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Impact of improved lane marking properties on the performance of Lane Keeping Assistance systems in varying circumstances

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Safe and Efficient OperAtion of AutoMated and Human DrivEN Vehicles in Mixed Traffic

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Enhancing Society Together

Impact of improved lane marking properties on the performance of Lane Keeping Assistance systems in varying circumstances

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Preface

It was april 2022 when I was travelling in a train in Northern France near Lens. I just came back from a football match of RC Lens when yellow markings and lamp posts on a parking lot caught my attention and I was wondering why they were yellow. I came to the realization that it would be interesting to further investigate these thoughts. My personal life was quite turbulent at that moment and travelling gave me inspiration to clear my mind and think about what inspires me. Experiences in other countries always give me the most inspiration to actively think about what I want to do.

Choosing a topic that you are interested in is an important step towards the start of your relationship with your thesis. Because that is basically how it feels like compared to all the previous courses that I followed for just a few weeks per course. After having a few meetings with Haneen Farah I was able to further specify the subject. She brought me into contact with Evert Klem from RHDHV. I want to thank them both for this opportunity to do this thesis as part of the SAMEN project. When I started in october 2022 I was enthusiastic but also overwhelmed by what had to be arranged to make this project a success. There were moments throughout the process where I thought that I would never make it and felt lost and drowned in the project. I feel grateful for all people that contributed to the project and helped out during difficult times.

Special thanks to all my committee members: Haneen Farah, Maria Salomons, Barys Shyrokau and Yongqi Dong, who supported throughout the process and gave valuable feedback during all meetings. From RHDHV I would like to thank Evert Klem for all his support content-related but also emotional. Also, I would like to thank Maria Oskina from RHDHV for helping out setting up the experiment and arranging equipment. From RWS I would like to thank Onno Tool, and André Kleis for their contributions on existing literature as well as driving during the experiment together with Michel Kusters and Mounir El Hassnaoui.

Financially I was worried at the start of the whole process that some hurdles had to be taken to arrange the budget for the experiment. After the confirmation from RWS and Michiel Beck from the Ministry of Infrastructure and Watermanagement, the preparations for the experiment could be taken to the next stage. I want to thank both 3M and Triflex for their contributions to the experiment and providing lane markings. A special word for Arnoud de Jong and Rik Nuyttens from 3M and Hans Huijink from Triflex for sharing their knowledge and helping out with some practical issues. One of the essential parts of the experiment was arranging the cars. I was most stressed about this, as this was crucial for a succesful experiment. A special word of gratitude for Arnoud de Jong of 3M and Maurice Iseger from Triflex for providing two cars. For the final car I was happy that my friend Rolf Heinrichs could help out to arrange a rental car through the company Wittebrug he is working for.

Personally it means a lot to me to mention all people that helped me out during my thesis. It is impossible though to list everyone that contributed. Some people contributed by talking with me. This can be either very small contributions or major ones. I want to reserve a special word for my parents André and Marja den Otter who were always there to support me during this long and sometimes difficult process. I sometimes felt bad about myself as I'm filling in what other people think. They helped me out by showing their support. Finally, I want to express my gratitude to all my friends that have helped me out during the process by either talking, showing support or just distract me with other activities like failing hilariously in Snooker or Valorant. It has been a rollercoaster ride emotionally at some moments, but let me conclude by saying that I love rollercoasters.

Abstract

In the upcoming decade Advanced Driver Assistance Systems (ADAS) will play an important role in improving traffic safety in the European Union (EU). The European Commission ordered that from july 2024 all new vehicles should be equipped with Lane Keeping Assistance (LKA) systems. LKA systems give force feedback to the driver if the vehicle crosses one of the lines of a driving lane. For detection of lane markings by the vehicle a camera, radar or LiDAR (Light Detection And Ranging) system is used. The majority of cars currently on the market uses a front camera in combination with sensors to detect objects. Several studies have been carried out in previous years to determine the effect of adverse circumstances, different types of sensors or lane markings on detection by LKA systems. Detailed knowledge about the effects of these circumstances combined on LKA system detection performance, is still missing. To be able to rely on LKA systems for lane marking detection, the performance should be at a high level. Increasing the quality of lane markings contributes to the performance of LKA systems. This research aims to identify the influence of lane marking properties and adverse scenarios on the detection ability of Lane Keeping Assistance systems in vehicles.

To obtain data, a field test was conducted where different state-of-the-art types of lane markings were placed on a test track in Lelystad. On the test track an old type I white paint lane marking was present and used as a reference to compare to three new lane markings. Two of the new lane markings were tapes provided by 3M, and the other one a cold spray plast provided by Triflex. Cold spray plast lane marking was placed permanently as it was not possible to remove it afterwards, while both tape markings were temporary and removed afterwards. Lane markings were placed parallel to each other so that all lane markings could be tested in the same circumstances. On the first day all runs were on a dry surface, while on the second day the asphalt on the track was kept wet constantly by a watering system. Rain was not included in the test, as it was dry during both days. On both days the same procedure was followed to obtain all data. First, luminance coefficient Qd and dry retroreflectivity value Rl were measured with a retroreflectometer on several locations on the test track per lane marking. Values were also measured for asphalt on the same location to determine contrast ratio. During sunset, test runs started towards and away from the sun. After sunset and in complete darkness the test runs were resumed with scenarios with and without oncoming traffic and with and without street lights switched on. On the next day, the same procedure was followed on a wet surface. Instead of Qd and Rl, wet retroreflectivity Rw was measured following a standardized protocol on the same locations as the previous day. Runs were recorded using two GoPro cameras per vehicle. One facing the dashboard with LKA indicator and the other one facing the road through the front window. Drivers were instructed to drive at a constant speed of 80 km/h. Detection by human was not a part of this research, although drivers were instructed to also give some voice comments for the recordings.

In total, 420 runs were recorded during both testing days, of which 6 were invalid. For the invalid runs either the speed was too low or the approach to the lane marking was not straight, leading to a lane switch during the run. 70 runs per vehicle per day were planned in 7 different scenarios leading to a total of 140 runs per vehicle and 210 runs per day. During daytime 3 runs towards the sun and 3 runs away from the sun per vehicle were planned. These were followed by 3 runs per vehicle in complete darkness during nighttime. After this, 4 runs per vehicle with opposing traffic followed, 2 runs with dipped beam headlights and 2 runs with main beam headlights. In the final 2 scenarios street lights were switched on and per vehicle the 4 runs for opposing traffic were repeated. This led to the number of 414 valid runs. All videos from the GoPro cameras were then compared and matched with the corresponding video of the other camera from the same vehicle.

After which the matching pairs of recordings were synchronized based on sound, so that it became visible when the LKA indicator on the dashboard indicated that no lane marking was detected. Exact position of the vehicle on the driving lane was not measured, so from the camera images it was only possible to determine the position of the vehicle once the LKA indicator showed that no lane marking was detected.

After analyzing all videos, three different categories were determined. Detection, no detection, or partial detection throughout the test run. The only scenario with a 100% detection rate was complete darkness, no street lights switched on, and no oncoming traffic. For both dry and wet surface, all lane markings were detected in complete darkness. This was as expected based on previous research. For other scenarios tested a worse detection rate was expected. Key findings are summarized below:

- Lane markings are 3,3 times more likely to be detected in dry circumstances compared to wet
- Driving towards a light source, either the sun or oncoming traffic decreases detection likelihood 4,5 to 5 times compared to a daytime situation driving away from the sun.
- Higher values of wet retroreflectivity (Rw) of lane markings increase performance of LKA systems.
- Oncoming traffic with main beam headlights switched on during night time, decreases detection likelihood by about 11 times.
- Higher values of luminance coefficient (Qd) for lane markings increase contrast with asphalt. This does not necessarily lead to a higher detection percentage as the contrast on the image detected by the camera is important. A bright light source shining into the camera negatively influences the contrast on the incoming image that the camera processes. Therefore, the effect of increased contrast between the lane marking and asphalt might be canceled out by the light source shining on both asphalt and lane marking.
- Influence of street lights was slightly positive in combination with oncoming traffic. Detection likelihood decreased about 3,4 times when street lights were switched on with oncoming traffic., compared to 4,7 times when street lights were switched off with oncoming traffic.
- All new lane markings performed significantly better than old white paint lane marking. Detection likelihood increased with 2,1 to 4,3 times.

This research confirmed that lane marking detectability is important as LKA systems in vehicles still rely mostly on cameras for detection. To facilitate a working LKA system, lane markings should be detectable in adverse circumstances where the driver might fail to detect the lane markings. Improving retroreflection and contrast leads to a higher detection ratio. This contributes to traffic safety and might prevent accidents. The influence of oncoming traffic in the dark and in combination with street lights should be further researched. Light type, brightness, height and angle all play a role in the image that the camera detects. It is recommended for future developments of lane markings to test in adverse circumstances with oncoming traffic or another light source in combination with a wet surface.

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Acronyms

ADAS Advanced Drivers Asisstance Systems.

AW All Weather.

EU European Union.

LDW Lane Departure Warning.

LKA Lane Keeping Assistance.

ODD Operational Design Domain.

RDW Rijksdienst Wegverkeer.

RI Refraction Index.

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1 Introduction

More than 90 percent of car crashes are a result of human error (Winkle, 2016). In recent years Advanced Driving Assistance Systems (ADAS) emerged on the vehicle market and this brings a lot of opportunities to further reduce the number of traffic accidents. If human errors can be eliminated by ADAS this should lead to a decrease of accidents. However, the number of accidents caused by system malfunction might increase. It is not expected that fully automated driving will happen anywhere in the near future. For the upcoming decade it is already difficult to exactly predict how penetration rates of automated vehicles will develop, as this depends on various factors(Deichmann et al., 2023) (Robson, 2023) (Ulrich et al., 2022). It is expected that penetration rates of automated vehicles will lie anywhere between 25 and 88 percent by 2045 in the United States of America (Bansal & Kockelman, 2017). This might be different in other countries, but this high level of uncertainty shows that the industry should be prepared for a wide range of possible scenarios.

A lower level of automation, has a higher penetration rate and is already present in a high percentage of vehicles currently on the road (Deichmann et al., 2023).Lane Keeping Assistance (LKA) systems help the driver to keep the vehicle within the lane by actively steering the car back into the lane if the car crosses one of the lines. Lane Departure Warning (LDW) systems give audiovisual signals that help the driver to stay within the lane. This might prevent single vehicle accidents where the driver is not able to keep the vehicle in lane for whatever reason. These type of accidents contribute significantly to road fatalities. Statistics show that single vehicle car accidents are the largest portion of accidents on European roads and contribute to 30-40 percent of fatalities. (Jahnz & Wartberger, 2023) (Insurance Institute for Highway Safety, 2022) LKA systems assist the driver performing his or her driving tasks and can contribute in decreasing accident numbers depending on road marking quality and detection rate. In the near future the cooperation between the human driver and LKA system will be crucial for a successful penetration and further development of automated driving. Decisions on an operational level by driver and LKA system might be different based on detection. Therefore, visibility and detectability of lane markings plays a crucial role in the detection for both human and LKA system and can help in reducing single vehicle accidents and preventing fatalities and injuries.

1.1 Focus and scope

This research primarily focuses on the detectability of different types of lane markings by LKA systems and cameras in various circumstances. Performance of human driver and willingness to switch the LKA system on will be discussed in the literature review. It is not the focus of this research, although it plays an important role in the performance and functioning of the LKA system. If the willingness of the driver to switch the system on is high, this can potentially lead to more accidents being prevented. For the development and penetration of automated vehicles, a high performance rate of LKA systems is desired. In this research the focus will be on the current situation on the road and upcoming years. For upcoming decades it is difficult to predict what exactly the distribution of tasks will be between human and vehicle. Types of lane markings that are applied, or in line with application regulations, in the Netherlands will be considered. The Netherlands is part of the European Union (EU) so this research will mainly focus on the situation in Netherlands and regulations on lane markings set out byEU

1.2 Relevance and impact

For various parties and organisations this research will be relevant. By improving understanding of the detectability of road markings by LKA systems, this research is a contribution to road safety.

Road marking companies will be able to see from the results where their markings over- or under perform their expectations. Based on this, they can consider what to focus on for future developments in road markings and used materials.

Drivers and other road users will be able to better understand under which circumstances a vehicle with LKA system might not be able to function properly and when the driver will be in control. For a driver it is difficult to detect which type of lane marking is applied on a road while driving. Having knowledge about adverse circumstances and performance of your LKA system, improves awareness.

Road authorities will be able to see if the theoretical norms also work in practice. Under special circumstances LKA systems might not detect the lane marking, while the marking meets the theoretical requirements set out by legislature.

Car manufacturers, as well as manufacturers from LKA systems can benefit from this research as well. For the development of future cameras and algorithms it is beneficial to gain knowledge on situations where detection is difficult.

1.3 Thesis structure overview

An overview of the following chapters and their content will follow below.

Chapter 2 contains the literature review. From previous research, the gaps are identified. This also provides a basis for a conceptual framework for this research.

Chapter 3 presents the research questions developed from the identified gaps. A conceptual framework to show the interactions between driver, LKA, and infrastructure is developed.

Chapter 4 shows the methodology, preparations and setup of the field test to obtain data on the detectability of lane markings.

Chapter 5 presents all data obtained from the field test with descriptive statistics. Any removed data points or irregularities are discussed here.

Chapter 6 analyzes the obtained data statistically. A regression analysis shows the correlation between variables and their influence on the detection performance of LKA systems.

Chapter 7 discusses the results and any implications. Contributions for involved parties are discussed as well as future relevance of this research.

Chapter 8 concludes this research by giving an answer to the research questions and giving recommendations for further research or master theses.

2 Literature review

A literature review was conducted to gain more knowledge about the relation between LKA systems, the driver and lane markings. Several field tests and simulator experiments have been performed. In the following subsections relevant literature will be discussed. Gaps in literature will be identified after which the research questions will be stated in the following chapter. Section 2.1 will discuss the penetration of automated driving and LKA systems as emerging technology in the European Union. After this, section 2.2 will discuss LKA and (ADAS) in more detail. Section 2.3 will elaborate on lane marking properties, followed by section 2.4 where the relation between ADAS, LKA and accident prevention will be elaborated on. Sections 2.5 and 2.6 discuss studies where tests have been performed with LKA systems and lane markings and the relation between the driver and lane markings respectively.

2.1 Automated driving and European legislation

Over the last few years, more cars are equipped with LKA systems or ADAS. As this research focuses on the interaction and relation between LKA systems, humans and lane markings, it is first important to understand what level of automation is used. Considering the definition of SAE International about automation levels for autonomous driving, LKA and ADAS systems are supporting features for the driver. The driver is still driving, but the systems can intervene and help the driver. In Figure 1 the SAE definition for different levels of automation are visible. LKA and ADAS systems are also present in higher levels of automation than level 2 and will also play a role in higher automation levels in the future. This research will focus on the near future and penetration of LKA systems in the European market. (SAE, 2021)

	SAE LEVEL 0™	SAE LEVEL 1™	SAE LEVEL 2™	SAE LEVEL 3™	SAE LEVEL 4™	SAE LEVEL 5™
What does the human in the driver's seat have to do?	**You are driving** whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			**You are not driving** when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	
	These are driver support features			These are automated driving features		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering **OR** brake/acceleration support to the driver	These features provide steering **AND** brake/acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	• automatic emergency braking • blind spot warning • lane departure warning	• lane centering **OR** • adaptive cruise control	• lane centering **AND** • adaptive cruise control at the same time	• traffic jam chauffeur	• local driverless taxi • pedals/steering wheel may or may not be installed	• same as level 4, but feature can drive everywhere in all conditions

Figure 1: SAE Levels(SAE, 2021)

LKA systems are mandatory in newly produced vehicle types in the European Union from july 2022 onward following the Vehicle General Safety Regulation (The European Parliament and the Council of the European Union, 2019). From july 2024 all new vehicles should be equipped with the aforementioned systems. Many vehicles on the road in the upcoming decade will be produced before 2022, which does not mean that there are no LKA or ADAS systems present in those vehicles. It can be assumed that from july 2024 the share of vehicles with these systems equipped will only increase and the penetration rate will get higher. In the long term future, vehicles with higher SAE levels will be seen more on the road. However it is uncertain which automation level will be reached in what time frame. Level 5 systems might be ready for market use from 2030 onwards, although this is an optimistic prediction (Ulrich et al., 2022). When systems are ready for market use, it could still take years to implement fully automated driving as many factors play a role. Legal frameworks have to be set up and political opinions and policies will play a role in the implementation of higher levels of automated driving. Predictions for level 4 and 5 implementation are therefore uncertain and experts from the field have indicated time frames varying from 2040 to 2060 or even 2070. (Lu, 2018) This is still decades ahead and the penetration rate of these systems is also uncertain. For the short term, there are still many older cars driving on the road that are not equipped with LKA or ADAS systems. Also, if the vehicle is equipped with LKA or ADAS, it is possible for drivers to switch the systems off. Considering this, there are three components that should be considered for the short term of the upcoming decade. Namely LKA systems, lane markings and the driver. Therefore the focus will be on Level 1 and 2 LKA systems.

2.2 LKA, LDW, and ADAS systems

LKA, LDW and ADAS systems in vehicles are developed by car manufacturers or related tech companies and therefore the systems differ per car brand. In general, the following definitions are given to these three acronyms. LKA systems help the driver to stay in their lane by making steering wheel adjustments when the driver is about to leave the lane without any indication. If the driver wishes to overrule the system, this is still possible. LDW systems give a warning signal when the driver is about to leave the lane without indication. This warning signal can be either audio or visual. ADAS is an overarching term for systems providing warning signals to drivers and possibly also intervening, but are not specifically about lane detection or lane keeping. ADAS systems also include parking or breaking assistance or cruise control. (Videantis, 2015)

LKA systems consist of hardware and software and get their data and information from the environment and infrastructure. Hardware of the systems consists of the sensors, communication devices and actuators, while the software consists of perception, planning and control. In figure 2 it is visualized how hardware and software in autonomous vehicles communicate. For LKA and LDW systems the data from sensors and cameras is most relevant as it detects lane markings. This leads to a perception of the environment and localization of the vehicle. Algorithms to position the vehicle and intervene with driver steering behaviour, when getting too close to one of the outer lines of a lane, differ per car brand (Pendleton et al., 2017).

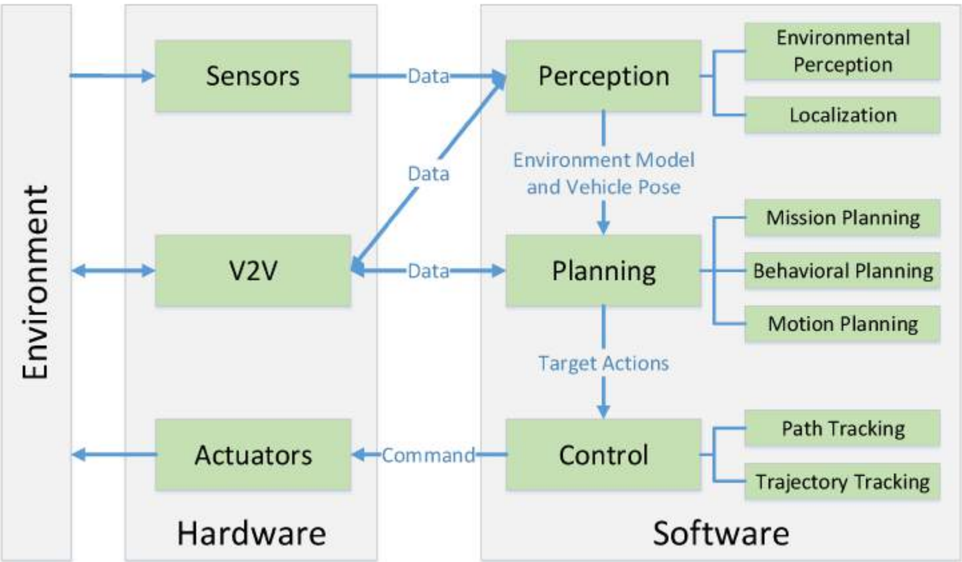


Figure 2: Autonomous vehicle system overview (Pendleton et al., 2017)

The Operational Design Domain (ODD) of the system is defined as the conditions under which the system is designed to function (Czarnecki, 2018). Multiple factors influence the ODD, this includes geographical, environmental or time of day restrictions. Road design limitations of the system might be tunnels, roundabouts, Taper connection or specific urban or rural road types. Other limitations might include a minimum speed in a range from 60-70 km/h and minimum retroreflectivity and contrast requirements of lane markings (Czarnecki, 2018). As this research focuses on the detection and perception of lane markings by LKA systems, the focus will be on the different detection methods that exist.

Perception of the environment and surroundings plays an important role in the detection process. Camera, radar or LiDAR (Light Detection And Ranging) is used in the detection process in vehicles. These are general technologies used to capture the environment. Cameras visually detect the environment capturing real-time images. The quality of the camera influences the performance of the LKA system. For a mono-camera it might be difficult to detect the road properly using only frontal images as the camera might not be able to detect all lane markings in case vision is blocked. After detection, an algorithm should transform the images and then communicate this back to the LKA system. Recently, deep learning technologies for lane detection and computer vision have also been researched, but that is considered out of scope for this research. The detection method of the camera can be improved using a stereo camera. The stereo camera stores the images as a disparity map of the road, after which the lanes are detected with an algorithm. (Kim et al., 2018) Radar

technology detects objects by sending out radio waves and detect the distance to objects. LiDAR is based on the same technology, but uses light pulses instead of radio waves. The light pulses are reflected by objects and position is based on this reflection time, depth of rays and intensity.(Ahmed et al., 2020) Therefore, LiDAR technology relies on the difference in reflection rate between the lane marking material and road material. Compared to camera technology, the edges of the markings are less important, as LiDAR is not processing an image of the road. This also means that shadows and glare should be of less influence for LiDAR. LiDAR is more expensive than camera detection though.

Main reason for LiDAR not being able to detect lane markings is eroded and wiped lanes. Success rate of detection ranged from 80 to 90 percent. (Ahmed et al., 2020) Also, weather conditions play a role in the detection process for LiDAR. Objects can be detected in more detail, but the downside is that in rainy conditions the system has more difficulties detecting lane markings because of the size of the particles and the wavelength. Reflectivity of lane markings plays a vital role in the detection process when using LiDAR (Feng et al., 2018). In section 2.4 lane marking properties will be further discussed. Currently, research is carried out to improve algorithms to increase detection rate. Further developments regarding algorithms, machine learning and computer vision will not be discussed here as they are considered out of scope for the purpose of this research.

2.3 Driver knowledge of LKA systems

LKA systems are mandatory in new car models, however this does not necessarily result in drivers using the LKA systems more frequently. Besides this, the behaviour of drivers might also change if they have to perform less tasks themselves. It is important to address in which circumstances the driver switches the system off, and to understand what is the knowledge of the driver about the system. De Guzman and Donmez (2021) used questionnaires to estimate the trust in the system by assessing the sensitivity and response bias. Sensitivity was defined as the ability to detect actual capabilities of ADAS and LKA systems among other systems in the questionnaire. Response bias of owners and non-owners showed their trust in LKA systems and ADAS and assessed if owners view on the capabilities of the system was more positive than for non-owners and thus biased. It was found that owners of LKA systems did not have a better awareness of the capabilities and limitations of the system than non-owners. Owners of these systems perceive the risk of accidents lower and the controllability of the vehicle higher than for non-owners. (Hagl & Kouabenan, 2020) Due to changes in driver behaviour when the systems are switched on, the systems might not have the safety effects that they were designed for. Drivers might have a positive response bias towards the LKA system, where they overestimate the capabilities of the system. Other important results of this research show some common misperception about LKA. Only 30-40% of the participants thought that glare negatively impacted the performance of the LKA system. Participants also indicated how likely they were to perform another task when their ADAS or LKA system was switched on. It shows that drivers rely on the system and therefore are more likely to perform other distracting tasks as eating, texting on their phone, or make a call (DeGuzman & Donmez, 2021).

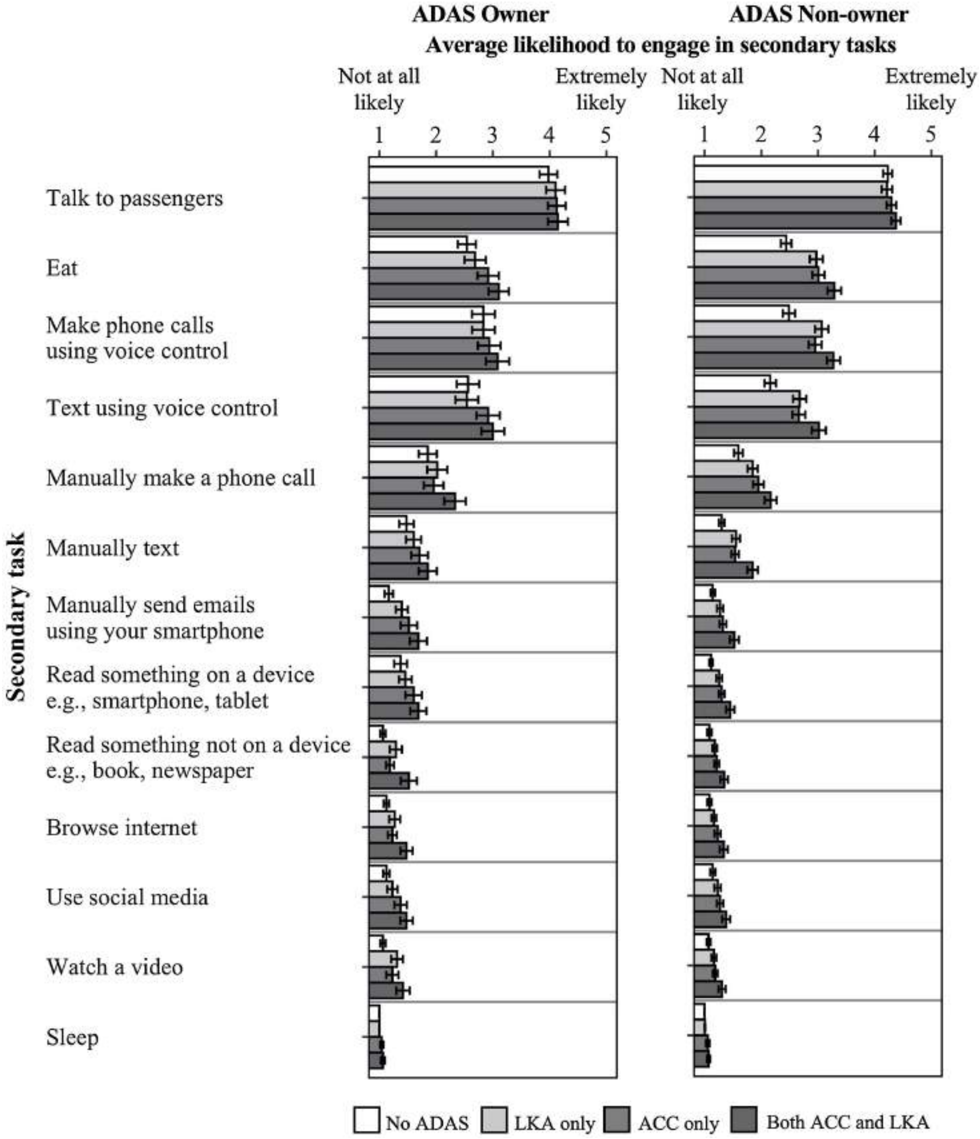


Figure 3: Distraction of other tasks (DeGuzman & Donmez, 2021)

Figure 3 shows that drivers are more likely to perform other tasks while driving. A lower level of awareness might be the result and therefore it is important that the LKA systems performs up to the level of expectation of the driver.

2.4 Lane marking properties

Properties of lane markings influence the ability of LKA systems and humans to detect the markings. Detection criteria are different for humans, cameras, and radar/LiDAR, which makes it important to evaluate criteria for visibility of lane markings. Considering human detection, several studies have been performed on the visibility of road markings and the effects that this has on the behaviour of the driver and overall road safety. These studies will be discussed in 2.5 and 2.6. First, the properties of lane markings that influence the visibility will be discussed.

For human vision, length and width of the markings play a role, as well as retroreflectivity and contrast. For LKA detection, these factors are important as well. Speed of the vehicle is also important, as LKA systems need a minimum speed of about 60 km/h as the lower boundary for their ODD, while for humans higher speeds mean less time to detect surroundings(Fiolic et al., 2020). Section 2.4.1 will explain how light is reflected back by lane markings. In Section 2.4.2 the role of the Refraction Index (RI) of materials in retroreflectivity of an object will be elaborated on. Section 2.4.3 will discuss contrast between objects.

2.4.1 Reflection of light rays on marking types

Retroreflectivity of an object can be expressed as mcd/lx/m2 which is milicandela per lux per square meter. In Figure 4 it is visibly simplified how light is reflected on a road surface. On the left, incident light will be diffused because the surface is rough. In the middle specular reflection is shown, which occurs in a mirror or any other smooth surface. On the right, small glass beads are placed on the surface. Incident light enters the glass beads and travels back in the same direction as where it came form, thus reflecting the incident light.

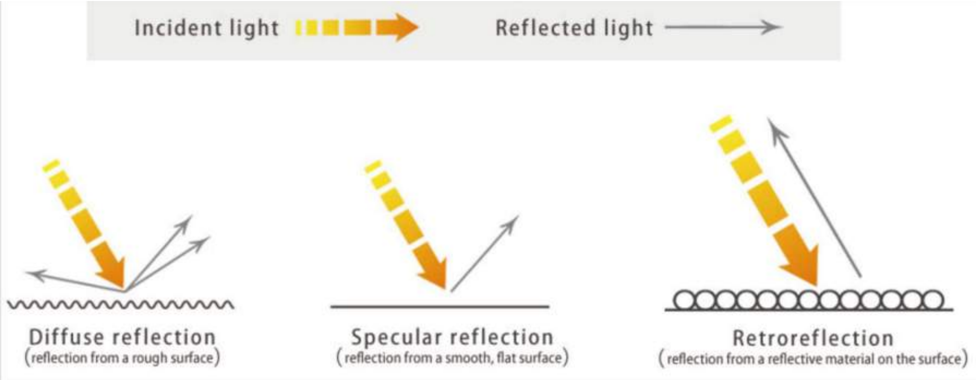


Figure 4: Reflection explained
(Huijink, 2023)

Two types of lane markings can be found on Dutch roads, Type I and Type II. Type I lane markings are completely flat and don't have any specific properties to reflect light. Type I lane markings can be white paint but also white tape. White paint would reflect the light diffuse as the surface area is still rough asphalt. In the case of flat white tape the incident light gets reflected in a specular way. In both situations, light is not reflected back to the vehicle and driver. Type II lane markings have retroreflective properties and are able to reflect light back towards the vehicle. Materials such as glass beads ,ceramics, crystal or even diamond can be added on the top layer of the lane marking. Refraction Index (RI) of these materials causes the light coming from the vehicle main beam to be reflected back towards the driver. (Huijink, 2023) In Figure 5 the reflection through the glass bead can be seen.

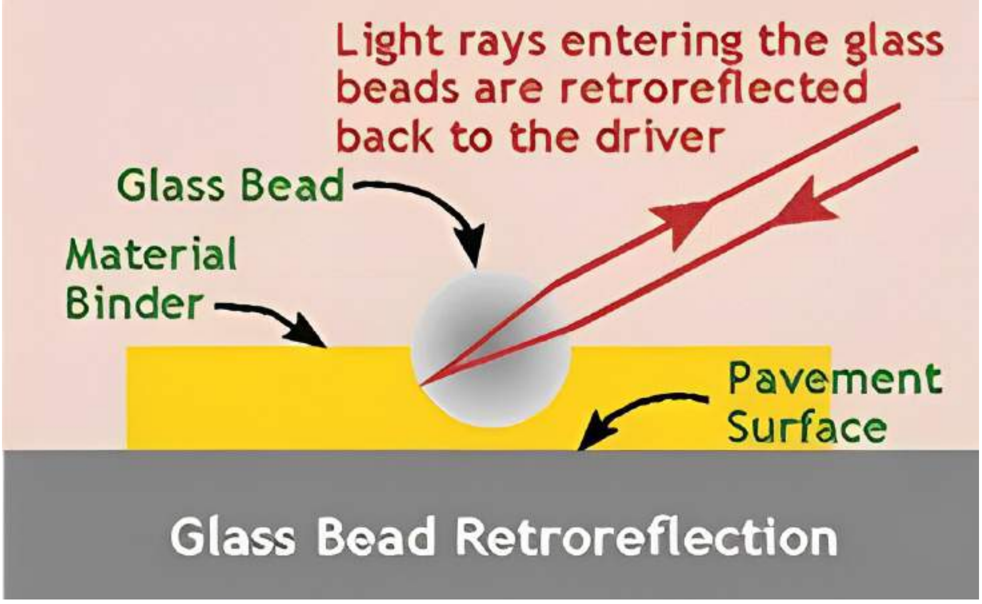


Figure 5: Retroreflectivity
(RetroTek, 2022)

Standard angles for incident and reflected light can be found in the European norm EN1436. In figure 6 it is visible that in the mentioned norm a distance of 30 meters is used to reflect incident light back. Using standardized averages this results in angles of 1.24 degrees for incident light and 2.29 degrees for reflection back to the driver or front camera(Babic et al., 2014).

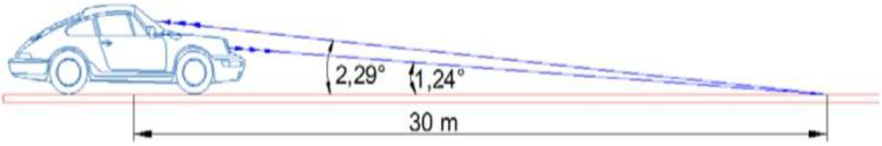


Figure 6: Reflection angles according to EN1436
(Babic et al., 2014)

2.4.2 Reflecting materials

Type and quantity of glass beads and material used affect the retroreflectivity of the markings. Higher retroreflectivity leads to higher visibility for the driver, although they increase disproportionally. (Fiolic et al., 2020) A minimum retroreflectivity value of 100 mcd/lx/m2 is required to have very good quality of road marking visibility. 80 mcd/lx/m2 might also be acceptable, however older drivers might not rate this as a good value for retroreflectivity. Values lower than 60 mcd/lx/m2 are considered poor quality. (Fiolic et al., 2020) (Estonian Road Authority, 2018) To give a visual idea of these reflective values, a pedestrian crossing with different levels of retroreflection is visible in figure 7.

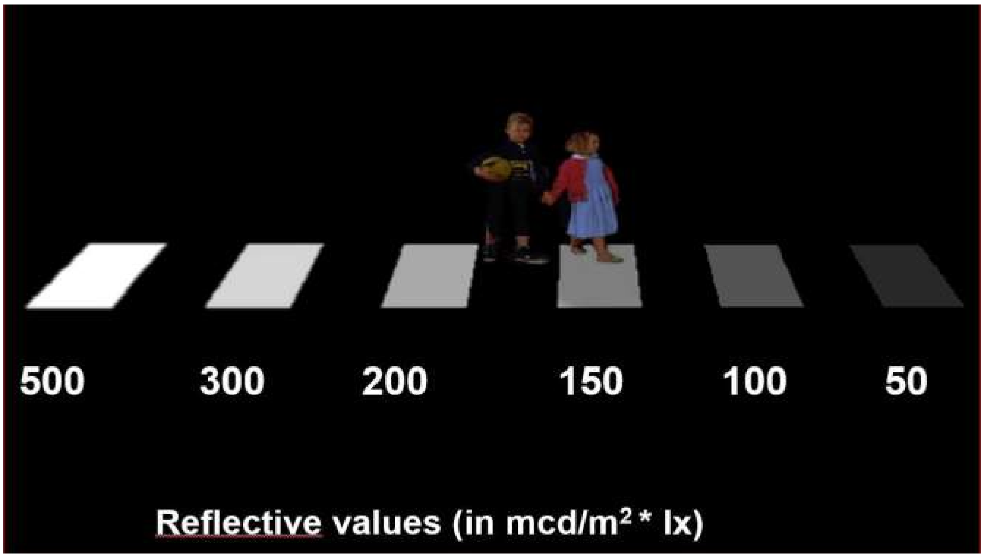


Figure 7: Reflective values visualized
(Huijink, 2023)

In a report from 2018, the European Union Road Federation indicated a minimum reflectivity value, Qd, of 150 mcd/lx/m2 in dry weather and 35 mcd/lx/m2 in wet circumstances (European Road Federation, 2018). Qd is the value for reflection in daylight. Two other reflection parameters are important, namely Rl and Rw. Both are also expressed in mcd/lx/m2. Rl, also called nighttime visibility, indicates the ability of a lane marking to reflect incident light from the vehicle head lights back to the driver in dark circumstances. Rw indicates the ability of the marking to reflect the incident light back to the driver in dark and wet circumstances. Refraction Index of the used material is the most important parameter for visibility as this determines how light is reflected back to the driver.

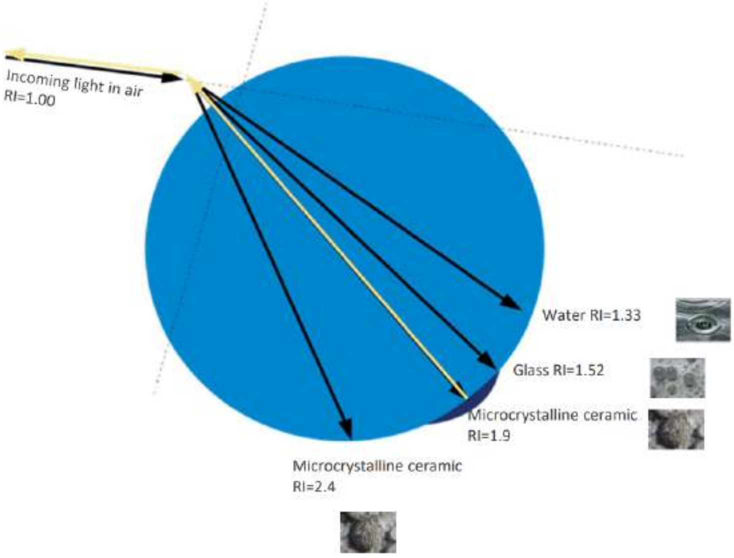


Figure 8: Refraction indices of different materials
(Huijink, 2023)

In figure 8 refraction indices of different materials are visible. Incident light is indicated with the black arrow, while the yellow arrow is the reflected light. Incoming light in air has a RI of 1.00. The light rays will be reflected through material towards the focal point and then reflected back. Ideally light is reflected back in an bundle towards the driver under the angle of 2.29 degrees that was visible in in figure 6. Water has a RI of 1.33 and glass a RIof 1.52. When materials age over years, and their shape might change, this can affect the refraction of the material. , In figure 8 microscopic images of materials are visible. Ceramics with a RI of 1.9 might be a good option for reflection when it is dry, however reflection changes when it is wet. When a film of water is on top of the lane marking, the light rays will first travel through the water, then the used material and then back through the water towards the driver. As water already has a RI of 1.33, this means that materials with a higher RI make the lane marking more visible in wet conditions as visible in figure 9. Ceramic with a RI of 1.9 would now be reflected in a diffuse way as it's no longer in the vocal point. It is also visible with the arrow going upwards that part of the incident light will not enter the material but is reflected in a specular way.

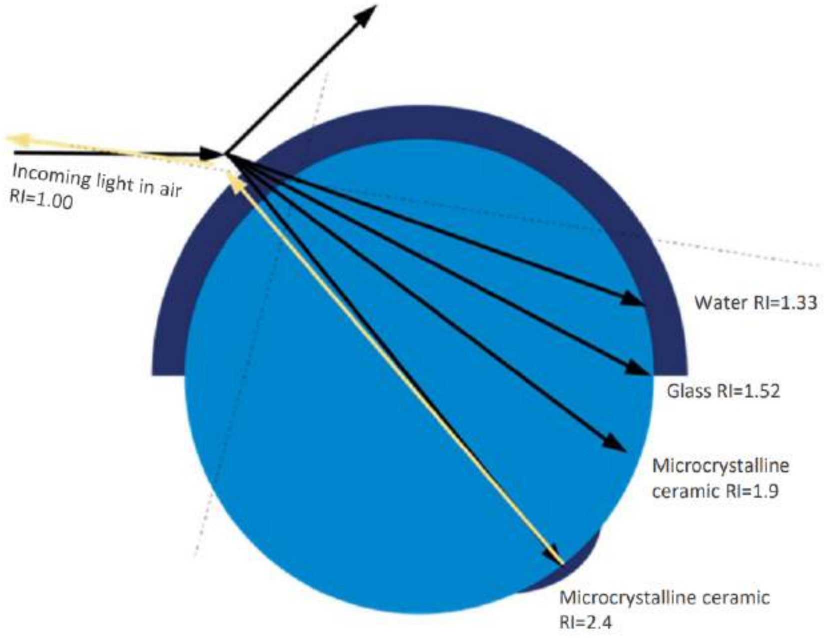


Figure 9: Refraction indices of different materials in wet conditions

(Huijink, 2023)

Although this is a simplified representation of reality where all arrows not exactly represent how light travels, it shows that rain and wet conditions have a significant influence on the refractive properties of a lane marking, depending on the materials used. Following images will further illustrate how it actually looks like when light shines on these optical materials in a laboratory set up. On the left side a mix of 1,9 and 2,4 RI materials are used in a 60 to 40 ratio. On the right side only glass pearls with RI 1,5 are used.

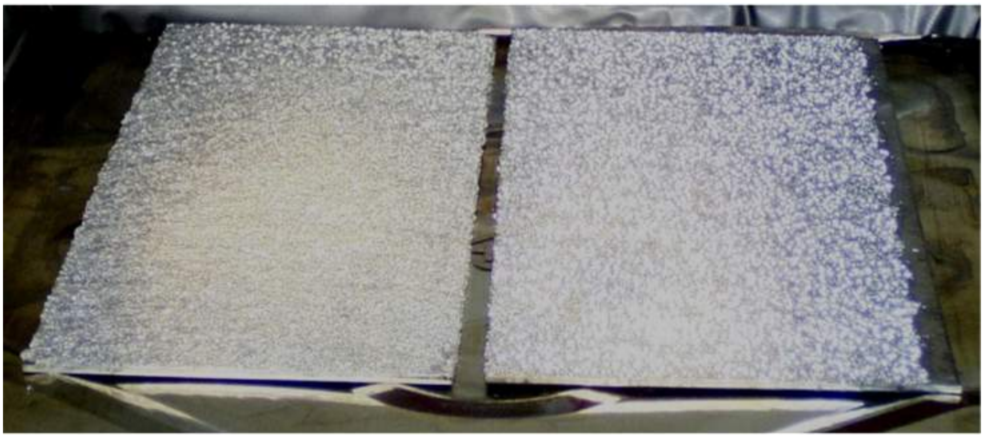


Figure 10: Reflection in laboratory setup dry conditions, left: 1,9 and 2,4 RI mix, right: glass pearls 1,5 RI
(Huijink, 2023)

In figure 10 it is visible that both optical materials used in lane markings, either glass beads or ceramics, are clearly visible to see. However, when put under a film of water in figure 11 the glass beads are barely visible. The mix is partly visible as ceramic materials with RI 2,4 are visible in wet conditions which is in line with figure 9

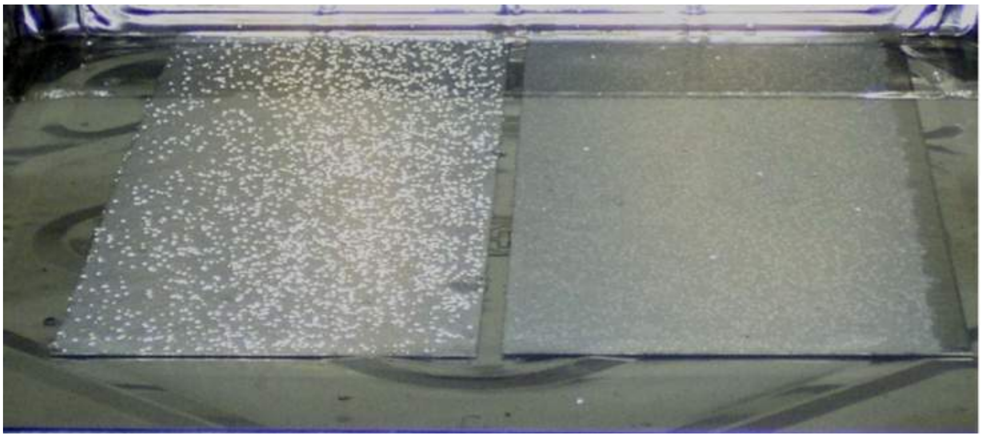


Figure 11: Reflection in laboratory setup wet conditions, left: 1,9 and 2,4 RI mix, right: glass pearls 1,5 RI
(Huijink, 2023)

2.4.3 Contrast with asphalt

Another important criterion for visibility of road markings is contrast. Contrast is defined as the difference in light and dark color tones between two colors. Black and white have the highest possible contrast. Spectral stimuli can appear different to the eye depending on chromatic surroundings. (Lotto & Purves, 2000)

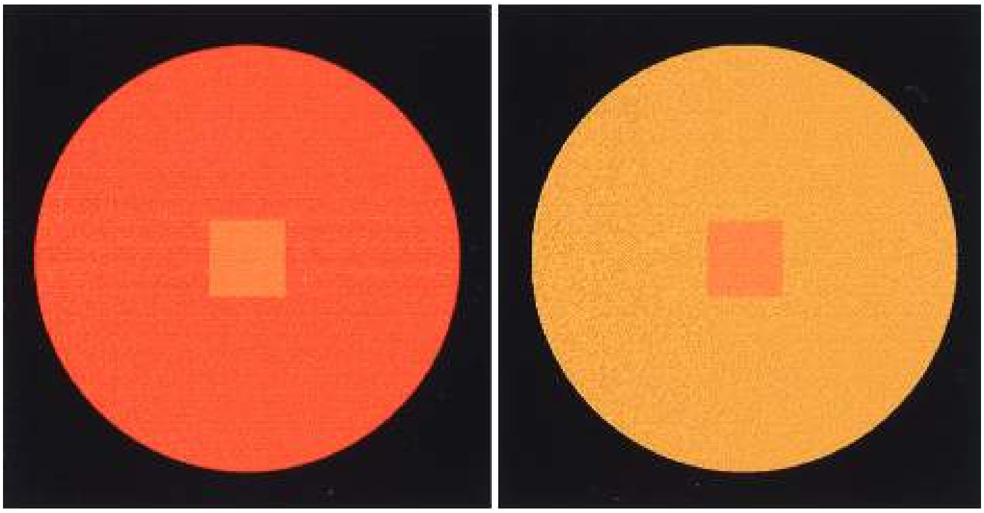


Figure 12: Example of contrast: Both middle squares have the same spectral return, but a different chromatic surrounding circle

(Lotto & Purves, 2000)

An example of contrast can be seen in Figure 12, where it is visible that the same spectral returns might appear different for the human eye or LKA systems when the background color differs. On the left side the background of the orange square is a tone of red, while on the right side the background is a tone of yellow. This makes the orange square appear darker on the right side and lighter on the left side (Lotto & Purves, 2000). It is not necessary to go into detail about all facets of the color spectrum and what influences the background has on spectral return, but this makes clear that the road surface and contrast ratio with the road marking plays a vital role in visibility.

Most road markings used worldwide are either white or yellow and in the Netherlands the standard road marking is white, while for road construction works a yellow marking is used. Where retroreflectivity is more important in nighttime conditions, contrast is in daytime conditions (Burghardt & Pashkevich, 2022). During nighttime the field of vision for human is impaired which changes the perception of colors and contrast between them (Fiolic et al., 2020). As standard road markings in the Netherlands are white, a darker chromatic surrounding will lead to higher contrast values. According to the European Union Road Federation minimum values for contrast ratio should be 1:3 with a desired ratio of 1:4 (European Road Federation, 2018). In practice this means that white lane markings on asphalt with darker color tones will have higher contrast values than on a grey concrete surface. There is no uniform color for asphalt in the Netherlands as it depends on road types, age and wearing.

2.5 Accident relation

LKA systems are expected to reduce single vehicle lane departure accidents worldwide. (Sternlund et al., 2017) (Tan et al., 2019) (Utriainen et al., 2020) Run-off accidents can be prevented by LKA systems and in combination with other ADAS systems like AEB (Automatic Emergency Breaking) accidents can be prevented, or at least the consequences of accidents can be mitigated. However, if the lane markings are not detected by the system, this will still lead to accidents if the system stops working. Research shows quantified numbers of LKA sensitive crashes. This paragraph will discuss research from Australia, China and Sweden.

Between 13-23 percent of crashes could be prevented by LKA in South Australia and 20-25 percent of these 13-23 percent are unlikely to be prevented considering the state of infrastructure. Prevention occurs when a driver risks losing control of the vehicle and leaving the driving lane potentially leading to an accident(Pieris et al., 2022). Peiris et al. (2022) quantified the proportion of these crashes that could not be prevented by the LKA systems because of poor road infrastructure and lane markings. What is not included in this research is the influence of the human driver on the detection of the lane markings and how alert the driver is when the system is switched on.

In Sweden Sternlund et al. (2017) tried to estimate the safety benefits and accident reduction of LKA systems. In the study was also referred to numbers from the USA where it was found that lane departures in single vehicle crashes account for 10 percent of total crashes, but about 30 percent of fatalities because of barriers, trees or other objects on the side of the road. In Sweden at least 30 percent of all crashes was due to lane departure. (Sternlund et al., 2017) It should be noted that LKA systems only work from approximately 60 km/h and higher. It depends per car brand and LKA system from which exact speed the system starts working. When driving at lower speeds, the LKA system will not be able to prevent any accidents as it is not functioning. Therefore, Sternlund et al. focused on a target crash type: single vehicle, head-on, speed between 70-120 km/h and roads not covered with ice or snow. 15 percent of single vehicle crashes fell into this category. LKA systems could prevent 53 percent of these crashes. Also considering head-on crashes and all speed categories, the total reduction of driver injury crashes by LKA systems was calculated to be about 30 percent. Recommendations for future research included situations where LKA is not working, for example in snowy and icy conditions. Also, more accident data could be used to get better knowledge about the exact types of crashes occurring on different road types.

In China, Tan et al. (2019) tried to estimate the number of crashes that can be reduced by LKA systems up until 2030 based on historical data. One of the main problems about predicting accident and fatality reduction is that it is unknown what the penetration rate will be, how well LKA systems perform in the future and what percentage of drivers switches the system off. This adds an additional prediction layer. It is expected that with a 100 percent penetration rate, injuries would be reduced with 12 percent and fatalities with 18 percent. When the same methods were used with European data instead of Chinese data on crashes, Tan et al. found significantly different results. They mentioned that the composition of traffic accidents per country or region is different which leads to these results. There were a few implications and gaps mentioned in this research as well. First of all, they assumed that the LKA system is working and switched on, however the driver might switch the system of. Adverse weather conditions are not considered here and should be included in further research as the LKA system might fail in these circumstances. When also considering the speed limitation of LKA systems, it was estimated that in only 11 percent of accidents the LKA system would have prevented the accident. (Tan et al., 2019)

In Finland Utriainen et al. (2020) analyzed the impact of LKA systems on accidents and which percentage could be reduced. In a similar way to the other studies discussed, data was obtained on accidents. After which it was determined what percentage of these accidents could be prevented by LKA. First of all, LKA should be present in the car and switched on. Then also other conditions should be met regarding speed, weather and lane marking visibility. It was assumed that in adverse weather conditions during the night the LKA systems could potentially not detect lane markings and therefore not prevent the accident. The conclusion was that 27 percent of single vehicle and head-on crashes could potentially be prevented by LKA systems. (Utriainen et al., 2020)

2.6 Performed tests with LKA systems and lane markings

Several different tests have been performed with LKA systems and lane markings. These tests were either on a test track where certain conditions and variables could be created, or in the field where a vehicle was driven on actual roads. In this section first the tests on track and then the field tests will be discussed.

On test tracks it is possible to test specific variables and their influence on the detection process on LKA systems. Also, it is possible to simulate any circumstances that might be difficult to find in a field test. In Malaysia a test was performed focused on South-Asian circumstances, simulating heavy rainfall using a rain simulator attached to a preceding vehicle. This test was not focusing on the performance of the LKA system, but used as a set-up and comparison for an infield test. Speed used in this test was 70 km/h and a distance of 300 meter for the test section was set up after a section of 100 meter for stabilizing the LKA system. (Mansor et al., 2020) It was not stated which type of lane marking was used in this test. No other field tests were found where a test was specifically designed to test the visibility of different lane markings under various circumstances

Most field tests had as goal to find road stretches where road marking visibility was not sufficient according to a National or Local Road Traffic Organisation and then analyze why the LKA system failed on these particular stretches. Mahlberg et al. found that the detection of lane markings in Indiana, USA, improved from 80 percent to 92 percent from 2020 to 2021. This was mainly due to construction works not being present in 2021, improving detectability. The data collection of 2021 was performed in winter, while in 2020 the data was collected in july. Salt residue was a factor that influenced LKA performance in a negative way as the contrast between road surface and marking became less. Other factors mentioned to play a role in the performance were time of day and weather conditions. (Mahlberg et al., 2021)

Babic et al. compared the lane marking detection quality between day and night time conditions for LKA machine vision. They used a Mobileye 630 camera system in a BMW car and GPS technology to precisely measure the location of the vehicle. The study focused mainly on the difference between day and night time vision of the camera and did not consider other gaps that were found in literature. Adverse weather conditions and influence of street lights were not considered. By driving on rural roads without street lights in Croatia during day and night the detection quality of the camera was compared. The conclusion was that the lane markings were 12 percent more visible during night time for the LKA system. Contrast ratio and retroreflection were probably higher during the night, although this was not measured. (Babic et al., 2021)

Several studies on lane markings have been performed in the past years by students of TU Delft. Reddy (2020) set up a field test with two vehicles of which one was equipped with a LKA system and the other one with a LDW system. Both vehicles drove several test runs in the province of Noord-Holland on different road types, with varying weather circumstances and during day and night. Time of day and weather circumstances were seen as one variable. Detection rate of lane markings was a performance indicator where the performance was categorized for lane markings on both sides of the driving lane. Besides the detection performance, the lane keeping performance was also analyzed by measuring the lateral and longitudinal position of the vehicle on the road. Most important results found were the following: The LKA system performance was worst in the scenario with rain during the night and streetlights switched on. During the night with street lights switched on was also the best performing detection, but in this scenario it was dry. Repair patches or even the shoulder could mislead the LKA system, which resulted in the system detecting a line which was not a lane marking. According to Reddy, speed did not seem to have an influence on the performance, as long speed was above the minimum of 70 km/h. However, speeds of 90 km/h led to a lower performance for an unknown reason, but this speed was only driven on a very small stretch. Lane width influenced the performance when lanes had a width less than 2.5 meter. The LKA system was still able to detect the lane markings, however the performance was negatively affected. Not considered in this study were type of lane marking, quality, surface quality, shoulder material, median type and the influence of opposing traffic with headlights switched on. (Reddy et al., 2020)

Van der Kooij (2021) set up a field test with three vehicles and LKA systems, a mono camera, stereo camera and a mono camera + infrared. All vehicles drove the same two test routes at the same time to. The field test was undertaken at three days in which no heavy rain no and glare was experienced. Sunset was a challenging condition for the cameras as the sun was directly shining into the camera on some parts of the route. During the route several parts did not comply with the ODD of the LKA system because of speed limits. Minimum speed for the systems to be activated was 60 km/h, so any parts inside build-up areas did not fell into the ODD. One of the vehicles used, a Subaru Outback could not detect the lane markings as the lane width fell out of the ODD. The system was designed for American highways and freeways with a width between 3.00 and 4.50 meter. This meant that only the mono camera and mono camera + infrared were compared. The regular mono camera remarkably had a better performance than the mono camera + infrared and would require further research as it was not expected. Performance of the mono camera was best in dry nighttime conditions, while the performance of the mono camera + infrared had the highest detection rate in sunset conditions. It was found that both sensor type and lane marking type play a significant role in detection. Type II lane markings, with retroreflective properties, had a higher detection likelihood. No heavy rain or glare was experienced in the experiment and therefore it could not be said if these variables would have a significant influence on the detection rate. Light rain was experienced, and it was found that street lights had a negative effect on LKA detection performance in dry conditions, and a positive effect in light rain conditions. This was not as expected and not in line with the results of Reddy (2020), as he found that street lights had a negative effect on detection in light rain conditinos. (Reddy et al., 2020) (van der Kooij, 2021) Retroreflectivity was not found to be significant because the values were higher than 100 mcd/lux/m2 and both cameras were able to detect this. Therefore all data points with values higher than 100 mcd/lux/m2 were removed. It was recommended to perform more tests with a lower quality lane marking and street lights.

2.7 Performed tests with lane markings and driver

In previous sections it was found that drivers might switch off the LKA system. Moreover, even though new European regulations stimulate the penetration rate of LKA sytems, there will still be many cars on the road without LKA systems this decade. Therefore, the visibility of lane markings for drivers will be discussed in this section.

Before the introduction of LKA systems, research focused on the ability of the human eye to detect lane markings. From the 1960s onward research has been carried out on lane markings. The studies are categorized in the impact on traffic safety and the impact on driver behaviour. (Fiolic et al., 2020) Several studies are discussed where road markings are used as a measure to reduce speed by using visual effects, changing the dimensions or using for example rumble strips. Some of these studies used a driving simulator while others used a test track to evaluate the behaviour of the driver.

Studies focusing on the impact on traffic safety, focus on the ability of the driver to detect road markings and the properties of the road marking that has an influence on this. Retroreflectivity of the marking plays an important role here, as discussed in section 2.3. Wet-night conditions were studied by Gibbons and Hankey. They used a test track where fifty-three participants drove a vehicle and four types of lane marking were tested. In wet conditions light reflected by glass beads gets scattered and diffused. Types of marking tested were standard tape with glass beads, wet retroreflective tape, semi-wet retroreflective tape and thermoplastic. Other variables were light, vehicle and surface. Results for detection distance are summarized in Figure 13(Gibbons & Hankey, 2015).

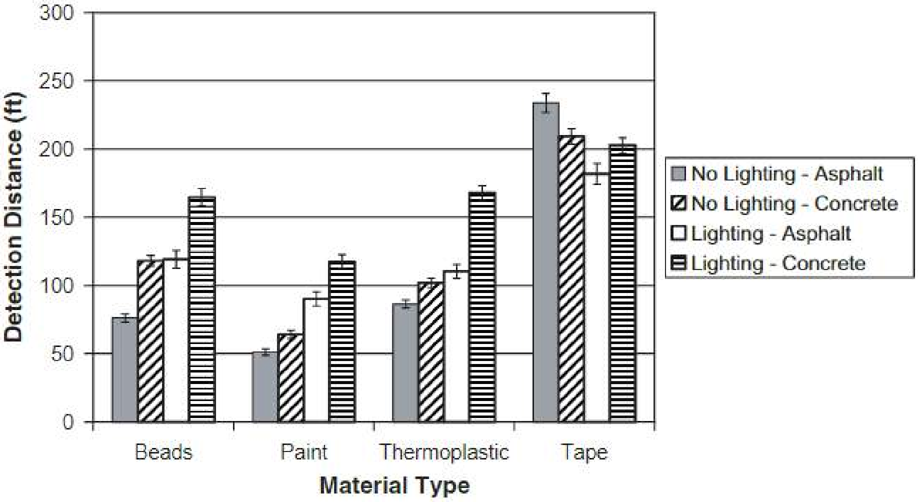


Figure 13: Detection distance for marking types
(Gibbons & Hankey, 2015)

Drivers had to indicate when they could first see the marking, therefore the study focuses on the detection distance of the lane marking. It does not necessarily say something about the continuous visibility. Wet retroreflective tape had the highest detection distance under all light circumstances and surfaces. Where for all other markings the detection distance was highest with lighting and a concrete surface, for tape it was highest with asphalt and no lights.(Gibbons & Hankey, 2015).

Gouribhatla et al. (2020) studied the influence of ADAS on driving behaviour using a driving simulator. Scenarios were developed for rural, urban and highway roads in different weather circumstances. They found that the LDW had a positive influence on the lane departures, meaning that those were reduced. No significant difference between the scenarios was found and therefore the conclusion was that ADAS and LKA help the driver to stay in lane, however further research should be conducted on situations where LKA does not detected the lane marking. Also weather simulations are difficult to simulate in a simulator as drivers might react differently to the environment when they have to drive in wet or windy circumstances(Gouribhatla & Pulugurtha, 2022)

Multiple studies evaluated variables that influence the visibility of lane markings. Quality, embedment, density of glass beads, age of marking, and road type all determine the visibility of road markings for drivers (Fiolic et al., 2020). In a project called IMPROVER and NIGHTVISION the visibility of lane markings in wet nighttime conditions were studied. This project carried out a simulator test, a field test and a test on a test track. The simulator test took place in France, while the on-road trial took place in the United Kingdom and track test in Austria. On the track in Austria three different markings were place on a total length of 1 km. Participants drove under dry, wet and wet/rainy circumstances which took a week in total. Sprinklers were used to create a wet surface and adjusted sprinklers to moisture the windshield and simulate rainy conditions.

Wet reflective type II markings increased comfort for drivers as visibility was better compared to regular paint markings. The test track was found to be the most comprehensive way to study the relation between driver and lane markings as it is the most convenient way to adjust factors. In a simulator the behaviour of the driver could be monitored in a safe and convenient environment, but it was more difficult to realistically simulate lane markings. On-road testing showed contradicting results compared to the simulator and test track. On a stretch where new type II lane markings were placed, accidents increased compared to old type I lane markings. It was not known if other factors influenced this and due to lack of budget the driving behaviour could not be monitored in a proper way. Recommendation for future research is to carry out more field tests and link them to LKA to get more knowledge about lane marking detection of LKA systems combined with the comfort level of the driver. (Diamandouros & Gatscha, 2016)

3 Research questions and conceptual framework

In the previous chapter, existing literature was reviewed and discussed. From this literature, several gaps were identified. Not all of these gaps will be researched. In section 3.1 the identified gaps will be discussed. After this, section 3.2 will present the research questions. In section 3.3 a conceptual framework for this research will be presented after which a hypothesis will be stated in section 3.4.

3.1 Identified gaps from literature

In the literature many field, simulator and track tests were performed with participants or LKA systems. However, most of these tests either focused on a particular variable or were having a focus on a road stretch to determine detectability on particular sections. With the transition to higher levels of automation, a high detection rate for LKA systems is important. In cases where the LKA systems will not be able to intervene, the driver should still be able to detect the lane marking. Several tests have been performed with driver simulators. It is difficult to test weather and road surface circumstances in a simulator and the performance of a LKA system can not be analyzed by simulator results only. Some tests have been carried out with on national roads in real traffic circumstances. Although this is of course a good way to test out both LKA and driver performance on a real road, there is a great variety in roads and quality of lane markings on roads. Environment is not fixed and variables can not be tuned. It was found in previous TU Delft studies that especially the visibility of lane markings for LKA systems in the night with wet conditions gave contradicting results. For human detection it was found that the type of lane marking influences the visibility, however this was not tested in adverse weather conditions. In order to get an overview of the performance of LKA systems, the system performance in a fixed environment should be known. This is a gap in research, that will be dealt with. The dataset that will be obtained should give an insight in the visibility of lane markings in good and adverse weather conditions during any time of the day. This will give information for any future tests on actual roads, as those tests can be performed in situations where LKA systems have the most problems. Combining a test with LKA systems and visibility for humans on a test track would be ideal, but is out of scope for this master thesis- as it would be too costly time and budget wise. A significant number of participants should be available on multiple days which would take recruiting time and budget. It should be remarked though that this is also a gap in literature. Research has been carried out about visibility for lane markings for humans as well as research about the understanding and usage of ADAS systems by humans. This interaction is important as it indicates when drivers would switch the LKA or ADAS systems off. This interaction will not be a part of the experimental setup for this research as it was not feasible.

3.2 Research questions

Gaps in research that were discussed before, have led to the following main research question:

How do the lane marking properties affect their visibility and detection by Lane Keeping Assistance systems in different scenarios?

This question is divided into four sub-questions. By answering them collectively, the main research question is answered.

1. How do the lane marking types and optic materials used, combined with road surface, influence the contrast and retroreflectivity?

2. How do the contrast and retroreflectivity of different lane marking types affect LKA performance?
3. What is the influence of luminosity, time of day, glare, dry/wet surface, and different LKA system cameras on lane marking detection?
4. What is the influence of headlights of opposing traffic on the detectability of lane markings for LKA systems?

These questions were partly answered by literature, but as explained in section 3.1, further research is needed to answer these questions. In the following section the developed conceptual framework is presented.

3.3 Conceptual Framework

In this part, the conceptual framework for this research will be discussed and visualized. First the interaction between driver, vehicle, ADAS and infrastructure is visualized and elaborated on. Based on the research gaps and research questions derived from literature, dependent and independent variables will be identified. After which the relationship between variables will be shown and a hypothesis will be stated.

In figure 14 the relationship between human, vehicle, ADAS and infrastructure is shown.

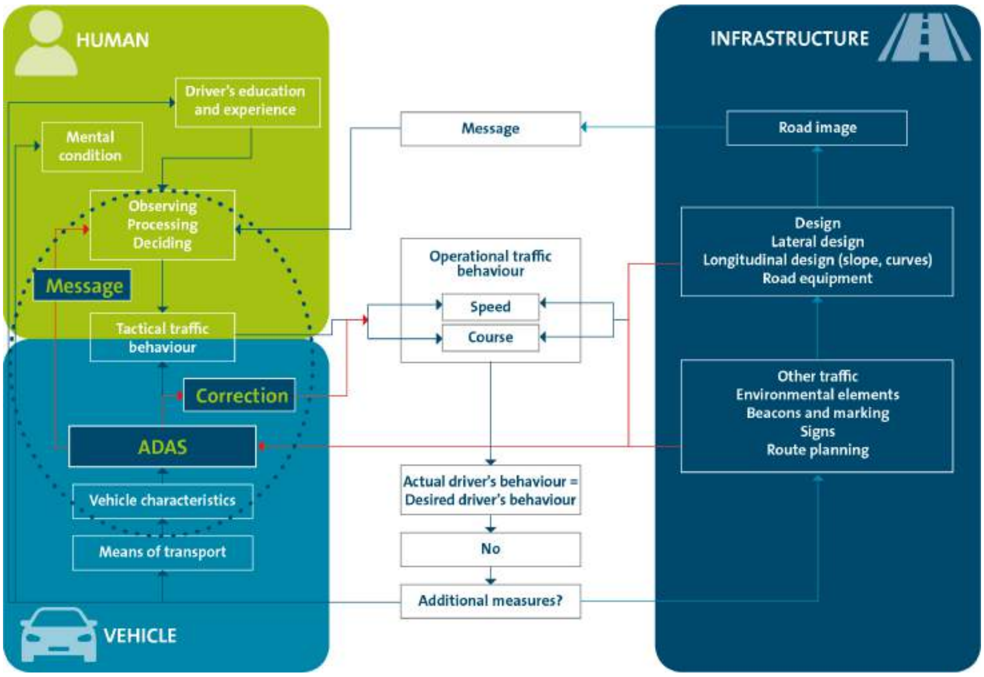


Figure 14: Interaction between ADAS, driver and infrastructure (RHDHV, 2022)

Starting at the right top, there is a road image which consists of everything around you as a driver that you can perceive while participating in traffic. Going to the right bottom, it is visible that this includes dynamic traffic elements, such as other traffic, and all static elements. The arrows from right bottom to top show that environmental elements, signs, beacons and also road markings lead to a road design. Design consists of lateral and longitudinal elements and all together this creates the road image. This image transmits a message to the human driver, who might perceive the message differently than other drivers depending on the described dynamic factors. The driver observes and processes this message and in combination with the education and experience of the driver, he or she makes decisions. These decisions form the tactical driving behaviour. This tactical driving behaviour leads to operational driving behaviour where the speed and course of the vehicle are affected by the drivers operations. If this is not as desired, additional measures might be taken by road authorities. Measures on the infrastructure side would lead to a different road image and then might change the behaviour of the driver. On the left bottom side, additional measures can also be taken in the vehicle. Means of transport or vehicle characteristics could be changed, and ADAS in vehicles can influence driving behaviour in two different ways. A message might be transmitted to the driver, for example in LDW systems where an audio or visual warning sign is transmitted. This message is observed by the driver, after which he or she adapts tactical driving behaviour based on this. ADAS can also make corrections, for example by LKA systems making corrections to the steering wheel. This directly influences the operational traffic behaviour as the course of the vehicle is changed.

To make figure 14 specific for LKA systems, lane detection and driver performance, dependent and independent variables were found in literature. All variables are listed in Table 1.

Table 1: Dependent and independent variables included in this research

Dependent	Independent
Contrast	Marking type
Retroreflectivity	Time of day
Human detectability	Weather
LKA detectability	Artificial light
Marking status	Marking dimensions
	Speed
	Driver
	LKA system
	Surface
	Vehicle type

Contrast is a dependent variable and depends on the surface and marking type. (Lotto & Purves, 2000) Other properties of the marking as age and degrading play a role as well, but are all considered under the same variable 'marking status'. Retroreflectivity of markings depends on the same variables. Visibility for humans and detection by LKA systems depends on the contrast ratio and retroreflectivity as well as all other independent variables listed. The relationships between these variables are visualized in figure 15

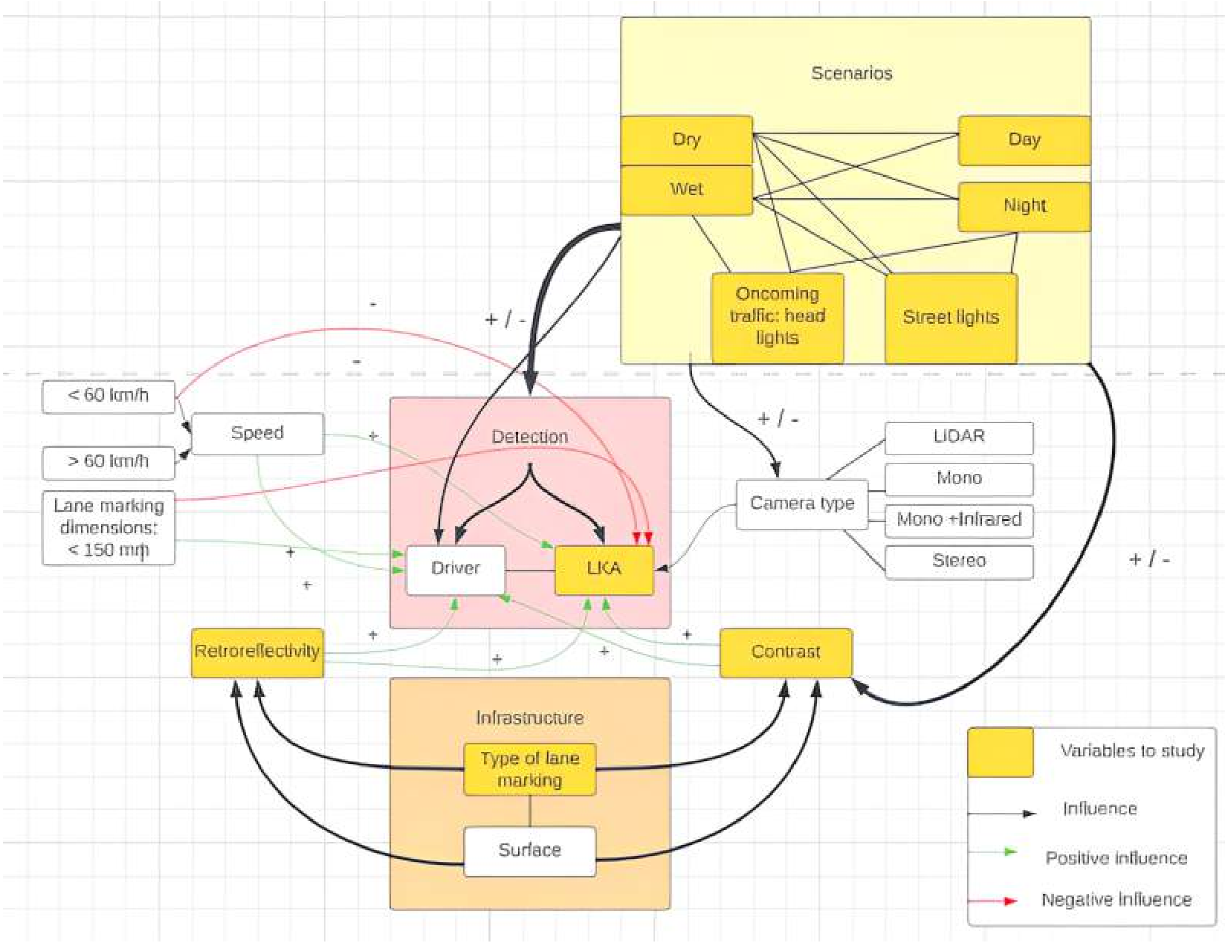


Figure 15: Conceptual framework

The framework consists of three main blocks, namely: detection, infrastructure and scenarios. Driver and LKA system are actively detecting lane markings, which are part of infrastructure together with the road surface. Type of lane marking has an influence on the contrast and retroreflectivity. More contrast and higher retroreflectivity should lead to a better visibility for both driver and LKA system. From literature it was concluded that width of marking smaller than 150 mm makes it difficult for LKA systems to detect markings. The same goes for speeds lower than 60 km/h. This is different for human, however increasing width and speed has a positive influence on detection. Different scenarios that are considered in this research are connected with lines in the scenario block. The scenarios consist of a wet or dry surface, daytime or nighttime and lights from opposing traffic and street lights switched on or off. It is possible that both are switched off, both switched on or one of them switched on and the other off. Some of these scenarios have been researched before, but not all of them and some gave contradicting results. The relationship and effects between the combination of scenarios and detection are noted with a plus and minus sign. The scenarios will also influence the observed contrast by the camera type. Four different camera types are considered in LKA systems. Detection performance of these cameras gets influenced positively or negatively by the different scenarios. In the literature review it was discussed which camera types performed better in which circumstances.

Speed and dimensions of lane markings have proven effect on visibility and detection. Therefore these variables will not be further tested in this study and kept constant. As long as the minimum ODD speed of the system is reached, it should bet able to detect lane markings. Type of lane marking and camera influences the detection for both human and LKA system.

3.4 Hypothesis

To be able to answer the formulated research questions, hypotheses are formulated to be tested and either confirmed or rejected. These hypotheses will help answering the research questions. Following hypotheses are formulated based on findings in literature:

1. Higher values for contrast and retroreflectivity lead to higher detection rates for lane markings.
2. Glare has a negative effect on detection by LKA systems when driving towards the sun during sunset or sunrise.
3. Wet circumstances have a negative effect on detection by LKA systems.
4. Nighttime conditions have a negative effect on LKA systems detection performance when it is wet.
5. Artificial light has a negative effect on LKA systems when the road surface is wet.
6. Opposing traffic with their headlights switched on in dark conditions has a negative impact on the visibility of lane markings for LKA systems

4 Methodology and Experimental Setup

This chapter will explain the setup of the field test and methodologies used to collect data that will provide answers to the research questions. Choices for tools, location and equipment will be explained.

4.1 Experimental setup and location

On a test track it is possible to simulate weather and light circumstances. Drivers are able to drive a route on the test track multiple times within a relatively short time span, making it possible to collect data on the performance of the LKA system. LKA system performance can be quantified by obtaining data on the detectability of lane markings as a performance indicator. The field test was carried out together with the companies 3M and Triflex. 3M provided two lane markings and Triflex one. Details about lane markings will be described in section 4.2.

The RDW (Rijksdienst Wegverkeer) test track in Lelystad was used as site for the field test. This site has been used before for field tests and RHDHV had direct contacts with the RDW to set up the test. A satellite image of the test track is visible in figure 16.

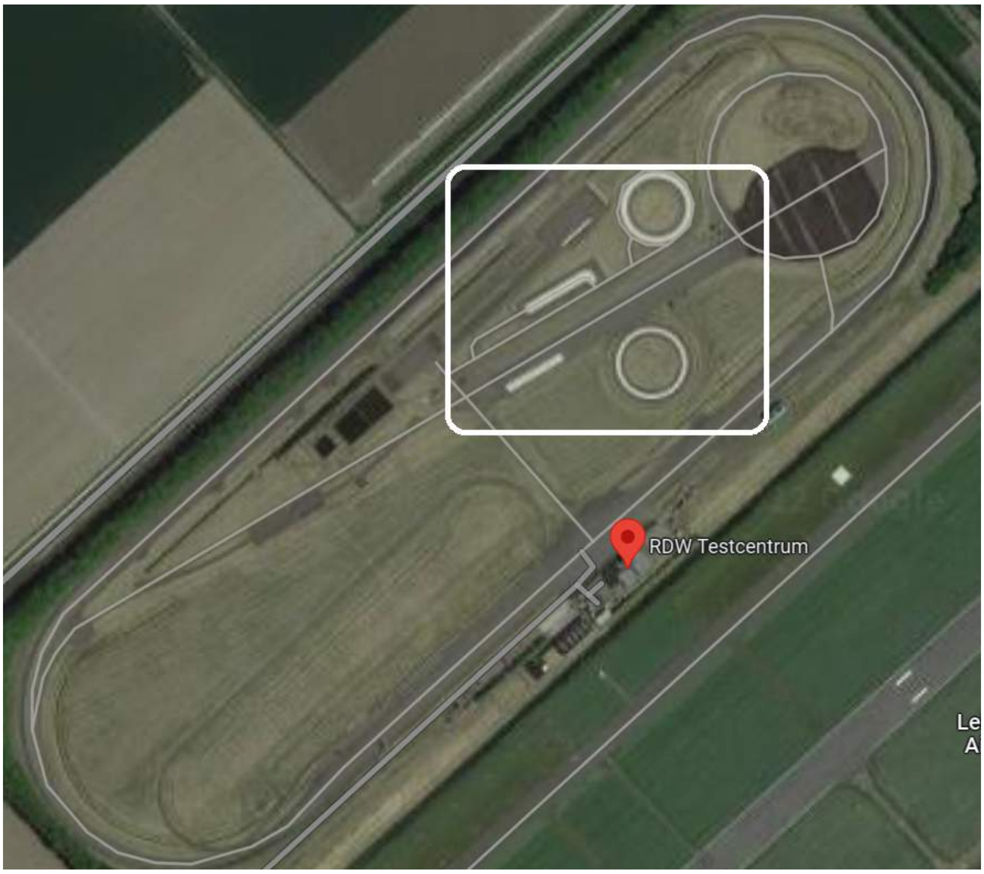


Figure 16: Satellite image of test track Lelystad with field test location in white square, coordinates: 52.459771 , 5.514800 (Google Maps, 2023)

In figure 17 an aerial overview of the diagonal of the site is shown. Layout of the set up of test drives will be discussed in section 4.5.

Figure 17: Aerial overview of test site

The test track consists of an oval with existing lane markings for 3 lanes. This made the oval unfeasible to use as it was impossible to remove existing lane markings. On the diagonal within the square in Figure 16 the white parts on the satellite image are used for slipping tests and were therefore not possible to use. Other parts of the diagonal were all possible to use. On one part of the diagonal there was an old lane marking with two driving lanes. In figure 18 these lanes on the diagonal are visible. At the far end of this image, the big circle visible in the right top of the satellite image in figure 16 is visible.

Figure 18: Diagonal RDW track

4.2 Type of markings

On the RDW test track an old white paint Type I marking was already present on the diagonal of the track as visible in figure 18. This white paint marking was already placed on the track several years ago. It is not known exactly how long ago, but the marking was deteriorated to some degree as visible in figure 18. As there is not one single marking that can be classified as a standard marking on Dutch A- or N-roads (highways and national roads), the old white paint marking was considered as a reference marking. It was also an option to take a completely new marking as reference, but that would be less realistic as lane markings on existing roads will on average also be several years old. The exact average is not known, but when one considers a replacement scheme of asphalt of a decade, then lane markings will have an average age of several years.

3M provided two different white tape markings, namely 380ESD and 380AW, where ESD and 380 have no special meaning as abbreviation and numbers, according to 3M and where AW stands for All Weather. ESD is a standard tape that is used on highways by 3M where the AW should give better reflection in wet and dark circumstances. Usually the tape is sprinkled with glass beads, while for the AW, materials with a higher refraction index are used as well as explained in chapter 2. Visually there is no difference between both tapes on a macro level. In figure 19 the roll of ESD tape is visible in the process of rolling out and after being applied.

Figure 19: Left: 3M ESD tape roll unpacking ; Right: 3M ESD tape applied on test track

Process of applying 3M AW tape was exactly the same as the application process of 3M ESD.

Triflex provided a coldspray plastic material that was sprayed onto the asphalt. As it was not possible to remove this marking, it was discussed with the RDW that the marking could be located on top of the old white paint marking. This was applied on a part of the old marking so that it was possible to drive in both directions for both markings. Thickness of the marking including sprinkled beads was not allowed to be more than 1 millimeter by RDW, while on public roads this would be around 3 millimeter. If the marking thickness would be more than 1 milimeter this could influence future braking tests on the test track. Having a thickness of 1 milimeter might have influenced the visibility slightly, although the main purpose of thickness is to prevent deterioration. As the marking was just sprayed onto the asphalt, it was completely new. Therefore the influence on visibility of the thickness should be negligible. As visible in Figure 20 this spray marking has a clear visible difference compared to both tape markings. Figure 20 zooms in on a few meters of the marking.

Figure 20: Triflex cold spray plast

4.3 Dimensions

All markings had a width of 150 millimeter, which is the same as standard on Dutch highways and national roads. A standard lane width would be 3,5 meters. For detection purposes it is not necessarily needed to have a complete driving lane with two lines of lane marking. As there was not enough tape material from 3M to reconstruct a driving lane with one solid line and one dashed line, it was decided to place one line of about 180-200 meters of each marking. It was tested in an earlier visit to the test track that LKA systems still detected the marking if it was only one line instead of a driving lane. Dashed lines have a standard ratio of 1:3 with 3 meters of marking and 9 meters without. So, it was possible to recreate a driving lane, but this would shorten the testing distance with 25 percent. Thickness of 3M markings was about 3 millimeter, which was higher than 1 millimeter indicated by RDW. It was possible as the tape would be removed afterwards. As only a single line was used, this is not an exact replication of a driving lane with a width of 3,5 meters. It was tested out that a distance of 5 meters between the lines should be enough for the cars to not detect it as a driving lane, but as two separate lines. Specifications on the layout of the test segments will be explained in the following section 4.5.

4.4 Layout on location

Layout of the test track with placement of all markings is visible in figure 21. On the southeast side the lane marking of 3M AW was placed. Northwest of 3M AW, 3M ESD was located. A thin white line of only 50 millimeters wide was located in the middle of diagonal. North of this was a two-lane road where the southern side lane marking was old marking and the northern side lane marking Triflex cold spray plast. The dashed center line was split between Triflex and old marking. Northeastern part was old marking and southwestern part Triflex. In figure 21 halfway is shown with a small green dashed line. As one line was used for detection, it should be noted that the dashed line was not necessarily of use. However, as Triflex marking was located relatively close to the grey split asphalt part, it could be used in case detection was a problem. Lanes were also used for setting up opposing traffic.

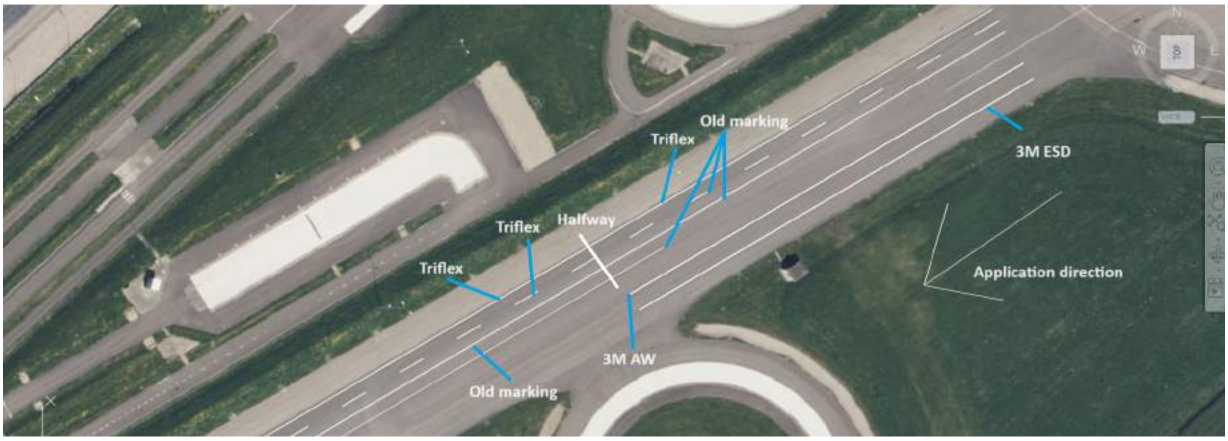


Figure 21: Placement of lane markings

In Figure 22 the dimensions of the test site are visible. Dimensions are shown on the east side of the track. Total length of the track is about 300 meters.

Figure 22: Dimensions test site

Because of visibility reasons, Figure 23 zooms in on the northeast side of the test track. Width dimensions for the lane markings are visible.

Figure 23: Width dimensions test site zoomed in

4.5 Base scenarios

All possibly adjustable independent variables of the experiment are listed below:

- Type of marking
- Time of day
- Weather
- Street light
- Oncoming traffic head light
- Marking dimensions
- Speed
- Drivers
- LKA system

In theory it was possible to adjust all these variables, and create a high number of scenarios, but that would practically make the experiment unfeasible. As all lane markings were place parallel to each other. Six base scenarios were created considering day/night, light/dark, wet/dry. In table 2 the six base scenarios are listed and referred to with a number. Per base scenario all markings would be tested.

Table 2: Base scenarios

	Day	Night	Night with street lights on
Dry	1	3	5
Wet	2	4	6

First, it was considered to test out two markings per day and use the test track for four days in total. Main constraint was that it was not possible to do wet tests on the same day as dry tests. During daytime the track already had to be made wet and it would not be possible to get the track to dry before nighttime. After exploring the option of testing all markings at the same time, it was possible to reduce the number of testings days to two. First day was used for dry tests only while the second day was used for wet tests. All parties involved agreed that it was not a problem to perform tests for all markings on the same day. Oncoming traffic was used in 3, 4, 5 and 6. In dark circumstances two cars were positioned on the left hand side of the lane marking as oncoming traffic. Due to safety reasons it was not possible to drive for those two cars. The first car had neon head lights, while the second car had halogen headlights.

4.6 Weather and time of day

Weather is a variable that could not be influenced and consists of many aspects. The test runs were planned in such a way that the first runs would start about one and a half hour before sunset when the sun was about 12 degrees above the horizon. The final daytime runs would end 45 minutes before sunset when the sun was about 5 degrees above the horizon. These runs were considered as daylight runs. One should note that visibility varies per season, month, day and time of day. Sunlight, clouds, wind are all factors influencing visibility. Testing days were confirmed with RDW at 18th and 19th of april 2023. In case of rain, two back up dates were arranged in the following week. Weather predictions were good, and during both days there was no rainfall. Temperature was between 8 and 14 degrees Celsius. On the first day there was some overcast, but the sun was clearly visible. On the second day the sky was clear and the sunset was causing glare in combination with water on the asphalt. Both days were fairly windy, about 5 Beaufort from direction north towards south. This caused some water to be blown of the lane markings and the eastern part of the track to less wet for the first few meters as the water was blown in the other direction. Both days had similar conditions, although visibility might have been slightly better on day 2. On both days the dark tests started an hour after sunset. Time of sunset these days was 20:46. This is the exact time when the sun sets below the horizon. However, this is not the time when it is considered to be dark. Before both testing days nautical sunset was determined to be the time to start the dark tests. When the sun is 12 degrees below the horizon, the phase of nautical sunset has been reached, which can be considered as dark. For the testing days 21:59 was the time of nautical sunset, so 22:00 was set as starting time for night time testing. There was almost no visible moon, as new moon was on 20th of april. Due to the remote location of the test track, no other light sources were visible in the surroundings.

4.7 Vehicles and speed

Three vehicles were used in the experiment, with different cameras and sensors. The focus was on the lane markings and not on the LKA system or vehicle performance. Therefore it was chosen to keep the speed as close to 80 km/h as possible, as this would also be the speed on N-roads or on some highways. This was also within the ODD for all chosen vehicles. Lowest boundary was 65 km/h, so normally all vehicles should have a working LKA system for any higher speeds. For the choice of vehicles several factors played a role. Vehicles had to be available on the testing days. There was budget to rent some cars, but it was also possible to use cars of people that would be on the test site anyway. First a selection was made based on the 100 best sold vehicle models in the Netherlands in 2022 according to autozine.nl. (Autozine, 2023) It was also an option to focus the choice for cars on detection type and include infrared or LiDAR. However, the average age of cars on the road in Netherlands is 11 years. Cars sold in 2022 will therefore be the average age somewhere around 2033 depending on economical and technological developments. It was therefore relevant for the near future to include vehicle models that were sold frequently and will have a relatively high share of the vehicle fleet in Netherlands upcoming decade. Car brands and manufacturers do not add any information about their cameras and sensors that give input to the LKA system. For this test it was important to take three different car models and brands so that at least results of the three cars would not be the same. Majority of the most sold cars models was using a combination of a front camera and sensors forming the input for the LKA system. Through secondhand car part website Proxyparts (Proxyparts, 2023) and contact with several car lease companies it was possible to find out the manufacturer of the front camera. Some car brands and models were using the exact same camera as other ones. To make sure that different cameras were included in the test, the car models were put into groups with similar, or the same, cameras. This also made it easier to rent a car as this gave the rental company multiple options to look for on the preferred dates. Car brands and models, and camera manufacturers will not be specified in this report as those brands and manufacturers were not actively participating in this research. Cars will simply be named car A, B and C. All cars were standard 5-seat passenger cars with equivalent dimensions. No trucks, pick-up trucks, vans were used.

4.8 LKA systems and display

Per car the LKA system and display worked slightly different. Car A first gave an orange blinking light signal on the dashboard while in case of a detected lane marking. If the vehicle came too close to the line, force feedback would intervene and steer in the other direction. Specifications of the LKA system were not provided or available from car manufacturers, so it's not clear how close to the line led to force feedback. In case of no detection, no signal was shown and force feedback was not working. The LKA system was relatively sensitive compared to the other cars. Which meant that if the approach was not parallel to the lane marking, the LKA system needed more adjustment time before it started working.

Car B was displaying a grey symbol in case of no detection, a white symbol in case of detection and an orange symbol in case of detection plus force feedback.

Car C showed a green symbol in case of detection, an orange symbol for detection plus force feedback and a grey symbol when there was no detection.

Figure 24: Left: Car A dashboard, Middle: Car B dashboard, Right: Car C dashboard. Blue arrow indicates the position of the LKA indicator symbol.

In figure 24 the display of the dashboard is visible for car A, B and C from left to right. For Car A the LKA indicator is visible in orange. This indicator light blinked when a lane marking was detected. Other indicators on the picture show speed, head lights switched on and ”ok?” as no speed signs were detected. In the middle the dashboard of car B shows a white symbol, meaning that in that situation a lane marking was detected and there was no force feedback. On the right, car C shows a green symbol, which means there was detection but no force feedback at that moment. Speed of 80 was from the last detected traffic sign, which was outside the test track.

4.9 Drivers

It was not feasible to recruit participants to drive. This would be too time consuming during the tests, especially in conditions where the sun sets fast and light conditions change quickly. On top of that, it was not possible in one of the cars to change driver because of insurance reasons. Car A was driven by the same driver for both days and all runs. Car B and C were driven by multiple drivers. This should not have influenced the test results as drivers were aware of the LKA system in the car. LKA systems should be able to function with all different driving styles. Drivers were instructed to drive as close to 80 km/h as possible. For some drivers it was difficult to keep the speed around 80 km/h as the camera that was filming the dashboard was right in front of the speed display. Afterwards, the videos were checked for any speed drops below the ODD of the LKA system. Drivers were instructed to drive parallel to the lane marking with the lane marking on their left side on a distance that they would normally also keep on a public road. In the middle of the run drivers steered slightly towards the lane marking to trigger force feedback.

4.10 Filming equipment

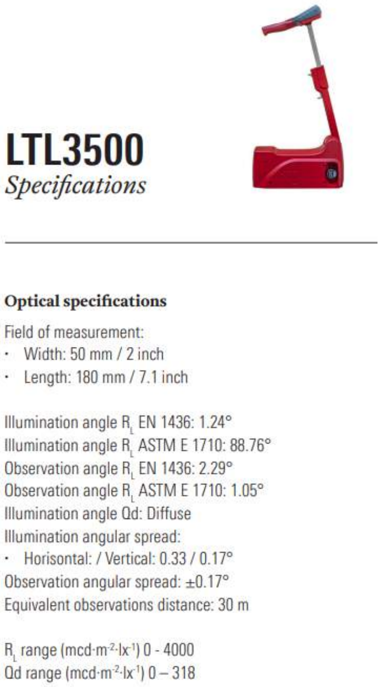
Detection of lane markings by front cameras and response of LKA systems had to be filmed, to be able to process results afterwards. Per car, two GoPro cameras were used. One camera filming the road from the middle of the dashboard and one camera filming the LKA indicator behind the steering wheel. In Figure 25 the setup of both GoPro cameras is visible in one of the cars. For every car the setup was similar, one camera in the middle of the dashboard, and the other one on the steering column. The camera was put on a mount and taped so that it would not move during driving. Per car the position of both cameras might be slightly different, based on the design of the car and best position to tape the cameras.

Figure 25: GoPro setup

All cameras were checked on battery life before the testing days. Not all would charge while using and connecting to a usb-port. As backup several powerbanks were brought to charge cameras in between runs. SD cards were also checked and spare SD cards were brought to the site. One of the cameras had an issue with brightness and the camera display screen would not light up. This made it difficult to see if the camera was recording. Drivers and passengers were instructed to start recordings when starting a run, and stop recording in case of any issues as unnecessary recording would drain the battery. Afterwards, all footage from 6 cameras was saved on an external hard drive and cloud. Videos were synchronized based on sound using Adobe Premiere Pro. These were saved as separate projects in which the videos can be loaded if needed. In this way it was possible to see the camera footage of the road and LKA indicator at the exact same moment.

4.11 Retroreflectivity and Contrast

Contrast ratio is an important variable to determine the visibility of the markings for LKA systems and human and depends on the contrast between the surface and marking and therefore on the material. Contrast can be calculated by dividing the values for retroreflectivity for markings and surrounding asphalt. Per lane marking it was possible to measure Qd and Rl, which are the values for reflectivity in daytime and nighttime conditions respectively. This was measured for the marking and asphalt on 12 locations at the start of the first testing day. The Delta LTL3500 retroreflectometer for measuring was brought and calibrated by a specialist of 3M from their lab in Germany. In figure 26 the specifications for the LTL3500 are listed.



LTL3500
Specifications

Optical specifications

Field of measurement:
- Width: 50 mm / 2 inch
- Length: 180 mm / 7.1 inch

Illumination angle R_L EN 1436: 1.24°
Illumination angle R_L ASTM E 1710: 88.76°
Observation angle R_L EN 1436: 2.29°
Observation angle R_L ASTM E 1710: 1.05°
Illumination angle Qd: Diffuse
Illumination angular spread:
- Horisontal: / Vertical: 0.33 / 0.17°

Observation angular spread: ±0.17°
Equivalent observations distance: 30 m

R_L range (mcd·m^{-2}·lx^{-1}) 0 - 4000
Qd range (mcd·m^{-2}·lx^{-1}) 0 – 318

Figure 26: Specifications Retroreflectometer Delta LT3500
(DELTA, 2023)

Exact GPS location and a microscopic image of the surface could be printed together with an overview picture facing forward. Because of light conditions inside the device it did not matter if measuring was done in light or dark conditions. In Figure 27 the display of the retroreflectometer is visible after a measurement.

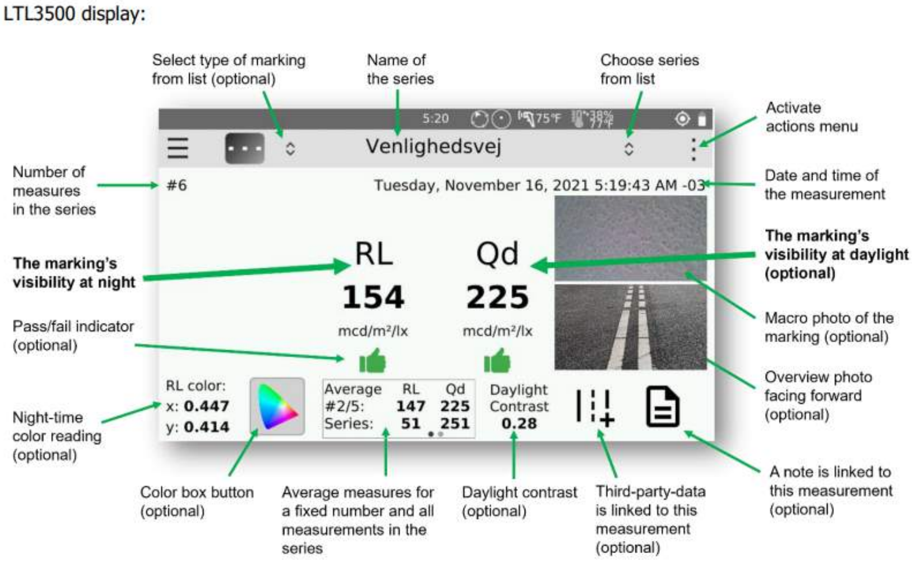


Figure 27: Delta LTL3500 display
(DELTA, 2023)

On the second day wet retroreflectivity, Rw, was measured. This is done by pouring a bucket of water on top of the marking, wait for one minute and then read the Rl value displayed. A bucket of 2 liter water was used per measurement. Ideally, this would be more, but this was not feasible with the size of the water tank that could be brought to the diagonal of the test track. A water tank of 60 liter was filled at the main building of the test track and brought to the diagonal.

Figure 28: Wet retroreflectivity test

In Figure 28 the retroreflectometer is visible during a wet retroreflectivity test for the cold spray plast marking of Triflex.

4.12 Opposing traffic

A realistic scenario where the LKA system might fail, was opposing traffic in dark circumstances. Especially on 1-lane N-roads oncoming traffic will face your car and also the front camera with their beam headlights. It was decided to use two vehicles as oncoming traffic as this could be realistic in 200 meters and also feasible. It was possible to see in this way if the LKA system would stop working right before or after passing the oncoming traffic. Due to safety reasons it was not possible to let the oncoming cars drive towards the test vehicle. In dark scenarios it was difficult to see the exact positions of opposing traffic even when using cones, so it was safer to let them stand still. On a real road the opposing vehicles will pass faster and the cameras are exposed to the light source for a shorter time. Besides testing dipped beam headlights, also main beam headlights were tested.

While this might be rare in a real road scenario, it was included in the test runs as it might give different results. The first opposing car had neon headlights, while the second car had halogen headlights. An example of the set up of opposing traffic can be seen in Figure 29.

Figure 29: Opposing traffic in wet dark conditions

Opposing traffic is positioned left of the test vehicle as would also be the case on a road. In between the vehicles is the tested lane marking for that particular run. On the right of the picture another lane marking is visible, but this was not detected as it was deliberately placed far enough away from the other lane marking. Only one lane marking with opposing traffic was tested at the same time for safety reasons.

4.13 Pilot visits

It was discussed if it would be possible to do a pilot day, but this would mean that the track had to be rent for another day. Instead, three track visits were planned before the actual testing days. There were some concerns that had to be tested and would have been tested in a pilot if that would have been possible. During the first visit, where it was also possible to drive on the test track, all possibilities for placing markings on the diagonal were investigated. A first drive at the original type I marking was also done to find out if LKA systems would detect this line at all, which was the case. Afterwards, a sketch was made to explore the option of placing all markings on the test track without being in each others way. Both 3M and Triflex agreed that it was possible for them to be on the test track on the same day and that it should be possible to place markings next to each other. Two more visits were planned. In the meantime on a public road it was tested out that 4,5 meter should be enough distance between markings to not be detected as a lane. This might be different per car brand though, so markings had to be placed at least 5 meters next to another marking. During the second and third visit it was discussed with 3M, Triflex, and RDW what was needed to place the markings. During the track visits the exact locations of marking placement were determined. It was also checked if other cars detected the old marking and how much time they needed to start detecting the lane marking. Basically there was no detection pick-up distance as the lane marking was detected even a few meters before the marking started. Finally, the height of the water put on track with the watering system had to be checked.

Figure 30: Water flowing onto the test track

In Figure 30 water is flowing onto the test track from a small pipe located on the right side of the picture. It would take about 15-20 minutes before the test track was completely wet and water spread out over the whole track. For the tape marking it was a concern if the standing water would be enough to cover the tape. Water was measured at a height of 5 mm on top of the asphalt surface, which was enough to cover the tape markings.

5 Data and Statistical Analysis

Two types of data are obtained from the field test as described in the previous chapter. The first type is all data on retroreflectivity and contrast, which can be extracted from the results of the retroreflectometer. This data is related to the properties of the lane markings. Second type of data is the detection data gathered in all runs for the 6 scenarios as described in the previous section. This chapter will give an overview of all collected data and additional information on any implications. Section 5.1 will first explain the process of obtaining data on contrast and retroreflection. In section 5.2 obtained data will be presented. In section 5.3 any implications during the collection of data with the test vehicles will be discussed. After this, collected data will be presented in section 5.4 as descriptive statistics.

5.1 Retroreflectometer

5.1.1 Retroreflectometer data collection

On both testing days data was obtained at the start of the testing day around 18:00 in the evening. Somebody from 3M specialized in operating the retroreflectometer came from Germany and was the only person allowed to operate the device. For all types of markings measurements to obtain day time visibility, Qd, and night time visibility, Rl, were planned to be performed at 3 locations, at both ends and in the middle. Due to some miscommunication there were 4 measurements performed for Triflex marking and 2 for the old marking. In figure 31 all measuring locations are marked with a yellow star and numbered in chronological order.

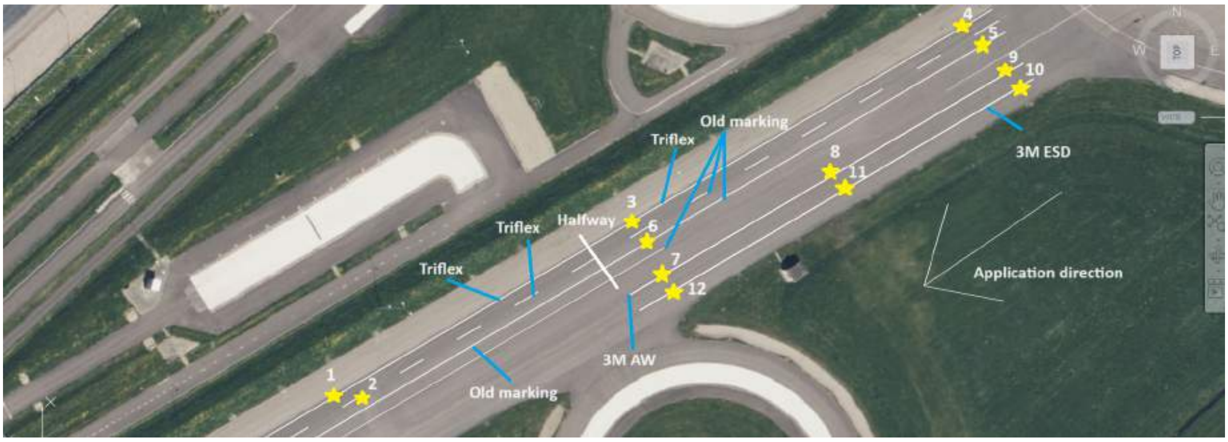


Figure 31: Retroreflectometer measuring locations

Normally, higher values are obtained in the direction of application, so both directions were measured. On all 12 locations the asphalt was measured as well, to obtain a value for Qd and Rl and then being able to calculate the contrast ratio based on Qd values. The retroreflectometer generated two images of the lane markings as discussed in section 4.11. One image being an overview of the location facing forward from the retroreflectometer and the other image being a macro image of the lane marking or surface where the retroreflectometer was placed.

On the second test day, wet tests were performed as described in the previous chapter. This was done for all 12 locations again, but only in application direction. Doing it twice on the exact same location is not possible as the marking already got wet. Making it wet again might lead to different values as water might cover different parts of the marking on a microscopic level. These tests were performed to obtain values for wet retroreflectivity, Rw. For experimental purposes it was also tried out to do a Rw test after the track was made wet by the watering system. This was not possible as the retroreflectometer gave an error due to too much water on the lane markings. To be able to obtain real-time while driving, a dynamic retroreflectometer mounted on a car should be used. This was too costly for this particular research.

As backup, physical forms were also brought to manually note down the test results that the retroreflectometer gave.

5.1.2 Retroreflectometer data analysis

For 12 locations values for Qd and Rl were obtained in application direction and in opposite direction. Same values were obtained for asphalt on those 12 locations, leading to 36 data points, visible in Table 3. All pictures taken by the retroreflectometer are visible in Appendix B. This contains overview pictures of the location and microscopic pictures of the lane marking that was measured.

Table 3: Retroreflectometer values: Daytime visibility (Qd) and Nighttime visibility (Rl). All values in mcd/m2/lux

	Qd application direction	Qd opposite direction	Qd asphalt	Rl application direction	Rl opposite direction	Rl asphalt
Location 1 (Triflex)	239	228	55	838	992	27
Location 2 (Triflex)	248	254	58	865	887	18
Location 3 (Triflex)	253	224	58	769	908	21
Location 4 (Triflex)	265	226	58	672	837	19
Location 5 (Old)	88	88*	32	28	28*	14
Location 6 (Old)	101	104*	54	35	31*	19
Location 7 (3M AW)	217	202	63	1453	784	17
Location 8 (3M AW)	221	216	42	1520	774	16
Location 9 (3M AW)	234	198	50	1870	959	14
Location 10 (3M ESD)	276	249	41	606	561	13
Location 11 (3M ESD)	295	305	49	706	691	20
Location 12 (3M ESD)	284	253	61	648	587	21

*For the old marking the application direction was not known. Measuring was done as if the application direction was similar to the new markings.

Taking the average values of the locations leads to Qd and Rl values for all 4 markings, as visible in Table 4.

Table 4: Retroreflectometer average and standard deviations Daytime visibility (Qd) and Nighttime visibility (Rl). All values in mcd/m2/lux

	Qd application direction	Qd opposite direction	Qd asphalt	Rl application direction	Rl opposite direction	Rl asphalt
Old marking	95±9	104±11	43±16	32 ±5	31±2	17±4
Triflex	251±11	233±14	57±2	786±86	906±65	21±4
3M AW	224±9	205±9	50±11	1614 ±224	839 ±104	16±2
3M ESD	285±10	269±31	50±10	653±50	613±69	18±4

*For the old marking the application direction was not known. Measuring was done as if the application direction was similar to the new markings.

Per marking, Rw was measured on the same locations as Qd and Rl. Results for all locations are visible in Table 5. Averages per lane marking type are indicated as well.

Table 5: Wet nighttime reflectivity (Rw) values, averages and standard deviation. All values in mcd/m2/lux

	Rw
Location 1 (Triflex)	295
Location 2 (Triflex)	161
Location 3 (Triflex)	424
Location 4 (Triflex)	602
Triflex average and standard deviation	**371** ±188
Location 5 (Old)	18
Location 6 (Old)	17
Old marking average and standard deviation	**18**±1
Location 7 (3M AW)	967
Location 8 (3M AW)	842
Location 9 (3M AW)	1270
3M AW average and standard deviation	**1026**±220
Location 10 (3M ESD)	332
Location 11 (3M ESD)	161
Location 12 (3M ESD)	373
3M ESD average and standard deviation	**289**±112

Contrast is a ratio and can be calculated in different ways. In this situation we have a light material, the white marking, on a dark background, the asphalt.

According to the European Union regulations, the following contrast ratio should be sufficient: (European Road Federation, 2018)

"Ensure a sufficiently high contrast ratio between marking and pavement. While a contrast ratio of 3:1 appears sufficient, increased reliability can be achieved with a 4:1 ratio, mitigating possible false readings caused by glare and other critical conditions.”

To calculate average contrast values the Qd values of markings are divided by Qd values of asphalt to give the contrast ratio. It was expected that Qd values should be slightly higher in application direction compared to the opposite direction. For all new markings the difference lies between 5 and 10 percent. For the old marking the application direction was not known, so the highest value will be taken, which was 104 mcd/m2/lux. For the Qd of asphalt the averages per location are taken to calculate contrast per marking. This gives the contrast values visible in Table 6 To be on the safe side, the minimum contrast values were also calculated by taking the highest value of Qd for asphalt, which was 63 mcd/m2/lux. In theory, this value could also be found at other locations on the track where no measurements were undertaken. Taking all the lowest values per marking from table 3, results in contrast values visible in Table 6. These values are all from opposite application direction and would normally not be the direction of driving.

Table 6: Average and minimum contrast values

Type of lane marking	Contrast ratio average and standard deviation	Minimum contrast ratio
Old marking	$1 : 2.42 \pm 0,58$	1,40
Triflex	$1 : 4.40 \pm 0,13$	3,56
3M ESD	$1 : 5.70 \pm 1,15$	3,95
3M AW	$1 : 4.31 \pm 0,86$	3,14

Higher standard deviations can be explained because of lower values for Qd for asphalt at some locations. Due to local composition of asphalt the Qd of asphalt fluctuates.

5.2 Field test data remarks

During the field test some occurrences led to data that could not be used. Some runs were aborted as the GoPro cameras were not working according to driver or passenger. From these runs there was no video material afterwards anyway, so this will be considered as non-existing data. A total of 420 runs were driven, of which 9 runs were invalid. In 4 of those runs the speed was too low. In dark wet conditions with opposing traffic it was difficult for drivers to keep speed to 80 km/h as they were driving conservatively due to bad visibility. It happened in 3 runs that speed dropped below the ODD of the vehicle, this was noted down afterwards when checking the video footage. In the other 6 invalid runs the wrong lane marking was approached in dark circumstances which resulted in a lane switch somewhere during the run. Due to bad visibility in dark wet conditions it was difficult for drivers to see the start of the lane markings, even though the start of all lines was marked with reflective cones. This led to 6 runs where the LKA system had difficulties picking up the detection of the lane marking at the start as the vehicle was too far from it and the driver was still steering towards the marking. This was noted down afterwards when checking the video footage and those 6 runs were marked as invalid. In vehicle C the LKA system stopped working during one of the runs on the second day. Driver assistance systems shut down and started up again after a few minutes. This run was excluded from the data set and.

The runs with artificial light did not go as planned beforehand. 2 out of 6 lights were not working on the testing days. It also turned out that reflection in the standing water on track came from light poles located around the oval instead of from the light poles located next to the diagonal. It was not possible to switch lights on or off separately. It was decided to do runs with lights on and opposing traffic as this could still be realistic for a combination of reflecting light. The scenario with just artificial lights switched on turned out to be not a proper representation of artificial lights, especially in a dry dark situation. This scenario was therefore excluded from the test and no data was obtained on this.

5.3 Descriptive statistics

In this section descriptive statistics will be presented based on the data captured by the GoPro cameras filming the road and LKA indicators on the dashboard. First, a general overview will be presented of the complete and filtered data set, after which some specific variables will be highlighted to gain more knowledge about possible correlations. Detection percentages are not an average but a percentage of the complete set of data points for a specific variable.

5.3.1 Filtered data set

In total there were 420 recorded runs performed by the 3 vehicles during the 2 testing days. Some runs might not have been recorded, but these runs are not present in the data set as there were no videos from it. Car A had 133 recorded runs, car B 142, and car C 145. Out of these 420 runs, the invalid runs were filtered. 9 invalid runs were found, of which 3 for car A, 0 for car B and 3 for car C. This means that 98,5 percent of the runs were valid and the total number of valid runs was 414. For car A all removed runs took place in dark conditions. 3 of the 6 total invalid runs were because the car A or car C did not have a straight approach towards the lane marking, while the other 3 were invalid because of too low speed. Car A was relatively sensitive to a straight approach, so it was decided to remove the data point with no straight approach. In another run, the driver took the wrong lane and the run had to be aborted. Last invalid data point for car A was because of a too low speed. For car C there was 1 run where the approach was not straight as the driver was first steering towards another line in dark conditions. Other 2 invalid data points were because of too low speed with opposing traffic having their main beam headlights switched on.

In Table 7 the detection percentage for all runs is visible. There were 3 possible outcomes: Detection throughout the whole run, no detection at all, or partial detection. Partial detection was marked as result for cases where during some parts of the run the LKA system showed an indicator light on the dashboard, but on other parts not. The indicator light had to be showing detection for at least 40 meters, which was equivalent to little over 2 seconds. After these 40 meters, the car approached oncoming traffic which was about 50 meters ahead. From this distance the effect of the headlights of the oncoming car might have influenced LKA performance.

Table 7: Detection percentage all runs

	Runs	Percentage
No detection	78	18,8%
Detection	305	73,3%
Partial detection	31	7,5%
Total	414	100%

5.3.2 Detection per car

To gain more insights in the performance per vehicle used, the detection percentages per car are visible in Table 8

Table 8: Detection percentages per vehicle

	Car A			Car B			Car C	
	Runs	Percentage		Runs	Percentage		Runs	Percentage
No detection	50	38.5%		6	4.2%		22	15.5%
Detection	75	57.7%		119	83.8%		111	78.2%
Partial detection	5	3.8%		17	12.0%		9	6.3%
Total	130	100%		142	100%		142	100%

Car A clearly has the lowest detection percentage, while car B only has 6 runs with no detection at all. Probably this had to do with the position of the front camera in car A. It was not possible to verify this as car manufacturers did not give any specific info about the LKA system in the car. Presumably the car had the front camera positioned above the license plate, which makes the angle to the lane marking smaller.

5.3.3 Glare detection

In glare conditions a distinction is made between driving towards the sun and away from the sun. Detection for all cars in these situations is visible in 9. As expected driving towards the sun results in a significantly lower detection percentage. Driving away from the sun, only 5 runs had no detection, which were runs with car A. In wet conditions the old marking was not detected at all.

Table 9: Detection percentages towards sun and away from sun

	Towards sun			Away from sun	
	Runs	Percentage		Runs	Percentage
No detection	21	28.4%		5	6.7%
Detection	52	70,3%		70	93.3%
Partial detection	1	1,3%		0	0.0%
Total	74	100%		75	100%

5.3.4 Night detection

In nighttime there were runs with and without opposing traffic. In Table 10 only the runs in complete darkness without traffic are visible. All markings were detected by all vehicles in complete darkness. It was expected that the performance would be good, although it was not expected that even the old marking was detected in wet conditions.

Table 10: Detection in dark conditions

	Runs	Percentage
No detection	0	0,0%
Detection	87	100%
Partial detection	0	0,0%
Total	87	100%

5.3.5 Wet and dry detection

A distinction was made between all runs performed in dry and wet conditions. The results are shown in Tables 11. It was expected that runs in wet conditions would have a lower detection rate by LKA systems, which is confirmed by the results in table 11.

Table 11: Detection percentages dry and wet surface

	Dry surface			Wet surface	
	Runs	Percentage		Runs	Percentage
No detection	23	10.3%		55	28.9%
Detection	194	87.0%		111	58.4%
Partial detection	7	3.1%		24	12.7%
Total	224	100%		190	100%

5.3.6 Opposing traffic detection

Three types of data were distinguished here to highlight. All data points for opposing traffic with dipped beam headlights, main beam headlights, and all runs where artificial lights were switched on. In the situation with artificial lights, there was opposing traffic for all runs. The results are visible in Table 12. Main beam headlights caused the lowest detection percentage, with only 43.4% detected. Almost all runs with partial detection were with opposing traffic. When the car came to a distance of 20-40 meters of the oncoming vehicle, that was standing still in this field test, the LKA system stopped detecting the lane marking in those runs. It picked up detection immediately after passing the vehicle in all instances with dipped beam headlights.

Table 12: Opposing traffic: dipped beam and main beam headlights

	Dipped beam			Main beam	
	Runs	Percentage		Runs	Percentage
No detection	22	22.2%		30	36.1%
Detection	64	64.7%		36	43.4%
Partial detection	13	13.1%		17	20.5%
Total	99	100%		83	100%

5.3.7 Detection per marking

Detection percentages per marking type are presented in Table 13. It is visible that the old lane marking has the lowest detection rate as expected. 3M AW had the highest detection percentage and the lowest percentage of runs where no lane marking was detected. This was as expected as the 3M AW tape is a state-of-the-art marking that should outperform 3M ESD based on the ceramic mix that is used in the tape for reflection. Triflex cold spray plast performed better than 3M AW during daytime conditions with glare and driving towards the sun. 3 runs of 3M AW had no detection in these conditions while Triflex cold spray plast had 0 runs where no lane marking was detected.

Table 13: Detection percentages per lane marking

	Old Marking			**Triflex**	
	Runs	Percentage		Runs	Percentage
No detection	34	31.5%		16	15.1%
Detection	66	61.1%		84	79.2%
Partial detection	8	7.4%		6	5.7%
Total	108	100%		106	100%
	3M ESD			**3M AW**	
	Runs	Percentage		Runs	Percentage
No detection	20	19.8%		8	8.1%
Detection	74	73.3%		81	81.8%
Partial detection	7	6.9%		10	10.1%
Total	101	100%		99	100%

5.4 Qualitative analysis

Based on the hypotheses stated in chapter 3, this section will discuss all results presented in the descriptive statistics.

Higher values for contrast and retroreflectivity should lead to a better visibility of lane markings according to literature. One would expect that the marking with the lowest values, has the worst visibility and the other way around for the highest values for contrast and retroreflectivity. Old marking had the lowest values for contrast and retroreflectivity and also the lowest detection rate, which was as expected. Highest detection rate was for 3M AW. This marking did have the highest wet nighttime retroreflectiveness (Rw), but contrast values for 3M ESD an Triflex were higher. Probably detection in wet and dark circumstances was better for 3M AW as the reflectiveness of this tape marking was better and therefore more visible when wet.

It seems obvious that glare and driving towards the sun has a negative effect on the detection performance of the cameras. Driving away from the sun has an overall detection of 93% while driving towards the sun only has a detection of 73%. It should be noted that it is difficult to simulate or recreate light circumstances caused by the sun and that the situation can change quickly. All of these runs were performed within a time frame of about 45 minutes. During sunset this can already significantly change light conditions as the sun traveled from 12 degrees above horizon to 6 degrees above horizon in these 45 minutes. Cameras might have faced worse light circumstances during the first run than during the last run. This should be considered when drawing conclusions.

In wet circumstances, detection rates are lower than in dry circumstances. There is significant difference with 58,4% detection in wet and 87,0% in dry. When it is completely dark, detection rate was 100% for dry and wet conditions. This means that glare in combination with a wet road surface and opposing traffic leads to more challenging images for the camera to capture than a on dry road surface.

In dark and dry conditions without opposing traffic, a 100% detection rate is reached. From the descriptive statistics it's not clear yet if wet conditions in nighttime lead to worse detection compared to daytime conditions.

Street lights in combination with opposing traffic lead to low detection rates. Especially main beam headlights from oncoming traffic lead to problems for the front camera, as only 43,4% of all runs had detection. As almost all runs with partial detection were runs with opposing traffic, this gives important information. In most cases the LKA indicator stopped working about 20-40 meters before the first oncoming vehicle. Right after passing the first vehicle it sometimes started working again and sometimes kept working while passing the second vehicle. This could also have to with the type of headlights as the first vehicle had neon headlights and the second vehicle halogen headlights. Similar to the scenario with sunset, there was a light source shining into the front camera from a relatively low angle.

6 Logistic Regression and Qualitative Analysis

In this chapter the previously presented descriptive statistics, will be evaluated. Relationships between variables will be discussed in more detail in a logistic regression analysis. The setup of the logistic regression analysis will be discussed in section 6.1. The model used for this will be explained in section 6.2, after which the results will be presented in section 6.3. The findings in combination with the qualitative analysis from the previous chapter will be presented in section 6.4.

6.1 Logistic regression model

This section explains the steps taken to find which variables affect the detection rate of lane markings through a logistic regression model. Software program SPSS was used for analysis of all data. The dataset extracted from camera footage was first put into different Excel sheets per camera per day, and after that put into one sheet to get the complete data set. In the separate sheets data was color coded for a better visualization when translating the data to code. These separate sheets are visible in Appendix B.

6.1.1 Coding of variables

All variables are listed in Table 14. A set of independent categorical variables presents all adjustable variables per run. All variables regarding contrast and retroreflectivity are continuous variables, however they were not continuously measured. Therefore, these properties are a part of the independent variable Lane marking, as specific values belong to a lane marking based on measured results. Detection is a truly independent variable as it depends on all other independent variables.

Table 14: List of variables and SPSS coding

Variables	Dependence	Variable Type	Values and coding
Vehicle	Independent	Categorical	1 (Car A), 2 (Car B), 3 (Car C)
Dry/wet	Independent	Categorical	0 (Dry), 1 (Wet)
Sunlight	Independent	Categorical	0 (Away from car), 1 (Towards car)
Time of day	Independent	Categorical	0 (Day), 1 (Night)
Oncoming traffic	Independent	Categorical	0 (No), 1 (Yes)
Street lights	Independent	Categorical	0 (Off), 1 (On)
Lane marking	Independent	Categorical	1-4 (Old marking, Triflex, 3M ESD, 3M AW)
Daytime retroreflectivity (Qd)	Independent	Continuous	104-285 mcd/m2/lux
Nighttime retroreflectivity (Rl)	Independent	Continuous	32-1614 mcd/m2/lux
Wet retroreflectivity (Rw)	Independent	Continuous	18-1026 mcd/m2/lux
Contrast	Independent	Continuous	2,42-5,70 Ratio
Detection	Dependent	Categorical	0 (No), 1 (Yes), 2 (Partially)

In SPSS the variables were coded as visible in Table 14. This resulted in 414 rows representing all runs, and per column one variable.

6.1.2 Relationship between variables

Detection of lane markings can be affected by the listed variables in Table 14. To be able to find a causal relationship between detection and these variables, statistical tests were performed. In order to find the variables that should be included in a logistic regression analysis, a chi-square test for independence was performed for all variables. With a chi-square test for independence a relation between detection and all other variables can be found. If the p-values in the chi-square test are smaller than 0,05, it means that the result for detection depends on that specific variable. With SPSS the chi-square tests were performed. In Table 15 the values for the chi-square tests are presented. Lane marking is considered as a nominal independent variable as the results for retroreflectivity and contrast are an average and therefore the same value is taken for every entry of a lane marking.

Table 15: Chi-square tests for independence

Variables	χ^2	p-value (2-sided)
Vehicle	56,748	<0,0001
Dry/wet	42,532	<0,0001
Sunlight	28,913	<0,0001
Time of day	16,813	<0,0001
Oncoming traffic	66,880	<0,0001
Artificial lights	10,166	0,006
Lane marking	21,005	0,002

As can be seen in Table 15 all variables have p-values lower than 0,05. Null hypothesis is that there is relation between the variables. The results of the Chi-square tests show that all p-values are smaller than 0,05, rejecting the null hypothesis and confirming that there is a relation between all these variables and detection. Highest values of χ^2 indicate the highest correlation, which means that oncoming traffic has the greatest correlation with detection according to the chi-square test. As all these variables have a significant influence, they are all included in a multinomial logistic regression analysis. A binomial logistic regression analysis would be possible if partial detection would be considered as no detection at all.

Before setting up the multinomial regression analysis, it was checked if no multicollinearity existed between independent variables. This happens when variables have a high correlation between each other. This was checked with chi square tests as well, because this shows correlation between categorical variables. For all p-values in table 16 smaller than 0,05 it means there is a correlation between those variables. As variables are presented in a matrix form, the same numbers for p-values were visible twice. Values of the upper triangular were deleted for simplicity.

Table 16: Chi square test variable matrix p-values

Variables	Vehicle	Dry/wet	Sunlight	Time of day	Oncoming traffic	Artificial lights	Lane marking
Vehicle	-	-	-	-	-	-	-
Dry/wet	0,804	-	-	-	-	-	-
Sunlight	0,767	0,943	-	-	-	-	-
Time of day	0,419	0,739	**<0,0001**	-	-	-	-
Oncoming traffic	0,894	0,138	**<0,0001**	**<0,0001**	-	-	-
Artificial lights	0,873	0,216	**<0,0001**	**<0,0001**	**<0,0001**	-	-
Lane marking	0,998	0,676	1,000	0,998	0,997	0,903	-

In table 16 multicollinearity relations are found between sunlight, time of day, oncoming traffic and artificial lights. This is explained by the fact that these variables are not truly independent in this particular experiment. During daytime, artificial lights were always switched off and there was no opposing traffic. On the opposite, artificial lights and opposing traffic were only used when there was no sunlight and it was dark. This is considered when setting up the multinomial logistic regression analysis.

6.1.3 Multinomial logistic regression analysis

For setting up the multinomial logistic regression, the variables with multicollinearity are clustered together into light scenarios. 7 light scenarios are distinguished:

- Base scenario: daytime, away from sun
- Daytime, towards sunlight
- Dark, without any lights
- Dark, oncoming traffic, dipped beam
- Dark, oncoming traffic, main beam
- Dark, street lighting, oncoming traffic, dipped beam
- Dark, street lighting, oncoming traffic, main beam

These scenarios were labeled in SPSS as a new variable called 'LightingScenario' and labeled from 0 to 7 as listed above. As SPSS takes the value with the highest number as reference in the regression analysis, all variables had to be re-coded. For the light scenarios the list below was used for interpretation of results.

All lighting scenario variables are compared to the base light scenario, and therefore re-coded as:

- **Base scenario: daytime, away from sun - 6**
- Daytime, towards sunlight - 5
- Dark, without any lights - 4
- Dark, oncoming traffic, dipped beam - 3
- Dark, oncoming traffic, main beam - 2
- Dark, street lighting, oncoming traffic, dipped beam - 1
- Dark, street lighting, oncoming traffic, main beam - 0

In table 17 the coding of variables used in the multinomial regression analysis is visible.

Reference categories for different variables are: **dry**, **old marking**, **car A** and the **base lighting scenario 6**. Car A is chosen as reference here as from descriptive statistics it was visible that car A had the worst detection performance. By comparing car B and car C to car A it will be possible to see if there is also any significant difference between car B and C.

Table 17: SPSS Re-Coding of variables: Reference variable in **bold**

Variables	Values and SPSS re-coding
Vehicle	**2 (Car A)**, 1 (Car B), 0 (Car C)
Dry/wet	**1 (Dry)**, 0 (Wet)
Lane marking	**3**, 2, 1, 0 (**Old marking**, Triflex, 3M ESD, 3M AW)
Detection	**2 (Yes)**, 1 (No) , 0 (Partial)

6.2 Results of logistic regression analysis

The logistic regression model will fit the data better than the null model at a 95% confidence level if the p-value is lower than 0,05.

Table 18: Model fitting information

	Model fitting criteria	Likelihood ratio tests		
Model	Log Likelihood	Chi-Square	Degrees of freedom	p-value
Final	373.832	223.893	39	**<0.0001**

In Table 18 it is visible that the p-value is <0,0001 and therefore the model fits the data better than the null model without any parameters. If all variables are having a significant influence on the outcome, is checked by likelihood ratio tests. If the p-value in the likelihood ratio test is lower than 0,05 this means the variable significantly affects detection performance with at least a 95 % confidence level. In figure 19 it is visible under that all variables have a p-value lower than 0,05 and are therefore having a significant effect on detection.

Table 19: Likelihood ratio tests

	Model fitting criteria	Likelihood ratio tests		
Variable	Log Likelihood of model	Chi-Square	Degrees of freedom	p-value
Vehicle	422.926	49.094	6	**<0.0001**
Lane marking	393.274	19.443	9	**0.022**
dry/wet	406.758	32.926	3	**<0.0001**
Light scenario	460.202	86.370	18	**<0.0001**

Chi-square value is highest for the variable light scenario, which means that this variable affects the detection outcome most. From these variables, lane marking affects the detection outcome least. This might sound surprising, however it can be explained. Strong correlation between light scenario and detection shows that in the majority of scenarios with oncoming traffic, there was no detection regardless of the lane marking, vehicle, or if the surface was wet. Strong correlation between vehicle and detection is explained by underperforming car A compared to the other 2 cars. These observations will be further discussed after the results of the multinomial regression analysis.

As all variables have a significant effect, the multinomial regression analysis is performed and the results presented in Table 20. For readability the light scenarios are numbered and not written out. P-values smaller than <0.0001 are reported as such and not with the exact value. Reference categories are: **detection, dry, old marking, car A, base lighting scenario 6**.

Table 20: Multinomial regression analysis: Parameter estimates

	Model fitting criteria	Likelihood ratio tests	
Detection: No	Degrees of freedom	p-value	Adjusted odds ratio
Vehicle A	Reference	Reference	Reference
Vehicle B	1	<0.0001	0.117
Vehicle C	1	<0.0001	0.238
Old marking	Reference	Reference	Reference
Triflex	1	0.005	0.344
3M ESD	1	0.040	0.464
3M AW	1	<0.0001	0.231
Dry	Reference	Reference	Reference
Wet	1	<0.0001	3.292
Light scenario 6	Reference	Reference	Reference
Light scenario 5	1	0.001	4.460
Light scenario 4	1	0.785	0.862
Light scenario 3	1	0.004	4.702
Light scenario 2	1	<0.0001	10.858
Light scenario 1	1	0.022	3.436
Light scenario 0	1	<0.0001	7.073
Detection: Partial			
Vehicle A	Reference	Reference	Reference
Vehicle B	1	0.152	2.046
Vehicle C	1	0.837	1.114
Old marking	Reference	Reference	Reference
Triflex	1	0.797	0.874
3M ESD	1	0.832	0.893
3M AW	1	0.605	1.303
Dry	Reference	Reference	Reference
Wet	1	<0.0001	4.069
Light scenario 6	Reference	Reference	Reference
Light scenario 5	1	0.605	1.603
Light scenario 4	1	1.000	1.000
Light scenario 3	1	<0.0001	14.890
Light scenario 2	1	<0.0001	59.810
Light scenario 1	1	0.096	4.116
Light scenario 0	1	0.001	12.940

If the p-value is above 0,05 there is no significant correlation between detection and the specific independent variable. As the majority of lane markings was detected, detection is the reference. In

Table 20 it is visible if there is a correlation between no detection or partial detection and all other variables. If the p-value is below 0,05, there is a correlation. The adjusted odds ratio then shows how much more or less likely the outcome is compared to the reference. As an example dry/wet is taken for no detection. With a p-value <0.0001 there is a correlation between no detection and a wet lane marking compared to the reference situation of a dry lane marking. The outcome no detection is 3.292 times more likely according to the adjusted odds ratio. When a value for adjusted odds ratio is smaller than 1, this should be read as: detection is 1, divided by adjusted odds ratio, more likely. As example, Triflex has a p-value of 0.005 and adjusted odds ratio 0.344. This means that detection is 2.9 times more likely than for the old marking. In following sections, adjusted odds ratio will be discussed and rounded by 1 decimal.

For category 1, no detection, several p-values are below 0.05. Both Car B and Car C are significantly more likely to detect lane markings than car A. Values of 0.238 and 0.117 for the adjusted odds ratio show that car B is 4.2 and car C 8.5 times more likely to detect the markings than car A. This does not necessarily mean that the LKA system of car A was not functioning properly. In wet conditions with a source of light facing the front camera, car A only detected Triflex lane marking once partially and 3M AW 4 times partially. It was suspected that the camera was positioned somewhere between the license plate and the bonnet.

All lane markings are significantly more likely to be detected than the old marking used as reference, as all p-values are below 0.05. The adjusted odds ratio shows that Triflex lane marking is 2.9 times more likely to be detected than the old lane marking. For 3M ESD and 3M AW these values are 2.2 and 4.3 times respectively

In wet conditions the lane marking is 3,3 times less likely to be detected than in dry conditions.

The different lighting scenarios are compared to the base scenario, which was dry circumstances during the day, driving away from the sun. It is visible that there is one scenario that shows no significant difference which is when it was completely dark. All lane markings were detected in all runs during complete darkness. Driving towards the sun leads to detection being 4,5 times less likely. When oncoming traffic switched their dipped beam lights on, detection was 4,7 times less likely, while for head beam lights this was 10,9 times. When street lights were switched on with oncoming traffic, likelihood of detection was 3,4 times less likely with dipped beam lights and 7,1 times less likely with main beam lights. This means that street lights increase the likelihood of detection when there is opposing traffic.

Partial detection means that the lane marking was detected for a part of the diagonal, and that the LKA system did not detect the lane marking for one or multiple other parts during the run. In the descriptive statistics it was already found 97 % of cases with partial detection involved oncoming traffic with their headlights switched on. In 20 it is visible that the p-value is smaller than 0.05 for wet conditions. It is 4.1 times more likely that the lane marking is partially detected in wet conditions than in dry conditions. In 3 lighting scenarios the p-value is below 0.05. This is for the scenarios with opposing traffic with dipped beam, main beam and main beam plus artificial street lights. For the latter, the likelihood of partial detection is 12.9 times more likely. For the scenarios with opposing traffic, dipped beam and main beam headlights partial detection was 12.9 times more likely for dipped beam and 59.8 times more likely for head beam lights respectively. Compared to the base scenario these values are high, which confirms that partial detection occurs in situations where oncoming traffic has their headlights switched on.

6.3 Findings

Results discussed in the previous section will be summarized below per variable. All variables included in the field test were significant for the outcome.

- Car A has a more sensitive detection, which led to the most invalid runs because of approaches that were not parallel to the lane marking. Car A performed significantly worse than car B and C. This was already visible in the descriptive statistics where lower detection rates for vehicle A were visible. Car B performed 9 and car C 4 times better than vehicle A which most probably had to do with the different detection angle of the front camera. With a wet surface the detection for the old marking and 3M ESD was 0 % with opposing traffic for car A, while 3M AW still was detected partially 4 times. During daytime and darkness detection was 100 % for 3M ESD, 3M AW and Triflex. These results show that vehicle A particularly had a lot of problems detecting lane markings when oncoming traffic was present and the surface was wet.
- Wet surface had a significant influence on detection for all cars as lane markings were 3.3 times less likely to be detected than on a dry surface. It was also 4.1 times more likely that the LKA system detected the lane markings partially.
- The old lane marking had the lowest detection rate, visible in the descriptive statistics. Following the results from the multinomial logistic regression, it is confirmed that detection for the old lane marking was significantly worse than for the new lane markings. Lane markings from 3M and Triflex were 2 to 4,5 times more likely to be detected. 2.1 times for 3M ESD, 2,9 for Triflex and 4,3 for 3m AW. In Table 21 contrast ratio and wet retroreflectiveness are visible together with detection likelihood. As expected, a higher contrast ratio did not lead to a higher detection likelihood by itself. 3M AW had the highest detection likelihood, although 3 out of 8 runs with no detection occurred during the day driving towards the sun. This is a situation where wet retroreflectiveness for a better nighttime visibility has less effect.

Table 21: Contrast and detection likelihood

	Contrast ratio	Rw	Detection likelihood
Old marking	1 : 2,42	18±1	1, reference
Triflex	1 : 4,40	371±188	2,91
3M ESD	1 : 5,70	289±112	2,16
3M AW	1 : 4,31	1026±220	4,33

- Glare had a significant effect on detection as it was 4,5 times less likely to detect lane markings when driving towards the sun than away from the sun.
- The effect of opposing traffic was similar to glare and made detection 4,70 times less likely. Switching main headlights on had the biggest influence and made detection highly unlikely.

7 Discussion

This chapter will discuss the conducted research. Section 7.1 will evaluate the results and compare them to previous findings. In section 7.2 implications and impact of the research will be discussed. Evaluation of the methodology will follow in section 7.3, after which the limitations will be discussed in section 7.4. Finally, in section 7.5 the future relevance of the research will be elaborated on.

7.1 Interpretation of results

The focus of this research was to test out different, state-of-the-art lane markings, and find how the lane marking properties influence the detectability by LKA systems. In previous studies it was found that detection with mono cameras was best in dry and dark circumstances. (Reddy et al., 2020) (van der Kooij, 2021). The results of this study are similar, as in 100 % of all runs in the dark all lane markings were detected. It was expected that during wet conditions in the night the performance would be worse and performance would be significantly different per lane marking. Expectation was that new lane markings would have a very high detection rate, and the old lane marking would perform significantly worse. However, even the old lane marking was detected in 100% of the runs in complete darkness, even when the track was wet.

Daytime visibility (Qd), Nighttime visibility (Rl), and wet retroreflectivity (RW) were measured before all runs. This gave valuable information about detection performance. It was expected that the old white paint marking would have almost no reflective properties compared to other lane markings and a lower contrast value as well. Data shows that the reflective properties are almost not existent for the old marking and contrast ratio was 1 : 2,42 on average which is lower than the norm of 1 : 3 (European Road Federation, 2018). Because of the mixture of reflecting materials in 3M AW lane marking, a lower contrast value was expected here, while Rw was expected to be highest of all markings. Contrast is lower than the lane marking of Triflex and 3M ESD, but all of them are above the 1 : 3 ratio (European Road Federation, 2018). The results show that the application direction matters when measuring contrast and retroreflectivity, as Qd values are about 5-10% lower in the opposite direction of how the lane marking was applied. For Rl only 3M AW showed a significant difference as the Rl value was almost twice as low as in the application direction. For Both Rl and Rw the lane marking 3M AW outperformed all other markings. Especially in wet conditions it was therefore expected that 3M AW would also outperform other lane markings, As mono cameras use contrast in their image to detect, retroreflectivity plays a role as well as this makes the lane marking more visible when it reflects the light back to the camera. Actual spectral return from objects does not change under any circumstances. Color of asphalt and lane marking remains the same, but changing the surrounding light affects the image that the camera uses as input for the LKA system.

Data shows that 3M AW and Triflex had similar performance with an overall total detection percentage of 81,8 and 79,2 percent respectively. The percentage of partial detection is higher for 3M AW though, 3 of 8 cases of no detection for 3M AW happened in dry circumstances driving towards the sun. This supports the fact that the 3M AW lane marking is expected to perform better in wet circumstances during the night. Considering the most challenging and adverse circumstances with opposing traffic and a wet surface during the night, lane markings performed as expected. The old lane marking performed worst in these circumstances with only 4% of these runs having detection. For the cold spray plast of Triflex, the vehicles show different results. Only car C was able to detect the lane marking in wet circumstances with oncoming traffic when street lights were switched on. Car B showed partial detection at all runs as the LKA indicator switched off about 20-40 meters before the first vehicle.

The results of the regression analysis show that car A performed significantly worse than the other 2 cars. The results of this vehicle are still considered valid as it is a vehicle that is also driving on public roads and should be able to detect lane markings properly. Clearly, the car did not perform up to standards, so this result is useful for car manufacturers and manufacturers of LKA systems to improve their performance and internal settings of the system. Settings regarding sensibility for detection, indicators and force feedback might be adjusted.

A wet surface made it 3,29 times less likely that a lane marking was detected than on a dry surface. This is as expected and confirmed by theory. (Huijink, 2023). Performance in dark conditions was worse when artifical street lights or opposing traffic were involved. The only scenario that did not show a significant change in detection performance to dry daytime conditions away from the sun, was completely dark conditions. All additional light in combination with a wet surface led to a decreased detection likelihood. Both driving towards the sun and towards opposing traffic led to a decreased likelihood detection of about 4,5 to 5 times. Common denominator for these scenarios is that a light source is shining right at the mono camera disrupting the image.

7.2 Implication of results

In previous research it was found that detection performance was lower in dark and wet conditions with artificial lights, however contradicting results were found. Opposing traffic was not further elaborated on as this can not be regulated on public roads. Contradicting results might have to do with the influence of opposing traffic. (Reddy et al., 2020; van der Kooij, 2021; Babic et al., 2021) Results of this research confirm the previous findings that in dark conditions without any street lights, performance of the mono cameras from the LKA systems is high. New types of lane markings are significantly more visible in challenging circumstances. Visibility for drivers should also be significantly better, however it is not known how they would rate the visibility in different circumstances (Gibbons & Hankey, 2015). Visibility of lane markings is important for both LKA system and driver. In situation where the LKA system does not detect the lane marking, the driver should still be able to. Therefore, it is valuable to have gained more knowledge about situations where the LKA is more likely to fail to detect lane markings. This experiment provides new insights in the influence of opposing traffic on the performance of LKA systems. In cases of partial detection, the LKA system did not detect the lane markings from about 20-30 meters before the oncoming vehicle and picked up detection at the moment the light source from the headlights was passed. It was not expected that detection stopped before the oncoming vehicle and picked up right after. Exact distances were not measured.

Car manufacturers and developers of LKA systems should be aware of the most adverse situations under which their system should still function properly. It is not expected that LKA systems still function in snow conditions as the lane markings are no longer visible when covered in snow. In a scenario with a wet road surface and opposing traffic on a National road, the system is still expected to function properly. Design of LKA systems, cameras and algorithms should focus on these circumstances where it is most difficult to detect lane marking, but still expected that the lane marking is detected. For road authorities it is too costly to replace all old markings by new markings as this is usually undertaken at the same time as replacing asphalt. Road stretches with the most single vehicle run-off accidents should be identified. On these stretches a working LKA system can be crucial in preventing accidents and potentially saving lives. When data on accidents is available for these road stretches, a pilot with a new lane marking can be a solution that is not too costly and has potential to improve safety. From literature it became clear that a properly functioning LKA system is only a first step. The driver will still be responsible and accountable for his or her own actions. Drivers sometimes over- or underestimate LKA and ADAS systems. When buying a new car, a driver should be well aware of what LKA systems can do, but also what they can not.

7.3 Evaluation of methodology

Previous research showed that either field tests on public roads, or on test tracks are a powerful method to obtain data regarding detection performance from LKA systems. On a test track it was possible to control a specific set of variables and recreate situations that can also occur on public roads. By combining all these situations on a test track and turn them into different scenarios, this research gives a complete overview of all situations that are practically possible to include in a field test.

In preparation of the field test, several visits to the test track were made to prevent any unexpected issues. All GoPro cameras were set up on site and this did not give any issues. One of the cameras turned out to have an issue with the screen as it was only visible in the lowest brightness. This gave some problems during daytime as it was very hard for drivers to detect if the camera was running or not. This lead to some runs were the camera did not record anything. There were some other runs where one of the cameras was not recording as one of the drivers accidentally switched a camera off instead of on. Drivers were instructed to also give some voice commentary as a back-up. All together this did not impact the results. It was also expected that not all runs would go as planned.

For measuring Rl, Rw and Qd a special retroreflectometer was brought from Germany including a specialist operating the retroreflectometer. Standard protocol for measuring was followed for all measuring locations. The device was calibrated, and no issues were encountered.

Preparations for the field test included time planning. Initial plan was to go to the test track for four days and test two markings per day, dry on one day and wet on another. Financially and practically it was better to do the test on two days as this also fit better with all agendas. After some rearranging and drawing it was possible to put all lane markings on the test track and do the test in two days. Time schedule that was proposed beforehand turned out to be accurate. Cars used in the test were chosen partially for practicality reasons. Condition was that it were cars with different mono cameras and cars that were sold at least in the top 100 car models of 2023 in the Netherlands so that using those cars is also realistic compared to public roads.

Setting up a multinomial logistic regression model, analyzing the influence of all variables, turned out to be a good tool to quantify the effect of variables and light scenarios. The values for Rl, Rw and Qd are continuous, but they were not measured for every single run. Therefore the average of the values was taken and labeled as a property of the lane marking. Lane marking was then one of the categorical variables. It was also possible to do a binomial logistic regression, by removing partial detection. This would be more simplistic if one counts a partial detection as no detection. Though it was not possible to quantify the partial detection with distances to opposing traffic, it still gave valuable insights.

7.4 Limitations

Although this research and the field test were prepared with out-most effort and care, there were some limitations. Some of the limitations were simply because it was not possible to include on the test track for several reasons. Other limitations were because of time and budget constraints. All limitations are listed below:

- Vehicle A performed worse in detecting lane markings as the system was more sensitive to driving straight. Detection sensors and camera seemed to be on a different position than for the other vehicles. As no further vehicle specifications will be given, it is not possible to say for sure, but drivers suspected that the cameras was not behind the front mirror, but above the license plate. Ideally, more cars would have been used to test different camera angles. This was not feasible regarding both time and budget.
- Old marking on the test track was a type I marking white paint which was already in place for several years. It was not known though how old the marking was, so it was labeled as old marking. At the RDW it was not possible to obtain the exact info on this. Therefore, the old marking was used as a benchmark. This is not the road marking that one would find on highways or national roads. There is not one standard type of marking on public roads and age of marking may differ from 0 up till 8 years.
- Asphalt on the test track might also not have been the same as on public roads, however this should not matter. Values for retroreflectivity and contrast were measured. New or darker asphalt would simply result in higher contrast and probably better detection results. For the purpose of this research worse asphalt actually leads to better results as it gives the opportunity for lane markings to excel.
- Triflex cold spray plast lane marking could not be removed after the field test. This meant that the lane marking thickness was not the same as it usually is. Maximum allowed by the test track was 1 millimeter, while it usually is 3 millimeter. It should not matter for detection, as the thickness is mainly for deterioration purposes.
- Applied lane markings were completely new. On public roads it would still take at least a few days before traffic drives on the road again. In the first weeks after application, Qd and Rl values are expected to increase slightly with a few percent as the very top layer of the lane marking does not give the most optimal reflection.
- It was not feasible to include human detection in this research. While it is important that human driver is able to also detect the lane markings in situations where the LKA system is not capable to do so.
- Making the surface wet was the most realistic method to simulate a wet surface on a public road. Weather conditions can greatly vary and it should be noted that the results in this field test might be different when the test is conducted in another season. This field test was conducted in spring, when light conditions might be different. It did not rain, so the results reflect a wet surface in dry conditions. Rain might also affect the detection performance of the camera.
- Artificial street lights were not as bright as on a public road because old type of lamp posts and lights was used. In dry conditions this had almost no effect as the light was not as bright as expected. In wet conditions, glare was created, but this came actually from the lights

around the oval, which was a few hundred meters away. In wet conditions, any light source can affect the visibility as soon as it reflects in the water

- Opposing traffic could not drive for safety reasons. Especially in the dark this was too dangerous, so it was decided to just position 2 vehicles next to the lane marking as if they were driving towards the test vehicle. This means that the cameras were exposed to the light for a longer time.

7.5 Future relevance of research

Lane markings are a crucial part of road infrastructure for both driver and vehicle and will remain important in the near future. It is therefore important to improve lane marking visibility so that both driver and LKA system are more likely to detect the lane marking. By obtaining more knowledge about the difficulties that cameras face when detecting lane markings, it is possible to further improve visibility by developing new types of lane markings. Light sources shining directly into the camera from a certain angle decrease detectability. Influence of street lights and how they are placed should be further researched. Opposing traffic should be included in tests when researching detectability of lane markings as in many occasions on public roads opposing traffic will be coming towards the vehicle on a continuous basis.

8 Conclusion

Single run-off accidents where the driver is not capable to keep their car in the lane can be prevented by LKA systems by intervening and keeping the vehicle on the road. Detection of lane markings is important for the system to operate properly. New techniques have been developed to detect lane markings using LiDAR or infrared. Most common in current vehicles with LKA systems is a mono front camera in combination with sensors. Per car brand and model software settings for detection might be different. Improving visibility of lane markings contributes to a higher detection rate. Previous research focused on different sensor types or on detection on public roads. This research compared detection for different lane markings in a controlled environment on a test track with a fixed set of scenarios. In this way the performance of lane markings could be evaluated and situations where detection did not occur identified. To answer the main research question, a set of sub-questions was formulated. These sub-questions will be answered first before the main research question will be answered.

1. How do the lane marking types and optic materials used, combined with road surface, influence the contrast and retroreflectivity?

From literature it was found that the combination of surface and lane marking determines the contrast and dry and wet retroreflectiveness, also known as day- and nighttime visibility. The combination of reflective materials on the top layer of the lane marking determines retroreflectivity. Using materials with a higher refraction index in combination with glass beads leads to a slightly lower contrast value, but significantly higher nighttime visibility and wet retroreflectiveness. By measuring the values during the field test, it was visible that values for daytime visibility, nighttime visibility and wet retroreflectiveness could differ per location because of the local composition of either lane marking or asphalt. Contrast and retroreflectivity of lane markings are influenced by the application type, refraction index of materials used, and asphalt type on which the lane marking is applied.

2. How do the contrast and retroreflectivity of different lane marking types affect LKA performance?

Contrast of the lane marking with asphalt, and retroreflection both influence the visibility of the lane marking for both human driver and detection cameras according to existing literature. The results of this research confirm that higher values for contrast and retroreflectivity lead to a higher detection rate. In dark and wet conditions the 3M AW marking with the highest nighttime visibility also had the highest detection rate. Contrast of 3M AW marking was lower than contrast of 3M ESD and Triflex marking. This resulted in a higher performance of 3M ESD and Triflex during daytime compared to 3M AW Detection performance of LKA systems improves for higher values of contrast and retroreflection. It can not be concluded what the effect is of only increasing contrast or only retroreflectivity as both values are a property of the lane marking. All new lane markings complied to European regulations for retroreflection and contrast, 150 mcd/m2/lux and 1:3 contrast ratio at least. Values for contrast and retroreflection were measured on different locations. None of these locations showed lower values for retroreflectivity and contrast than the European norm. During runs in complete darkness, detection was 100%, which confirms that all lane markings could be detected at any given location.

3. What is the influence of luminosity, time of day, glare, dry/wet surface, and different LKA system cameras on lane marking detection?

It was found that completely dark conditions did not have a significant different result on detection performance compared to the base scenario. The base scenario was during the day, in dry circumstances driving away from the sun. In complete dark circumstances the detection performance of all markings was even better than during daytime. Effects of the sun at a height 6 to 12 degrees above the horizon were visible. This caused glare, which decreased detection likelihood. All independent variables that were used in the multinomial logistic regression had an independent influence on the likelihood of detection. Driving towards the sun decreased detection likelihood with 4.5 times compared to driving away from the sun. In wet surface conditions detection likelihood decreased 3.3 times compared to a dry surface. Vehicle A performed significantly worse than vehicle B and C. This shows that not all vehicles on public roads will be able to detect lane markings with the same performance standard. It was suspected that the camera of vehicle A was positioned between license plate and bonnet. This could not be verified with manufacturer. It can not be concluded that the camera or LKA system performed worse. It is known from literature that the angle of incoming light plays a role, which was probably why car A underperformed. The influence of luminosity will be answered at the following question as different light scenarios were created.

4. What is the influence of headlights of opposing traffic on the detectability of lane markings for LKA systems?

For opposing traffic so called light scenarios were created in combination with street lights. Street lights were either switched on or off and opposing traffic used their dipped beam or main beam headlights. Compared to the base scenario without opposing traffic during the day, LKA systems performed significantly worse. In dark conditions with oncoming traffic having their dipped beam headlights switched on, detection was 4.7 times less likely than during the day without oncoming traffic. This is similar to the result of driving towards the sun, which made detection 4.5 times less likely. Main beam headlights made detection 10.9 times less likely compared to the scenario during the day without any opposing traffic. Switching on street lights slightly increased the performance. Detection was now 3.4 times less likely with dipped beam and 7.1 times less likely with main beam compared to during the day without opposing traffic.

Besides no detection, there was also a significant likelihood of partial detection in both scenarios with main beam and in the scenario with dipped beam and no artificial lights. This shows that the light source has a significant influence on the performance of the cameras affecting their detection performance.

Main research question was formulated as follows:

How do the lane marking properties affect their visibility and detection by Lane Keeping Assistance systems in different scenarios?

From the data it became clear that a higher contrast ratio and retroreflectiveness positively influence the detection of lane markings by LKA systems. Especially wet retroreflection Rw is important for nighttime visibility, as 3M AW showed significant improvements in detection compared to lane markings with lower values for Rw. Challenging scenarios and adverse circumstances contribute to a lower detection performance even when the lane marking has high values for Rw or high values for contrast ratio with asphalt. Common denominator in most of these adverse circumstances is a light source directed at the front camera, either the sun or opposing traffic. Contrast and reflection of the surface an lane marking does not change in these situations, but the contrast that the LKA systems and algorithm see on the detection image might be different as the light source makes the image a whiteout where contrast disappears. It was not possible in this research to have access to the front camera images of the exact moments that the LKA system was not detecting the lane marking. As long as the contrast on the processed image is high enough for the LKA system to detect the lane marking, the system will detect the lane marking. If it does not detect, it either means that the lane marking properties contrast and retroreflection are not sufficient enough, or an external light source influences the image.

8.1 Future recommendations

This research tried to give more insights in the detection of different lane markings and answer questions on how LKA systems detect them in a set of scenarios. The results have led to more questions that can be answered in future research. Below, a list of recommendations will be presented for future research and practicalities during the field test.

- The artificial street lights on the test track were not the same as types used on most highways and national roads in the Netherlands. It would be useful to study the effect of different types of lights, as well as the placement, height, brightness and angle.
- This study did not focus on the different sensor types, vehicles and LKA systems. Previous research did focus on LiDAR, radar infrared, and different camera types. Research comparing those would be useful and beneficial if this can be done in cooperation with car brands or manufacturing industries. It turned out to be not feasible for this study, but would give more insights in the process.
- Predicting algorithms were not included in this research and briefly discussed in the literature review. Any future developments can be tested with challenging and adverse scenarios described in study. In situation where the camera is not able to detect a marking, the algorithm can still detect based on a prediction.
- No data was collected about vehicle position on the road. It was visible though that Car B responded differently in situations with opposing traffic. Force feedback of the system only intervened while driving over the line, while without opposing traffic the system intervened before driving over the line. Probably this was a setting from the specific car brand where force feedback only happened in case the lane marking on the processed image was clear enough. If a research can be performed with cooperation of one or multiple car brands, this would be beneficial.
- This field test showed scenarios in which LKA systems do not detect lane markings. In these situations only the driver is responsible for detection. Future research could focus on driver detection performance in these adverse scenarios.
- This field test gave useful insights in the detectability of lane markings. Developments in the future for new type of lane markings can be tested with a similar field test. On public roads it is difficult to test multiple lane markings within a short time.
- It is recommended to conduct further research on the influence of opposing traffic and the type of headlights used. A blinding effect for the camera, might cause the camera to see a white-out instead of a proper image of the road ahead.

- Only cars were used in this field test, while trucks or buses are higher and incoming light will therefore be from a different angle. As it was suspected in this research that one of the cars had a different position of the front camera with a lower angle, it would be useful to study different vehicles and angles of incoming light.

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A Appendix: A, Retroreflectometer pictures

Figure 32: Location 1 (Triflex) application direction

Figure 33: Location 1 (Triflex) opposite direction

Figure 34: Location 1 asphalt

Figure 35: Location 2 (Triflex) application direction

Figure 36: Location 3 (Triflex) application direction

Figure 37: Location 4 (Triflex) application direction

Figure 38: Location 5 (Old marking)

Figure 39: Location 6 (Old marking)

Figure 40: Location 6 (Old marking)

Figure 41: Location 6 asphalt

Figure 42: Location 7 (3M AW) opposite direction

Figure 43: Location 8 (3M AW) application direction

Figure 44: Location 8 (3M AW) opposite direction

Figure 45: Location 8 (3M AW) application direction

Figure 46: Location 9 (3M AW) opposite direction

Figure 47: Location 10 (3M ESD) opposite direction

Figure 48: Location 10 (3M ESD) application direction

Figure 49: Location 11 (3M ESD) opposite direction

Figure 50: Location 11 (3M ESD) application direction

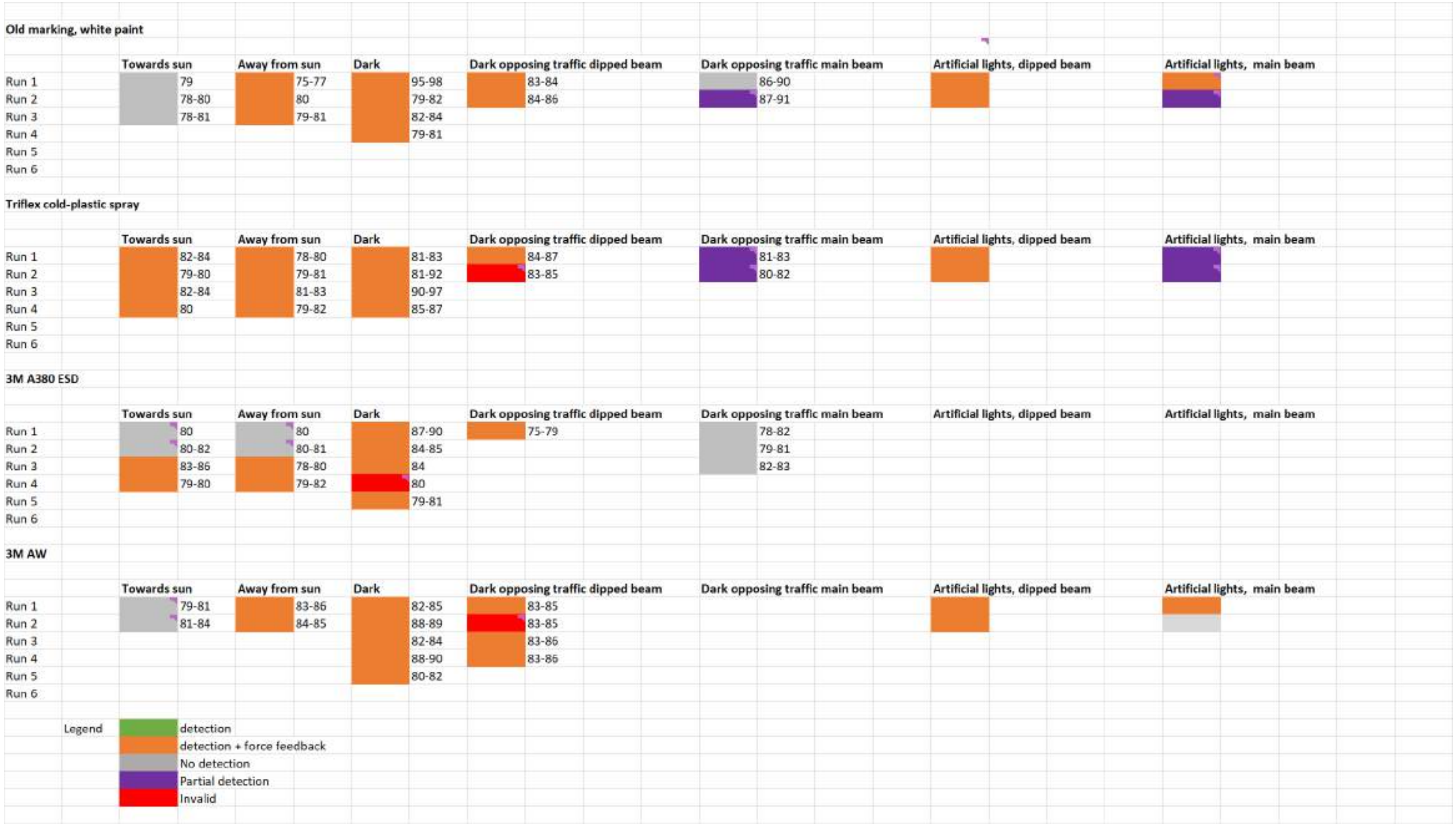
Figure 51: Location 11 asphalt

Figure 52: Location 12 (3M ESD) opposite direction

Figure 53: Location 12 (3M ESD) application direction

Figure 54: Location 12 asphalt

B Appendix: B: Data visualized



Old marking, white paint

	Towards sun	Away from sun	Dark	Dark opposing traffic dipped beam	Dark opposing traffic main beam	Artificial lights, dipped beam	Artificial lights, main beam
Run 1	⬜ 79	🟧 75-77	🟧 95-98	🟧 83-84	⬜ 86-90	🟧	🟧
Run 2	⬜ 78-80	🟧 80	🟧 79-82	🟧 84-86	🟪 87-91	🟧	🟪
Run 3	⬜ 78-81	🟧 79-81	🟧 82-84				
Run 4			🟧 79-81				
Run 5							
Run 6							

Triflex cold-plastic spray

	Towards sun	Away from sun	Dark	Dark opposing traffic dipped beam	Dark opposing traffic main beam	Artificial lights, dipped beam	Artificial lights, main beam
Run 1	🟧 82-84	🟧 78-80	🟧 81-83	🟧 84-87	🟪 81-83	🟧	🟪
Run 2	🟧 79-80	🟧 79-81	🟧 81-92	🟥 83-85	🟪 80-82	🟧	🟪
Run 3	🟧 82-84	🟧 81-83	🟧 90-97				
Run 4	🟧 80	🟧 79-82	🟧 85-87				
Run 5							
Run 6							

3M A380 ESD

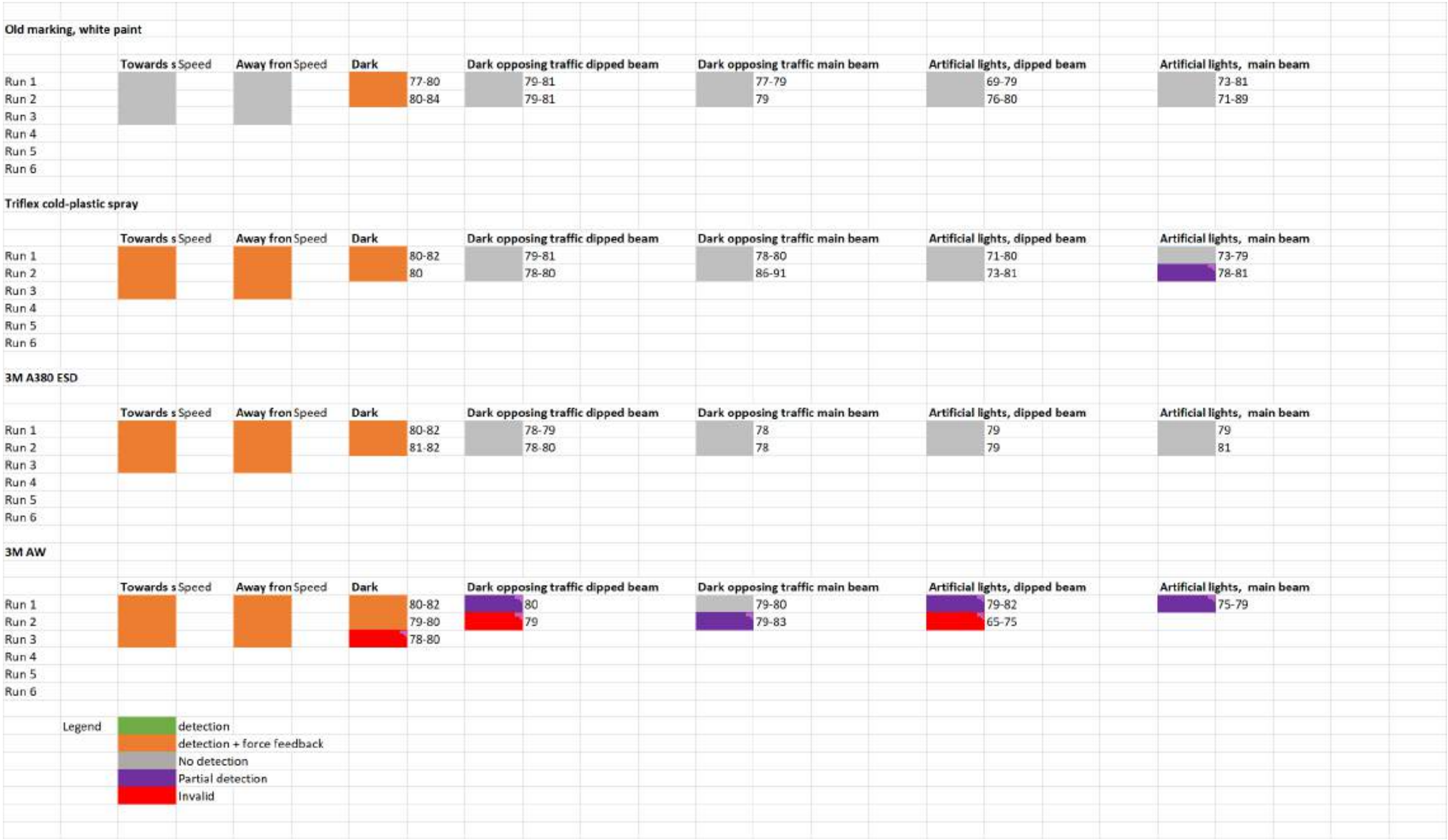
	Towards sun	Away from sun	Dark	Dark opposing traffic dipped beam	Dark opposing traffic main beam	Artificial lights, dipped beam	Artificial lights, main beam
Run 1	⬜ 80	⬜ 80	🟧 87-90	🟧 75-79	⬜ 78-82		
Run 2	⬜ 80-82	⬜ 80-81	🟧 84-85		⬜ 79-81		
Run 3	🟧 83-86	🟧 78-80	🟧 84		⬜ 82-83		
Run 4	🟧 79-80	🟧 79-82	🟥 80				
Run 5			🟧 79-81				
Run 6							

3M AW

	Towards sun	Away from sun	Dark	Dark opposing traffic dipped beam	Dark opposing traffic main beam	Artificial lights, dipped beam	Artificial lights, main beam
Run 1	⬜ 79-81	🟧 83-86	🟧 82-85	🟧 83-85		🟧	🟧
Run 2	⬜ 81-84	🟧 84-85	🟧 88-89	🟥 83-85		🟧	⬜
Run 3			🟧 82-84	🟧 83-86			
Run 4			🟧 88-90	🟧 83-86			
Run 5			🟧 80-82				
Run 6							

Legend
- 🟩 detection
- 🟧 detection + force feedback
- ⬜ No detection
- 🟪 Partial detection
- 🟥 Invalid

Figure 55: Car A day 1 data



Old marking, white paint

	Towards s Speed	Away fron Speed	Dark	Dark opposing traffic dipped beam	Dark opposing traffic main beam	Artificial lights, dipped beam	Artificial lights, main beam
Run 1	⬜	⬜	🟧 77-80	⬜ 79-81	⬜ 77-79	⬜ 69-79	⬜ 73-81
Run 2	⬜	⬜	🟧 80-84	⬜ 79-81	⬜ 79	⬜ 76-80	⬜ 71-89
Run 3	⬜	⬜					
Run 4							
Run 5							
Run 6							

Triflex cold-plastic spray

	Towards s Speed	Away fron Speed	Dark	Dark opposing traffic dipped beam	Dark opposing traffic main beam	Artificial lights, dipped beam	Artificial lights, main beam
Run 1	🟧	🟧	🟧 80-82	⬜ 79-81	⬜ 78-80	⬜ 71-80	⬜ 73-79
Run 2	🟧	🟧	🟧 80	⬜ 78-80	⬜ 86-91	⬜ 73-81	🟪 78-81
Run 3	🟧	🟧					
Run 4							
Run 5							
Run 6							

3M A380 ESD

	Towards s Speed	Away fron Speed	Dark	Dark opposing traffic dipped beam	Dark opposing traffic main beam	Artificial lights, dipped beam	Artificial lights, main beam
Run 1	🟧	🟧	🟧 80-82	⬜ 78-79	⬜ 78	⬜ 79	⬜ 79
Run 2	🟧	🟧	🟧 81-82	⬜ 78-80	⬜ 78	⬜ 79	⬜ 81
Run 3	🟧	🟧					
Run 4							
Run 5							
Run 6							

3M AW

	Towards s Speed	Away fron Speed	Dark	Dark opposing traffic dipped beam	Dark opposing traffic main beam	Artificial lights, dipped beam	Artificial lights, main beam
Run 1	🟧	🟧	🟧 80-82	🟪 80	⬜ 79-80	🟪 79-82	🟪 75-79
Run 2	🟧	🟧	🟧 79-80	🟥 79	🟪 79-83	🟥 65-75	
Run 3	🟧	🟧	🟥 78-80				
Run 4							
Run 5							
Run 6							

Legend		
	🟩	detection
	🟧	detection + force feedback
	⬜	No detection
	🟪	Partial detection
	🟥	Invalid

Figure 56: Car A day 2 data

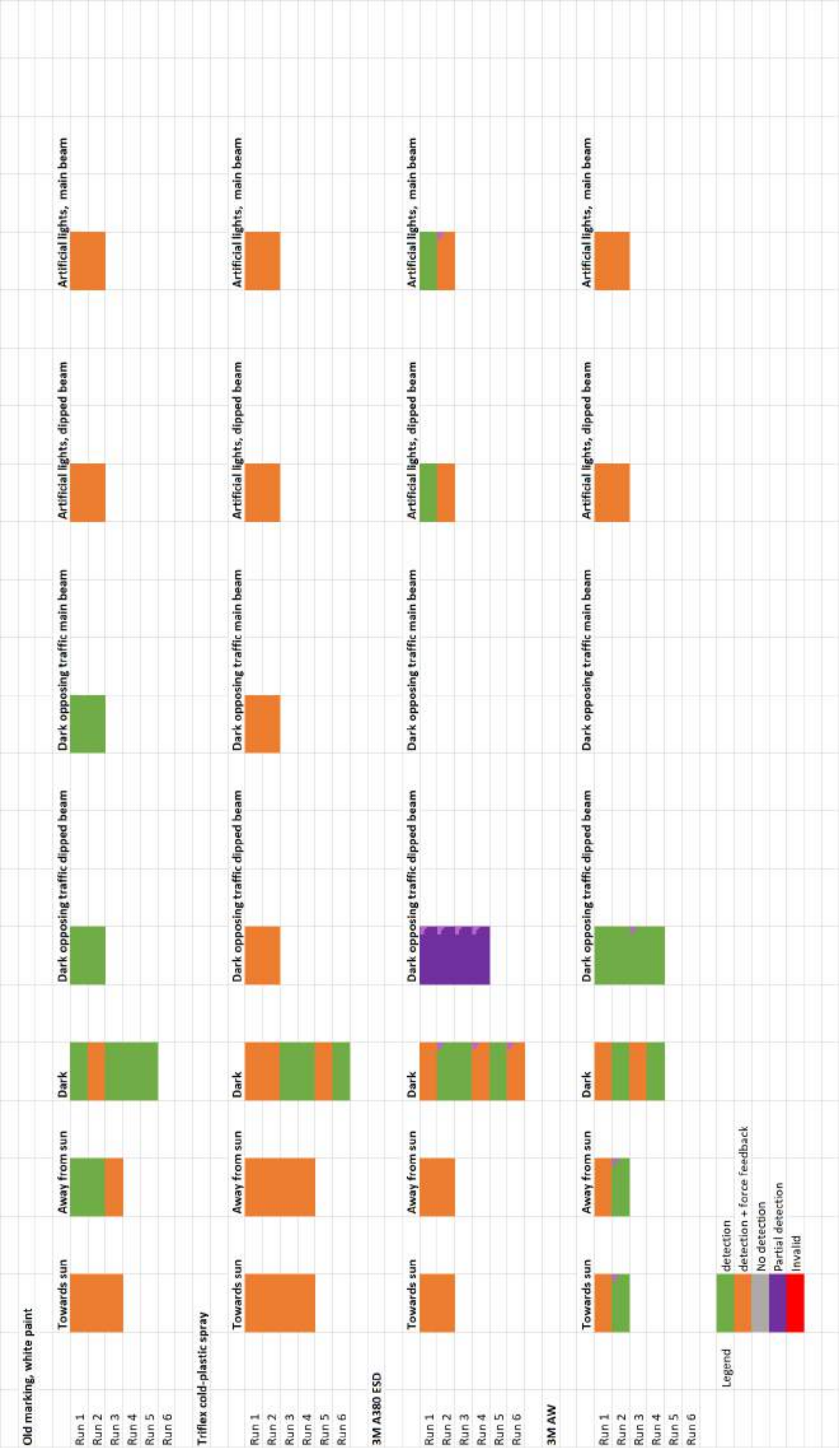
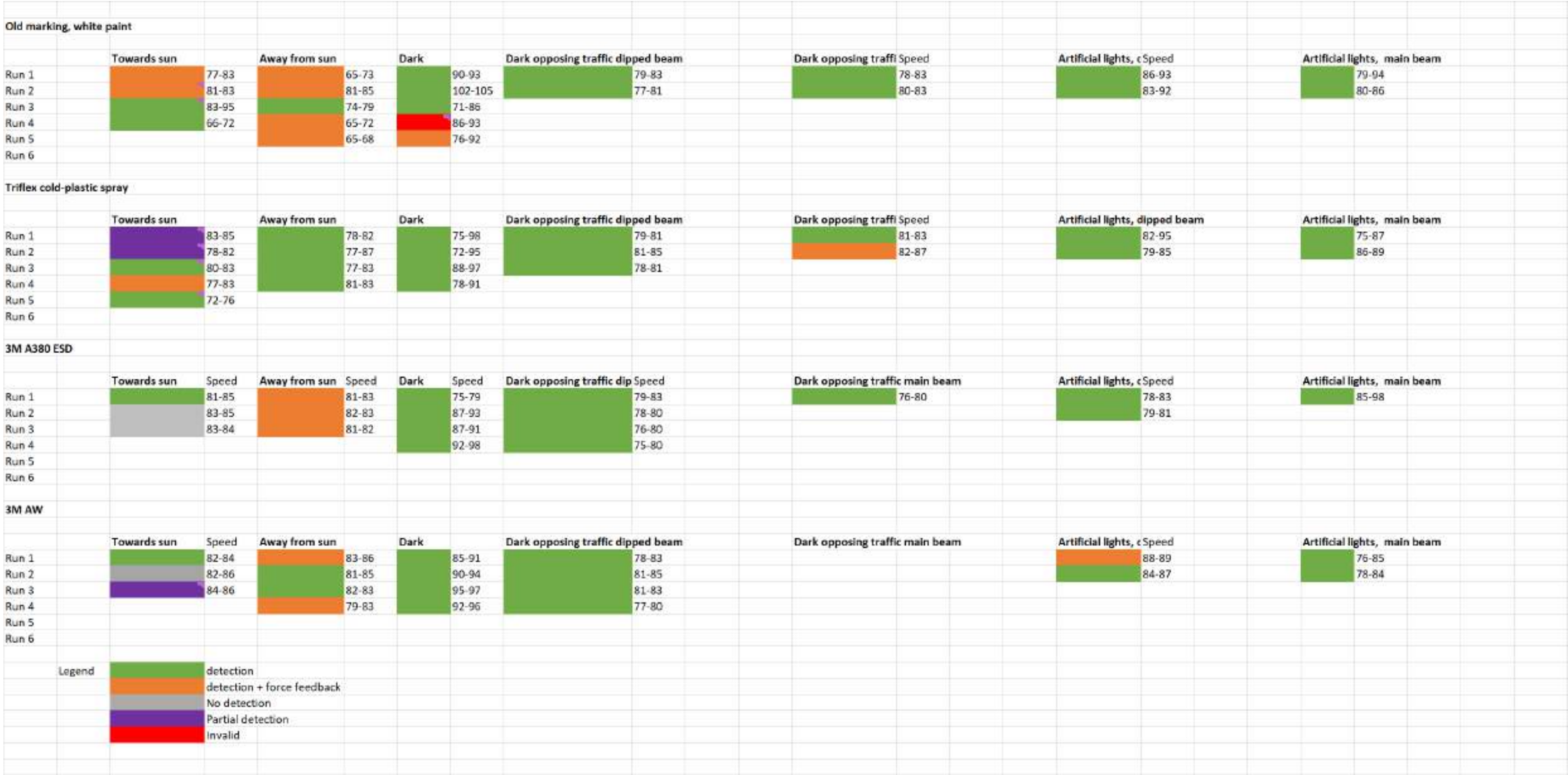


Figure 57: Car B day 1 data

Figure 58: Car B day 2 data



Old marking, white paint

	Towards sun		Away from sun		Dark		Dark opposing traffic dipped beam		Dark opposing traffi	Speed	Artificial lights, c	Speed	Artificial lights, main beam	
Run 1	🟧	77-83	🟧	65-73	🟩	90-93	🟩	79-83	🟩	78-83	🟩	86-93	🟩	79-94
Run 2	🟧	81-83	🟧	81-85	🟩	102-105	🟩	77-81	🟩	80-83	🟩	83-92	🟩	80-86
Run 3	🟩	83-95	🟩	74-79	🟩	71-86								
Run 4	🟩	66-72	🟧	65-72	🟥	86-93								
Run 5			🟧	65-68	🟧	76-92								
Run 6														

Triflex cold-plastic spray

	Towards sun		Away from sun		Dark		Dark opposing traffic dipped beam		Dark opposing traffi	Speed	Artificial lights, dipped beam		Artificial lights, main beam	
Run 1	🟪	83-85	🟩	78-82	🟩	75-98	🟩	79-81	🟩	81-83	🟩	82-95	🟩	75-87
Run 2	🟪	78-82	🟩	77-87	🟩	72-95	🟩	81-85	🟧	82-87	🟩	79-85	🟩	86-89
Run 3	🟩	80-83	🟩	77-83	🟩	88-97	🟩	78-81						
Run 4	🟧	77-83	🟩	81-83	🟩	78-91								
Run 5	🟩	72-76												
Run 6														

3M A380 ESD

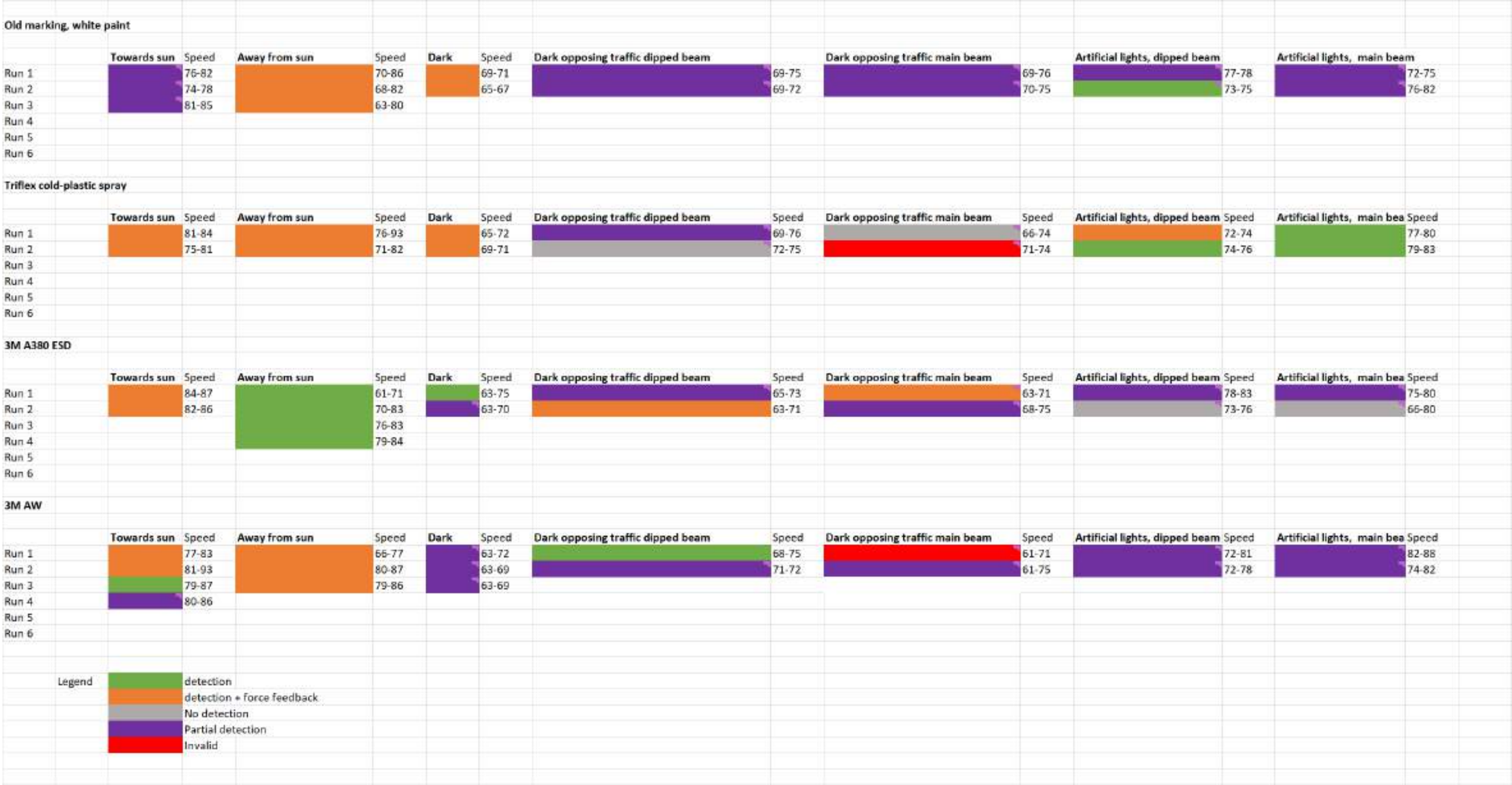
	Towards sun	Speed	Away from sun	Speed	Dark	Speed	Dark opposing traffic dip	Speed	Dark opposing traffic main beam		Artificial lights, c	Speed	Artificial lights, main beam	
Run 1	🟩	81-85	🟧	81-83	🟩	75-79	🟩	79-83	🟩	76-80	🟩	78-83	🟩	85-98
Run 2	⬜	83-85	🟧	82-83	🟩	87-93	🟩	78-80			🟩	79-81		
Run 3	⬜	83-84	🟧	81-82	🟩	87-91	🟩	76-80						
Run 4					🟩	92-98	🟩	75-80						
Run 5														
Run 6														

3M AW

	Towards sun	Speed	Away from sun		Dark		Dark opposing traffic dipped beam		Dark opposing traffic main beam		Artificial lights, c	Speed	Artificial lights, main beam	
Run 1	🟩	82-84	🟧	83-86	🟩	85-91	🟩	78-83			🟧	88-89	🟩	76-85
Run 2	⬜	82-86	🟩	81-85	🟩	90-94	🟩	81-85			🟩	84-87	🟩	78-84
Run 3	🟪	84-86	🟩	82-83	🟩	95-97	🟩	81-83						
Run 4			🟧	79-83	🟩	92-96	🟩	77-80						
Run 5														
Run 6														

Legend		
	🟩	detection
	🟧	detection + force feedback
	⬜	No detection
	🟪	Partial detection
	🟥	Invalid

Figure 59: Car C day 1 data



Old marking, white paint

	Towards sun	Speed	Away from sun	Speed	Dark	Speed	Dark opposing traffic dipped beam		Dark opposing traffic main beam		Artificial lights, dipped beam		Artificial lights, main beam	
Run 1	🟪	76-82	🟧	70-86	🟧	69-71	🟪	69-75	🟪	69-76	🟪	77-78	🟪	72-75
Run 2	🟪	74-78	🟧	68-82	🟧	65-67	🟪	69-72	🟪	70-75	🟩	73-75	🟪	76-82
Run 3	🟪	81-85	🟧	63-80										
Run 4														
Run 5														
Run 6														

Triflex cold-plastic spray

	Towards sun	Speed	Away from sun	Speed	Dark	Speed	Dark opposing traffic dipped beam	Speed	Dark opposing traffic main beam	Speed	Artificial lights, dipped beam	Speed	Artificial lights, main bea	Speed
Run 1	🟧	81-84	🟧	76-93	🟧	65-72	🟪	69-76	⬜	66-74	🟧	72-74	🟩	77-80
Run 2	🟧	75-81	🟧	71-82	🟧	69-71	⬜	72-75	🟥	71-74	🟩	74-76	🟩	79-83
Run 3														
Run 4														
Run 5														
Run 6														

3M A380 ESD

	Towards sun	Speed	Away from sun	Speed	Dark	Speed	Dark opposing traffic dipped beam	Speed	Dark opposing traffic main beam	Speed	Artificial lights, dipped beam	Speed	Artificial lights, main bea	Speed
Run 1	🟧	84-87	🟩	61-71	🟩	63-75	🟪	65-73	🟧	63-71	🟪	78-83	🟪	75-80
Run 2	🟧	82-86	🟩	70-83	🟪	63-70	🟧	63-71	🟪	68-75	⬜	73-76	⬜	66-80
Run 3			🟩	76-83										
Run 4			🟩	79-84										
Run 5														
Run 6														

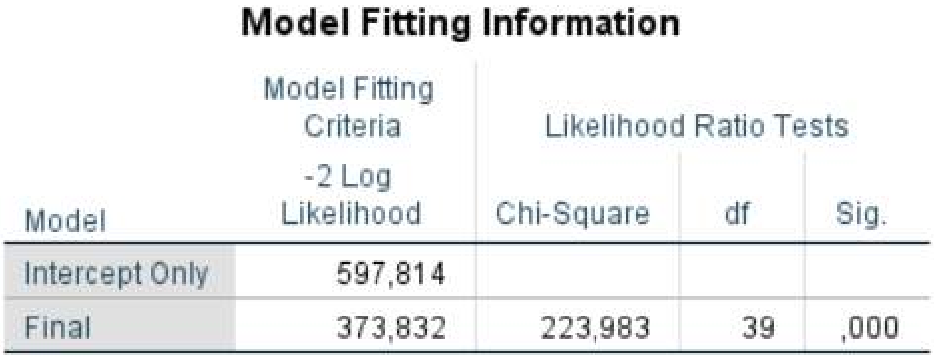
3M AW

	Towards sun	Speed	Away from sun	Speed	Dark	Speed	Dark opposing traffic dipped beam	Speed	Dark opposing traffic main beam	Speed	Artificial lights, dipped beam	Speed	Artificial lights, main bea	Speed
Run 1	🟧	77-83	🟧	66-77	🟪	63-72	🟩	68-75	🟥	61-71	🟪	72-81	🟪	82-88
Run 2	🟧	81-93	🟧	80-87	🟪	63-69	🟪	71-72	🟪	61-75	🟪	72-78	🟪	74-82
Run 3	🟩	79-87	🟧	79-86	🟪	63-69								
Run 4	🟪	80-86												
Run 5														
Run 6														

Legend		
	🟩	detection
	🟧	detection + force feedback
	⬜	No detection
	🟪	Partial detection
	🟥	Invalid

Figure 60: Car C day 2 data

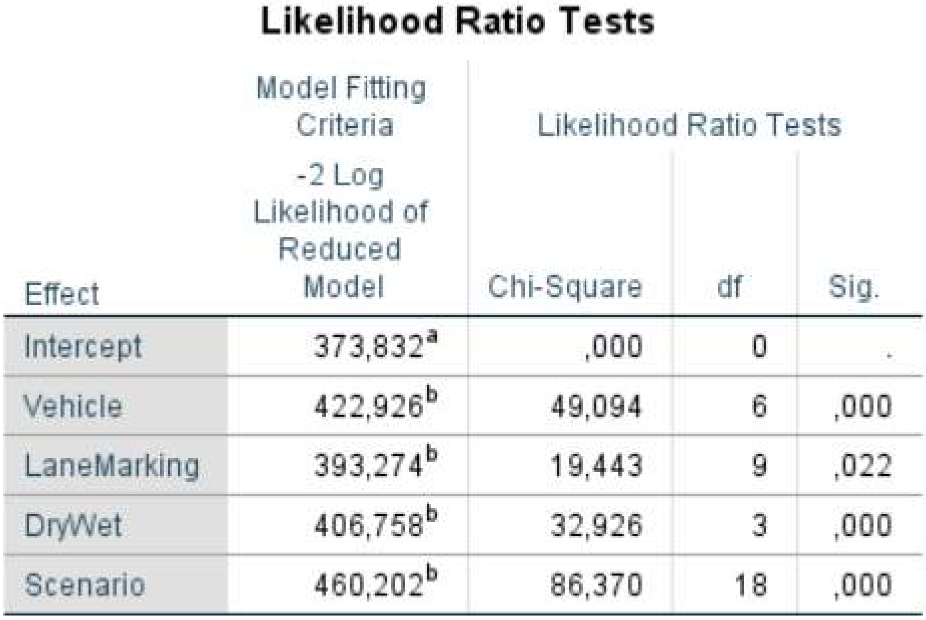
C Appendix: C Statistical tests



Model Fitting Information

Model	Model Fitting Criteria	Likelihood Ratio Tests		
	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	597,814			
Final	373,832	223,983	39	,000

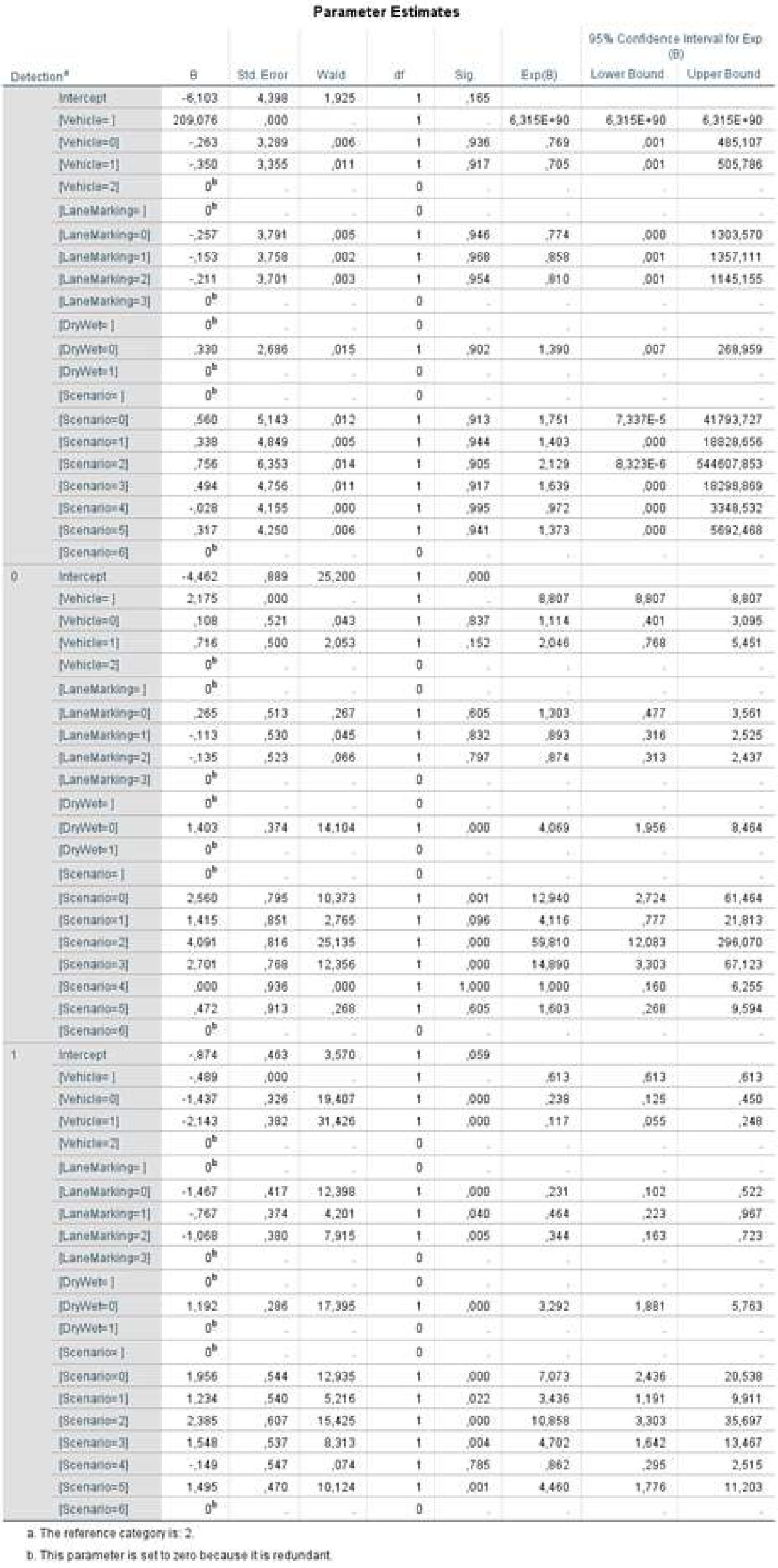
Figure 61: Model fit



Likelihood Ratio Tests

Effect	Model Fitting Criteria	Likelihood Ratio Tests		
	-2 Log Likelihood of Reduced Model	Chi-Square	df	Sig.
Intercept	373,832[a]	,000	0	.
Vehicle	422,926[b]	49,094	6	,000
LaneMarking	393,274[b]	19,443	9	,022
DryWet	406,758[b]	32,926	3	,000
Scenario	460,202[b]	86,370	18	,000

Figure 62: Likelihood ratio tests



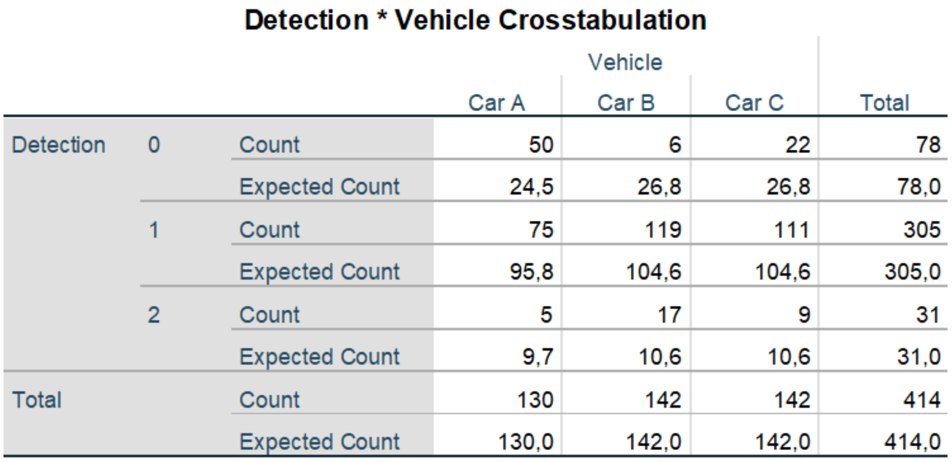
Parameter Estimates

Detection[a]		B	Std. Error	Wald	df	Sig.	Exp(B)	95% Confidence Interval for Exp (B)	
								Lower Bound	Upper Bound
	Intercept	-6,103	4,398	1,925	1	,165			
	[Vehicle=]	209,076	,000	.	1	.	6,315E+90	6,315E+90	6,315E+90
	[Vehicle=0]	-,263	3,289	,006	1	,936	,769	,001	485,107
	[Vehicle=1]	-,350	3,355	,011	1	,917	,705	,001	505,786
	[Vehicle=2]	0[b]	.	.	0	.	.	.	.
	[LaneMarking=]	0[b]	.	.	0	.	.	.	.
	[LaneMarking=0]	-,257	3,791	,005	1	,946	,774	,000	1303,570
	[LaneMarking=1]	-,153	3,758	,002	1	,968	,858	,001	1357,111
	[LaneMarking=2]	-,211	3,701	,003	1	,954	,810	,001	1145,155
	[LaneMarking=3]	0[b]	.	.	0	.	.	.	.
	[DryWet=]	0[b]	.	.	0	.	.	.	.
	[DryWet=0]	,330	2,686	,015	1	,902	1,390	,007	268,959
	[DryWet=1]	0[b]	.	.	0	.	.	.	.
	[Scenario=]	0[b]	.	.	0	.	.	.	.
	[Scenario=0]	,560	5,143	,012	1	,913	1,751	7,337E-5	41793,727
	[Scenario=1]	,338	4,849	,005	1	,944	1,403	,000	18828,656
	[Scenario=2]	,756	6,353	,014	1	,905	2,129	8,323E-6	544607,853
	[Scenario=3]	,494	4,756	,011	1	,917	1,639	,000	18298,869
	[Scenario=4]	-,028	4,155	,000	1	,995	,972	,000	3348,532
	[Scenario=5]	,317	4,250	,006	1	,941	1,373	,000	5692,468
	[Scenario=6]	0[b]	.	.	0	.	.	.	.
0	Intercept	-4,462	,889	25,200	1	,000			
	[Vehicle=]	2,175	,000	.	1	.	8,807	8,807	8,807
	[Vehicle=0]	,108	,521	,043	1	,837	1,114	,401	3,095
	[Vehicle=1]	,716	,500	2,053	1	,152	2,046	,768	5,451
	[Vehicle=2]	0[b]	.	.	0	.	.	.	.
	[LaneMarking=]	0[b]	.	.	0	.	.	.	.
	[LaneMarking=0]	,265	,513	,267	1	,605	1,303	,477	3,561
	[LaneMarking=1]	-,113	,530	,045	1	,832	,893	,316	2,525
	[LaneMarking=2]	-,135	,523	,066	1	,797	,874	,313	2,437
	[LaneMarking=3]	0[b]	.	.	0	.	.	.	.
	[DryWet=]	0[b]	.	.	0	.	.	.	.
	[DryWet=0]	1,403	,374	14,104	1	,000	4,069	1,956	8,464
	[DryWet=1]	0[b]	.	.	0	.	.	.	.
	[Scenario=]	0[b]	.	.	0	.	.	.	.
	[Scenario=0]	2,560	,795	10,373	1	,001	12,940	2,724	61,464
	[Scenario=1]	1,415	,851	2,765	1	,096	4,116	,777	21,813
	[Scenario=2]	4,091	,816	25,135	1	,000	59,810	12,083	296,070
	[Scenario=3]	2,701	,768	12,356	1	,000	14,890	3,303	67,123
	[Scenario=4]	,000	,936	,000	1	1,000	1,000	,160	6,255
	[Scenario=5]	,472	,913	,268	1	,605	1,603	,268	9,594
	[Scenario=6]	0[b]	.	.	0	.	.	.	.
1	Intercept	-,874	,463	3,570	1	,059			
	[Vehicle=]	-,489	,000	.	1	.	,613	,613	,613
	[Vehicle=0]	-1,437	,326	19,407	1	,000	,238	,125	,450
	[Vehicle=1]	-2,143	,382	31,426	1	,000	,117	,055	,248
	[Vehicle=2]	0[b]	.	.	0	.	.	.	.
	[LaneMarking=]	0[b]	.	.	0	.	.	.	.
	[LaneMarking=0]	-1,467	,417	12,398	1	,000	,231	,102	,522
	[LaneMarking=1]	-,767	,374	4,201	1	,040	,464	,223	,967
	[LaneMarking=2]	-1,068	,380	7,915	1	,005	,344	,163	,723
	[LaneMarking=3]	0[b]	.	.	0	.	.	.	.
	[DryWet=]	0[b]	.	.	0	.	.	.	.
	[DryWet=0]	1,192	,286	17,395	1	,000	3,292	1,881	5,763
	[DryWet=1]	0[b]	.	.	0	.	.	.	.
	[Scenario=]	0[b]	.	.	0	.	.	.	.
	[Scenario=0]	1,956	,544	12,935	1	,000	7,073	2,436	20,538
	[Scenario=1]	1,234	,540	5,216	1	,022	3,436	1,191	9,911
	[Scenario=2]	2,385	,607	15,425	1	,000	10,858	3,303	35,697
	[Scenario=3]	1,548	,537	8,313	1	,004	4,702	1,642	13,467
	[Scenario=4]	-,149	,547	,074	1	,785	,862	,295	2,515
	[Scenario=5]	1,495	,470	10,124	1	,001	4,460	1,776	11,203
	[Scenario=6]	0[b]	.	.	0	.	.	.	.

a. The reference category is: 2.

b. This parameter is set to zero because it is redundant.

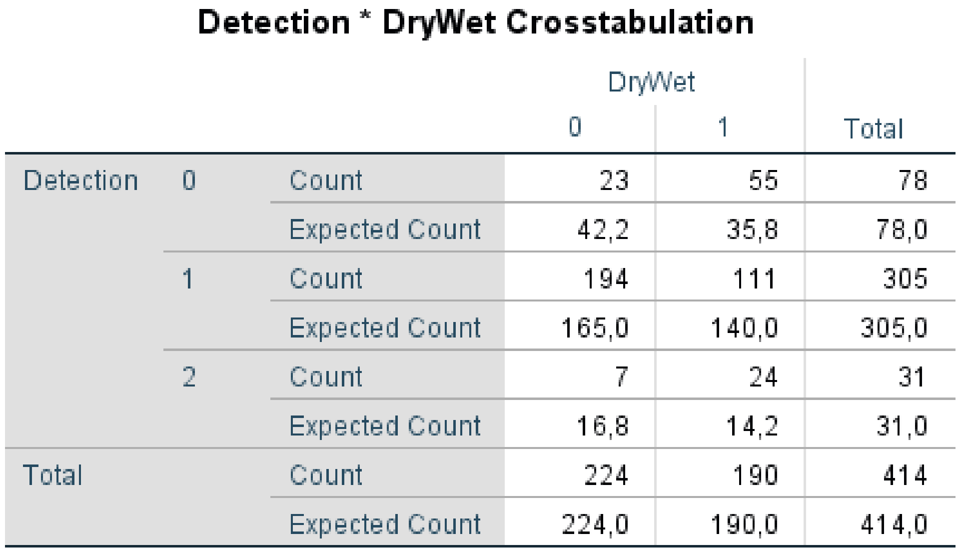
Figure 63: Logistic regression results



Detection * Vehicle Crosstabulation

			Vehicle			
			Car A	Car B	Car C	Total
Detection	0	Count	50	6	22	78
		Expected Count	24,5	26,8	26,8	78,0
	1	Count	75	119	111	305
		Expected Count	95,8	104,6	104,6	305,0
	2	Count	5	17	9	31
		Expected Count	9,7	10,6	10,6	31,0
Total		Count	130	142	142	414
		Expected Count	130,0	142,0	142,0	414,0

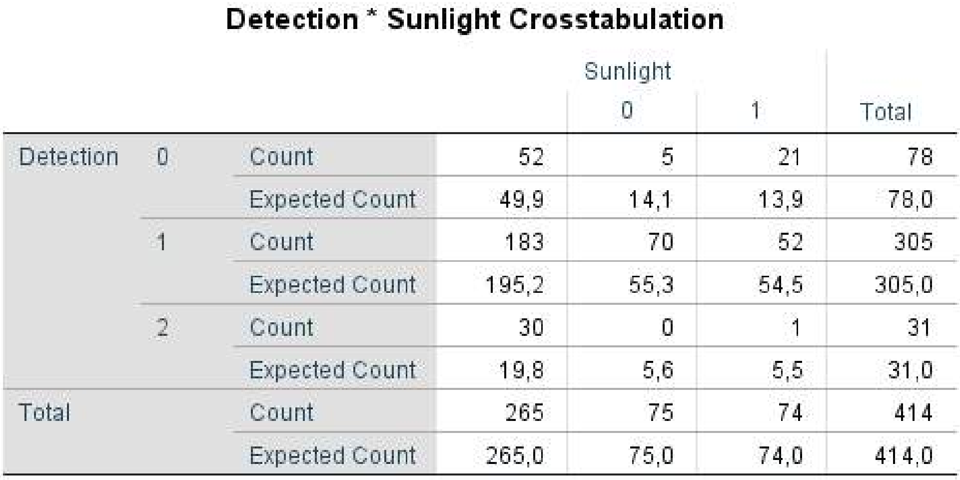
Figure 64: Vehicle * detection crosstabulation



Detection * DryWet Crosstabulation

			DryWet		
			0	1	Total
Detection	0	Count	23	55	78
		Expected Count	42,2	35,8	78,0
	1	Count	194	111	305
		Expected Count	165,0	140,0	305,0
	2	Count	7	24	31
		Expected Count	16,8	14,2	31,0
Total		Count	224	190	414
		Expected Count	224,0	190,0	414,0

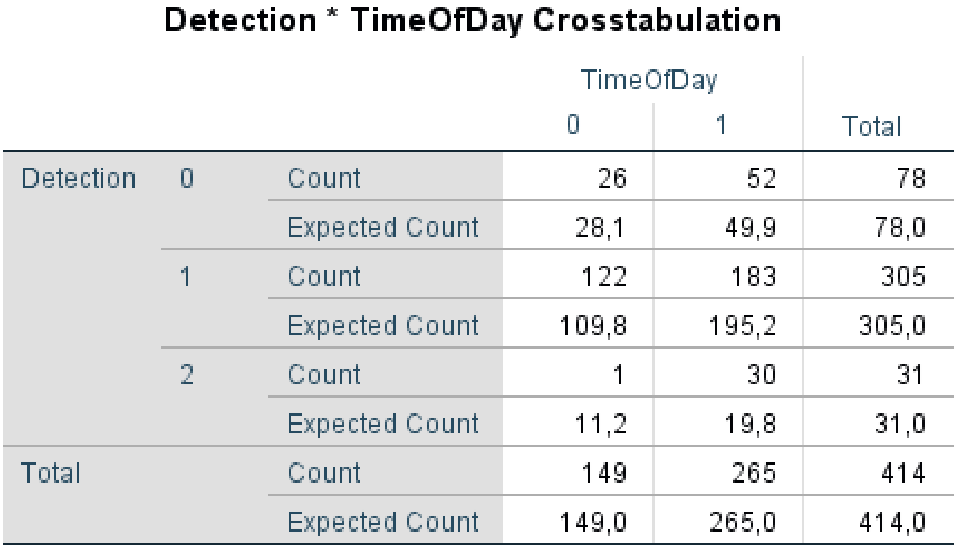
Figure 65: Dry/wet * detection crosstabulation



Detection * Sunlight Crosstabulation

				Sunlight		
				0	1	Total
Detection	0	Count	52	5	21	78
		Expected Count	49,9	14,1	13,9	78,0
	1	Count	183	70	52	305
		Expected Count	195,2	55,3	54,5	305,0
	2	Count	30	0	1	31
		Expected Count	19,8	5,6	5,5	31,0
Total		Count	265	75	74	414
		Expected Count	265,0	75,0	74,0	414,0

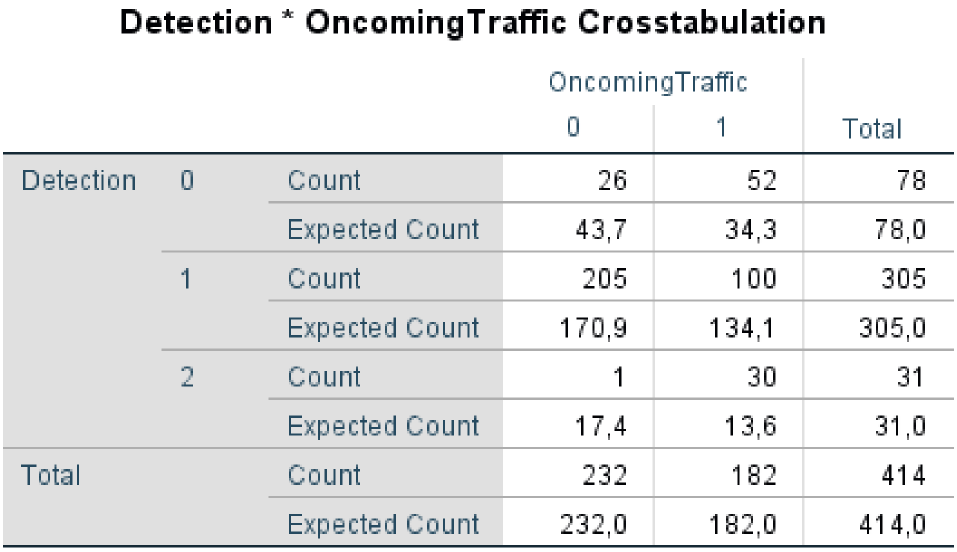
Figure 66: Sunlight * detection crosstabulation



Detection * TimeOfDay Crosstabulation

			TimeOfDay		
			0	1	Total
Detection	0	Count	26	52	78
		Expected Count	28,1	49,9	78,0
	1	Count	122	183	305
		Expected Count	109,8	195,2	305,0
	2	Count	1	30	31
		Expected Count	11,2	19,8	31,0
Total		Count	149	265	414
		Expected Count	149,0	265,0	414,0

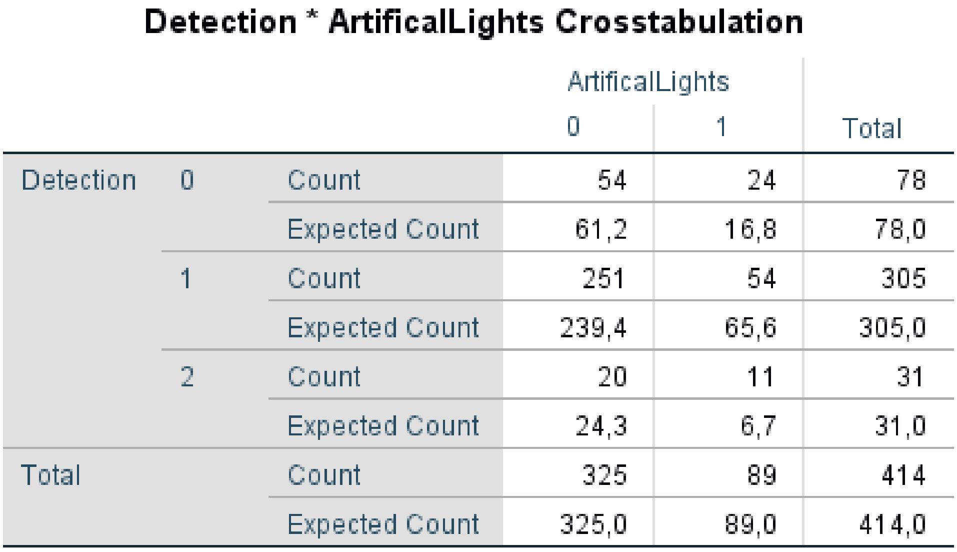
Figure 67: Time of day * detection crosstabulation



Detection * OncomingTraffic Crosstabulation

			OncomingTraffic		
			0	1	Total
Detection	0	Count	26	52	78
		Expected Count	43,7	34,3	78,0
	1	Count	205	100	305
		Expected Count	170,9	134,1	305,0
	2	Count	1	30	31
		Expected Count	17,4	13,6	31,0
Total		Count	232	182	414
		Expected Count	232,0	182,0	414,0

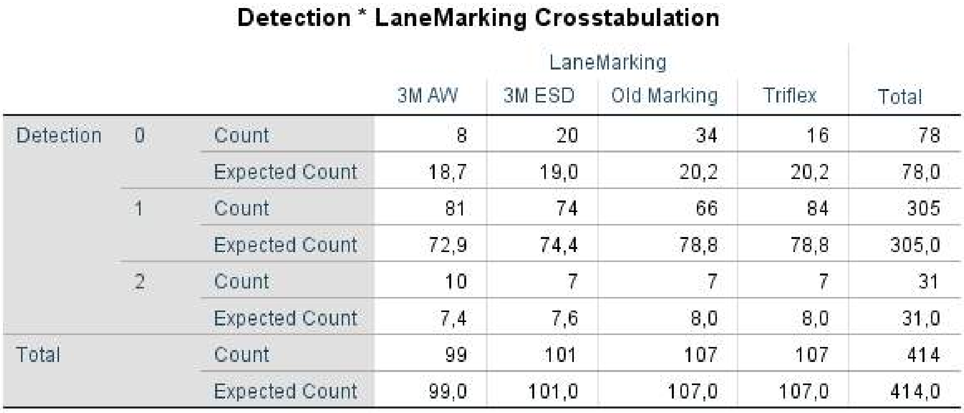
Figure 68: Oncoming traffic * detection crosstabulation



Detection * ArtificalLights Crosstabulation

			ArtificalLights		
			0	1	Total
Detection	0	Count	54	24	78
		Expected Count	61,2	16,8	78,0
	1	Count	251	54	305
		Expected Count	239,4	65,6	305,0
	2	Count	20	11	31
		Expected Count	24,3	6,7	31,0
Total		Count	325	89	414
		Expected Count	325,0	89,0	414,0

Figure 69: Artificial lights * detection crosstabulation



Detection * LaneMarking Crosstabulation

			LaneMarking				
			3M AW	3M ESD	Old Marking	Triflex	Total
Detection	0	Count	8	20	34	16	78
		Expected Count	18,7	19,0	20,2	20,2	78,0
	1	Count	81	74	66	84	305
		Expected Count	72,9	74,4	78,8	78,8	305,0
	2	Count	10	7	7	7	31
		Expected Count	7,4	7,6	8,0	8,0	31,0
Total		Count	99	101	107	107	414
		Expected Count	99,0	101,0	107,0	107,0	414,0

Figure 70: Lane marking detection crosstabulation