria that we will see in the upcoming sections. The main parameters that we considered for the notification are size, topology, position, colors in addition to the critical distance. The notifications are designed using a sketch website [67].

5.6. Scenarios

The participants drive the car in two different environments. The first environment is a plain road where there are no side buildings so the driver can focus only on the front car. This scenario is meant to isolate the driver from any visual distractions and to determine the response in the case of a lonely road (for example the highway). The second scenario is with different scenery where the driver may experience distractions when looking at the side windows. In both scenarios, the driver is asked to follow a car and try to catch up to it without collision. The front car suddenly stops or decreases speed drastically and the driver should avoid colliding with it. We used a critical distance measure in order to set the right time for displaying the notification. We used the time difference between the first notification appearance and the first time the driver brakes. In this experiment, we studied both gamers especially those who played racing games before and non-gamers to see if there is a perception difference between them when driving.

5.7. Test cases

This part is the core part of our implementation. After setting up the driving scenarios we setup these test cases to study the behaviour of the participants when receiving the FCW in each case. The implemented designs include 3D, 2D and animated warnings. Different notification locations are chosen for the study. Various outdoor lightening and weather conditions are considered as well. In the last part, we provided two cases for the post notification with and without post notification in order to study the effect of the safe zone acknowledgement in each scenario and test case.

5.7.1. Size

The notification layout is implemented such that it allows changing the design size. All designs are implemented inside one layout and we exported a mean to change the size of the notification as one object. Changing the size does not mean scaling the graphical design even though it is possible to do so for a single color image. It is rather one object with different notifications where each one has its own size.

5.7.2. Location

As we have seen earlier in the Forward Collision chapter, the notification location is an important factor in the HUD. The bottom row locations are preferred locations so these are the locations we considered. We used three bottom row locations: left, middle and right positions. It is also because in real cars it may distract drivers to look slightly upward which can be dangerous.

5.7.3. Color

The color is an important factor for human response. It is used for designing the three notifications. The colors used are mostly red as we will see later. This is true for the static warning design, but it is slightly different for the other two designs. The colors used in the 3D design are gradient not only a single color.

5.7.4. Topography

We implemented 3D and 2D notifications with the same common parameters such as the notification lifetime and the safe zone. When designing the 3D notification, we aimed for reducing the distraction and the processing time of drivers. We will see how the topology affects the driver's cognition in the evaluation chapter. The same location parameters are used in Unity3D. Only the notification display is different from the 2D design.

5.7.5. Animation

We implemented animated notification containing five frames (Figure 19). We designed it as a sequence of images that show the effect of animation. The reason for using the animation is to draw the driver's attention in case the warning size is not large enough or when the outside illumination is too bright and it may constitute homogeneous background that hides the warning.

5.7.6. Lifetime

The total lifetime of the notifications is the same duration the driver is inside the threat zone. This parameter is controlled by the critical distance obtained from Equation 3. We used this formula to enable the notification only during the threat period. This formula is easy to implement on real cars because of the proximity sensors that modern cars have. Participants are asked at the end of the experiment whether they prefer a larger safe distance each time an FCW appears.

5.7.7. Outdoor Weather And Light Conditions

We used two different light conditions: day and night. In addition, we used clean sky and rainy weather scenes. In the rainy scene, the thunder sound is activated and the vision is somehow foggy outside the windshield.

5.7.8. Post Threat Notification

It is a notification that is displayed after driving at a distance that is larger than the critical distance. We did not add a threat-safety acknowledgement notification but we asked the participants whether they want it in their cars. Although we hypothesize that it is not desired because it will just add redundant information to the driver but we will check its validity after performing the evaluation. This approach is a common practice in games but in actual cars, this notification can be distracting.

5.7.9. Critical Distance And TTC

Equation 3 is used to calculate the distance between the driver's car and the front cars. This equation can be used in real life scenarios as well. The distance between the driver's and the front car can be easily obtained from the car object inside Unity3D. This applies to all the notifications we designed. We analyze the response time by calculating the time difference between the first appearance of the collision warning and the first time the driver brakes.

$$d = (v_{driver} - v_{front}) * t \quad (3)$$

d : the distance between the driver's car and the front car
v_{driver} : the driver's speed
v_{front} : the front car speed
t : the elapsed time

5.8. FCW Warning Designs

Considering the previous criteria, we designed three different notifications: Single-frame (D1), animated (D2) and 3D animated (D3).

5.8.1. Static Notification

This notification is a single image (Figure 18) that is displayed as a notification. We use a single red color to increase the driver alertness and also because it is intuitive to perceive.

Figure 18. Single frame warning (D1)

5.8.2. Animated Notification

This design is composed of 5 frames (Figure 19). The colors used are chosen so that it makes it easier to respond to the warning during daylight (the black color on the car sides) while perceiving the danger from the red color.

5.8.3. Animated 3D Notification

The design consists of rotating arrows shown in Figure 20 to make it clear for the driver to perceive the increasing threat. We used gradient colors and the arrows to alert the driver to consider changing the direction or decrease the speed.

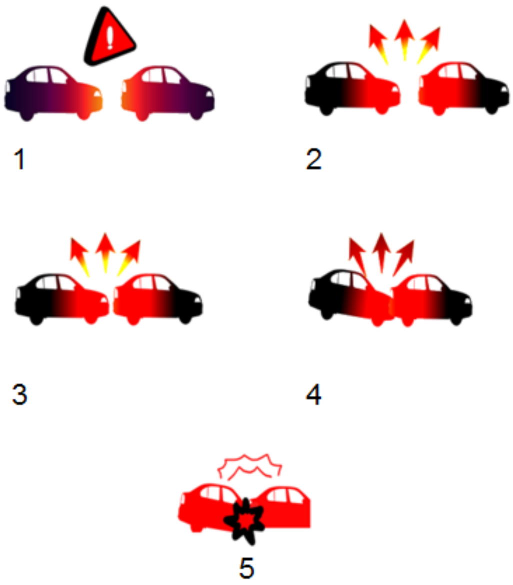

Figure 19. Animated FCW design (D2)

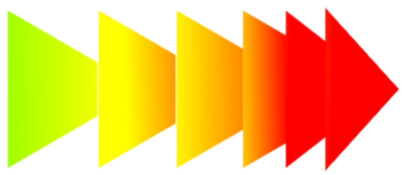

Figure 20. 3D FCW design (D3)

5.9. Visualizations

In each experiment, we used test cases for clear sky (Figure 24), night time (Figure 25) and rainy weather (Figure 26). Figures 21, 22 and 23 correspond to static, animated and 3D warning visualizations, respectively. The visualizations are taken from daylight .

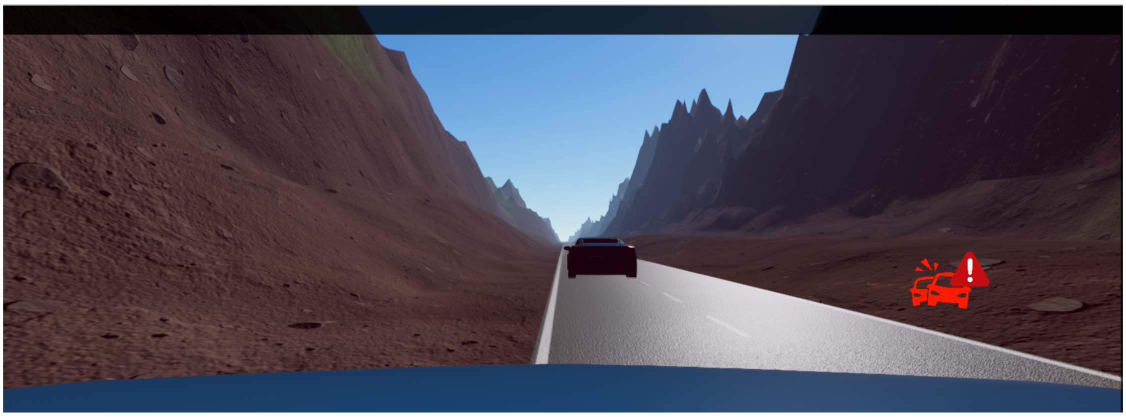

Figure 21. Single frame visualization

Figure 22. Animated FCW visualization

Figure 23. Animated 3D visualization

Figure 24. Clear sky visualization

Figure 25. Night visualization

Figure 26. Rainy weather visualization

6. EVALUATION

In this chapter, we evaluate the different designs. In the evaluation plan, we evaluate the correlation between the driver's response time and the survey answers. This chapter consists of three sections. The first section discusses the designs from a driver's perspective. The participant will have a questionnaire which is mentioned in the next section. The second section discusses data collection using questionnaires and driving performance. The last part is the analysis and the interpretation of results.

6.1. Experiment Setup

The purpose of conducting this experiment is to compare the different designs against each other. There is no pre-assumption of the best design in terms of design. The decision is based on a driver's response time. We want to study how intuitive can be a simple and a bit complex designs as well as their effect on drivers. Another aspect is how drivers interact with necessary information displayed on the HUD during the threat and after leaving the threat zone. We targeted the human cognition in critical situations and compared them to what drivers would usually do. We collect data about all the designs for both before and after the driving experiment. There is a gaming-related question in order to verify weather racing game experience can affect the study. In each driving scenario and test case, we collect participant's preferences in order compare it with his performance. To make the experiment more natural, we talk to the participants while driving. We considered displaying the safe-zone notification acknowledgement for all designs and asked the participants about considering it. This approach is a common practice in HMIs but we want to study the relevance of the post threat notification in driving.

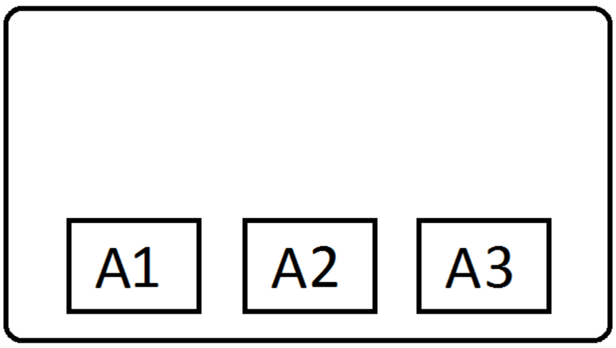

Figure 27. Notification considered locations

The location shown in Figure 27 refers to the geometrical centers of the notifications.

6.2. Data Collection

The driving task data is a combination of both the measured response time and the answers obtained from users. Questions are evaluated using the Likert scale. The questionnaire is defined in the following section.

The following questions are asked after all tests of each design are done. Questionnaire 1:

1. The design is intuitive (*)
2. The warning is useful
3. I agree that the warnings should be on the bottom row
4. The rainy weather does not affect my response time
5. The notification size is appropriate
6. There is no need to adjust the warning transparency during the night
7. I prefer a static warning than a flickering one (**)
8. I want the FCW system in my car

Question (*) is asked only once for each design. Question (**) is asked only when testing D1. The following questions are asked after testing all the designs. Questionnaire 2:

1. Would you like to see a notification after leaving the critical distance?
2. Which visualization do you prefer?
3. Do you play racing games?
4. Does the threat distance need to be adjusted after displaying the first warning?
5. What improvements would you like to add?

The experiment was conducted on eight participants. All of them are students or researchers at the University of Oulu. They all have driving license. Only four of them played racing wheel before. At the beginning of the experiment, we explained the driving task for each participant. The first task is to drive at high speed and try to get ahead of the front car which performs sudden deceleration. The participant has to brake to respond to the warning shown on the screen in order to avoid collisions. The second task is to answer a questionnaire (questionnaire 1) before proceeding to the next design. The third task is to answer questionnaire 3 which is a compact overview of the subjective evaluation for the entire experiment designs.

In questionnaire 1, Likert scale form is used. Each question is answered by providing a 1-5 score. Possible scores are: 1,2,3,4, and 5. The score 1 corresponds to strong disagreement with the given statement, whereas score 5 corresponds to a strong agreement. The evaluation of each design is performed by calculating the average score of each participant. The average score for each design is calculated by adding the scores of each question then dividing by the number of questions which is 8.

6.3. Data Analysis

In this section, the warning positions and the user experience are discussed in more details.

6.3.1. Warning Positions

In this section, we discuss the performance of each notification by analyzing the response time of the driver, the different warning positions and the number of collisions. The response time versus the driving condition (day, night and with rain) is shown in Figures 28, 29 and 30. Each participant performs 72 tests to cover all cases. In order to make the visualization easier, we have split the plots into three subplots based on the notification position (left, middle and right). In addition, the number of collisions is collected from each test case.

Figure 28 corresponds to the data collected from the participants when testing the static notification. On the left position, the participants made 11 collisions, 5 collisions on the middle position and 3 collisions on the right position. On average, the left position is the best during the night in terms of response time. The right position is the best during the day, whereas the middle position is the best when there is rain.

Figure 29 corresponds to the data collected from the participants when testing the animated notification. On the left position, the participants made 4 collisions, 5 collisions on the middle position and 3 collisions on the right position. On average, the right position is the best during the day and the left position is the best when there is rainy weather, whereas the middle position is the best during the night.

Figure 30 corresponds to the data collected from the participants when testing the 3D notification. On the left position, the participants made 5 collisions, 2 collisions on the middle position and 5 collisions on the right position. On average, the middle position is the best during the night and when the weather is rainy.The middle position is the best during the day, night and rainy weather.

To sum up, the bottom right is best used with the static and the animated warning during the day. The bottom left and right positions are best used with night and rainy weather respectively. The middle bottom is good to use during the night and the rainy weather.

Next, we analyze the feedback for questionnaire 1. In Figures 31-33, the question scores of the three designs are plotted.

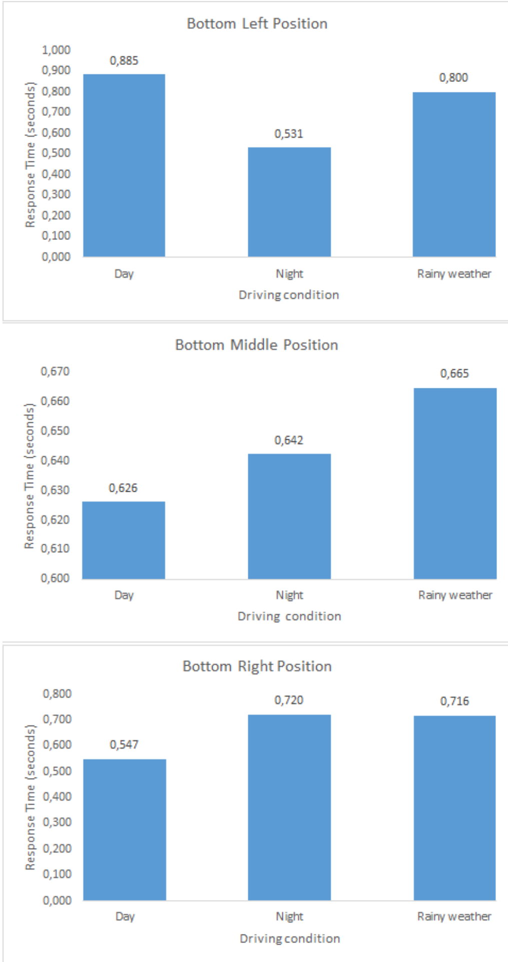

Figure 28. The average time response of the static warning

6.3.2. User Experience of FCW Warning

The charts of the answers for the single-frame (static), animated and 3D designs are depicted in Figures 31-33. The participants do not want to have a complex design in their car. Half of the participants prefer D1 and the other half prefer D2 but no one prefers D3. For some participants, D2 is a little distracting to have as a warning. They report that they tried to focus on the animation when it first appears, which is an issue. Participants who do not prefer D1 suggest adding a flickering effect to it because they want to have an effect on the warning. We notice that even though D3 is not preferred as D1 and D2 but it is better than D2 in terms of time response when displayed on the middle position. In addition, it has the best performance among the other designs if it is used in the middle position.

One participant wanted to have D3 during the rainy weather and one participant suggested changing the color of D1 gradually as the danger increases. Four participants suggested adding an audible warning along with the visual design. The users who preferred D1 did have the smallest response time and it is the same for D2.

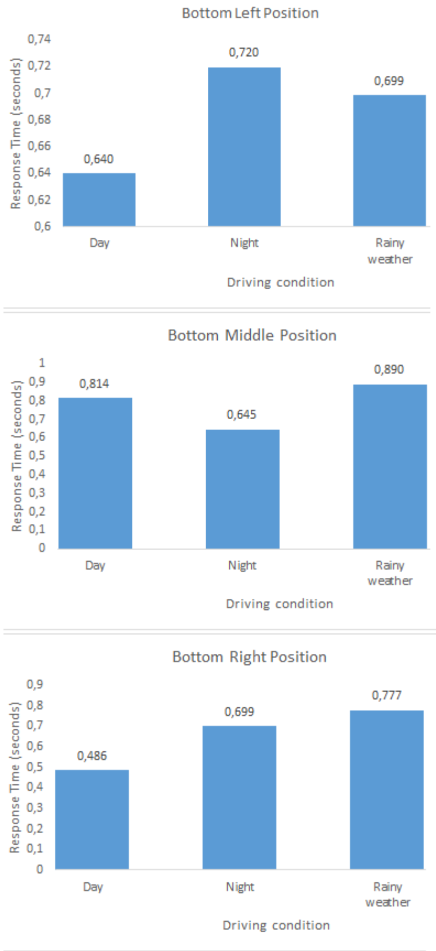

Figure 29. The average time response of the animated warning

The participants found the designs D1 and D2 intuitive and useful but they preferred either D1 or D2. They were satisfied with the bottom locations but they had different preferences. The participants did not find the weather a factor of affecting their performance with the same percentage but with a less percentage for D3. They did not find the weather condition an issue when responding to the warning and some find it is even easier to avoid collisions because they are highly alerted during this weather. The transparency is questionable for D3 because of the argument that driving during the day (in case of a sunny day) the warning might not be noticed because of the windshield reflections. For D1 and D3, the transparency should be adjusted according to the ambient light as well but with less insistence. The participants who wanted the transparency of the second design, D2, to be increased argued that the animation makes it easy to spot so there is no need for using full colors.

The flickering option of D1 can be either enabled or disabled because some participants find it easy and less scary to have a static warning whereas others wanted a flickering one but with a frequency around 5 Hz so that they can see the warning during the off-duration.

The most preferred design is D1 and the least preferred one is D3. Even though the design preference is 50% for D1 and 50% for D2, when the participants were

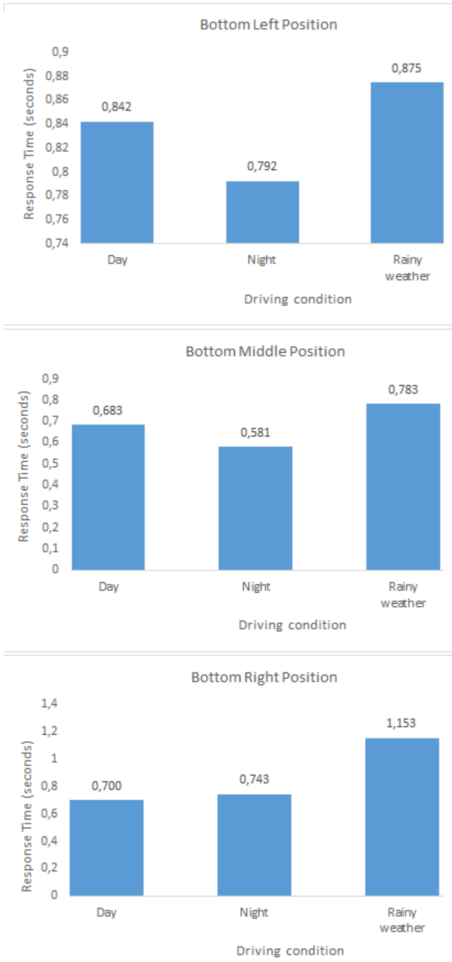

Figure 30. The average time response of the 3D warning

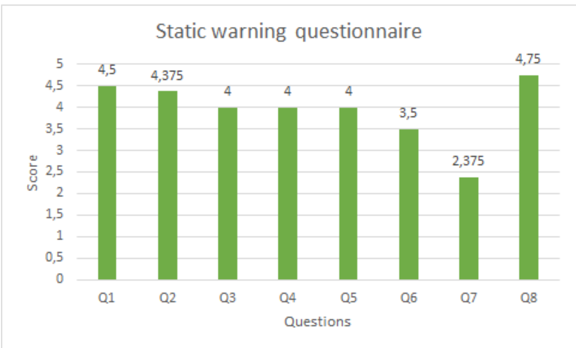

Figure 31. Questionnaire 1 scores for D1

asked what design they want in their cars they preferred D1. As they argued, the animation makes it a bit distracting even though the animation itself is intuitive, they argue.

During night and rainy weather conditions, the drivers make fewer collisions. Some participants reported that they are more careful during these conditions. Participants suggested improving the static notification by making in it flicker in case drivers do not respond to it. Having an animated warning can be either

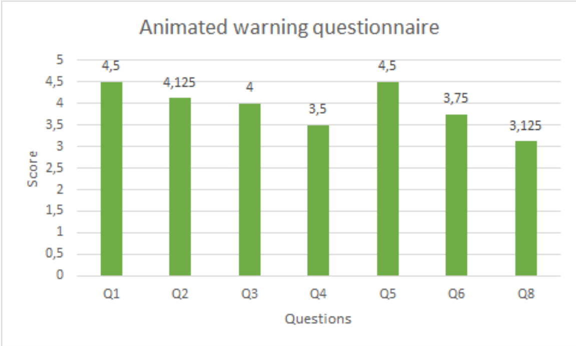

Figure 32. Questionnaire 1 scores for D2

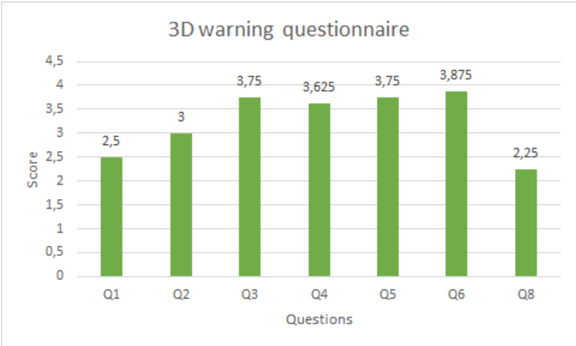

Figure 33. Questionnaire 1 scores for D3

useful or distracting, as reported by the participants. The 3D design is not desired in the HUD. The bottom row is desired by participants, but there is a suggestion to consider the center position.

The preferred size is almost one-fifth the windshield height. The bottom left location of the windshield is the most preferred. There is an agreement that the red color should be present in the warning, but using a gradually changing color (from yellow to red) is highly recommended. A 2D warning is preferred over its 3D counterpart. A static warning is preferred and highly effective than an animated one. The warning should be visible as long as the car is in the threat zone, which increases with the car speed. The post threat notification can be included in the car for more relief. Less visibility makes drivers more careful so even 2D and 3D warnings can be shown in this condition.

Because the automotive industry is software oriented, deploying visualizations on the HUD is mostly performed using special frameworks. There are automotive frameworks and libraries that are used for creating AR applications. Automotive software is compliant with AUTOSAR, so deploying AR applications is possible and the time complexity is not an issue. The AR applications are usually highly optimized because of the assumption that resources are limited.

7. CONCLUSION

In this work, we implemented three different FCW designs: static, animated and 3D. We conducted the experiment on eight participants and we found that complex designs are preferred to watch and process but simpler and intuitive designs are most practical when it comes to fast decision making.
We tested the three designs in three different conditions: day, night and with rain. The participants are verbally distracted throughout the experiment to simulate real-life driving scenarios. The response time for both static and animated warnings is less than the average response time (1 second). For the 3D warning, the response time is less than 1 second when the warning is displayed on the bottom middle and left position. For the bottom right position, the response time is more than 1 second. The reason for this can be the fact that participants usually drive on the left side.

The analysis of the results reveals an interesting finding. Most collisions occur during daylight condition. During darkness and rain conditions there is less number of collision. The reason can the extra attention that drivers have when the road is not clear (in case of night and rain scenarios). The proposed designs perform well but they can be improved even further if locations are changed at runtime rather than selecting a predefined position. Drivers want to have a good visualization in their car but when they are driving, they want to see a simpler one with the minimum processing time required.

As a future project, we would like to test these designs on actual cars and have a larger number of participants. We would like to deploy these designs and improve them even further by implementing them in a way that the warning's location changes on the HUD depending on the front car projection on the HUD and its distance from the driver.

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