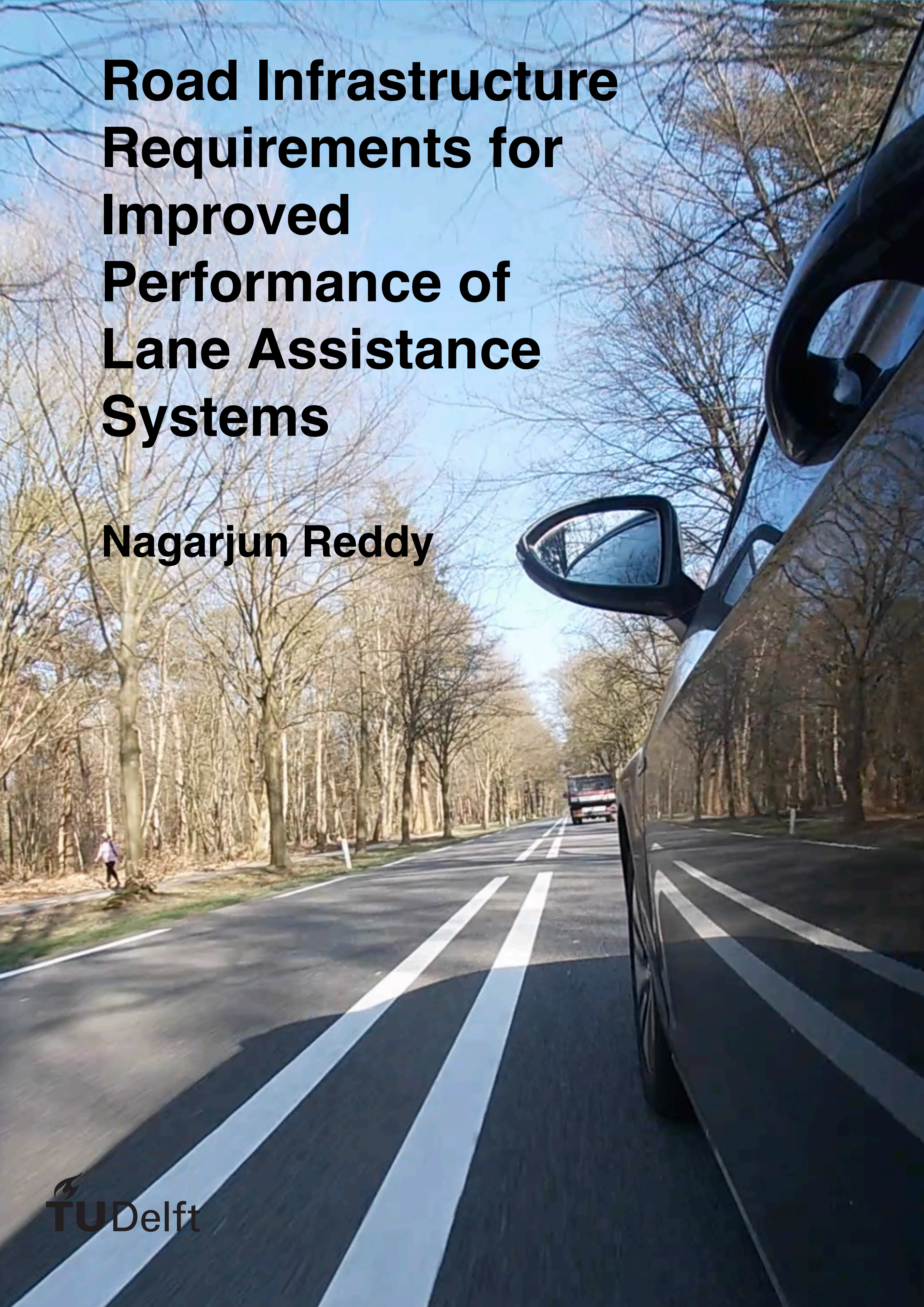

Road Infrastructure Requirements for Improved Performance of Lane Assistance Systems

Nagarjun Reddy

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by

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Nagarjun Reddy
Delft, November 2019

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List of Abbreviations

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
CAN	Controlled Area Network
CACC	Cooperative Adaptive Cruise Control
HFACS	Human Factors Analysis and Classification System
I2V	Infrastructure to Vehicle
LDW	Lane Departure Warning
LKS	Lane Keeping Systems
LiDAR	Light Detection and Ranging
MLP	Mean Lateral Position
ODD	Operational Design Domain
OEMs	Original Equipment Manufacturers
PRF	Potential Risk Field
PDRF	Probabilistic Driving Risk Field
PNH	Provincie Noord-Holland
RSR	Refined Safety Requirement
SR	Safety Requirement
SAE	Society of Automotive Engineers
SDLP	Standard Deviation of Lane Position
SSMs	Surrogate Safety Measures
STAMP	Systems Theoretic Accident Modelling and Processes
STPA	Systems Theoretic Process Analysis
TLC	Time to Lane Crossing
TLD	Time to Lane Departure
UCA	Unsafe Control Action

Executive Summary

Introduction

The rapid advent of automated vehicles has raised much interest in understanding the impacts of this technology on present-day transportation, its strengths and limitations. As of 2022, the new EU regulation makes it mandatory that all vehicles sold in the EU will have a set of automated safety systems to increase safety on roads (European Commission 2018). Whether these systems will increase safety is important to determine. It has thus become increasingly relevant, especially for road authorities, to take action and initiative towards understanding the effects of these systems and their implications on the existing road infrastructure. Road authorities need to understand what adaptations in the road infrastructure are needed to expect the safe operation of automated vehicles.

Most existing studies look at full automation levels and total market penetration rates to predict infrastructure changes. However, these conditions are not expected anywhere in the immediate future. The focus of this research is to investigate the safe performance of current Lane Assistance Systems (Lane Keeping Systems (LKS) and Lane Departure Warning (LDW)) from the perspective of the road authority, the Provincie Noord-Holland (PNH).

The main research question of this research is:

What changes need to be made to the road infrastructure to increase the performance of Level 1 Automated Vehicles with Lane Assistance Systems?

This research develops a methodology for the road authority (PNH), to conduct extensive risk analysis, resulting in specific requirements for expecting an improved performance of these systems. It also demonstrates the operationalisation of these requirements through a field test.

Research Method

The framework of the methodology is formulated by using the Systems Theoretic Process Analysis (STPA), based on the Systems Theoretic Accident Modelling and Processes (STAMP). The STPA provides systematic and sequential steps for conducting an extensive risk analysis of a System. The first step defines the scope and objectives of the analysis, which entails defining the System that is to be studied, enumerating its hazardous states and losses exhaustively. The next step involves representing the System as the Control Structure by constructing the entire System, its controllers, components, sub-components, and describing how they interact with each other. The next step identifies the Control Actions and the corresponding controllers. For each of the identified Control Actions, the procedure looks at the various possible Unsafe Control Action (UCA). A UCA is a Control Action, that, under the worst or extreme environmental conditions, will lead to one or more Hazard. Finally, for each of these identified UCAs, the various possible causes leading to them are explored systematically. These result in the formulation of the Refined safety requirements (RSRs) for each specific causes/loss scenario.

To operationalise the RSRs, a field test was conducted on about 600 km of provincial roads in North Holland. Two vehicles/systems are used in this test: The Volkswagen e-Golf with its LKS and the Toyota Auris with its LDW system. Both vehicles were driven together for the entire test route. Co-drivers in both the vehicles logged the driving environment conditions on a laptop. The test sessions were scheduled on different days and different times of day to cover all kinds of visibility conditions. The LKS requires a minimum speed of 65 km/h to be active, while the LDW requires a minimum speed of 50 km/h to be active. This research focuses only on the interaction between the driving environment and these Lane Assistance Systems. The human driver is out of the scope of this study.

The indicators used to measure lane detection capability are: “Percentage No Lines Detection” and “Percentage Both Lines Detection”. These indicators are used to evaluate the performance of the systems in different scenarios. For the Golf with the LKS, the position of the vehicle on the lane was measured using image processing. Mean Lateral Position (MLP) and Standard Deviation of Lane Position (SDLP) are used to evaluate its lane-keeping performance. Lateral Position or Lane Position is the distance between the centre of the lane and the centre of the vehicle axle. The indicators proposed were measured in different scenarios, and the effect of the driving environment on the performance was estimated using statistical significance. Finally, the infrastructure requirements are proposed by combining the results of the STPA and the field test data analysis.

Results and Conclusions

The STPA analysis results in a set of Refined Safety Requirements. These are classified as Infrastructure Requirements, Algorithm Requirements, In-vehicle Communication Requirements, and Hardware Requirements. This research focuses on Infrastructure Requirements, which are presented in Table 1. Some highlights of these requirements are providing sufficient transition sections between consecutive curves, designing curves with sufficient radii, ensuring high contrast on the pavement only between the lane markings and the pavement, and incorporating the capabilities of the Lane Assistance Systems in road design. The performance of the LKS and LDW enabled vehicles is evaluated from the field test to identify its affecting factors. The results for both the systems are combined to measure detection performance. Figures 2 and 3 show the effect of visibility conditions and speed on detection performance. Overall, the detection rate is relatively high with the vast majority of the detection states being “Both lines detected”.

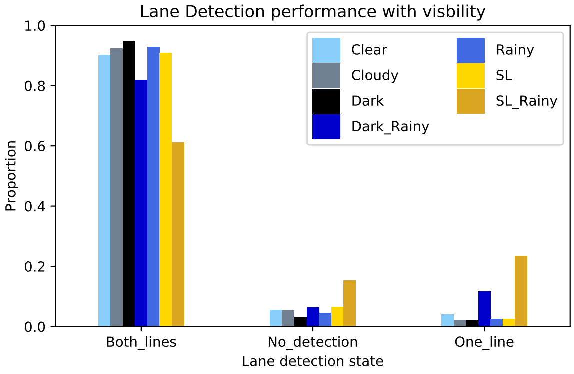


Figure 2: Lane Detection in different visibility conditions

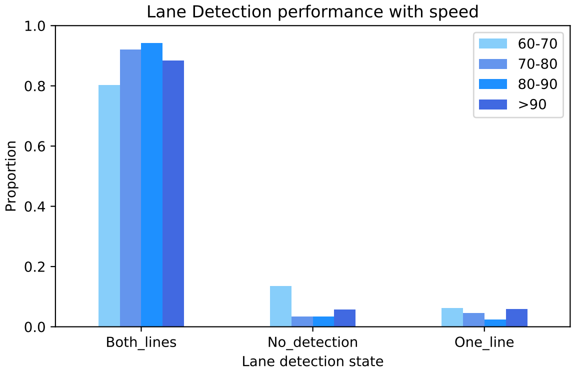


Figure 3: Lane Detection at different speeds

Regression modelling is adopted to obtain a probabilistic insight. A Generalised Linear Mixed Model is used to estimate detection performance in different visibility conditions. The “No lines” detection category is used as the reference for estimating the “Both lines” detection state. Some important results are now discussed.

As compared to the “Dark” visibility condition, all other visibility conditions, except for the “Rainy” condition, have a significantly lower probability of “Both lines” detected. When driving in “Rainy” condition, there is significantly a greater probability of “Both lines” detection as compared to “Dark” condition. This seemingly counter-intuitive result is possibly due to almost all the logged “Rainy” conditions being “Light Rain”. Also, the probability of “Both lines” detection in “Rainy” condition is very close to being insignificant as compared to “Dark” condition. Therefore, it is taken that “Dark” condition has the highest probability of “Both

Table 1: Infrastructure Requirements

Infrastructure Requirements from STPA
- Roads must have a pavement design and drainage system well enough to prevent slippery roads for vehicles.
- There must be a sufficient transition section between two simultaneous reverse curves, taking into account the max steering torque of the vehicle, the speed limit of that road stretch, the width of the lane, the radius of the curves, and reaction time of the LKS.
- Reduced speed limit signs must be placed well before sharp curves to enable safe manual takeover by the driver.
- There must be a sufficient transition section between two simultaneous curves, taking into account the max steering torque of the vehicle, the speed limit of that road stretch, the width of the lane, the radius of the curves, and reaction time of the LKS.
- Lane markings must be sufficiently distinct and recognisable, offering high contrast with the pavement.
- There must not be high contrast differences between pavement and immediate shoulder of the road that might be recognised as the lane edge.
- Lane markings must be consistent with respect to the function of the road they are on, to ensure that LKS cameras can be better trained to detect them.
- The radius of the curves must be such that the vehicles can navigate them taking into account the max steering torque, the width of the lane, the speed limit of that road stretch, and reaction time of the LKS.
- The road and roadside infrastructure must be designed to assist the detection of the lane markings to prevent high contrast differences with objects other than lane markings, but also to prevent contrast reduction between lane markings and the pavement in different visibility conditions.
- There must be no marks remaining from reconstructed roads that might indicate lane boundaries different from the new actual lane boundaries.
- The road design must be done taking into account the Sight Distance of the cameras of these automated systems and Reaction Time needed for execution of LKS steering correction.
- There must not be roadside objects that cast shadows resembling lines (such as crash barriers, from roadside buildings or other infrastructure, or from trees that have a particularly long bark).
- There must be no asphalt repair patches on the road that might be recognised as a lane marking.
- The width of the lanes must be designed to safely accommodate the safe lane position limit of the LKS vehicles.

lines” detection. The visibility conditions ranked in decreasing order of probability of “Both lines” detected are “Dark”, “Rainy”, “Cloudy”, “Clear”, “Streetlights”, “Dark and Rainy”, and “Streetlights and Rainy”.

The developed Generalised Linear Mixed Model also captures the effect of Speed on detection performance. It is seen that driving at 60-70 kmph and at >90 kmph, has a significantly lower probability of having “Both lines” detection as compared to that at 80-90 kmph. Also, the probability of “Both lines” detection is significantly more than twice at >90 kmph than at 60-70 kmph, with 80-90 kmph as the reference speed category.

A Multiple Linear Regression model is constructed for lane-keeping performance using lane position (or Lateral Position) as the indicator. It was seen that Lane widths below 250 cm result in a Lane Position that is about 6 cm significantly more left than on roads having Lane widths over 250 cms. It was also observed that driving on left curves made the LKS to keep about 6.7 cms significantly more left than on straight sections. Driving over 90 kmph tended the LKS to keep about 8 cm significantly more right than 70-80 kmph (although it must be noted that the amount of driving above 90 kmph is very less), and driving at 80-90 kmph tended the LKS to keep about 1.6 cm significantly more left than 70-80 kmph.

Using defined performance thresholds shown in Table 2, the driving environment conditions were classified into the different performance categories as shown in Table 3. This type of classification is used to operationalise the Refined Safety Requirements (RSRs) from the STPA. For instance, one of the RSR was that “The width of the lane must be designed to safely accommodate the safe lane position limit of the LKS vehicle”. The results show that lane widths above 2.5 m have high performance, but not lesser lane widths. The Road Authority, when considering to implement this RSR, must test the performance of the vehicles on different lane widths, and then decide on the acceptable lane widths by looking at the acceptable performance level.

Table 2: Performance evaluation thresholds for the Indicators

Indicator	**High Performance**	**Medium Performance**	**Low Performance**
Percentage No Lines Detection	<= 5%	>5%, <=10%	>10%
Percentage Both Line Detection	>90%	<=90%, >85%	<=85%
MLP[1]	<= +-2 cm	> +-2 cm, <= +-4 cm	> +-4 cm
SDLP	<= 15 cm	> 15 cm, <=30 cm	>30 cm

[1] Mean and Median Lateral Position

Table 3: ODD Levels of Service

Level of Service	**Visibility condition**	**Speed category**	**Lane width**	**Type of curve**
High Performance	Dark, Rainy, Cloudy, Clear	70-80, 80-90	>= 2.5 m	Straight section, Right curve
Medium Performance	Streetlights, Dark_Rainy	>90		
Low Performance	Streetlights_Rainy	60-70	< 2.5 m	Left Curve

Thus, from the STPA and the field test, there were several useful insights into the effect that road infrastructure has on the performance of the Lane Assistance Systems. It is crucial to keep in mind the nature of these effects and to incorporate these requirements in combination with the conventional road design guidelines and practices.

Recommendations

Road authorities need to be aware of the nature of the interactions between the Lane Assistance Systems with the driving environment, and also the resulting risks. The STPA analysis, based on the STAMP model, provides an extensive and detailed overview of these interactions and their risks. It also specifies certain safety requirements that must be met in order to expect safe operation of these systems on the roads.

Some recommendations for future use of the STAMP model, specifically the STPA are:

- There should be a “probabilistic link” between the Unsafe Control Action (UCA) and the defined Losses. Incorporation of the probability of a Loss, given an UCA, would provide a much better insight into the risk associated with that UCA.
- Similarly, there must be a link between the Loss Scenarios and the UCAs. This is because the occurrence of a specific Loss Scenario could increase the probability of the corresponding UCA by a different magnitude than other Loss Scenarios.

- After deriving the RSRs, in order to make the results more handy to use, it is recommended that appropriate indicators be identified to evaluate the extent of adherence to the requirements by the relevant System components. For instance, *"Lane markings must be sufficiently distinct and recognisable, offering high contrast with the pavement"* was one of the RSRs. Two indicators can be identified here: the visibility of the lane marking, and the contrast with the pavement. This assists in the operationalisation of the RSRs.

Some recommendations for conduction of field tests with similar objectives are:

- Firstly, understanding the actual mode of operation of the ADAS would be invaluable. Therefore, it would be beneficial to collaborate with vehicle manufacturers.
- It is recommended to collect lane marking quality and lane marking configuration data. This data would add much value by providing much more insights into the factors that affect the performance of the ADAS.
- Steering wheel data is also highly recommended to be collected for evaluating ADAS such as LKS and LDW. Indicators such as Steering Reversal Rate, Steering response time, and Number of steering reversals describe the vehicle driving behaviour much better.
- It is recommended to perform field tests with vehicles from different manufacturers, as done in this research, to account for market variability.

Some other practical recommendations for the Road Authority stemming from this research are:

- The road authority must maintain an up-to-date digital database of the infrastructure that it manages. The resolution of this database would be useful when it covers components such as type of lane markings, their configuration, pavement type, and roadside infrastructure. It is advised to connect these components to the respective hectometer for easy reference.
- Additionally, a database for maintenance-related information is important. This could, for instance, contain the quality of the lane markings and pavement quality in addition to other aspects of the road. This database needs to be updated regularly after periodic maintenance.
- There must be a collaboration among the road authorities to share knowledge and experience to ensure consistency in terms of road design standards, and also in terms of outlook towards ADAS enabled vehicles. Furthermore, a collaboration with the vehicle authority and also the vehicle manufacturers needs to be made to agree on the accepted performance standards for driving on the roads with mixed traffic.
- Road authority can increase the awareness of drivers that use these vehicles by informing them of the limitations of these vehicles, especially at a scenario-specific level (for example, informing users that their ADAS systems might not perform safely on curves or at crossings, so they have to take precaution to stay alert)

A new way of thinking is needed to adapt roads for automated driving systems. There is an important role for the road authorities to fully understand and take proactive actions to become ready for the deployment of automated vehicles on the road network. Simultaneously, there is also a significant role of the car manufacturers to ensure that their systems are properly tested, and the users are well informed of the limitations of these systems. Ideally, a close collaboration between road authorities and the car manufacturers is required to best ensure a safe driving experience.

1

Introduction

The rapid advent of automated vehicles has raised much interest in understanding the impacts of this technology on present-day transportation, its strengths and limitations. As of 2022, the new EU regulation makes it mandatory that all vehicles sold in the EU will have a set of automated safety systems to increase safety on roads (European Commission 2018). Whether these systems will increase safety is important to determine. The increasing appearance of (partially) self-driving cars on public roads is witnessing some scepticism due to accidents reported during the use of these vehicles. Until now, there have been five driver fatalities (Vlasic and Boudette 2016, Boudette 2016, Green 2018, Sutton 2019, Volz 2019) and one pedestrian fatality (Lubben 2018) involving self-driving vehicles. These have raised concerns among the public as well as authorities and policymakers. The industry (the car manufacturers) is conducting extensive testing for their systems to identify their limitations and improve their safety. Authorities are seeking to collaborate more with the industry partners, in addition to increasing regulations surrounding this technology. Original Equipment Manufacturers (OEMs) who conduct testing in the state of California in the United States are obligated to publish reports on disengagements, which mean the situations requiring the driver to take over control, indicating limited capabilities of the automated vehicle systems.

There have been several studies done based on these disengagement and accident reports (Lv et al. (2018), Dixit et al. (2016), Favarò et al. (2018)). With increasing driving miles, the trust of drivers on these automated vehicles increased, which is suggested by the increase in takeover time during disengagements. In addition to this, there have been studies on accident reports involving self-driving vehicles, especially in the USA (Favarò et al. (2017)). There was found to be a significant correlation with autonomous miles travelled with the number of accidents. These show that although these systems are yet to be proven safe, drivers tend to trust them. The California Department of Motor Vehicles has mandated that the disengagements as well as accidents involving automated vehicles be made available to the public. The major issue with these published reports is the lack of quality and quantity of data (Hawkins (2019)). This research experienced that detailed data from car manufacturers regarding the operation of their (semi-)automated vehicles are not openly available, presumably due to competitive reasons. It has thus become increasingly relevant, especially for road authorities, to take action and initiative towards understanding the effects of these systems and their implications on the existing road infrastructure. Their main interest is to understand what adaptations in the road infrastructure are needed to expect the safe operation of automated vehicles.

Conventional road infrastructure is designed taking into account human capabilities. Automated vehicles, including Advanced Driver Assistance Systems (ADAS), have different capabilities, limitations and behaviour compared to human drivers, thereby warranting a new perspective on road infrastructure design. Some studies predicted what the roads of the future could look like (Lamb et al. (2011), Washburn and Washburn (2018)). However, most of these studies look at full automation levels and total market penetration rates. These conditions are not expected anywhere in the immediate future. Presently, the most popular (semi-)automated vehicles are those equipped with ADAS such as Cruise Control, Adaptive Cruise Control (ACC), Cooperative Adaptive Cruise Control (CACC), LKS, LDW, Traffic Jam Assist, and Blindspot Assist. Therefore, the crucial question for road authorities is how to ensure that the existing road infrastructure can cater to the needs of human drivers who are assisted by these ADAS, mainly because these systems take (partial) control of the driving tasks. Naturally, the goal of road authorities is to ensure the safe performance of these vehicles among other human-driven (traditional) vehicles.

The focus of this research is to investigate the performance of current Lane Assistance Systems (Lane Keeping Systems (LKS) and Lane Departure Warning (LDW)) from the perspective of the road authority, the PNH. The Provincie Noord-Holland (PNH), being the road authority, is responsible for designing, constructing, and maintaining the provincial roads in the Province of North Holland. Understanding the limitations of existing automated vehicles and expecting these systems to be increasingly used on the provincial roads, the PNH would like to increase the safe Operational Design Domain (ODD) of these vehicles for LKS and LDW systems to increase traffic safety.

This research develops a methodology for the road authority, to conduct extensive risk analysis, resulting in specific requirements for expecting better performance of these systems. This research also demonstrates the operationalisation of these requirements. The scope of this research is limited to physical infrastructure only.

2

State of the art and Research Questions

2.1. Infrastructure for automated vehicles

One of the most widely debated aspects of automated driving is the implications for road infrastructure. Research and some official reports from knowledge bodies are concerned of what the roads of the future must look like, both from a general perspective (Lamb et al. 2011) and from the perspective of automated vehicles. Existing research on infrastructure requirements of automated driving can be classified broadly into Physical Infrastructure and Digital Infrastructure (Farah 2016, Farah et al. 2018).

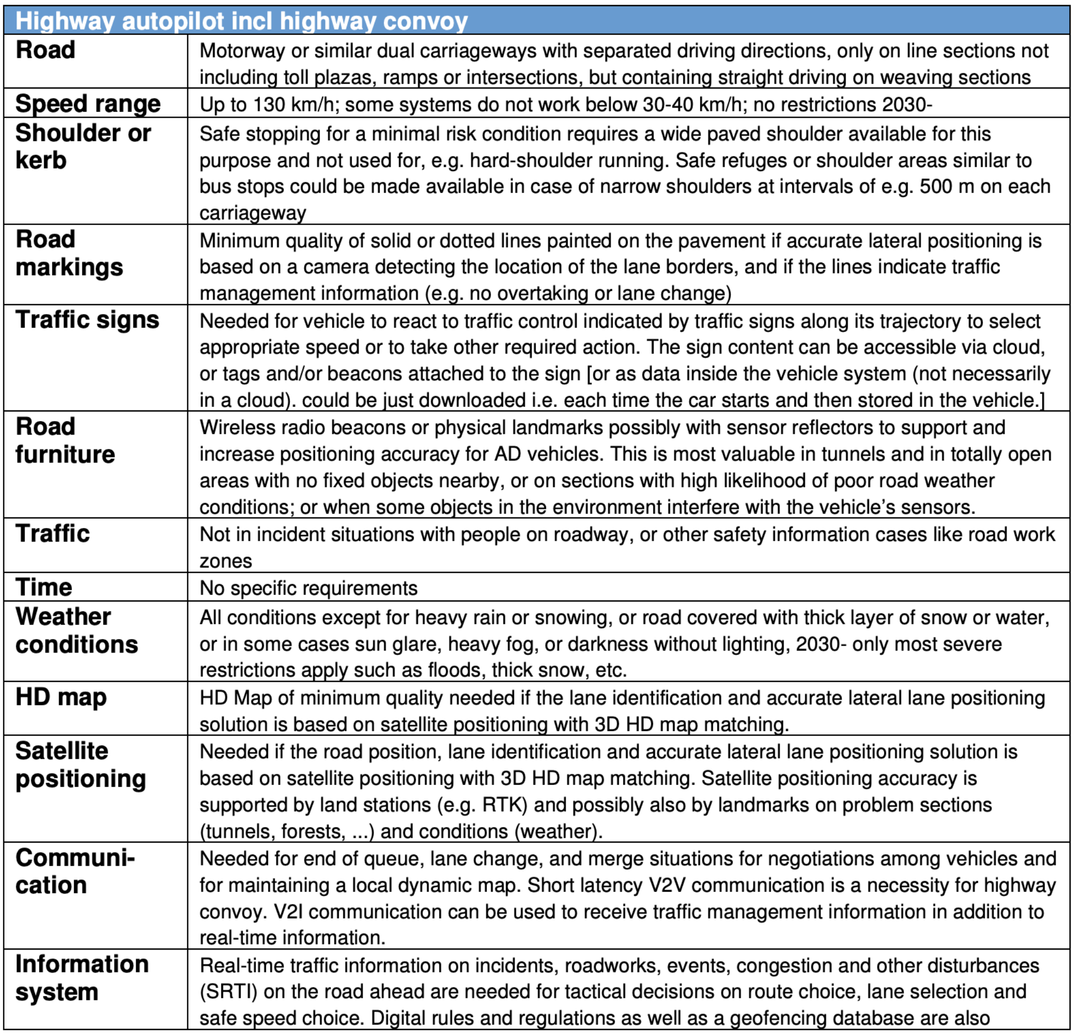
One of the essential requirements from the perspective of automated driving technology is consistency in infrastructure. It is increasingly becoming important during the current "transition phase" as these ADAS systems rely on the same existing road infrastructure primarily designed for human drivers. The functioning of the LKS and LDW systems depends on the lane markings. It is therefore essential that for systems such as these, the roads lane markings are visible and consistent. Catapult Transport Systems UK (2017) highlights the importance of having consistent road markings and signage by stating that poor quality or unconventional use of lane markings could confuse these systems, potentially also leading to accidents. It has also been a topic of criticism from industry stakeholders (Tesla, VOLVO North America) on the state of road infrastructure, particularly when they complained about the poor state of lane markings that caused their vehicles to perform poorly (Sage 2016). Inconsistency in lane markings results in systems such as Lane Keeping Systems or Lane Departure Warning systems to be confused and fail to identify the correct boundary of the lane, which has direct implications on traffic safety.

Huggins et al. (2017) goes on to extend the significance of lane markings by suggesting that they could be designed keeping in perspective the expected driving behaviour of the vehicles. For instance, this could mean differentiating and guiding the behaviour of vehicles with the use of single lines, double lines or hazard markings. So infrastructure, such as road markings, can not only function to provide a well-constrained direction of driving to these systems but also influence the driving behaviour itself to what is desirable by the infrastructure provider. In this light, the role of infrastructure thus becomes to not only to support automated driving but also to influence it desirably. Huggins et al. (2017) also speculates that the pavement must be consistent without cracks or drainage sealing marks that could confuse the system. Therefore, concerning road infrastructure, the road markings and the pavement itself are of primary importance, especially for ADAS focusing on lane-keeping or lane departure.

Chen et al. (2016) investigated the consequences to the long-term service performance of physical road infrastructure after the advent of the implementation of Automated Vehicles on a large scale. It found that with the use of Automated Vehicles, the decreased wheel wander and increased lane capacity could accelerate rutting, but the increase in traffic speed would negate this effect. It concluded that the influence depends much on the practical road and traffic conditions. These results were defined for Automated Vehicles in which the driver does not directly control the steering, acceleration, and braking.

Aigner et al. (2017) provided a prediction of the ODD for a Level-4 Highway autopilot including highway convoy. Table 2.1 shows the predicted ODD conditions for the defined Level-4 vehicle. For road markings, it recommends that there must be “Minimum quality of solid or dotted lines painted on the pavement if accurate lateral positioning is based on a camera detecting the location of the lane borders” thus highlighting the importance of visible lane markings. It also expects that the system is able to operate in all weather conditions except for severe conditions such as heavy rain or snow. All the recommendations are theoretical.

Table 2.1: ODD for Level-4 Highway autopilot (Aigner et al. 2017)



Highway autopilot incl highway convoy	
Road	Motorway or similar dual carriageways with separated driving directions, only on line sections not including toll plazas, ramps or intersections, but containing straight driving on weaving sections
Speed range	Up to 130 km/h; some systems do not work below 30-40 km/h; no restrictions 2030-
Shoulder or kerb	Safe stopping for a minimal risk condition requires a wide paved shoulder available for this purpose and not used for, e.g. hard-shoulder running. Safe refuges or shoulder areas similar to bus stops could be made available in case of narrow shoulders at intervals of e.g. 500 m on each carriageway
Road markings	Minimum quality of solid or dotted lines painted on the pavement if accurate lateral positioning is based on a camera detecting the location of the lane borders, and if the lines indicate traffic management information (e.g. no overtaking or lane change)
Traffic signs	Needed for vehicle to react to traffic control indicated by traffic signs along its trajectory to select appropriate speed or to take other required action. The sign content can be accessible via cloud, or tags and/or beacons attached to the sign [or as data inside the vehicle system (not necessarily in a cloud). could be just downloaded i.e. each time the car starts and then stored in the vehicle.]
Road furniture	Wireless radio beacons or physical landmarks possibly with sensor reflectors to support and increase positioning accuracy for AD vehicles. This is most valuable in tunnels and in totally open areas with no fixed objects nearby, or on sections with high likelihood of poor road weather conditions; or when some objects in the environment interfere with the vehicle’s sensors.
Traffic	Not in incident situations with people on roadway, or other safety information cases like road work zones
Time	No specific requirements
Weather conditions	All conditions except for heavy rain or snowing, or road covered with thick layer of snow or water, or in some cases sun glare, heavy fog, or darkness without lighting, 2030- only most severe restrictions apply such as floods, thick snow, etc.
HD map	HD Map of minimum quality needed if the lane identification and accurate lateral lane positioning solution is based on satellite positioning with 3D HD map matching.
Satellite positioning	Needed if the road position, lane identification and accurate lateral lane positioning solution is based on satellite positioning with 3D HD map matching. Satellite positioning accuracy is supported by land stations (e.g. RTK) and possibly also by landmarks on problem sections (tunnels, forests, ...) and conditions (weather).
Communi-cation	Needed for end of queue, lane change, and merge situations for negotiations among vehicles and for maintaining a local dynamic map. Short latency V2V communication is a necessity for highway convoy. V2I communication can be used to receive traffic management information in addition to real-time information.
Information system	Real-time traffic information on incidents, roadworks, events, congestion and other disturbances (SRTI) on the road ahead are needed for tactical decisions on route choice, lane selection and safe speed choice. Digital rules and regulations as well as a geofencing database are also

Van Driel et al. (2004) studied the effect of edgelines and centre lines on driving behaviour for human driving. It also studied the effect that the driving environment has on driving behaviour. It found that having an edgeline when there is no centre line causes an increase in driving speed. Replacing centrelines with edgelines caused a decrease in driving speed. It also found that roadside infrastructure, such as shoulder width affects driving behaviour. For instance, wider shoulder widths caused the driver to drive closer to the edge, and narrow shoulder widths caused the driver to drive closer to the centre. Thus, the road and roadside infrastructure certainly have an effect on human driving behaviour. It could be useful to compare with the driving behaviour of automated vehicles.

Some studies already investigated which infrastructure changes are possible with the full market penetration of automated vehicles. The most commonly expected changes are that the width of the lanes could be narrower as automated vehicles are capable of maintaining a constant position within a lane, as speculated in some studies (Farah et al. 2018, Morsink et al. 2016, Huggins et al. 2017, Johnson et al. 2016). However, until complete penetration, as well as complete automation, which could take quite a long time, these systems would drive on existing roads that mainly cater to human drivers' drivers' needs. Therefore, the focus of the road authorities in the immediate and mid-term future is to see how to design the road infrastructure for mixed traffic composed of human-driven and partially automated vehicles. The scope of this research is, therefore, the current and foreseeable future road infrastructure where ADAS systems, such as LKS and LDW, are being used. Very little research connects the performance and capabilities of these systems and the expectations of their developers with the prevailing road infrastructure conditions and the expectations of the road authorities.

Morsink et al. 2016 provides an exploration of the relationship between automated vehicles and road design. Rijkswaterstaat (Dutch Ministry of Infrastructure and Water Management), and CROW (Centre for Regulation and Research in Ground-, Water- and Road-Construction and Traffic Technology) received this report. Some interesting predictions were that the radius of curves could become smaller with automated vehicles as they are expected to perform better and drive on curves at higher speeds as well. The report also proposed that on multi-lane curves, manually driven vehicles could be allowed to drive on the outer lanes (higher radius), while automated vehicles would be allowed on the inner lanes (lower radius). Other propositions were that width of lanes could be reduced (expecting more stable steering), improving quality and uniformity of lane markings, reduction in intensities of lights at intersections.

Nitsche et al. (2014) conducted a study on the requirements of road infrastructure for automated driving based on literature review and an online questionnaire filled by experts and stakeholders. The results were qualitative and highlighted the influencing factors for automated driving. Specifically, for Lane Assistance Systems, the influencing factors from the study are shown in Figure 2.1. These factors are complex urban road environments, quality of lane markings, temporary road work zones, poor visibility due to bad weather, and irregular or damaged road edges or kerbs. Other aspects of the road infrastructure, such as low curve radii, slippery road surface, and poor visibility, were determined to be of medium importance.

The most notable attempts to operationalise the infrastructure requirements are in the aspect of lane marking quality. For instance, ERF presents the effect of reduction in quality of lane markings on their readability. Although this focuses on human drivers, it also extends to propose a "good lane marking" that would ensure they are readable for human drivers as well as automated systems such as LKS and LDW. Reflectivity of the lane marking has been the most defined aspect of the quality of lane markings (ERF, EuroRAP 2013, Davies 2016). Such a "good lane marking" is defined as that which is visible to human drivers as well as automated vehicles irrespective of lighting conditions, weather conditions, and age of the driver.

ODD becomes relevant for a larger perspective of infrastructure requirements for automated vehicles. ODD is almost inseparable from the different transition levels of automated driving. Given the high importance of defining the ODD for automated vehicles, the vague nature of its description, and also its very definition is surprising. According to the Society of Automotive Engineers (2018), ODD refers to the operating conditions under which a given automated driving system is designed to function. These may include environmental, geographical, or other restrictions. For example, an ACC system could be designed to operate at specific levels of speed (high, medium, or low) (Society of Automotive Engineers 2018). The ODD of a (partially) automated vehicle system generally consists of the physical aspects of the driving environment that must meet a certain condition or level of performance for the system to

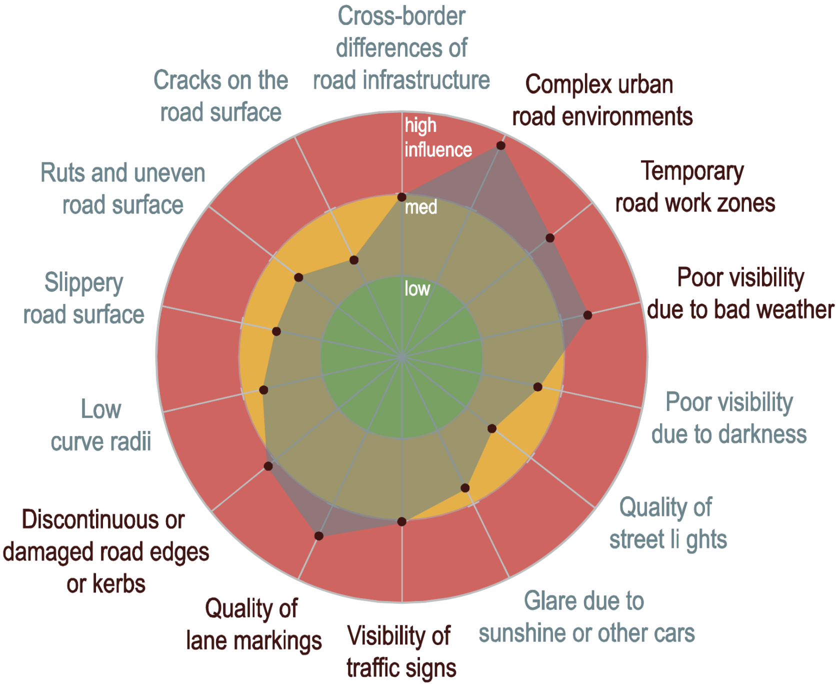


Figure 2.1: Factors influencing lane assistance systems (Nitsche et al. 2014)

operate safely and well. The OEMs of these systems usually set these requirements themselves. As an example, Tesla provides a list of conditions that could negatively influence the performance of its Lane Assist function of the Model S (Tesla 2018). These are summarised in Table 2.2.

Table 2.2: Operational Design Domain requirements of Tesla Model S

Conditions negatively affecting the performance of Lane Assist in Tesla Model S (Tesla 2018)
- Poor visibility due to rain, fog, snow
- May not detect the edge of the road, especially if there is no curb
- Excessively Worn out Lane markings, or old markings still visible, adjusted road markings due to road works, or disturbances with, for example, lanes branching off, crossing over, or merging
- Bright light facing the camera(s) (from sunlight)
- Narrow or winding roads
- Objects or Strong shadows cast on lane markings due to landscape objects
- Driving on sharp corners or curves at high speeds
- Vehicle travelling below 30 mph or above 90 mph

As is evident, the ODD limitations or requirements that OEMs specify are often vague and incomplete. There is a missing link in the definitions of these ODDs in the form of the expected performance of the automated driving systems they refer. Generally, those conditions under which the automated driving system is expected to “function” are termed as ODDs. There is no clear indication of the precise definition of “function”, including the definition provided by the SAE mentioned before. “Functionality” can be interpreted as “being able to operate”, in the sense that the automated driving system would be able to “be active”, with no indication of the level of performance (including safety) of the resulting functionality. This is an incomplete picture of providing the ODD for an automated driving system.

Moreover, different OEMs provide different requirements and limitations, which adds to the difficulty of road authorities to provide road infrastructure for these systems. Furthermore, the methodology behind defining these stated ODD limitations are also not explicitly provided by the OEMs, presumably due to competitive reasons. They only reveal that the vehicle tests are in closed test courses or test drives on public roads, where experienced drivers drive them (Waymo, General Motors 2018). Therefore, this research regards the ODD for a ADAS system as a driving environment performance indicator. Given a certain ADAS system, the driving environment could be within the ODD or outside the ODD. If outside, the changes required to bring it inside the ODD of these systems is needed. Road authorities would prioritise this process. After this, the specific individual components of the road infrastructure can be considered to modify for better performance of the systems. Chapter 3 (Methodology) discusses this.

Overall, there is a consensus in the literature regarding the qualitative road infrastructure requirements for automated driving. The shortcoming of these studies seems to be that there is a lack of defined quality standards based on empirical evidence. They either provide only a qualitative indication of the requirements for assumed levels of automation, and assumed the performance of automated vehicles, or, in the case of lane markings, they provide a quantitative standard for it but not reflecting on the consequent performance of automated vehicles. Therefore, this research aims to test and validate these speculations quantitatively, and also define the precise nature of the relationship between the automated vehicle system's performance and the road infrastructure, during the transition period of automation.

2.2. Performance Evaluation of Lane Assistance Systems

To identify the infrastructure changes that would be needed to cater to these systems, it is logical to evaluate the performance of these systems in the current infrastructure conditions. The first step in system performance evaluation is to identify and define the performance indicators that are relevant and useful. In the ensuing paragraphs, several studies are discussed that aim to or involve measuring the performance of the lane-keeping task. Most of these studies, however, aim to measure the lane-keeping performance of human drivers. At the same time, it is essential to evaluate the detection of the lanes by the system. Concerning only the lane-keeping performance, this research assumes that the lane-keeping performance indicators of human driving (discussed below) are also applicable for LKS system driving.

Das et al. (2019) looked at the effect of fog conditions on the lane-keeping performance of manual driving, using “Lane Offset” as an indicator. Lane Offset is the deviation from the centre of the lane. While Das et al. (2019) considered the Lane Offset to have a positive sign when deviating to the right, and negative when deviating to the left, other studies such as Wang and Zhao (2017) follow the opposite sign convention, that is, a negative sign when deviating to the right, and a positive sign when deviating to the left. Lane Offset, also sometimes referred to as Lateral Offset, and has been applied in other studies involving lane-keeping controller design as an indicator to evaluate the lane-keeping performance of the controller Chu et al. (2018). The Lateral Offset is given a better definition in the form of MLP, which is the average Lateral Offset over a stretch of road. This has been used in several studies as an important indicator of performance of driving (Montella et al. (2011), Van Driel et al. (2004), Verster and Roth (2011)).

Another indicator which is commonly used is the SDLP, which was also used for manual driving in other studies (Green et al. (2004), Li et al. (2018), Peng et al. (2013), Verster and Roth (2011), Van Driel et al. (2004)). By highlighting the contrary views existing on the validity of this SDLP indicator, Li et al. (2018) had some interesting observations concerning its use. A LKS that exhibits low SDLP does not necessarily mean good performance. The system may show low SDLP only because it follows a certain distracted driving behaviour. It could be attributed to the road infrastructure, which often contains several components that could distract the detection, for example detecting pavement repair patches, shadows, or edge of the road instead of the lane marking. It could also be that the system detects only the left or right lane marking, and thereby drives closer to it, reducing the SDLP, but not contributing to safe driving. Such viewpoints are held by some other studies too (Mehler et al. (2012), Reimer (2010)). On the other hand, other studies view low SDLP as safe driving behaviour Engström et al. (2005). Therefore, it may not be that SDLP directly indicates the safe driving behaviour of LKS. However, it certainly can be regarded as a performance measure of the system, and in combination with the MLP, regarded as a measure of safety.

Another indicator, the Time to Lane Crossing (TLC) was used by Li et al. (2018) to evaluate the driving performance. TLC was, again, used for human drivers, which could be in this case used for LKS as well. TLC was defined by Glaser et al. (2005) as the time required for the vehicle to cross the road edge, given its trajectory. Glaser et al. (2005) also provided a method to calculate it, primarily through making assumptions when not having complete road information. Tarko (2012) also proposes using the Time to Lane Departure (TLD), which can be measured at every instant assuming a straight trajectory, or with constant lateral speed.

As is evident from the above paragraphs, there have been several studies done that involve measuring the performance of Lane Assistance Systems with their definitions of variables. Hence, it becomes necessary to decide on standardised definitions for these variables and parameters to ensure the possibility of a sensible comparison between studies. The report from the Society of Automotive Engineers (2015) shares this objective. This report includes widely used standard definitions of performance indicators of lateral control. In addition to the indicators discussed previously, another indicator, this report also introduces the Number of Lane Departures. The report not only provides the various definitions for the indicators, but it also describes the possible methods to measure them, along with the standard values of the indicators. Chapter 3 discusses the indicators, their definitions and the methods used to calculate them.

This research classifies the indicators discussed above as Surrogate Safety Measures (SSMs). These measures intend to provide an ex-ante evaluation of the (safety) performance of the systems they concern. They are proactive and also efficient measures in terms of costs with measuring the safety of road traffic. Risk Field is an indicator that is increasingly being used(Wang et al. (2015), Wang et al. (2016), Bhusari (2018)). The concept that safety, or rather, “unsafety” can be regarded as a combination of risk and consequence, forms the basis of this indicator. Risk Field aims to model the objective risk on the road that combines the “potential risk” from static objects (such as lane markings and curb edge), and “kinetic risk” from moving objects (other vehicles on the road). Risk Field can be used to measure the risk on the road and to evaluate the performance of the system concerning this risk measurement.

Other works that study the performance of Lane Assistance Systems use indicators that focus on the steering wheel (Östlund et al. (2005), Johansson et al. (2004)). The popularly used indicators are discussed in Johansson et al. (2004). These are Standard Deviation of steering wheel angle, High-frequency component (HFC) of steering wheel angle, Steering wheel reversal rate (SRR), Steering wheel action rate (SAR), and Steering entropy. An even more extensive list of indicators with respect to the steering wheel is provided by Wierwille et al. (1996). An overview of the indicators is presented in Table 2.3.

The limitations of the indicators presented need to be understood to use them to evaluate the performance of such systems. These limitations are corresponding to their application. It will be discussed later under Methodology (Chapter 3).

Table 2.3: Performance indicators and the studies where they have been discussed.

Performance Indicator	Discussed in
Lateral Offset, or MLP	Das et al. (2019), Wang and Zhao (2017), Chu et al. (2018), Montella et al. (2011), Van Driel et al. (2004), Verster and Roth (2011), Society of Automotive Engineers (2015), Blaschke et al. (2009)
Standard Deviation of MLP	Green et al. (2004), Li et al. (2018), Peng et al. (2013), Verster and Roth (2011), Van Driel et al. (2004), Mehler et al. (2012), Reimer (2010), Engström et al. (2005), Society of Automotive Engineers (2015)
TLC, TLD	Li et al. (2018), Glaser et al. (2005), Tarko (2012), Society of Automotive Engineers (2015)
Risk Field	Wang et al. (2015), Wang et al. (2016), Bhusari (2018)
Number of Lane Departures	Society of Automotive Engineers (2015)
(Standard Deviation of) Steering wheel angle	Johansson et al. (2004), Östlund et al. (2005)
High frequency component (HFC) of steering wheel angle	Johansson et al. (2004)
Steering wheel reversal rate (SRR)	Markkula and Engström (2006), Kountouriotis et al. (2016), Johansson et al. (2004), Society of Automotive Engineers (2015)
Steering wheel action rate (SAR)	Johansson et al. (2004)
Steering entropy	Johansson et al. (2004)

2.3. Systems Theory Perspective

After the performance evaluation of Lane Assistance systems, it is the objective of this research to identify the factors that affect the performance of these systems, such as weather conditions, road and road-side infrastructure, through an examination of the correlations between the various factors of the driving environment and the performance of the systems.

Hughes et al. (2015) provides a comprehensive overview of all the existing safety models across multiple disciplines, from transport to education and construction, leading to a total of 121 different models. It states that Systems Theory was the most influential concept across these domains and models. A System is said to be consisting of interrelated components, with a common objective. Larsson et al. (2010) also emphasises the relevance of Systems Theory for road safety. It compares the traditionally accepted "Road-user approach" and the contemporary "Vision Zero" (Tingvall and Haworth (1999)) approach, by highlighting that accidents occur as a result of unforeseeable interaction of different components of the road system.

According to Salmon et al. (2012), there are currently three popular accident causation models: Rasmussen's framework of risk management, Reason's Reason's Swiss Cheese model, and Leveson's Leveson's STAMP model. Rasmussen's risk management framework Rasmussen (1977) considers safety as an emergent property resulting from the interactions between different hierarchical layers of an organisation, where the upper levels impose decisions on the lower levels, which in turn provide feedback to the higher levels, leading to a sort of vertical integration. Rasmussen (1977) also introduced the Accimap (depicted in Figure 2.2), a generic graphical representation of the failures, and the decisions and actions leading up to them. The Swiss Cheese model (Figure 2.3) by Reason (Reason (1990)) views accidents

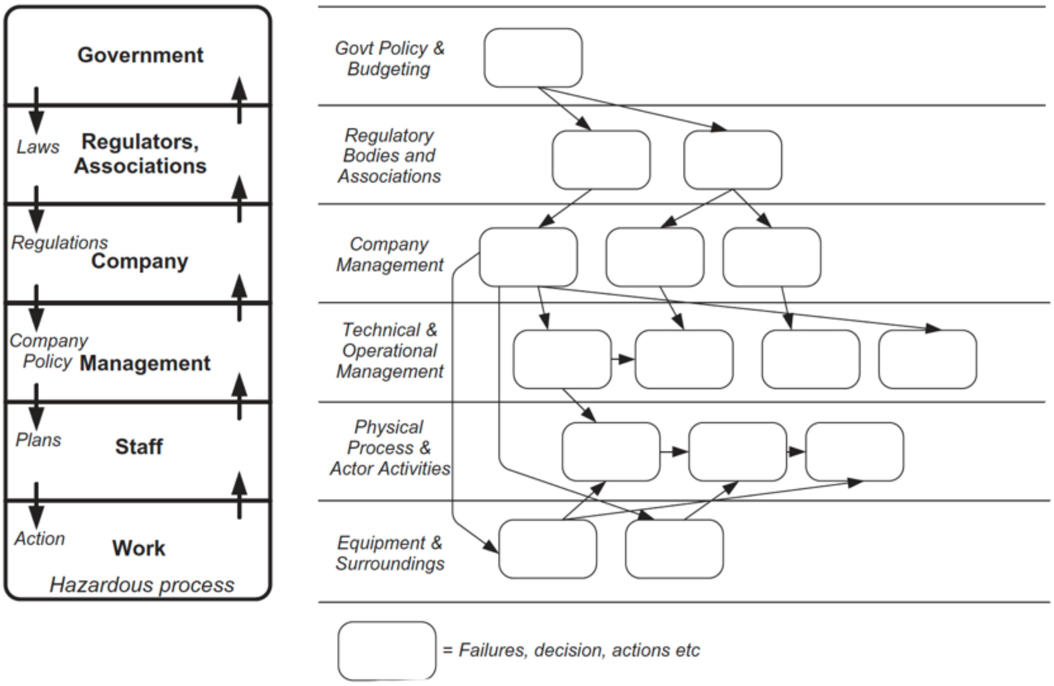


Figure 2.2: Rasmussen's risk framework (Salmon et al. 2012)

as events that are “waiting to happen”. Various layers of barriers that offer a sequence of measures to avoid the situation from manifesting into an accident “protect” these accidents. These barriers have “holes” that indicate failures of those respective layers. This model encourages investigators to identify the latent failures, and the “active” causes of the failures, which is very useful. Another model, which was inspired by, and is an extension of the Swiss Cheese model, is the Human Factors Analysis and Classification System (HFACS) that was developed by Wiegmann and Shappell (2003) for aviation accident analysis. The HFACS adds a taxonomical methodology to the Swiss Cheese model, thereby providing failure categories for the different levels of failure in the Swiss Cheese model. The third model, STAMP (Leveson (2004)), views systems as hierarchical control processes with the higher-level components establishing constraints on the lower-level components. The lower-level components, in turn, give feedback to the higher-level components on the constraints imposed and their appropriateness (Figure 2.4). STAMP analysis describes the system's control structure and identifies the failures leading to the accident by providing a taxonomy of failure modes.

Salmon et al. (2012) presented a critical comparison of the three models. The Rasmussen model is very comprehensive in the sense that it takes into consideration every level of the system up to strategic levels such as the government. Given sufficient data, it is possible to characterise failures in terms of the processes and relationships within levels and between different levels. However, this model does not explore the causes of bad decisions due to its inability to include cognitive states of actors such as situational awareness. Also, the analysis tends to be subjective as no failure taxonomies are existing to ensure a systematic analysis, which makes it suitable only for single case studies as opposed to analyses of multiple cases. The HFACS, providing a taxonomical approach, allows for multiple case study analyses to be done and compared and results analysed in an aggregated way. However, this strength becomes a limitation, especially when used in applications outside aviation as most of the failure modes are aviation specific. Salmon et al. (2010) attempted to use the HFACS to analyse road accident data and observed that the data currently gathered from accidents do not take into consideration the possibility of systemic effects and also that there are components of the HFACS that are not completely applicable for road transport. Moreover, HFACS cannot classify some data with its taxonomies. Concerning STAMP, data on the control structure

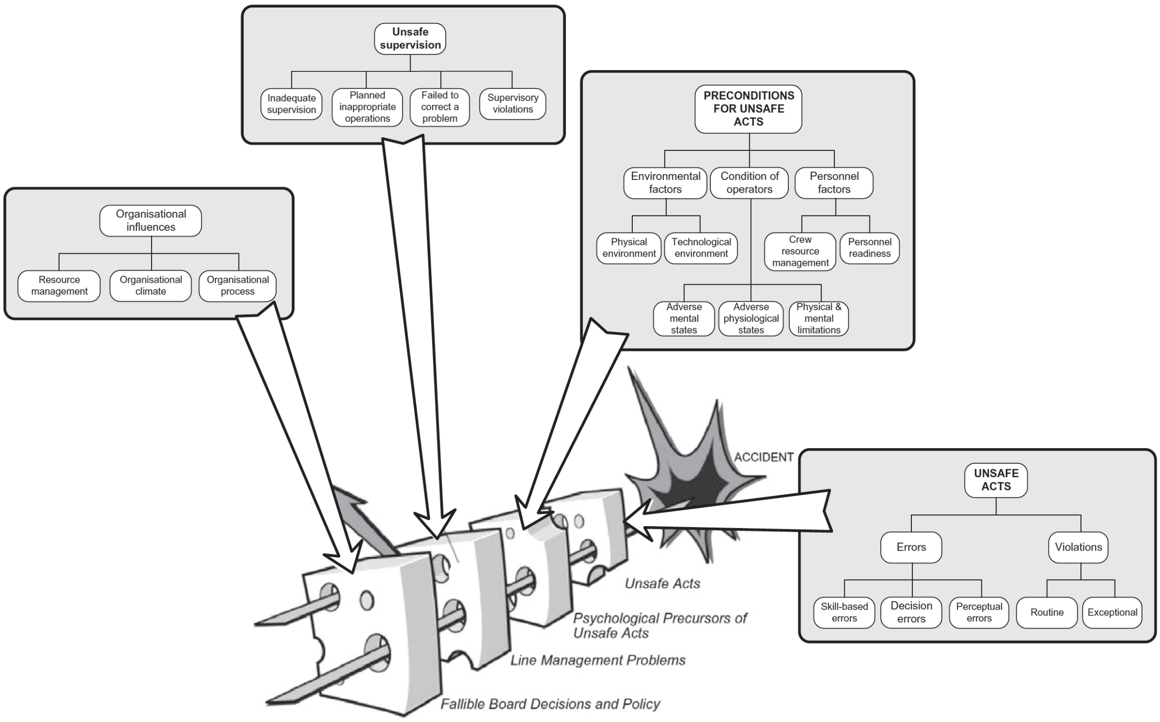


Fig. 2. HFACS taxonomies overlaid on Reason's Swiss cheese model.

Figure 2.3: Reason's Swiss Cheese Model with taxonomies of HFACS (Salmon et al. 2012)

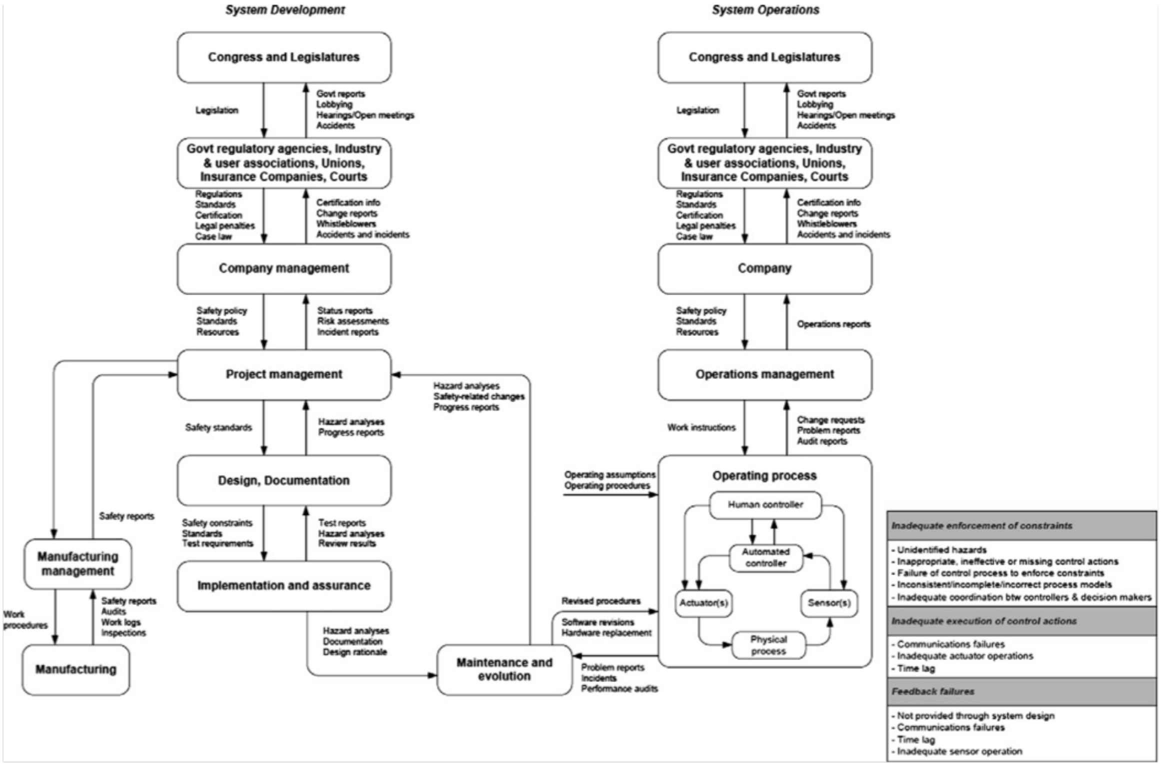


Figure 2.4: STAMP's failure taxonomy and generic system control structure (Salmon et al. 2012)

and the constraints is a major requirement to get a complete understanding of the system control loops. STAMP is not suitable for organisational and complex human decision-making failures due to its difficulty in differentiating taxonomy. This limitation makes the STAMP more suitable to be used for technical failures.

The STAMP model is especially interesting because of its suitability for complex systems. As opposed to chain models such as Swiss Cheese model where accidents are said to occur because of a sequence of failures of components, STAMP takes into consideration the relationships, or constraints that exist between different components of the system, and identify the constraints failures (Leveson (2004)). STAMP is expected to capture complex socio-technical systems by identifying and defining the various components, their hierarchies, and constraints, all viewed together as a control system. The advantage of using the STAMP model is that it has been developed especially for software systems and automated systems. STAMP is a conceptual model, therefore is not directly applicable to solve real-world problems. Therefore, a newly designed tool based on STAMP, called STPA, can be used to analyse real-world systems. This method has been described by Alvarez Gomez (2017) with an example of an ACC system. The steps involved in a STPA are defining accidents, hazards, safety constraints, identifying unsafe control actions, defining safety requirements and constraints, and finally, generating refined safety requirements. Chapter 3 discusses this in detail.

STAMP has been applied already on real-world problems. Laracy and Leveson (2007) applied the STAMP model in the means of STPA to analyse the risks emerging in critical infrastructure systems such as air transportation networks. Nelson (2008) analysed the LEX Comair 5191 flight accident using the STAMP model. It observed that STAMP could capture the complexities of systems and be analytically consistent with reality. STPA was also used to conduct a safety assessment of the US Ballistic Missile Defense System (Pereira et al. (2006)). This application posed some demanding requirements from the methodology such as to consider hazards and causes due to complex system interactions, to guide the analysis conduction, addressing the entire system comprehensively including the software, hardware, operators, procedures, and to focus on the aspects with the greatest impact on safety. The STPA was found to be successful in meeting these requirements. Some other applications where the STAMP and STPA have been successful are in the analysis of a railway accident in China (Ouyang et al. 2010) and the design of a Crew Return Vehicle in the design phase (Nakao et al. 2011).

Therefore, the STAMP model is successful in analysing complex systems and providing insights into understanding the risks involved in these systems due to the interacting relationships between the systems' various components. The STPA is a Hazard Analysis technique. It looks at the various components and the failure modes in a systematic way. However, it does not operationalise the failures and the requirements by itself. In this research, the operationalisation of the relationships between components, the failure modes and safety requirements is crucial. Incorporating this in the STPA will be discussed under Methodology (Chapter 3).

2.4. Research Gap and Objective

Although there has been a lot of research and studies done concerning ADAS and infrastructure for automated driving, there still exists a significant disconnect between the two. Though there is a lot of anticipation and prediction about the future road infrastructure, hardly any of them base it on concrete evidence. This is mainly because the focus is primarily on the “distant future”, where the vehicles would be fully automated and have complete market penetration. This makes it practically impossible to make any predictions with a high degree of certainty. However, there have been some efforts to understand the infrastructure requirements for some specific functions of automated driving such as Lane Assistance Systems. These do emphasise the importance of defining performance levels for enabling the proper functioning of these ADAS systems. While this is useful, there is still missing links between infrastructure components and their effect on ADAS safe performance. Existing research does not concretely define this relation.

There is also a significant gap in using Systems Theory in this context. Systems Theory has been used to describe the functioning of the vehicle controllers. However, there is a need to use this concept to explain the relationships of a System that comprises of different types of components or sub-systems such as road infrastructure, weather conditions, and the ADAS system, primarily to estimate the relationships concretely and objectively. There is also a need for standard guidelines or performance benchmarks that infrastructure must meet to expect a certain level of performance from ADAS systems.

In order to address these aspects, this research focuses on identifying the factors that affect the performance of Lane Assistance Systems (consisting of LKS and LDW systems in this research). This process consists of evaluating the performance of the Lane Assistance Systems under different conditions of the driving environment and then identifying the factors of this driving environment that affect their performance.

2.5. Research Question

The main research question of this research is:

What changes need to be made to the road infrastructure to increase the performance of Level 1 Automated Vehicles with Lane Assistance Systems?

This research formulates the following sub-research questions to answer the main research question:

1. What methods can be used to explain the impact of components of the driving environment on the performance of the Lane Assistance Systems?
2. What performance indicators can be used to assess the performance of Lane Assistance Systems?
3. In what way do the components of the driving environment impact the performance of Lane Assistance Systems?
4. What performance levels or levels of service must the driving environment offer to expect better performance of Lane Keeping Systems?

Sub research question 1 focuses on the available methods that would be able to help in understanding the effect of the components of the driving environment on the performance of the LKS and LDW systems, choosing the most useful method, and determining its method of application to this research. As discussed, this research selects the STAMP model as the theoretical foundation for the research. STPA is the analysis method that is based on STAMP, which will be used to study the impact of the driving environment components on the Lane Assistance Systems performance.

Sub research question 2 looks at the LKS and LDW systems themselves. The objective is to identify, define and measure the performance indicators for these systems to evaluate their performance in different driving environments. This involves selecting the relevant indicators, their measurement, and then evaluating the performance with respect to benchmarks.

Sub research question 3 aims to link the driving environment to the performance of the LKS and LDW systems. This research uses regression modelling to estimate the driving environment's effect on the performance of the system. This would result in estimating relationships between the driving environment components and the performance of the LKS and LDW systems.

Sub research question 4 extends the existing relationships between the components of the driving environment and the performance of the Lane Assistance Systems to a predictive context. The characterisation of these components and their effect on the performance of the

Lane Assistance Systems will be used to develop performance levels or standards that the driving environment must adhere to in order to expect a certain level of performance from these Lane Assistance Systems.

The road authority can use these results to get a deep insight into road infrastructure changes needed to improve the performance of the Lane Assistance Systems. Also, on the other hand, the road authority will be able to understand the impact that changes to the road infrastructure will have on the performance of the Lane Assistance Systems, thus answering the main research question.

3

Methodology

3.1. Methodology Structure

Following the research questions of this study, this chapter structures the methodology in the following way. First, formulating the STAMP model makes the foundation for designing the methodology as described earlier. This process involves the theoretic description of the System under consideration, and its extensive risk analysis using the STPA, which results in specific safety requirements. Then, this chapter describes the operationalisation of these requirements through a field test. Here, the methods for performance measurement of the lane assistance systems are defined, followed by the estimation of the effects of the driving environment on the performance of these systems. Finally, this chapter proposes the strategy for developing Infrastructure Levels of Service.

3.2. The STAMP model

The STAMP model is useful to gain an understanding of a System that contains several components and sub-components of similar or different nature interacting with each other in several ways. In the context of this research, the lane assistance systems “interact” with components of the road infrastructure and the environment when they drive. Note: At this point, it is good to clarify the possible confusion when referring to the “System” and lane assistance “systems”. Henceforth, “System” will refer to the set of the earlier said components (road infrastructure, environment, and lane assistance systems). In contrast, this report refers to lane assistance systems as “lane assistance systems” or “vehicle systems” or just “systems”.

The STPA, based on the STAMP model, will be used as the basis of the framework for formulating the methodology. The STPA provides systematic and sequential steps for conducting an extensive risk analysis of a System. Essentially, the following summarises these steps:

1. Defining the purpose of the analysis
2. Modelling the Control Structure
3. Identifying the Unsafe Control Actions
4. Identifying Loss Scenarios

The first step is to define the scope and objectives of the analysis. This entails defining the System that is to be studied, enumerating its hazardous states and losses exhaustively. Some terms need to be definitions to perform this step:

System - This is the set of components that the analysis considers. The System typically contains the components that can be controlled or modified in any particular way. Along with defining the System, the state of the System also can be defined, which indicates the condition or status of the System at any instant.
Losses - These are the states of the System or the events that must be avoided by the System. These are typically the consequences of the System becoming unsafe. These losses are what the analysis and the methodology aim to avoid. The Losses can also be ranked according to the order of importance.
Hazards - These are the states of the System, which under extreme (or the worst) environmental conditions, will lead to one or more Losses.
Constraints - These are the conditions that must be satisfied in order to prevent Hazardous conditions from occurring, and therefore, also the Losses.

The next step is the formulation of the Control Structure. In the STAMP model, a System is assumed to be a control problem, with the higher-level controllers enforcing constraints on the lower level controllers and components to achieve a particular goal. Therefore, this step involves constructing the entire System, its controllers, components, sub-components, and how they interact with each other. The Control Structure typically includes the following:

Controllers - These are the decision making components that are key to executing changes to the state of the System.
Control Actions - These are the “outputs” from the controllers containing the command that the relevant part of the System executes. A controller can have more than one Control Action
Feedback - The information generally communicated back to the controllers describing the state of the System.
Process Models - These are the conceptual constructs of the assumptions made by the controller about the controller process. In other words, these are the beliefs that the controller has about the functioning of the process it is controlling.

After drawing the Control Structure, the next step identifies the Control Actions and the corresponding controllers. For each of the identified Control Action, the procedure looks at the various possible Unsafe Control Actions. An **Unsafe Control Action** is a Control Action, that, under the worst or extreme environmental conditions, will lead to one or more Hazard. The method proposes four scenarios for each of the identified Control Actions to arrive at the Unsafe Control Actions:

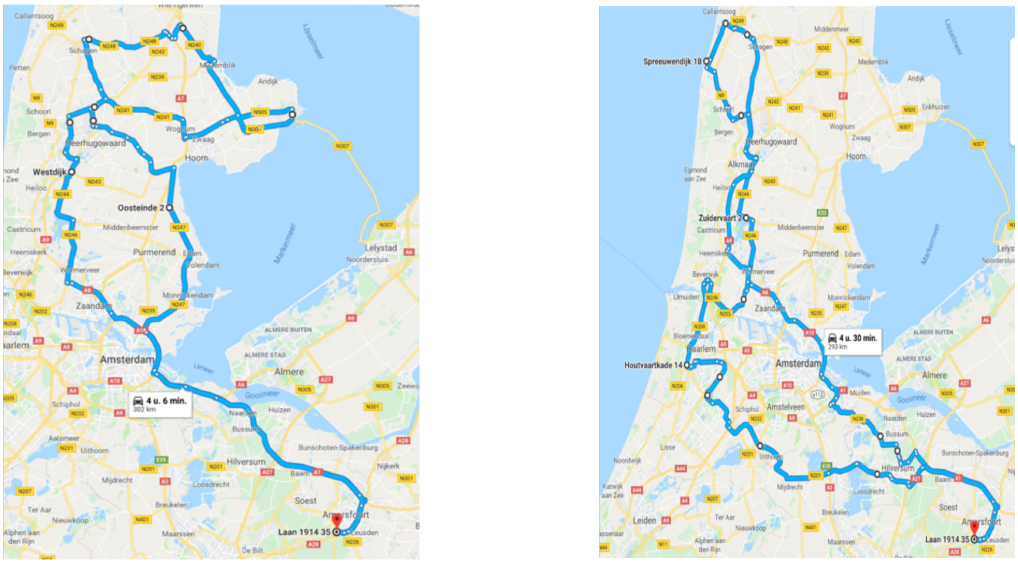
1. **Not providing the Control Action causes Hazard** -As is self-explanatory, this happens when not providing a Control Action causes a Hazard.
2. **Providing Control Action causes Hazard** - This is when providing the Control Action still causes a Hazard, for instance, due to the Control Action provided not being as required.
3. **Control Action applied too early/too late** - This is when the Control Action has been applied before it was needed or applied later than when it was needed
4. **Control Action stopped too soon/ applied too long** - This is for duration based control mechanisms, when the Control Action is being applied, but is stopped sooner than what was needed, or continued being applied longer then what was needed.

Finally, for each of these identified Unsafe Control Actions, the various possible causes leading to them are explored systematically. These result in the formulation of the safety requirements for each specific causes/loss scenario. Thus, this is how the methodology applies the STPA on the System. Chapter 4 discusses the application and the results. The demonstration of the use of this methodology based on STPA, is done through a pilot test that is discussed below.

3.3. Field test set-up

After the conceptual design of the methodology, the specific safety requirements are obtained, which are theoretical. To operationalise these requirements, a field test was conducted on the provincial roads of North Holland, Netherlands. Provincial roads offer a level of service only second to the National Motorways. Two vehicles were used in this study: The Volkswagen e-Golf and the Toyota Auris, selected based on their popular usage in the Netherlands. The Golf has a Lane-Keeping System, whereas the Auris has a Lane Departure Warning System. These two vehicles are used to evaluate the performance of their Lane Assistance Systems on different road infrastructure conditions.

For this purpose, a test route of about 600 kilometres in length was planned. The test route was divided into two routes, to be covered during two different sessions for practical feasibility. Figure 3.1 depicts the two routes. The intention was to cover as many different types of road environments as possible. The test sessions had an equal number of day and night sessions in order to account for the time of day differences. The test drives were done in March 2019 (on 1 Mar, 7 Mar, 8 Mar, 12 Mar, 13 Mar, 20 Mar, and 22 Mar). Day test drives started around 10.00 am. Night test drives usually started between 6.30 pm and 7.00 pm when it was dark. The test sessions were scheduled to cover different weather conditions such as clear weather, cloudy, and rainy. Table 3.1 indicates the different types of infrastructure covered in the test. The route starts and ends in Amersfoort, the head office of Royal HaskoningDHV. The routes also have two stop points, which serve to charge the Golf, which is electric, and also as a break for the drivers and co-drivers.



(a) Route 1

(b) Route 2

Figure 3.1: The 2 routes driven in different sessions

During the test, each vehicle had a driver and a co-driver. The task of the driver in the Golf was to drive the vehicle with the LKS activated, while manually controlling the longitudinal driving task of acceleration and braking. The driver was allowed to take manual control of the steering when the driver felt the need to. The task of the driver in the Auris was to drive the vehicle with the LDW activated. This involved the driver to manually control both the longitudinal and lateral driving task. The task of the co-driver was to log the driving environment conditions in a log-book on a laptop. Table 3.2 shows a comprehensive list of the instructions/tasks that the driver and co-drivers followed in both the vehicles. Both vehicles drove together for the entire test route. For both the test routes, the test sessions cover four different scenarios:

Table 3.1: Various types of road infrastructure covered on the routes

Criteria	Criteria Variations covered
Speed Limit (kmph)	60, 80, 100
Number of lanes on road	1, 2, 3-lane roads
Longitudinal Curvature	Straight, single curves, S-shaped curves
Curb	Existing curb and No curb
Median	Existing median and no median
Road side objects	Trees, bushes, Road signs, No objects
Shoulder	Soil, sand, grass, No shoulder (Bushes, Trees, etc)
Guard rails	Continuous, Individual piles, No guard rails

Table 3.2: Instructions/Tasks for the driver and co-drivers of the vehicles

Vehicle	Actor	Tasks
Volkswagen Golf	Driver	- Activate LKS - Manually control speed (acceleration and brake pedal) - Take manual control of steering whenever felt needed - Inform co-driver when take over is performed
	Co-driver	- Navigate - Log changes in the driving environment in the log book - Log when there is change in control of steering between driver and LKS system
Toyota Auris	Driver	- Activate LDW system - Manually control speed (acceleration and brake pedal) - Manually control steering wheel throughout - Keep vehicle in centre of road
	Co-driver	- Navigate - Log changes in the driving environment in the log book

1. Day test in clear sunny weather
2. Day test in rainy weather
3. Night test in clear weather
4. Night test in rainy weather

Therefore, for each test route, there are 8 (4-scenarios X 2 vehicles) data sets. Both vehicles had a GPS logger (GPS position logged every second), a mobile phone for navigation, a laptop for a logbook to manually log the changes in the driving environment, and cameras. There were a total of 5 GoPro video cameras on the Golf, and two cameras on the Auris. Figure 3.2 shows the camera positions. Figure 3.3 shows example images from these cameras. As there are two vehicles, and two routes (Route 1 and Route 2, as described in methodology), and day and night conditions, the number of test sessions covering these three criteria are presented in Table 3.3. There is an extra test session for the Volkswagen Golf on Route 1 during the day. This is done due to certain issues with the camera of the Volkswagen Golf during another test session. Table 3.4 summarizes the data collected from the logbook concerning the driving environment. The cameras are used for image recognition through which additional data - namely, the position of the vehicle in the lane - is obtained. Table 3.5 summarises the data concerning the vehicle along with its source.

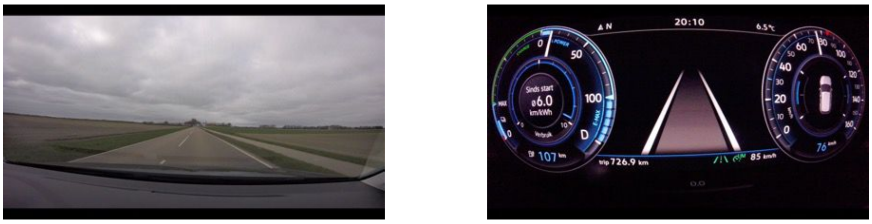
(a) Windscreen and Dashboard camera position

(b) Steering wheel camera position

(c) Left camera position

(d) Right camera position

Figure 3.2: Positions of the 5 cameras



(a) Still from Windscreen camera position (b) Still from Dashboard camera position

(c) Still from steering wheel camera position

(d) Still from Right camera position (e) Still from Left camera position

Figure 3.3: Still images from the 5 camera positions

Table 3.3: Test sessions overview

Session	Number of test sessions
VW Day Route 1	3 (2 + 1 extra day ride)
Toyota Day Route 1	2
VW Day Route 2	2
Toyota Day Route 2	2
VW Night Route 1	2
Toyota Night Route 1	2
VW Night Route 2	2
Toyota Night Route 2	2

The vehicles always drove at/below the speed limit of the road, which was mostly 80 km/h for provincial roads not in the city. There was no minimum speed specified for the drivers of the vehicles. This was left to the discretion of the drivers. However, these systems have certain minimum speeds that are necessary for them to be activated. The drivers were encouraged to drive at the maximum speed limit of the road when possible. The LKS system of the Golf requires a minimum speed of 65 km/h to be active. The LDW system of the Auris requires a minimum speed of 50 km/h to be active.

As previously stated, the data collection mainly consisted of Go-Pro cameras, GPS logger, and a manual logbook. The GPS logger was run on an Android mobile phone. So, the accuracy of the GPS location could be about 5 meters radius, varying with the kind of driving environment. The GPS is used to measure vehicle speed, and to know the road on which the vehicles were travelling, so the level of accuracy is acceptable. The co-drivers of both cars

Table 3.4: Driving environment data collected from manual logbook

Data Category	Data collected
Weather conditions	Day/Dusk/Night Sunny(or clear)/Partly cloudy/Mostly cloudy/Light rain/Heavy rain/Fog/Snow
Pavement condition	Wet/Dry Mud/Sand/Dirt
Road works	Road works present/Not present
Lighting conditions	Street lighting Shadows Backlight (from sun, or oncoming vehicles headlights)

Table 3.5: Vehicle status data collected from pilot test

Data Category	Data Collected	Source/Method of collection
Status of LKS/LDW	-No lines detected -Left line detected -Right line detected -Both lines detected	-Image recognition from Dashboard camera
GPS	-GPS position of vehicle	-GPS logger in the vehicle
Speed	-Speed of vehicle	-Calculated using GPS positions
Steering Control	-Driver in control -LKS in Control	-Manual Logbook

logged the manual logbook. They recorded the weather conditions manually and subjectively. The weather conditions logged, therefore, do not have objective measurements such as the intensity of rainfall, or visibility in fog. Other data such as dirt on the road, wet road, street lighting, shadow on the road, are all subjectively recorded by the co-drivers. These are binary, that is, it is only recorded whether the conditions existed or not (for example, street lighting present / not present).

The co-driver of the Volkswagen Golf also logs the share of driving between the manual driver and the LKS. The co-driver logs every instant when the driver gives control to the LKS, and also the instant when the driver takes back control. The driver communicates verbally when there is a control transition, after which the co-driver logs the transition. There is a time delay in logging due to this process. This needs to be corrected when takeover time needs to be used in the analysis.

The LKS status is detected using image recognition of the dashboard of the car. It is thus detected when the LKS detected both lines, no lines, left line, or right line. These detection states, which will be used as performance indicators, must be used, keeping in mind an important assumption. These states are derived from the dashboard of the car itself via image recognition. This cannot be directly interpreted to be the actual state of the lane markings at that location. For instance, the LKS displaying that no lines are detected does not necessarily mean that there are no lines. It could be that the display shows there are no detected lane markings, but in reality, there could be lane markings present. This probability of inconsistency is ignored due to there being extremely few such instances.

3.4. Performance evaluation

The first step to understanding the factors impacting the performance of the LKS and LDW systems is to evaluate the performance of these systems. With respect to this, a differentiation is made between **Functionality** and **Performance**. The functionality explains if the system was able to operate or unable to operate. Note that this does not include how well the system did its task. For example, functionality can identify when the LKS was able to detect the lane markings (or at least, when the display indicates that it detects the markings), and when it was unable to.

3.4.1. Detection Performance

For both the vehicles, there are four states of detection possible to be observed from the dashboard:

1. No lines detected
2. Left line detected
3. Right line detected
4. Both lines detected

The “Left line detected” and “Right line detected” are combined into “One line detected”. These three states (“No lines”, “One line”, and “Both lines”) are indicators of the functionality of the LKS and LDW systems. For this research, only “No lines” and “Both lines” are used as indicators because “No lines” indicates the non-functioning of the system, and “Both lines” indicates the ideal functioning of the system. The systems are always kept activated during the experiment.

Two indicators are used for detection performance measurement: “Percentage Both Lines Detection” and “Percentage No Lines Detection”. “Percentage Both Lines Detection” for a specific driving condition is defined as the percentage of occurrences of both lines detection, with respect to all the detection states for that driving condition. “Percentage Both Lines Detection” for a specific driving condition is similarly defined as the percentage of occurrences of no lines detection, with respect to all the detection states for that driving condition.

Additional performance indicators are decided for measuring the lane-keeping performance of the systems. This applies only to the LKS. As already discussed under Literature Review, several performance indicators can be used for LKS systems (Table 2.3). The feasibility of measuring them with the data collected from the pilot test (Tables 3.4 and 3.5) must be discussed. The indicators involving the steering wheel measurements such as steering wheel angle, or steering wheel reversal rate, are excluded as there is no data of the steering wheel and its positions. The indicators used are Lateral Position or the MLP, and the Standard Deviation of MLP. The definitions of these indicators are established before looking at the method of their measurement.

3.4.2. Lateral Position, or MLP

The Lateral Position, or Lateral Offset, is measured as the distance between the centre of the vehicle front axle and the lane centre. The right-handed coordinate system is followed to report this measurement, that is, the distance towards the right is positive, and towards the left is negative. Figure 3.4 depicts the definition of the Lateral Offset. This is also in accordance with the Society of Automotive Engineers (2015). Another possible definition is to measure from only one of the lane edges. However, measuring from the lane centre is the most accurate, and is also possible due to there being two cameras on either side of the vehicle. This way, it will also be free from errors that could arise by assuming constant lane width. The Lateral Position is calculated according to formula 3.1 shown below:

$$Lateral\_Position = 0.5 * (Left\_Distance - Right\_Distance) \tag{3.1}$$

It may be noted that this indicator uses the same reference point in all parts of the road. For instance, on a curve, human drivers generally tend to drive closer towards the centre of the road than away (Johnson et al. 2016). An automated vehicle may not behave similarly to human drivers. However, this aspect is important when evaluating or comparing automated vehicle performance with that of human driving. Therefore, this research also investigates the Lateral lane position for straight and curved road segments.

The MLP is defined as the average Lateral position measured over a defined stretch of distance. The MLP is then calculated by dividing the sum of the Lateral positions over that stretch by the number of data points on that stretch. This is calculated and reported separately for straight and curved road segments.

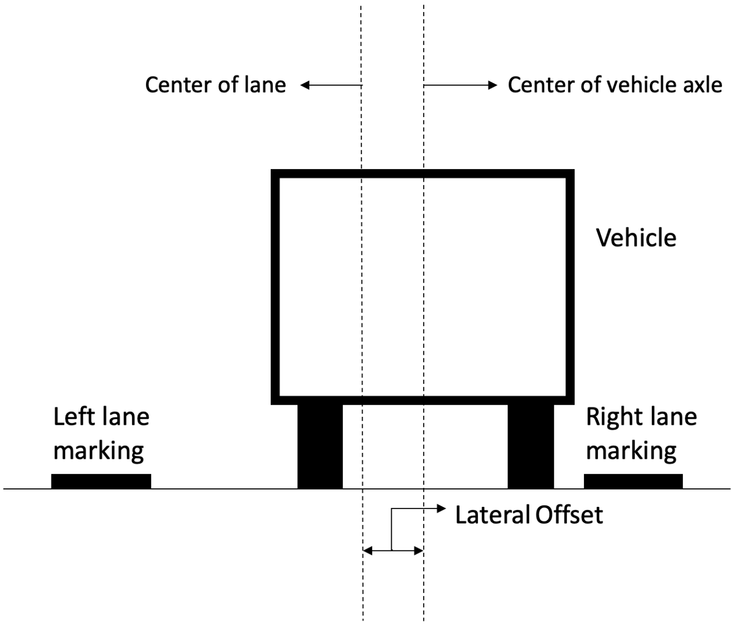


Figure 3.4: Measurement of the Lateral Offset

3.4.3. Standard Deviation of Lane Position SDLP

This is the most popularly reported indicator for the performance of lane keeping, mostly for human driving. SDLP indicates the stability of the LKS system by giving an indication of its variability. It is calculated using the formula 3.2 below (according to Society of Automotive Engineers (2015)):

$$\mathrm{SDLP} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2}, or \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{3.2}$$

where,
x_i = The i-th value of Lateral lane position
$\bar{x}$ = Mean lateral position of sample
N = Number of data points in the sample

Generally, N is sufficiently large that both formulae provide almost the same result. The Lateral lane position values used in calculating the SDLP are the same as defined previously.

Moreover, the SDLP is calculated over a certain distance or time. Generally, it is advised to measure the SDLP for 30 seconds or more (Li et al. (2018)). Again, in line with the reasoning already discussed, the SDLP is measured and reported separately for straight and curved road stretches.

After defining and measuring the decided performance indicators, this research builds regression models to understand the effect of different driving environment conditions on the performance of the systems. Following this, the performance is evaluated by benchmarking. This is done by benchmarking with respect to the available standards for the indicators in literature or other safety evaluation reports. Also, the evaluation is done relative to the data collected. This results in a relative evaluation and identification of good and poor performance of the system with respect to the test itself.

3.4.4. Operational Design Domain

The performance indicators discussed until now were for the LKS and LDW systems, that is, the automated vehicle. These systems operate in the presence of certain driving conditions that include the road infrastructure, as well as weather conditions. These driving conditions can impact the performance of an automated vehicle. The driving conditions characterised and defined in this research are non-exhaustive.

As automated vehicles' performance may depend on the driving conditions, the OEMs prescribe a certain set of conditions that are necessary for these systems to operate. Literature Review already defined the set of driving conditions where an automated vehicle system is expected to function, as the Operational Design Domain (ODD) of that automated vehicle system. Concerning the vehicles used in the pilot test, the manuals of the Volkswagen Golf (Volkswagen 2017) and the Toyota Auris (Toyota 2018) provide information on the conditions when the LKS and LDW systems, respectively, are expected to operate and the conditions that could impact their performance. Both manuals distinguish these into two types of conditions. The first set of conditions are "hard requirements". These are those conditions that must be met, for the systems to be able to function and even to activate. These are termed as the ODD of that particular automated driving system. For example, if the driving environment is inside-ODD for the LKS, then the LKS can be activated, and it can stay active (the level of performance is irrelevant). This corresponds to the "Functionality" aspect of performance discussed earlier in this section. These are enumerated in Table 3.6, being derived from the Operating Manuals of the Toyota Auris and the Volkswagen Golf.

Table 3.6: ODD according to the Manuals of the Auris and Golf

Toyota Auris (LDW)	**Volkswagen Golf (LKS)**
Speed more than about 50kmph	Speed above 65 kmph
System recognises white or yellow lines	Lane limits have been recognised
Width of the lane at least 3 m	
Direction indicator not operated	
Driving on a straight road, or curve with min radius 150 m	
No system malfunctions	

In addition to the "hard requirements", these manuals also indicate driving conditions that could negatively affect the performance of these systems. Table 3.7 enumerates these conditions, which are also derived from the Operating Manuals of the Toyota Auris and the Volkswagen Golf (Volkswagen 2017, Toyota 2018). The Toyota Auris provides much more information regarding the conditions that would affect the performance of the LDW system, compared to the Volkswagen Golf for the LKS. This information is crucial for the driver and the road authority to know as these conditions directly affect the safety of the vehicle on the road. There is a disconnect between the significance of this information and the vague nature of the description of these conditions in the manual. Moreover, the stochasticity in the amount information provided between the two OEMs is also significant. The Golf, for example, provides only four vague conditions under which the LKS may function poorly. The characterisation and definition of the conditions are left to interpretation.

Table 3.7: Factors of driving conditions affecting performance of the Lane Assistance Systems according to the Manuals of the Auris and Golf

Toyota Auris (LDW)		**Volkswagen Golf (LKS)**
-Shadows running parallel to lines	-When headlight of oncoming vehicle penetrates the camera	-Bad weather
-Driving in area without lines	-Driving at places where road splits/roads coming together	-Bad road conditions
-Interrupted lines, or lines with cat eyes (reflective markings) or stones present	-Driving on slope	-Road works
-Lines are difficult to see through sand	-Driving on road sloping left or right or on a winding road way	-Mountain peaks
-Driving on wet surface due to rain	-Driving on unpaved or uneven road	
-Yellow lines more difficult to read than white	-Sharp turn	
-Lines run over curb	-Very narrow or very wide lane	
-Driving over clean surface, such as concrete	-Car moving up and down often due to road condition	
-Driving on clear surface due to reflected light	-Car has just changed lanes or crossed an intersection	
-Area with sudden change in brightness, such as entrance and exit of tunnel		

Drawing from the fact that the ODD of an automated vehicle system consists of a driving environment (that include the road infrastructure, roadside infrastructure and weather conditions), the driving conditions along a stretch of road are evaluated to identify whether it is inside or outside the ODD. This is defined as:

1. Inside-ODD: These are set of driving conditions in which the respective automated driving systems are said to be able to function. These are enumerated in Table 3.6 for the Auris's LDW and the Golf's LKS. This is derived from the manufacturer's manual.
2. Outside-ODD: These are the set of driving conditions in which the respective automated driving systems are unable to function. If the driving conditions do not meet all the requirements in Table 3.6, then they are outside ODD.

The driving environment is further classified with respect to the performance of the LKS and LDW in it:

(a) High Performance-ODD

(b) Medium Performance-ODD

(c) Low Performance-ODD

Firstly, a given set of driving conditions are checked if they are Inside or Outside ODD. Then, the performance of the automated driving system is measured using the indicators discussed before. For each of these indicators, thresholds are defined in order to classify it among the secondary categories: High, Medium, and Low Performance. This classification is done for each performance indicator separately. The performance thresholds for each indicator are shown in Table 3.8. These thresholds are based on existing literature (Society of Automotive Engineers (2015), Green et al. (2004), Sayer et al. (2011), Aziz et al. 2018) that use performance indicators for human driving. The "average" performance measured using these indicators for human driving has been defined as "High Performance". The medium and low-performance thresholds have been decided using reasonable logic and expectation.

Table 3.8: Classification based on thresholds for performance indicators

Indicator	High Performance	Medium Performance	Low Performance
MLP	<= 10cm	> 10 cm, <= 20 cm	> 20 cm
SDLP	<= 0.3 m	> 0.3 m, <= 0.5 m	> 0.5 m

3.5. Summary

This research firstly defines the System (composed of the Road Authority, the Lane Assistance System, and the driving environment components) and analyses the relationships between its components using the STPA method based on STAMP theory. This results in a set of Refined Safety Requirements. This study then conducts a field test with two vehicles, one with a Lane Keeping System (LKS) and another with a Lane Departure Warning (LDW) system. The data from the field test is analysed to evaluate the performance of the systems. Then, regression models are constructed for the performance indicators in order to gain an insight into the effect of driving environment conditions on the performance of the systems, which is classified into different performance thresholds. This performance threshold classification in combination with the corresponding driving environment results in the operationalisation of the refined safety requirements. The final road infrastructure requirements would be a combination of the theoretical refined safety requirements for infrastructure, and the operationalised refined safety requirements.

4

STPA Analysis

The underlying objective of this research is to provide a methodology for the road authority, that can be used to gain an extensive understanding of the working and interactions of lane-keeping systems, their driving infrastructure, and environment. The output of the methodology provides a detailed list of specific requirements to ensure the safety of the System. This Chapter deals with the designing of such a methodology, based on the STPA and STAMP. Chapter 3 already discussed this method. The application to the scope of this research forms this Chapter.

4.1. Purpose of Analysis

The first step involves defining the analysis purpose, including the scope and definitions of specific terms. The foremost step to the analysis is to define the System, its boundaries, and its components.

System - The System under consideration is the combination of the road infrastructure, its components, and the LKS. The components of the road infrastructure are enumerated in Table 4.1.

Table 4.1: Components of the road infrastructure included in the selected System

Road infrastructure components	
Pavement type	Lane Marking Quality
Lane Marking Type	Width of the lane
Radius of the curve	Speed limit of road section
Median type	Median width
Shoulder type	Shoulder width
Road signs	Street light posts
Trees alongside road	Dirt on road

These components, along with the LKS, constitute the System in the definition of this research. This “System” is the focus of this analysis, and ideally encompasses the components that can be modified, or which are under some degree of control. The “environment” of this defined System constitutes the weather conditions (Time of day, Rain conditions, Cloud conditions, Wetness of pavement), and the human driver. These are components not inside the domain of control as defined by this research, but they interact with and impact the System. Therefore, it is important to also include the environment in the analysis, along with the System. The road authority does have a significant level of control on the human driver behaviour (for example, through regulations). It could even be that the road authority has a higher level of control over the behaviour of human drivers than on the LKS (OEMs). Still, this research defines the System without the human driver due to the research scope. Moreover, executed changes are more certain for road infrastructure and the LKS. Figure 4.1 depicts the defined System and the environment.

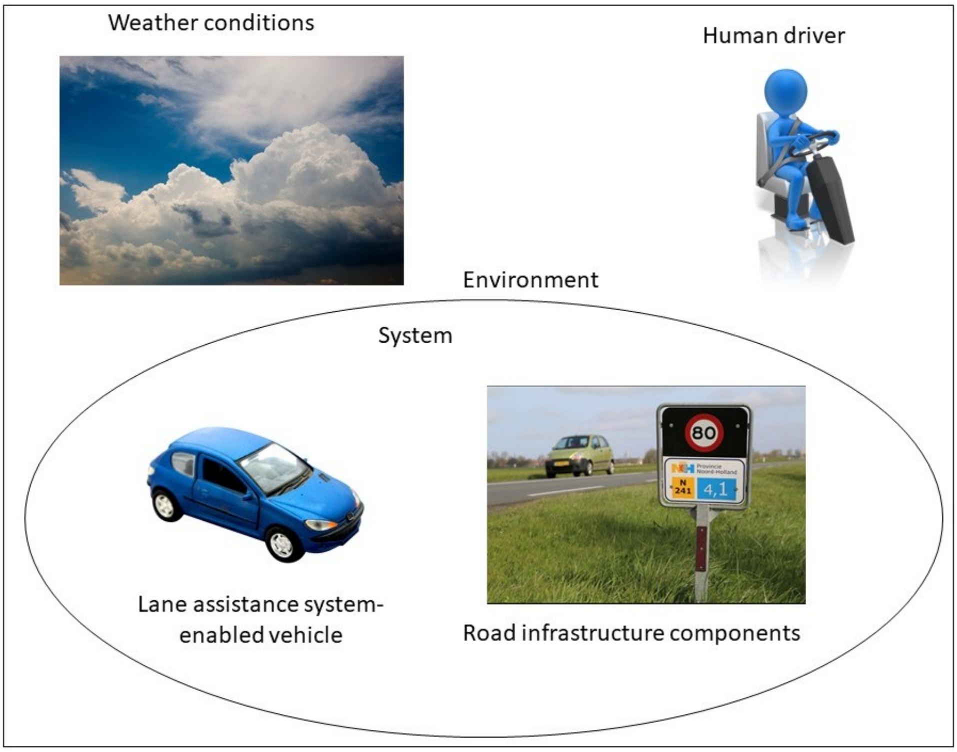


Figure 4.1: Depiction of the System and its environment

After defining the System and the environment, the next step is to define the Losses. For the System, the following Losses are defined:

- **Loss 1**:Loss of life or injury to people inside the LKS-enabled vehicle
- **Loss 2**:Loss of life or injury to people outside the LKS-enabled vehicle
- **Loss 3**:Damage to LKS-enabled vehicle
- **Loss 4**:Damage to other vehicles
- **Loss 5**: Damage to road/roadside objects
- **Loss 6**:Loss of safe driving experience for road users (subjective safety)
- **Loss 7**:Loss of time for road users
- **Loss 8**:Loss to the image of the road authority (PNH)
- **Loss 9**: Loss to the image of the vehicle manufacturer (OEMs)

These losses are ranked according to their order of importance. As the methodology is for the road authority, this research involved a short survey where employees working in the roads and mobility department were asked to rate these Losses according to their order of importance. For this, the losses are first grouped into categories:

- Losses related to life: Loss 1 and Loss 2
- Losses related to vehicles: Loss 3 and 4
- Losses related to infrastructure: Loss 5
- Non-physical user losses (travel time and comfort): Loss 6 and Loss 7
- Non-physical authority losses (loss of the image of Province): Loss 8 and Loss 9

A total of employees participated. The resulting order of importance of the Losses: Loss of life, Loss related to infrastructure and vehicles, Non-physical authority losses, and Non-physical user losses. The next step is to define the Hazards or the conditions that lead to Losses in extreme environmental conditions. These Hazards also link with one, or more than one, or all the Losses previously identified. Two Hazards are defined:

- **Hazard 1**: LKS-enabled vehicle position does not maintain a safe distance from the lane edges, or deviates too much from the centre. [This Hazard is linked to all the Losses because, in an extreme environmental condition, this could result in an accident]
- **Hazard 2**: LKS cannot be active on the lane. [This Hazard is also linked to all the Losses because, in an extreme environmental condition, this could result in an accident]

These hazards lead to the direct formation of some System constraints, which must be satisfied to prevent the System from being in a state of Hazard, and eventually leading to Losses. Therefore, the constraints are linked to the Hazards. The methodology identifies four constraints:

- **Constraint 1**: LKS-enabled vehicle must maintain a safe distance from the lane edges [Hazard 1]
- **Constraint 2**: It must be possible to activate the LKS on the lane [Hazard 2]
- **Constraint 3**: If LKS-enabled vehicle violates safe distance from the lane edge, the system must be capable of detecting this Hazard, and reducing or preventing the loss [Hazard 1]
- **Constraint 4**: If LKS cannot be activated, then the system must ensure this is detected, and it must reduce or prevent the losses [Hazard 2]

nclear

4.2. Control Structure

The STAMP theory regards the System as a control problem. As discussed earlier, the System is regarded to be composed of some controllers, which exert some constraints on the lower level controllers; the controllers ensure that components under their control domain stay within the defined constraints. The controllers also have certain objectives during the control process. In the case of the System considered here, there are two controllers: The LKS and the Road Authority. Figure 4.2 shows the Control Structure. The functioning of the LKS and LDW are obtained from the publicly available patents (Busch et al. 2019, Sherony and Hada 2017).

In the figure 4.2, the red boxes depict the two **Controllers**, namely the Road Authority, and the LKS. The red arrows are the **Control Actions**. Here, there are two Control Actions, one for each Controller. The Road Authority has one Control Action, which is to modify the infrastructure. The LKS has a Control Action to modify the steering behaviour of the vehicle. The blue lines indicate the **feedback loops**. These, again, are two in number, one to each Controller. The feedback loop to the Road Authority indicates the performance evaluation of LKS, which is monitored by the Road Authority in order to decide on making infrastructural changes. The other feedback loop is to the LKS Controller. Once the steering action has taken

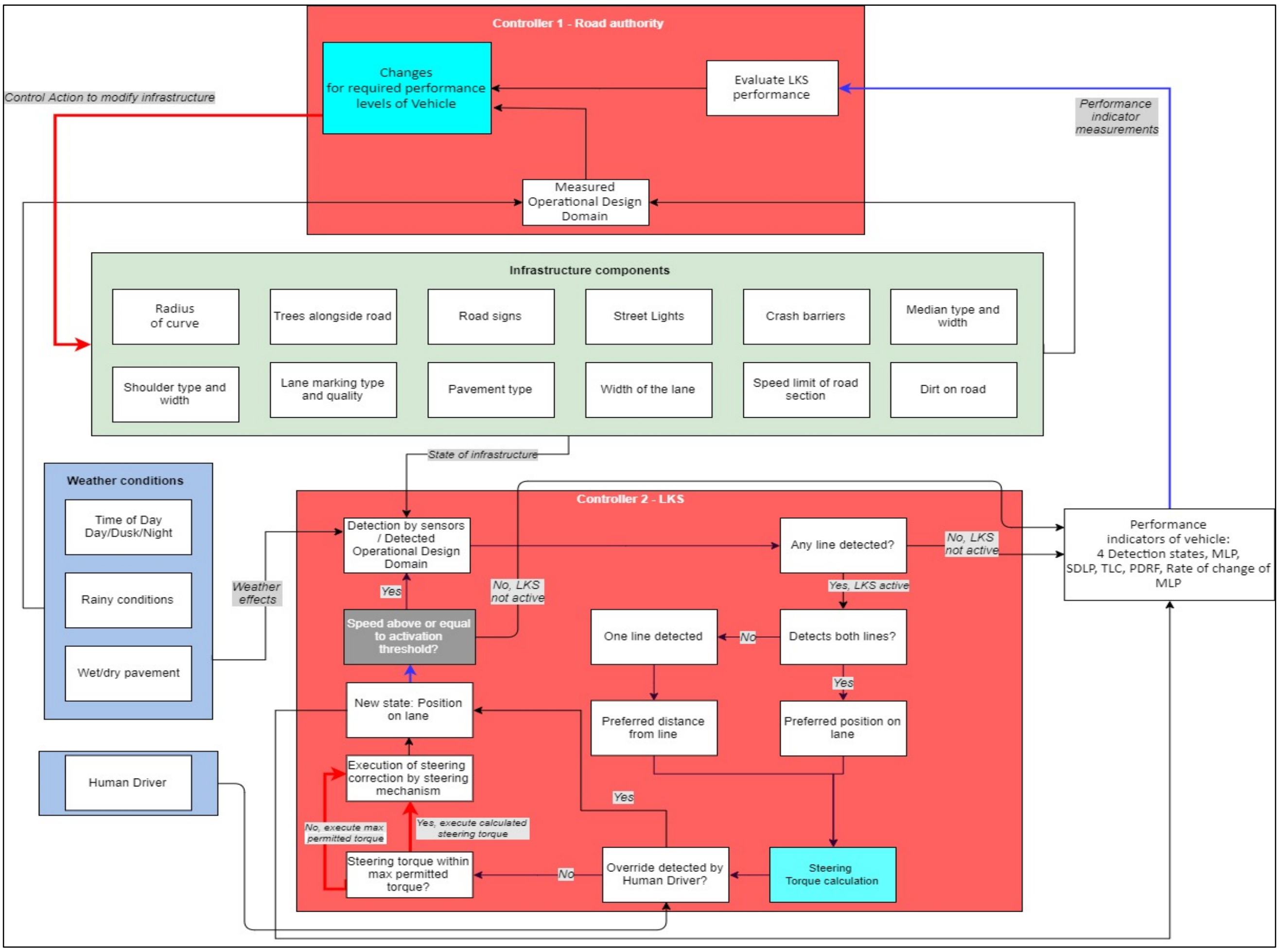


Figure 4.2: Control Structure of considered System and environment

place, the vehicle is now in a new position in the lane. This new position is detected again by the LKS, leading to another set of the LKS's control loops. The contents of the red boxes are the **Process Models**. These are the assumptions made on how the Controller functions. The Control Structure's depiction of the System and interaction between its components and with the environment can be explained as follows.

The LKS Controller starts with the activation test (indicated by the Dark grey box in the LKS controller model), that is whether the vehicle speed is equal to or higher than the activation threshold speed. If the speed criteria are satisfied, then the detection by the sensors of the vehicle begins. The sensors detect the infrastructure, and this detection is affected by weather conditions. The driving conditions detected by the system together is termed as the Detected Operational Design Domain. The LKS next tries to detect any lines in the environment. If there are no lines detected, then the LKS is inactive. If there are lines detected, then it is checked how many lines are detected. If both lines are detected, then the LKS tries to achieve the preferred position on the lane. This preferred position is internally hardcoded and is not available in the public domain. Therefore, it can be assumed to be the centre of the lane, which can be verified later with empirical data. If only one line is detected, then the preferred distance from the line is the objective (this distance, also being hardcoded), which again can be verified with empirical data. The corresponding objective enters the control algorithm (shown in the light blue box), which calculates the necessary steering torque correction. Before the execution of this steering torque, the algorithm checks if there is human driver intervention. If there is detected human intervention, then the calculated torque is not executed, leading to a new position in the lane resulting from the human intervention. If there is no detected intervention, then the calculated steering torque is executed, leading to a new position in the lane. This process continues as is shown.

The infrastructure components are enumerated and depicted in the green box. The LKS vehicle sensors detect these components, which are also measured by the Road authority along with weather conditions. The weather conditions and the infrastructure components, together constitute the measured Operational Design Domain. The Road Authority evaluates the performance of the LKS vehicle and simultaneously measures the ODD. Using this information, the Road Authority makes changes to the infrastructure to expect some required performance of the vehicle. It then implements these changes on the road infrastructure components. Thus, the figure 4.2 depicts a representation of the complex relationships between components of the System and the environment in a Control Structure.

4.3. Unsafe Control Actions

The next step after drawing the Control Structure is to identify the UCAs. As defined in Methodology, UCAs are Control Actions, that under extreme environmental conditions, lead to one or more Hazards.

In the considered System, there are two Control Actions: Modification of Steering Behaviour by the LKS Controller, and Modification of infrastructure components by the Road Authority. For each of these two Control Actions, four scenarios (explained in Methodology) are considered to arrive at the UCAs systematically:

1. Not providing the Control Action causes Hazard
2. Providing Control Action causes Hazard
3. Control Action applied too early/too late
4. Control Action stopped too soon/ applied too long

For each Control Action, the method investigates the possible UCAs in each scenario. Table 4.2 shows the resulting analysis overview . Each of the UCAs has the context along with its linked Hazard. Every UCA must have a Source (which usually the Controller itself), and the Type (whether it is provided/not provided/too early or too late/stopped too soon or applied too long). It must also have the Control Action, the context (the specific scenario being described), and its linked Hazard. Each of the UCAs is briefly explained below:

- **UCA-1**: *In case of both lines detected, LKS does not steer back when vehicle deviates from lane centre beyond the safe threshold [H1].* This UCA is relatively straightforward as it refers to the scenario where the LKS does not exert steering correction to bring the vehicle back into the lane when the vehicle has deviated the centre of the lane by the unsafe distance. This is only applicable when both lines are detected because the LKS aims to keep the vehicle exactly in the centre of the lane when it detects both lines.
- **UCA-2**: *LKS provides steering correction when not required on a straight stretch [H1].* This UCA refers to any instant when the vehicle is on a straight road and does not need steering correction, but the LKS provides steering correction. This could result in unnecessary oscillating driving behaviour on the road.
- **UCA-3**: *LKS steering over-correction due to steering applied too early ahead of the location where needed [H1].* This UCA refers to situations where the LKS steers ahead of the location where it was needed, for instance, executing steering action for an oncoming curve before the vehicle is actually on the curve, leading to deviation from the centre.
- **UCA-4**: *LKS steering correction stopped too soon, when longer duration was needed [H1].* As is evident, this UCA refers to the situation when the LKS provides the steering correction of shorter duration than needed. Therefore, the vehicle is not back to the safe position in the lane yet.

- **UCA-5**: *In case of one-line detection, LKS does not steer back when vehicle deviates from lane edge beyond the safe threshold [H1].* The only difference with UCA-1 is that this UCA refers to the scenario where only one line is detected, and therefore, the LKS aims to keep the vehicle at a specific distance from that line.
- **UCA-6**: *LKS provides too less steering correction [H1].* This UCA describes the situations when the steering correction torque applied by the LKS is insufficient to bring the vehicle back to the safe lane position. Therefore, the vehicle is still outside the safe lane position area.
- **UCA-7**: *LKS steering correction applied too late, after the location where needed [H1].* This UCA is the invert of UCA-3. It refers to the situation where the LKS applied the steering correction after the needed location. For instance, the steering correction is applied when the vehicle has already entered far into a road curve.
- **UCA-8**: *LKS steering correction applied too long, when shorter duration needed [H1].* This UCA is the invert of UCA-4. If the LKS steering correction is being applied for a duration longer than what is needed, then the vehicle crosses over to the opposite side of the lane outside the safe lane position area.
- **UCA-9**: *LKS provides excessive steering correction [H1].* This UCA is the invert of UCA-6. It is the situation when the LKS provides steering correction excessively, or more than needed, causing the vehicle to move to the other side of the lane (over-correction), leaving the safe lane limit.
- **UCA-10**: *LKS provides steering correction towards the opposite (or wrong) direction [H1].* This UCA, again, a self-explaining one, refers to the situation when the LKS, when supposed to steer left(or right), instead steers right (or left), leading to the vehicle leaving the safe lane limit.
- **UCA-11**: *Road authority does not provide any lane markings on LKS-enabled vehicles plying roads [H2].* This UCA refers to the infrastructure perspective. If the Road Authority does not provide lane markings on roads that LKS-enabled vehicles drive on, then it leads to non-detection of the lanes when driving, which could be dangerous depending on the situation.
- **UCA-12**: *Road authority provides deteriorated lane markings on LKS-enabled vehicles plying roads [H2].* This UCA refers to the Road Authority providing lane markings, but of deteriorated quality. This also relates to the maintenance of the road and lane markings. Deteriorate lane markings could lead to non-detection by the LKS, leading to potentially dangerous situations.
- **UCA-13**: *Road authority, on consecutive curves, designs the second curve to start too early in the section [H1].* This UCA refers to a specific situation where there are consecutive curves on the road. This could be, for instance, two curves with opposite curvature (S-shaped curves), or two curves of same sided curvature. The absence of a transition section between the two curves could be potentially hazardous as the LKS, which is steering in the first curved section, could need some time to change its steering behaviour. A sudden change in the curvature could lead to the vehicle deviating from the safe lane position.
- **UCA-14**: *Road authority does not provide transition section/ relaxing section after a curve before encountering the straight section [H1].* This UCA is similar to the previous UCA. The only difference is that this refers to the transition between a curve and a straight section only, with the same logic as before.
- **UCA-15**: *Road authority provides lane markings of less width on LKS-enabled vehicles plying roads [H2].* This situation is possible in some roads, where the lane marking type is such that its width is very less than the standard width of lane markings. This could lead to the LKS not being able to detect the lane marking at all, leading to potentially dangerous situations.

- **UCA-16**: *The road authority provides reduced speed limits too close to sharp curves [H1].* This scenario represents the roads where there are some sharp curves. Due to these sharp curves, the road authority provides reduced speed limits on the curves. However, the reduced speed limit section starts only immediately before the curve starts, thereby not giving enough time for the manual takeover by the human driver (due to possible LKS deactivation by slower speed). This could lead to perilous situations.
- **UCA-17**: *Road authority designs curves of radius too sharp for LKS on LKS-enabled vehicles operating roads [H1].* This UCA is straightforward as it refers to the Road Authority providing curves designed with radius too sharp for the LKS to be able to navigate, leading to inability to stay within the safe lane limit.
- **UCA-18**: *Road authority, takes too long to correct any wrong existing infrastructure component [H1, H2].* This is a generic UCA. It refers to the Road Authority, making corrections to wrongly designed or incompatible infrastructure for LKS vehicles. If the Road Authority delays these corrections, then unsafe conditions exist for these vehicles on those roads.
- **UCA-19**: *Road authority provides lane markings that are confusing to LKS, on LKS-enabled vehicles plying roads [H1, H2].* The Road Authority may provide lane markings that could confuse the LKS. Having multiple lane markings, especially during road works that have temporary lane marking, could be misread by the LKS, leading to the possibility of non-detection, and also to deviation from safe lane position limit.
- **UCA-20**: *Road authority enforces speed limit lower than what is needed for LKS to be active, on LKS-enabled vehicles plying roads [H2].* This refers to road sections where the Road Authority enforces speed limits that are lower than the minimum threshold needed for the LKS to be active. This causesLKS deactivation that is a hazard as the objective is to ensure the operation of LKS vehicles on roads.
- **UCA-21**: *Road authority provides lane markings covered with dirt [H2].* This UCA, is similar to UCA-12, as it also refers to the condition of the lane markings. Lane markings, if covered by dirt, lead to the risk of non-detection by LKS, leading to potentially dangerous situations.
- **UCA-22**: *Road authority, when reconstructing a road, does not remove visibility of old road marks [H1].* Reconstructing old roads is a standard function of the Road Authority. When doing this, special attention needs to be kept, as improper reconstruction could lead to the old road markings/ old road pavement, still being visible on the surface of the new road. This could confuse the LKS, leading to deviation from the safe lane position limit.
- **UCA-23**: *Road authority provides trees too close to the lane edge [H1].* This UCA refers to roadside objects. If trees are too close to the lane edge, then it is possible that the LKS detects the trees and tries to avoid the “obstacle”, causing potential deviation from the safe lane position limit.

Table 4.2: Identification of Unsafe Control Actions

Control Action	**Not Providing Causes Hazard**	**Providing Causes Hazard**	**Too early, too late**	**Stopped too soon, applied too long**
Modify steering behaviour	**UCA-1**: In case of both lines detected, LKS does not steer back when vehicle deviates from lane center beyond the safe threshold [H1]	**UCA-2**: LKS provides steering correction when not required on a straight stretch [H1]	**UCA-3**: LKS steering overcorrection due to steering applied too early ahead of the location where needed [H1]	**UCA-4**: LKS steering correction stopped too soon, when longer duration was needed [H1]
	UCA-5: In case of one-line detection, LKS does not steer back when vehicle deviates from lane edge beyond the safe threshold [H1]	**UCA-6**: LKS provides too less steering correction [H1]	**UCA-7**: LKS steering correction applied too late, after the location where needed [H1]	**UCA-8**: LKS steering correction applied too long, when shorter duration needed [H1]
		UCA-9: LKS provides excessive steering correction [H1]		
		UCA-10: LKS provides steering correction towards the opposite (or wrong) direction [H1]		
Modification of infrastructure	**UCA-11**: Road authority does not provide any lane markings on LKS-enabled vehicles operating roads [H2]	**UCA-12**: Road authority provides deteriorated lane markings on LKS-enabled vehicles operating roads [H2]	**UCA-13**: Road authority, on consecutive curves, designs the second curve to start too early in the section [H1]	
	UCA-14: Road authority does not provide transition section/ relaxing section after a curve before encountering the straight section [H1]	**UCA-15**: Road authority provides lane markings of less width on LKS-enabled vehicles operating roads [H2]	**UCA-16**: The road authority provides reduced speed limits too close to sharp curves [H1]	
		UCA-17: Road authority designs curves of radius too sharp for LKS on LKS-enabled vehicles plying roads [H1]	**UCA-18**: Road authority, takes too long to make a correction to any wrong existing infrastructure component [H1, H2]	
		UCA-19: Road authority provides lane markings that are confusing to LKS, on LKS-enabled vehicles operating roads [H1, H2]		
		UCA-20: Road authority enforces speed limit lower than what is needed for LKS to be active, on LKS-enabled vehicles operating roads [H2]		
		UCA-21: Road authority provides lane markings covered with dirt [H2]		
		UCA-22: Road authority, when reconstructing a road, does not remove visibility of old road marks [H1]		
		UCA-23: Road authority provides trees too close to the lane edge [H1]		

These UCAs can be directly converted to initial Safety Requirement (SR)s. These Safety Requirements typically are inversions of the UCAs. Two examples are shown below:

UCA-1: In case of both lines detected, LKS does not steer back when vehicle deviates from lane centre beyond the safe threshold [H1].
The corresponding Safety Requirement is:
SR-1: In case of both lines detected, the LKS must steer back when vehicle deviates from lane centre beyond the safe threshold[H1].

UCA-11: Road authority does not provide any lane markings on LKS-enabled vehicles operating roads [H2].
The corresponding Safety Requirement is:
SR-11: Road authority must provide lane markings on LKS-enabled vehicles operating roads [H2]

The complete list of the UCAs and their corresponding SRs can be found in Table A.1 in Appendix.

4.4. Identifying Loss Scenarios

After identifying from the Control Structure, the next step of the analysis entails the identifications of Loss Scenarios. Loss Scenarios describe the factors or causes that led to the UCA, and consequently to the Hazards. This, therefore, deals with constructing scenarios during the operation of the System, which could cause an UCA.

These scenarios can be constructed using two strategies: one is to understand the cause leading to the occurrence of the UCA, and the other is to investigate the execution of the UCA that resulted in the Hazard. The former deals with the sensors, feedback processes, the control process, and the control algorithm while the latter deals with the actuators and the other components of the process in the execution phase of the control action. The scenarios leading to the occurrence of the UCA can be further classified into the unsafe behaviour of the Controller, and the Controller receiving inadequate information or feedback. Further classification of the scenarios dealing with the execution phase involves the control path and other factors of the control process. Figure 4.3 depicts this classification overview.

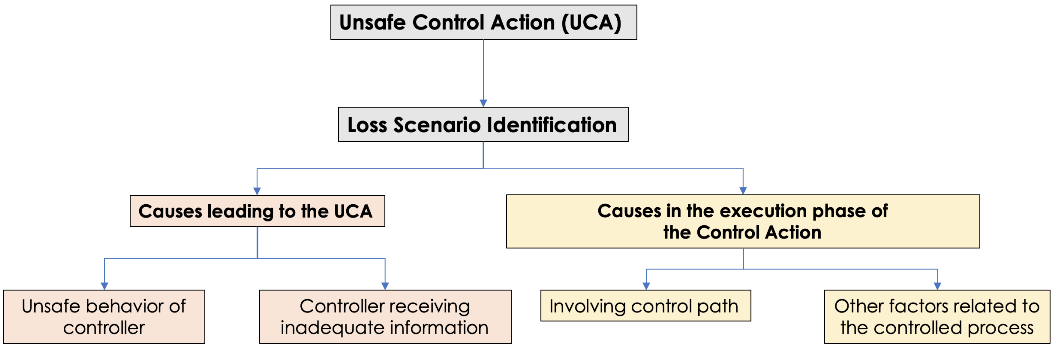


Figure 4.3: Classification of Loss Scenarios for identification of UCAs

It is needed to formulate or identify, using the taxonomy just defined, all the possible loss scenarios that could lead to the UCA. This Chapter does not explicitly discuss Loss Scenarios for all the UCAs. As an example to demonstrate the methodology, this Chapter discusses the process for one UCA. Note that all the Unsafe Scenarios have a link to their corresponding UCA and the Hazard.

UCA-1: In case of both lines detected, LKS does not steer back when vehicle deviates from lane centre beyond the safe threshold [H1]

Unsafe Controller Behaviour

- This UCA could be caused due to issues with the physical operation of the Controller itself. It could be due to the power to the LKS controller failing, leading it not function [UCA-1], causing the vehicle to deviate from the lane centre beyond the safe threshold [H1].
- There could also be inadequacies with the control algorithm. When the LKS control algorithm has a different safe lane position limit, causing LKS not to steer back [UCA-1], causing the vehicle to deviate from the lane centre beyond the safe threshold [H1].
- There could be input from another controller that leads to the UCA. In this case, if the human driver lets the LKS steer the instant when both lines are detected, whereas the LKS Controller needs a certain time period to start steering control, resulting in the LKS Controller not operating [UCA-1], causing the vehicle to deviate from lane centre beyond the safe threshold [H1].
- There could also be imperfections in the process model of the Controller. The LKS control algorithm may determine the vehicle position incorrectly with respect to the lane markings, causing LKS not to steer back [UCA-1] when the vehicle deviates the lane centre beyond the safe threshold [H1].
- Continuing the loss scenarios with respect to process models, it could happen that the LKS Controller has detected another object, such as the edge of the road instead of the lane marking, therefore not executing steering correction [UCA-1] when the vehicle deviates the “real” lane centre beyond the safe threshold [H1].

Causes of inadequate feedback/information

- There could be instances where there is no feedback received by the Controller. For instance, when there is a signal disconnection between the sensors and the LKS Controller may be due to wire disconnect or power failure, the detected lines are not communicated to the Controller. It leads to no action taken by the LKS Controller [UCA-1], causing deviation from lane centre beyond the safe threshold [H1].
- If there is feedback, but when it is inadequate, it could also result in UCAs, such as when dirt on sensor degrades sensor detection capability leading to inadequate detection of lane markings, therefore not executing steering correction [UCA-1]. It causes the vehicle to deviate from the “real” lane centre beyond the safe threshold [H1].
- Again a case of inadequate feedback, in bad weather conditions, sensors detection capability degrades, leading to inadequate detection of lane markings, causing the LKS not to steer back [UCA-1] causing the vehicle to deviate from the lane centre beyond the safe threshold [H1].

Involving control path

- There could be situations where the Controller does not execute control action due to processes in the control path. The human driver in steering control could override the LKS Controller enabling it ineffective [UCA-1], causing the vehicle to deviate from the lane centre beyond the safe threshold [H1].
- Issues occurring in the control path could also involve the actuators. A signal disconnect between LKS Controller and steering mechanism (actuator), causing calculated steering correction not being executed [UCA-1], leading to deviation from the lane centre beyond the safe threshold [H1].

Involving control process

- There could be situations where UCAs occur due to something going wrong in the control process itself, leading to the Controller not executing the control action. Suppose the LKS is inactive, but due to the display having a time lag, it shows that both lines are detected, when in fact LKS is not controlling steering action [UCA-1], leading to deviation beyond the safe threshold from the lane centre [H1].
- There could be situations in the control process that prevent the control action from executing completely. If the steering mechanism executes the steering correction, but the vehicle does not move accordingly due to slippery road surface (due to rain), causing the vehicle not to steer back [UCA-1], leading to it deviating from the lane centre beyond the safe threshold [H1].

Thus this is how the loss scenarios are identified using a structured approach to explain the potential causes of the UCAs. Appendix tables present the complete list of all the UCAs and their identified loss scenarios.

4.5. Refined Safety Requirements

After the identification of the possible Loss Scenarios UCAs, the method involves translating these Loss Scenarios into Refined Safety Requirement (RSR)s. These are more specific level requirements in order to prevent the respective loss scenarios from occurring, therefore also reducing the possibility of the UCA occurring, and consequently leading to the Hazard(s). The RSR for two Loss Scenarios is shown below:

Loss Scenario - LKS control algorithm has a different safe lane position limit, causing LKS not to steer back [UCA-1] causing the vehicle to deviate from the lane centre beyond the safe threshold [H1].

- *Refined Safety Requirement* - The safe lane position limit hard-coded in the LKS controller must be within the safe threshold as agreed by authority/OEMs by research.

Loss Scenario - The LKS Controller has detected another object, such as the edge of the road instead of the lane marking, therefore executing steering correction [UCA-2] when vehicle already within safe lane position threshold, causing deviation from lane centre beyond the safe threshold [H1]

- *Refined Safety Requirement* - The sensors must be calibrated to recognize lane markings (including their various types), and be able to differentiate them with “lines” occurring in the environment.
- *Refined Safety Requirement* - There must not be large contrast differences between pavement and immediate shoulder of the road that the vehicle may recognize as the lane edge.
- *Refined Safety Requirement* - There must be no marks remaining from reconstructed roads that might indicate lane boundaries different from the new actual lane boundaries.
- *Refined Safety Requirement* - There must not be roadside objects that cast shadows resembling lines (such as crash barriers, from roadside buildings or other infrastructure, or from trees that have a particularly long bark).
- *Refined Safety Requirement* - There must be no asphalt repair patches on the road that might be recognized as a lane marking.

The complete list of the RSRs for all the Loss Scenarios can be found in Appendix Tables A.2, A.3, A.4, A.5, and A.6. Naturally, there are a lot of RSRs that repeat across different Loss Scenarios, both because there are Loss Scenarios that are applicable for more than one UCA. However, there are also RSRs that apply to more than one Loss Scenario. Therefore, for a concise overview, a list of unique RSRs is presented in a classified form divided into Infrastructure Requirements, In-vehicle Communication Requirements, Algorithm Requirements, and Hardware Requirements. The Infrastructure Requirements are presented in Table 4.3. The In-vehicle Communication Requirements, Algorithm Requirements, and Hardware Requirements are presented in Appendix Tables A.8, A.9, and A.10 respectively.

Table 4.3: Refined Safety Requirements: Infrastructure Requirements

Infrastructure Requirements	
Roads must have a pavement design and drainage system well enough to prevent slippery roads for vehicles.	The radius of the curves must be such that the vehicles can navigate them taking into account the max steering torque, the width of the lane, the speed limit of that road stretch, and reaction time of the LKS.
There must be a sufficient transition section between two simultaneous reverse curves, taking into account the max steering torque of the vehicle, the speed limit of that road stretch, the width of the lane, the radius of the curves, and reaction time of the LKS.	There must be no marks remaining from reconstructed roads that might indicate lane boundaries different from the new actual lane boundaries.
There must be a sufficient transition section between two simultaneous curves, taking into account the max steering torque of the vehicle, the speed limit of that road stretch, the width of the lane, the radius of the curves, and reaction time of the LKS.	There must not be roadside objects that cast shadows resembling lines (such as crash barriers, from roadside buildings or other infrastructure, or from trees that have a particularly long bark).
There must not be large contrast differences between pavement and immediate shoulder of the road that the vehicle may recognize as the lane edge.	There must be no asphalt repair patches on the road that might be recognized as a lane marking.

This research adds another step to the formulation of the RSRs. Given that the user of the STPA analysis is the road authority, it is possible to further focus the RSRs towards the Infrastructure Requirements. The method does this by looking at how the road infrastructure could be used to support other RSRa or what role road infrastructure must play to increase the effectiveness of other RSRs. This is tabulated in Table 4.4. Two other suggestions for infrastructure are:

RSR: *"The radius of the curves must be such that the vehicles are able to navigate them taking into account the max steering torque, the width of the lane, the speed limit of that road stretch, and reaction time of the LKS."*

Additional recommendation: Digital Infrastructure to Vehicle (I2V) communication could be provided before curves to advise manual takeovers.

RSR: *"In case of human driver override and extreme deviation from safe lane position limit, the vehicle could provide gentle and non-dominating haptic feedback to the driver"* ***and*** *"In case of human driver override, a subtle notification to the driver indicating deviation from the safe lane position limit must be provided to alert the driver of the potentially dangerous situation"*

Additional recommendation: In situations of relatively high risk such as curves, rumble strips could be useful as lane markings to alert the driver when going over or beyond the lane marking boundary.

Some other such recommendations stemming from the RSRs are:

- High-friction road surfacing on relatively risky sections such as on curves
- Warning signs for drivers to be more alert and ready to take over control could be placed at critical sections.
- Speed limits could be reduced at critical sections such as sharp curves to mandate manual driving.

These are included as the recommendations output of the STPA analysis. Similarly, it is possible to focus on the perspective of the other RSR categories and to formulate additional focused requirements. This is beyond the scope of this research as the research focuses on the road infrastructure from the road authority's perspective.

Table 4.4: Additional Infrastructure focused requirements

RSR	RSR Category	Additional role of Infrastructure/Road authority
There must not be high contrast differences between pavement and immediate shoulder of the road that might be recognized as the lane edge There must be no marks remaining from reconstructed roads that might indicate lane boundaries different from the new actual lane boundaries There must not be roadside objects that cast shadows resembling lines (such as crash barriers, from roadside buildings or other infrastructure, or from trees that have a particularly long bark) There must be no asphalt repair patches on the road that might be recognized as a lane marking	Infrastructure	Must be added to inspection and maintenance procedures and to road design guidelines.
The radius of the curves must be such that the vehicles are able to navigate them taking into account the max steering torque, the width of the lane, the speed limit of that road stretch, and reaction time of the LKS	Infrastructure	Reduced speed limit signs must be placed well before sharp curves to enable safe manual takeover by the driver.
The sensors must be calibrated to recognize lane markings (including their various types), and be able to differentiate them with "lines" occurring in the environment The LKS control algorithm must be properly tested to ensure that it determines the position of the vehicle in the lane accurately, within an acceptable error range.	Hardware Algorithm	Lane markings must be sufficiently distinct and recognisable, offering high contrast with the pavement. Lane markings must be consistent with function of the road they are on, to ensure that LKS cameras can be better trained to detect them.
The sensors must have an acceptable level of detection performance in different visibility conditions that could occur.	Hardware	The road and roadside infrastructure must be designed in order to assist the detection of the lane markings to prevent high contrast differences with objects other than lane markings, but also to prevent contrast reduction between lane markings and the pavement in different visibility conditions.
The camera must cover the road environment downstream upto a distance that is calculated incorporating the minimum and maximum speed of the vehicle (consequently the time needed to travel that distance), and the time needed for executing steering action.	Hardware	The road design must be done taking into account the Sight Distance of the cameras of these automated systems and Reaction Time needed for execution of LKS steering correction.
The safe lane position limit hard-coded in the LKS controller must be within the threshold as agreed by authority/OEMs by research.	Algorithm	The width of the lanes must be designed to safely accommodate the safe lane position limit of the LKS vehicles.

5

Data Processing and Overview

The data used in this research is collected through the case study set-up already discussed in detail in Methodology Chapter 3. This Chapter deals with the data from the case study, its processing, and critical review.

The data processing was primarily done by Royal HaskoningDHV. The output provided from the data processing was a csv file containing the data logged in the logbook (discussed previously in Methodology), and video files of the cameras from the test drive. The csv file consisted of data from the test for every second (excluding some missing or erroneous instances) of the pilot test. The rows of the csv file contained the time instances every second, for all the days of the test. The columns and column descriptions of the csv directly relevant for the research are enumerated in Table 5.1. The columns not mentioned in the table are those that indicate the other output files (for example, a column indicating the location of the GPS log file, and a column indicating the video file name). These are skipped in Table 5.1. This data covers all the test sessions. In addition to this, for one of the day test sessions involving the Volkswagen, the distance from either sides of the tyres to the adjacent lane marking was derived using image processing. The resolution of this dataset was one measurement every second. This dataset was then synced to the larger dataset using timestamps, for that particular test session only.

5.1. Data insight and filtering

5.1.1. Primary dataset

An overview of the quantity of data such as duration of data per vehicle can be seen in Table 5.2T there has been an extra day ride for the Volkswagen on Route 1. Apart from that, the number of test sessions have been planned to be the same for each scenario. This is important when evaluating and comparing across scenarios.

There are some essential observations and steps to take before diving into analysing the data. Firstly, the dataset covers the entire test session, including stops and breaks. Therefore, there are data points when the vehicles were at a standstill or travelling at very low speeds. It is also essential to recall that the Lane Assistance Systems of both vehicles have certain minimum speed requirements in order to operate. The Toyota Auris's LDW requires a minimum speed of about 50 kmph, and the Volkswagen Golf's LKS requires a minimum speed of about 65 kmph. While accelerating from a lower speed, the LKS activates from 65 kmph, but while decelerating from higher speed, the LKS remains active until 60 kmph. This research only considers the data points where the vehicles were travelling above the minimum speed as the focus is on the operation of the systems when they are active. Therefore, it is logical to consider only the data points where both systems can be active (that is, above

Table 5.1: Columns in the csv file from the pilot test as output of data processing

Column Name	Description/Categories
Row Nr	Unique numbering of the different datapoints (rows)
Day and Time	The date and time during the test for every row
Road Authority	Road authority that has jurisdiction over that location during the test
Hectometer	The hectometer value at that particular location during the test
Road number	The official road number of the road during that location of the test
LKS status	No line detected ; Only left line detected ; Only right line detected ; Both lines detected
Car	Volkswagen ; Toyota
Test ongoing	Test on-going ; No test on-going
Time of day	Day ; Dusk ; Night
Street Lighting	Street lighting off ; Street Lighting on
Weather conditions	Sunny/Clear ; Partly cloudy ; Mostly cloudy ; Light rain ; Heavy rain ; Fog
Backlight	No backlight ; Backlight (from sun or oncoming headlights)
Shadow on the road	Shadows on the road ; No shadows on the road
Road is dirty	Road dirty ; Road clean
Road is wet	Road wet ; Road dry
Road works	No road works ; Road works present
Driver in control	LKS in control ; Driver in control
Failed curve	No failed curve ; LKS failed negotiating a curve
Other remarks	Comments by co-driver
GPS latitude	GPS latitude
GPS longitude	GPS longitude
GPS speed	Speed calculated from GPS

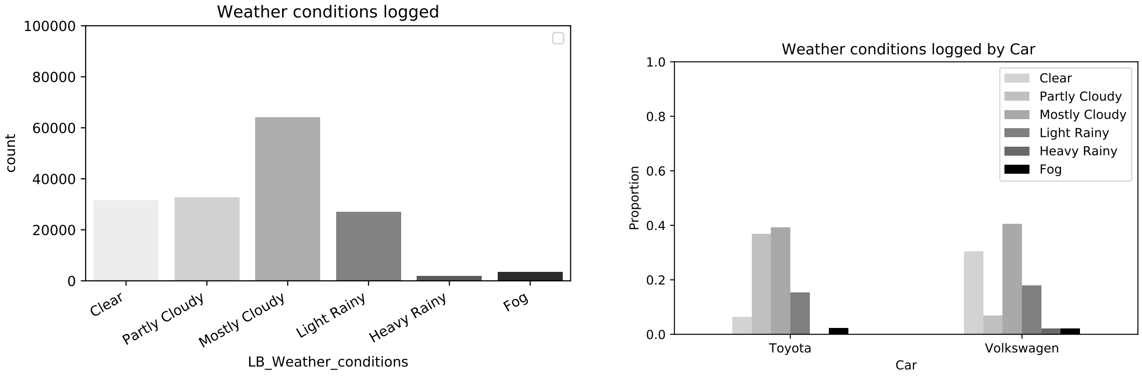
Table 5.2: Descriptive Overview of the csv dataset

Description	Duration in seconds
Total number of data points	160,451 (about 45 hours)
Number of data points for Toyota Auris (LDW)	72,239 (about 20 hours)
Number of data points for Volkswagen Golf (LKS)	88,213 (about 25 hours)
Number of data points when both vehicle speeds above 60 kmph	107,605 (about 30 hours)
Number of data points of day rides	82,828 (about 23 hours)
Number of data points of night rides	74,100 (about 21 hours)

60 kmph). As is shown in Table 5.2, there is about 30 hours of driving when both vehicles were above 60 kmph.

For the variables “Backlight”, “Shadow on the road”, “Road is dirty”, and “Road is wet”, initial checks revealed that the number of instances of these situations is very few. The accuracy and reliability of this data are also weak, mainly because of manual data logging. Therefore, the analysis will not use these variables. There are also some instances of “Road works” in the data. However, the speed limit during road works on Provincial roads is generally 50 kmph, which is below the activation threshold of both the LKS and LDW systems. Therefore, the analysis also does not consider road works. Hence, the main variables that are studied are “Time of Day”, “Weather conditions”, “Street Lighting”, and “Speed”.

Some preliminary analysis provides a quick insight into the field test and the Lane Assistance Systems. This descriptive analysis does not go deep into the correlations, significance, or causes. It is merely to gain an understanding of the overall picture to help narrow down on the relevant aspects. Figure 5.1a shows the total distribution of weather conditions logged. There is a pretty uniform distribution of weather conditions, except for heavy rain and fog, which have very few observations. The driving condition in “Fog” during the test is questionable as the visibility during that day was about 100 meters. Therefore, the analysis excludes the “Fog” driving condition. Figure5.1b shows the distribution of weather conditions for each vehicle. As the two vehicles were driving together at all times, the distribution of weather conditions for both cars should be similar. However, this is not the case as is seen with the big discrepancy of “Clear” and “Partly cloudy” weather conditions, between the two vehicles. This is due to the different perceptions of the co-drivers in both cars about the weather conditions. This kind of overview is important to have as it shows that when the data sources are different, data collection could interpret the same situation differently. Therefore, this discrepancy needs to be corrected to make it uniform. For this, the analysis defines new categories. First, “Clear” and “Partly Cloudy” are combined to form the “Clear” category. “Mostly Cloudy” forms the “Cloudy” category. “Light Rain” and “Heavy Rain” are combined to form the “Rainy” category. Figure 5.2 shows the new distribution for each car. This makes the weather distributions between the two vehicles much more uniform.



(a) Combined weather conditions distribution

(b) Weather conditions distribution per car

Figure 5.1: Weather conditions distribution

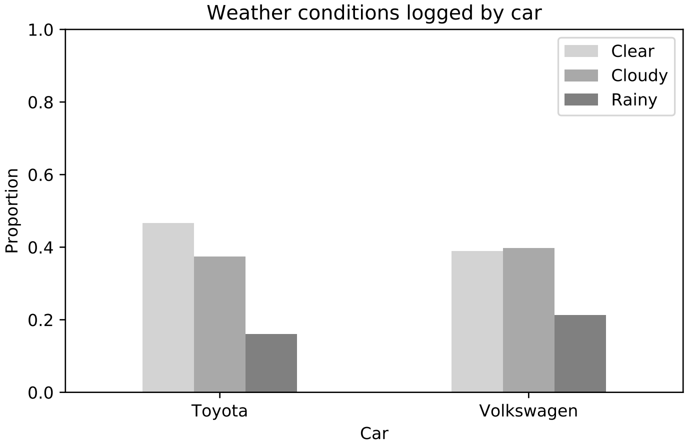


Figure 5.2: Combined weather categories

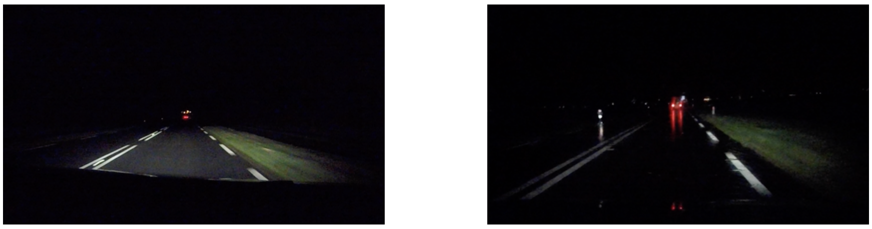
The purpose of using the variables such as weather conditions is to see the effect of different weather conditions on the detection performance of the Lane Assistance Systems. From the perspective of the car’s cameras, visibility is a crucial factor that plays a role. It is therefore required to study the effect of different visibility conditions on the detection performance of these vehicles. When the perspective changes from weather conditions to visibility conditions, the time of day and street lights also come into the picture as they significantly affect the visibility conditions. The analysis combines them into a “Visibility” variable that contains seven categories, namely “Clear”, “Cloudy”, “Rainy”, “Dark”, “Dark and Rainy”, “Street

Lights (SL)", and "Street Lights and Rainy (SL_Rainy)". "Clear", "Cloudy", and "Rainy" refer to day-time conditions and are self-explanatory. "Dark" refers to nighttime driving, with no street lights and no rain. "Dark-Rainy" is nighttime driving with rain only. "SL" is driving under streetlights, during the night. "SL_Rainy" indicates driving under streetlights during the night, in the rain. These categories cover all the possible visibility conditions exposed to these vehicles. For a better visual of these categories, Figure 5.3 shows stills from the windscreen camera. Figure 5.4 shows the distribution of these visibility conditions. There is a good amount of driving done in all the conditions. Although relatively little for "Rainy" and "SL_Rainy", there are still a good number of observations.

(a) Still image of Clear condition

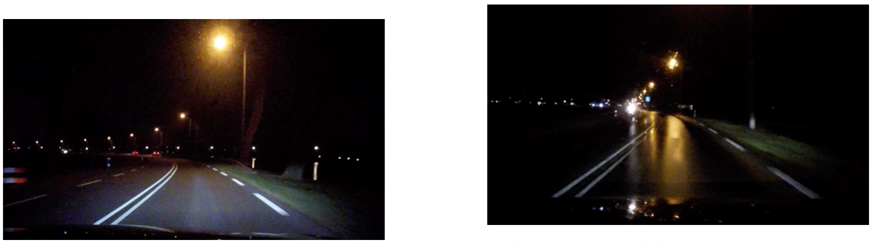
(b) Still image of Cloudy condition

(c) Still image of Rainy condition



(d) Still image of Dark condition

(e) Still image of Dark Rainy condition



(f) Still image of Streetlight(SL) condition

(g) Still image of Streetlight (SL) Rainy condition

Figure 5.3: Still images of all visibility conditions

The "GPS speed" variable of both vehicles is converted from a continuous to a categorical variable. Figure 5.5 shows the categories and their distribution and proportions for both vehicles. The number of observations is well distributed, except for the ">90" category. "70-

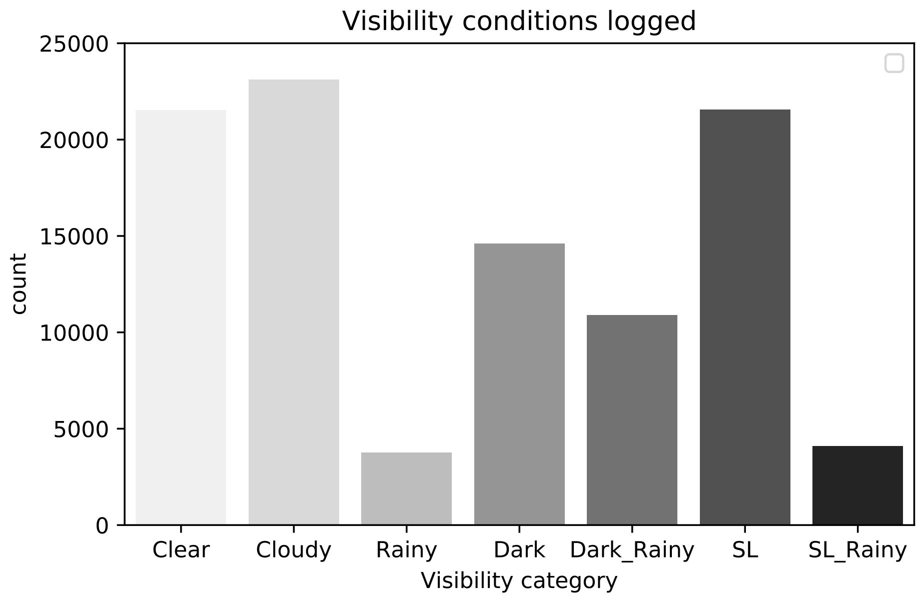
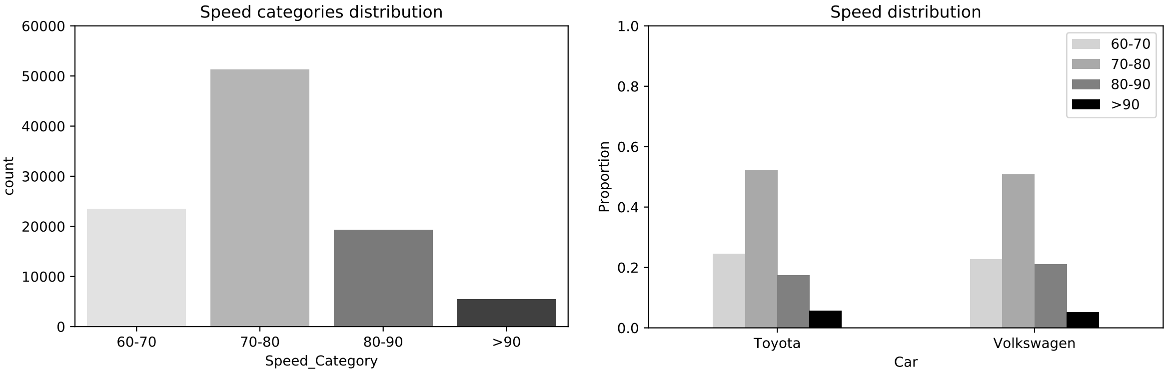


Figure 5.4: Distribution of the visibility categories

80” has the most observations because Provincial roads mostly have a speed limit of 80 kmph, and the drivers were instructed to drive at the speed limit of the road. Figure 5.5b shows the proportion of the speed categories for both cars. There is a consistent distribution of the speed categories between both cars.



(a) Speed categories distribution combined

(b) Speed categories distribution per car

Figure 5.5: Speed distribution

5.1.2. Vehicle position data

As mentioned earlier, besides the detection performance of the LKS and LDW, this research also studies the lane-keeping performance of the LKS. For measuring the lane-keeping performance, the analysis uses the indicators MLP and SDLP. In order to calculate these indicators, the position of the vehicle in the lane needs to be determined. However, the field test did not record this data, and there were no precise devices such as Light Detection and Ranging (LiDAR) or Controlled Area Network (CAN) bus that can provide this data automatically. The only possible source of this data is the cameras installed on both sides of the car. These cameras capture the front wheels of the car along with the adjacent lane marking. Figure

5.6 shows the left and right camera views. From these images, it is possible to extract the distance from the wheel to the adjacent lane marking using image recognition. There are two issues with measuring distances from these camera images:

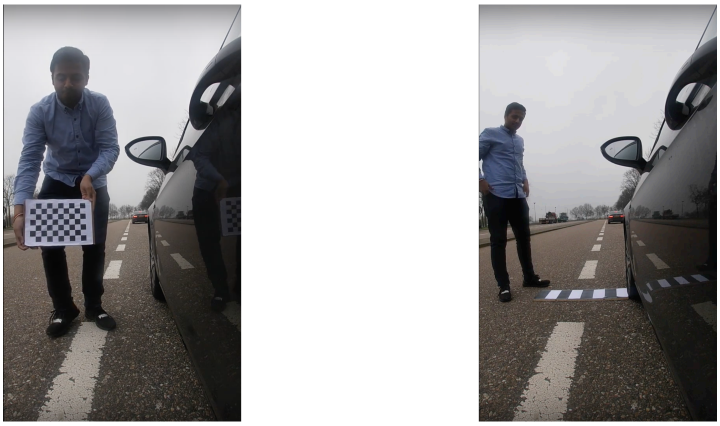
- There is a lack of any “ground truths” for measurement.
- The issue of the fish-eye lens distortion that occurs, meaning a pixel in one area of the picture does not have the same dimensions as a pixel in another area.

The test drive involved two additional steps to address these issues. At the start of every camera video, the field test staff performed a calibration task and a validation task. The calibration task involved holding a black-and-white checker-board at different positions of the camera view (as shown in Figure 5.7a). This is used to calibrate the pixel dimensions in different positions of the camera image, given the true dimensions of the checker-board. The validation task involved placing a black-and-white striped wooden plank perpendicular to the wheel of the car (as shown in Figure 5.7b). This is used to firstly define the angle of the line of measurement of the distance between the wheel and the lane marking, and secondly, to validate the measurements, given the true dimensions of the wooden plank.

(a) Left camera view

(b) Right camera view

Figure 5.6: Left and Right camera views



(a) Checker-board for calibration

(b) Striped plank for validation

Figure 5.7: Calibration and validation tasks

Image recognition involved identification of edges of objects in the image (Figure 5.8a), recognition of lane markings (Figure 5.8b), and measuring distance from the lane marking to the wheel (Figure 5.8c). An external party did the actual coding through the Province of North-Holland.

(a) Identifying edges (b) Recognition of lane markings

(c) Distance measurements

Figure 5.8: Image recognition steps

The output of this dataset was the distance from the left wheel to the left lane marking, and the distance from the right wheel to the right lane marking. The process measured these distances every second. From the width vehicle width and the left and right measurements, the lane width can be calculated, and naturally also the lane position (defined as the distance between the vehicle axle centre and the lane centre). So, this resulted in the lane position measurement at a resolution of one second. Due to budget and time constraints, this data was only available for one of the day test drives. Therefore, this results in limited possibilities of analyses. Still, this data allows for some useful analysis.

The distribution of the lane width calculated is seen in Figure 5.9. The lane width distribution, with a median of 280 cms is consistent with actual lane widths on provincial roads. As is seen, there are also some stretches with 260 cms, which represent some of the smaller roads. The distribution also has some larger lane widths, which could be due to road broadening at curves, or other road markings at a farther distance, especially in the absence of lane markings. In addition to this data, the type of road stretch was logged manually for this one test session. This process logged the type of curve (Straight section/ Left curve/ Right curve) per second of the field test. This enriches the data of the driving environment. Figure 5.10 shows the distribution of duration of driving on straight, left, and right curves. Naturally, most of the driving is on straight sections. The proportion of left and right curves being almost equal is useful for analysis.

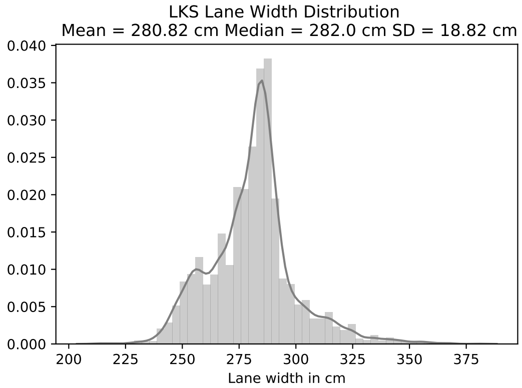


Figure 5.9: Lane width distribution

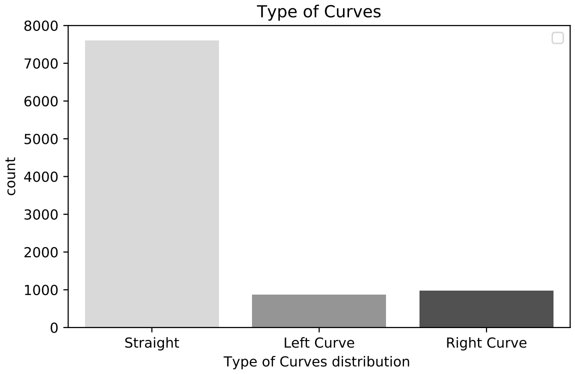


Figure 5.10: Type of stretch distribution

This lane position data was synced with the detection states and environment conditions dataset using timestamps. The next Chapter discusses the analysis.

6

Performance Evaluation

Chapter 3 discussed the indicators for evaluating the performance of these systems. This Chapter will first focus on getting a descriptive overview of the data relevant for performance evaluation, then building regression models using the data, and then discussing the results of the performance evaluation. Finally, this Chapter presents the evaluation results, followed by some observations made during the field test.

6.1. Performance Evaluation

6.1.1. Detection Performance

Both vehicles display the detection status on their dashboards (as already shown in Figure 3.3b of Methodology). From image recognition, it is possible to derive detection of both lines, detection of the left line, detection of the right line, and detection of no lines. The analysis combines the detection of left and right line into “one line” detection as differentiating detection of the left or right line gives no useful information at this level of study. Therefore, three categories of detection are defined: “Both lines detected”, “One line detected”, and “No lines detected”.

Bar plots are used to get a notion of the effect of visibility on the detection performance of the two vehicles. Figure 6.1 shows the effect of visibility on the detection performance of the LKS. The distribution is normalised for the duration of driving in each of the visibility conditions. Therefore, the proportion of both lines, one line, and no lines detected add up to 1 for each visibility condition. The majority of the states are both lines detected (about 90%), and about 5% are of no lines detected, and a few with one line detected. This, by itself, indicates that the LKS can detect a vast majority of the lane markings (Note, however, this only is what the car says it detects. It does not have any bearing on the actual situation on the road, but the analysis assumes that these detection states are indicators of performance). Focusing on both lines detected distribution, there seems to be almost a uniform proportion across the visibility categories. There are two noticeable dips, one for the “Dark_Rainy” condition, and the other for the “SL_Rainy” condition.

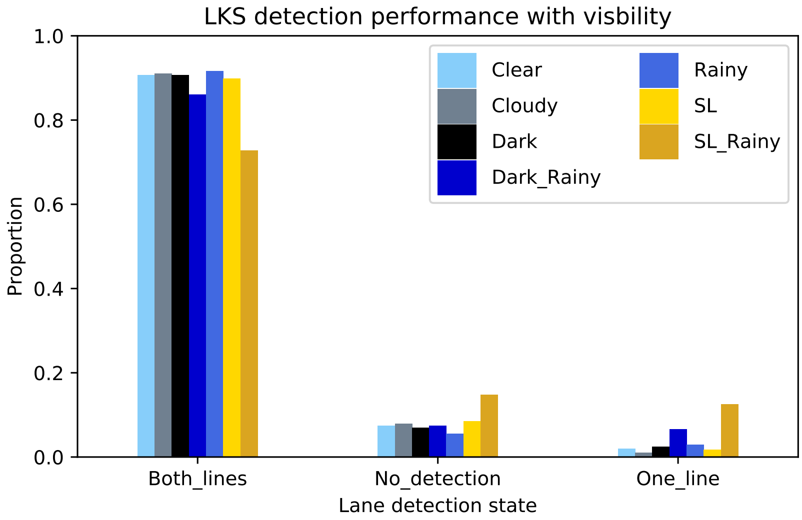


Figure 6.1: LKS Detection distribution at different visibility conditions

Figure 6.2 shows the distribution of detection categories with visibility conditions for the LDW. Here again, most of the states are both lines detected. Here, the distribution is less uniform than for the LKS. There are two evident deteriorations in both lines detection in the “Dark_Rainy” and “SL_Rainy” conditions. This trend is similar to the LKS’s both lines detection. However, for the LDW, the drop in performance is much more pronounced. It is also worthwhile to note that both lines detection in “Dark” condition is the highest compared to other conditions. These results will also be discussed later in this Chapter.

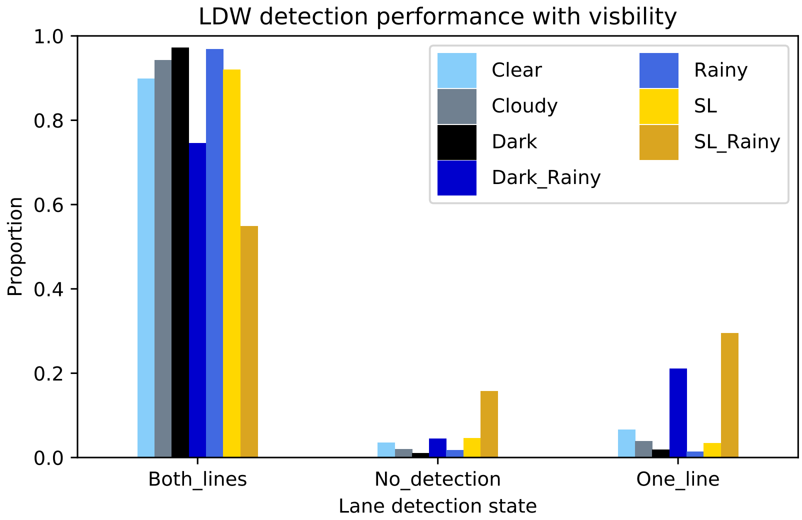


Figure 6.2: LDW Detection distribution at different visibility conditions

Similar to visibility, the effect of speed on detection performance can be studied. Figure 6.3 shows the distribution of detection states of LKS at the defined speed categories. Here again, the distribution is normalised for the duration of driving in each of the speed categories. Therefore, the proportion of both lines, one line, and no lines detected add up to 1 for each speed category. Again obviously, both lines detection constitutes the majority. The share of both lines detected increases sharply from 60-70 kmph to 70-80 kmph but approximately staying the same from there. It is worthwhile to recall that the LKS activates from 65 kmph while accelerating, and remains active up to 60 kmph while decelerating. These results will also be discussed later in this Chapter.

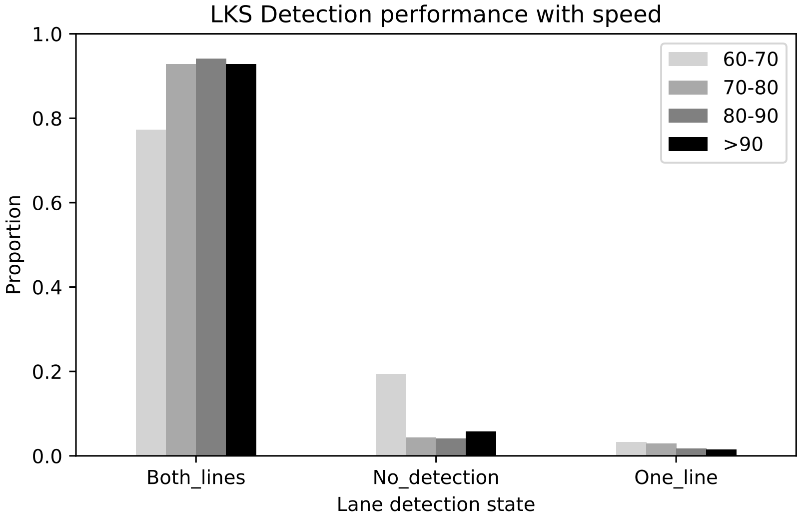


Figure 6.3: LKS Detection distribution at different speed categories

A similar distribution plot for the LDW is shown in Figure 6.4. Once again, the vast majority of the detection states is both lines detected. There seems to be a difference here as compared to the LKS with the both lines detection trend. Here, both lines detection seems to increase uniformly up to 70-80 kmph and then witnesses a slight decrease. As compared to the LKS, there are fewer instances of no lines detected and more instances of one line detected. Further discussion of these results is done later in this Chapter.

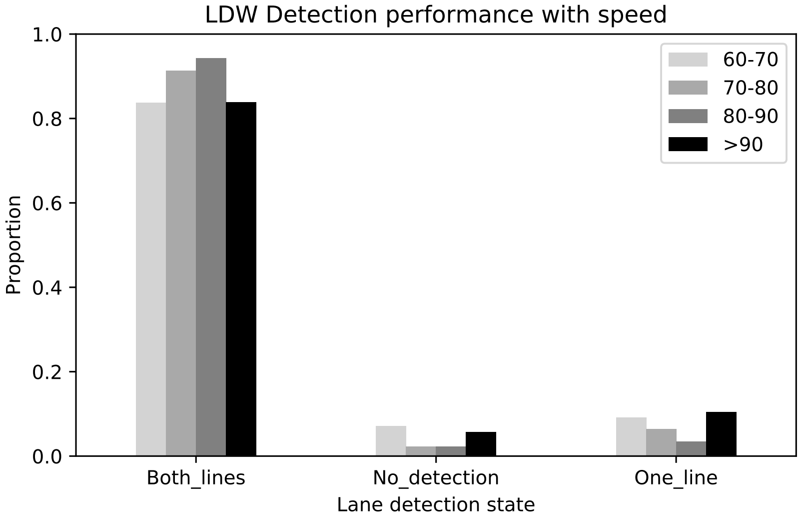


Figure 6.4: LDW Detection distribution at different speed categories

6.1.2. Lane Keeping Performance

As already discussed in Chapter 5, the lane position is calculated every second for one of the day test drives. As it was only one test session, there was no variation of visibility conditions.

Figure 6.5 shows a box plot to visualise the change in Lane position at different speed categories. There is a tendency of Lane Position to move towards the negative side, which by the definition of the formula means that it keeps to the left side of the lane centre. There is also a tendency to keep towards the right for speeds above 90 kmph. These results are filtered to include the instances when the LKS was in control of steering, to exclude the human driver behaviour.

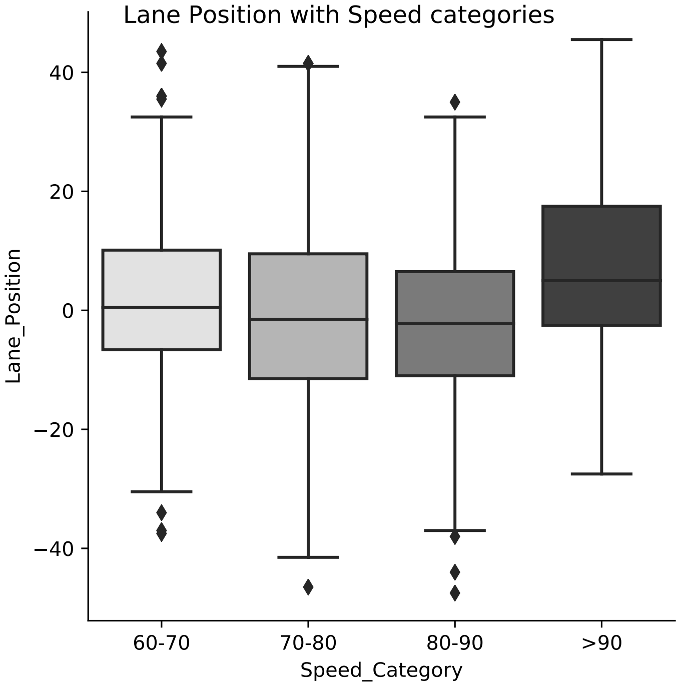


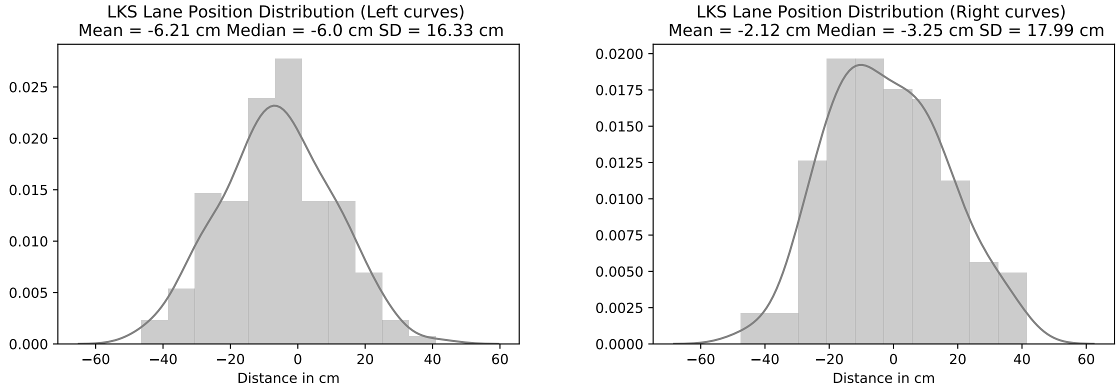
Figure 6.5: Lane positions at different speed categories

As discussed in Chapter 5, the nature of curves was logged for this test drive, namely Left curves, Right curves, and Straight sections. Figure 6.6 shows the distribution of the lane position on these three sections. Figure 6.7 shows a box plot of Lane Position for the different sections.

The Median is a better measure to compare the distributions than the Mean. As the purpose is to understand the behaviour of the LKS steering, it makes more sense to use the Median. Moreover, using the Mean increases the influence that human driving has on the position measurements (the human driver determines the Lane Position when the driver provides control to the LKS). That is, although the analysis excludes human driving, the instant of transition from manual driving to LKS, the position in the lane where this transition occurs depends on the human driver. Therefore, this has a larger effect on the Mean than the Median. Also, due to image recognition measurements, there are some extreme measurements, which impact the Mean. Therefore, from the figures, it can be observed that on Left curves, the LKS tends to keep more to the left (Median -6.0 cm) than on Right curves (Median -3.5 cm). On straight sections, the LKS tends to keep only a little to the left (Median -1.0 cm). The standard deviations of the Lane Position are also higher on curves than on straight sections.

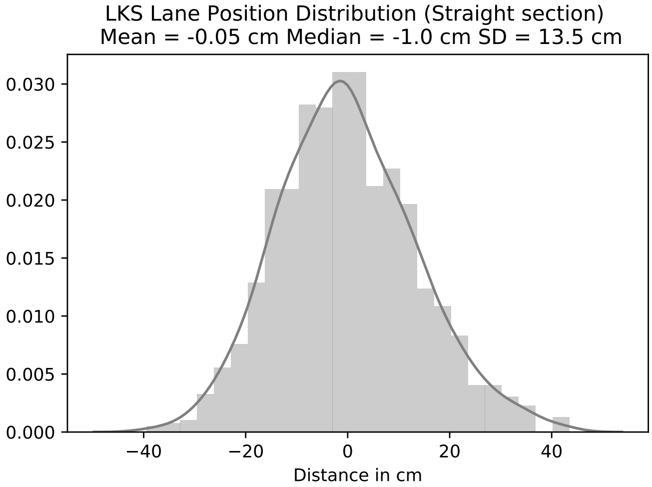
6.2. Regression Modelling

In order to get a better understanding of the data, especially to understand the effects that the driving environment has on the performance, this research proposes regression modelling. In order to build a regression model, it is essential to identify the predicted variable and



(a) Lane position distribution on Left curves

(b) Lane position distribution on Right curves



(c) Lane position distribution on Straight sections

Figure 6.6: Lane Position distributions on different sections

the predicting variable(s). As the objective of the model is to explain the performance of the LKS and LDW systems, the predicted variables must be performance indicators. Given the nature of data that is available, it makes sense to separate the regression modelling into two models. The first model focuses on detection performance (LKS and LDW), and the second model focuses on the lane-keeping performance (LKS). Building these models is discussed below.

6.2.1. Detection Performance models

In order to build a regression model for detection performance, the analysis identifies the predicted variable to be the detection state, which could take one of the three values: Both lines, One line, or No lines. The predicted variable is, therefore, categorical. The available predicting variables are Visibility condition and Speed category, which is possible for both the LKS and LDW systems for all the test sessions. For the day test session where lane position data is available, the regression model can also contain Curve type and Lane Width as predicting variables. First, building a regression model for all the test drives is discussed.

To get a sense of the data, some descriptive statistics are performed. First, the frequencies of the detection states, speed categories, and visibility conditions were calculated to get a sense of the distribution of the data. Also, the variables are re-coded for the purpose of statistical tests and regression. This is reported in Table 6.1. The re-coded values will be used consistently in all further analysis discussed henceforth. It can be seen that the “Both

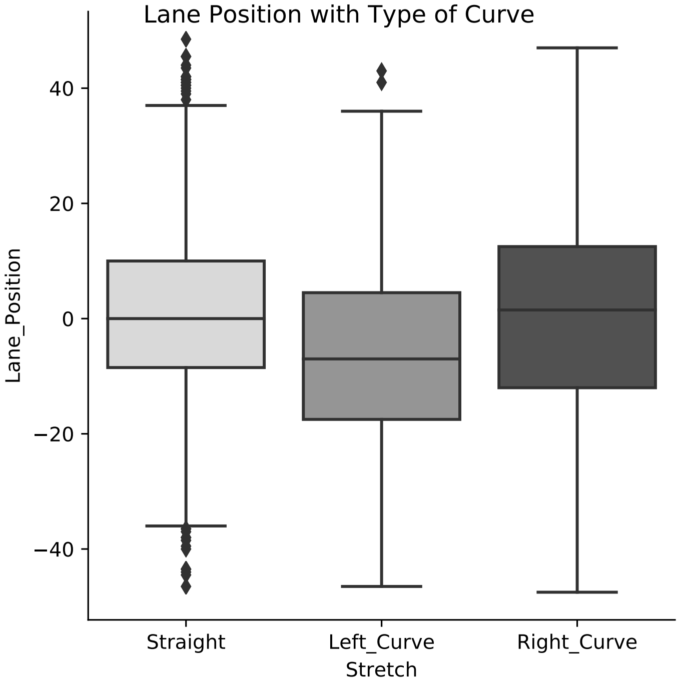


Figure 6.7: Lane positions on different curve types

lines" detection state greatly dominates the detection state variable.

Table 6.1: Frequency table and re-coding of Detection state, Speed category, and Visibility condition variables

Variable	Values	Re-coded value	Frequency	Percent (within variable)
Detection status	Both lines	2	89095	89.5
	One line	1	5842	5.9
	No lines	0	4563	4.6
	Total		99500	100.0
Speed category	60-70	0	23490	23.6
	70-80	1	51253	51.5
	80-90	3	19328	19.4
	>90	2	5429	5.5
	Total		99500	100.0
Visibility condition	Clear	0	21532	21.6
	Cloudy	1	23100	23.2
	Rainy	2	3758	3.8
	Dark	6	14599	14.7
	Dark_Rainy	3	10887	10.9
	SL	4	21542	21.7
	SL_Rainy	5	4082	4.1
	Total		99500	100.0

Next, the Speed and Visibility variables have been checked whether they have an association with the Detection states. As they are all categorical variables, Chi-Square test will be used to check the association of the predicting variables with the predicted variable. The cross tabulation between Detection state and Speed category is presented in Table 6.2, and the results of the Chi-Square test between them is presented in Table 6.3. The Chi-Square statistic is statistically significant at the 95% confidence interval. This indicates that the alternative hypothesis is true, which means that Detection State and Speed category are not independent of each other, so they have an association. Therefore, this justifies the choice of Speed category as a predicting variable for detection state.

Table 6.2: Cross tabulation of Detection state and Speed category

			Speed category			
			0	**1**	**2**	**3**
Detection state	**0**	Count	3169	1715	313	645
		Expected count	1379.2	3009.2	318.8	1134.8
	1	Count	1445	2323	317	478
		Expected count	1077.2	2350.4	249.0	886.4
	2	Count	18876	47215	4799	18205
		Expected count	21033.6	45893.3	4861.3	17306.8

Table 6.3: Chi-Square test: Detection state and Speed Category

	Value	**df**	**Asymptotic Significance (2-sided)**
Pearson's Chi-Square	3730.282	6	<0.001
0 cells (0.0%) have expected count less than 5. The minimum expected count is 248.97			

The cross tabulation between Detection state and Visibility conditions is presented in Table 6.4, and the results of the Chi-Square test between them is presented in Table 6.5. Again, the Chi-Square statistic is statistically significant. This indicates that the alternative hypothesis is true, which means that Detection State and Visibility conditions are not independent of each other, so they have an association. Therefore, this justifies the choice of Visibility conditions as a predicting variable for detection state.

Table 6.4: Cross-tabulation of Detection state and Visibility category

			Visibility category						
			0	**1**	**2**	**3**	**4**	**5**	**6**
Detection state	**0**	Count	1204	1250	172	690	1419	627	480
		Expected count	1264.2	1356.3	220.6	639.2	1264.8	239.7	857.2
	1	Count	889	515	94	1271	540	959	295
		Expected count	987.4	1059.3	172.3	499.3	987.9	187.2	669.5
	2	Count	19439	21335	3492	8926	19583	2496	13824
		Expected count	19280.3	20684.4	3365	9748.5	19289.3	3655.1	13072.3

Table 6.5: Chi-Square test: Detection state and Visibility Category

	Value	**df**	**Asymptotic Significance (2-sided)**
Pearson's Chi-Square	6460.581	12	<0.001
0 cells (0.0%) have expected count less than 5. The minimum expected count is 172.34.			

With respect to the one test session where Lane width and Curve type data is available, it could be interesting to check if any of them have an association with the detection state. To make it more useful and representational of reality, the Lane width is divided into 5 categories: <250 (re-coded as 0), 250-270 (re-coded as 1), 270-290 (re-coded as 2), 290-310 (re-coded as 3), and >310 (re-coded as 4). The cross tabulation between Detected states and

Lane Width is shown in Table 6.6. It can be immediately observed that 7 cells (constituting 46.7%) have expected counts of less than 5. This violates the assumption of Chi-Square tests that not more than 20% of the expected counts must be below 5. Therefore, Chi-Square test cannot be used. Also, it is observable that the Detection States of 0 and 1 have extremely few observations. Therefore, there is too little information to conclude anything about association. So, the possible effect of Lane Width on Detection state is ignored. The cross tabulation between Detection state and Curve type (re-coded as 0 for straight sections, 1 for left curves, and 2 for right curves) is shown in Table 6.7.

Table 6.6: Cross-tabulation of Detection state and Lane width category

			Lane Width				
			<250	**250-270**	**270-290**	**290-310**	**>310**
Detection state	**0**	Count	1	2	24	9	6
		Expected count	3.3	10.3	22.0	5.1	1.3
	1	Count	1	1	2	0	0
		Expected count	0.3	1	2.1	0.5	0.1
	2	Count	117	372	773	177	40
		Expected count	115.4	363.7	774.9	180.4	44.6

Table 6.7: Cross-tabulation of Detection state and Curve type

			Curve type		
			Straight	**Left_curve**	**Right_curve**
Detection state	**0**	Count	83	10	17
		Expected count	88.6	10.6	10.8
	1	Count	10	4	3
		Expected count	13.7	1.6	1.7
	2	Count	2544	302	300
		Expected count	2534.7	303.7	307.6

In order to estimate a model that predicts the Detection state using the Speed category and Visibility condition, the model type needs to be selected. A single model is estimated for both vehicles as the objective here is to estimate the effect of driving conditions on Lane Assistance Systems, and not individual vehicles specifically. As the predicted variable is categorical with three values and the predicting variables are also categorical, a Multinomial Logistic Regression model is chosen. As different systems/vehicles would probably have inherently different levels of performance, a mixed model with a random intercept is estimated. The coefficients of the predicting variables are assumed to be constant. The SPSS tool is used to build the regression model. To build the model, the "Generalized Mixed Linear Model" is used in SPSS (Version 25), as the distribution of the predicted variable (that is, detection states) is not normally distributed. The model incorporates the variables Speed category and Visibility conditions as Fixed effects and adopts a random intercept. The coding of variables is the same as previously used. The reference predicted variable is set to "No lines detected". The next section presents and discusses the results.

Results

Firstly, the observed and predicted detection states is tabulated in Table 6.8. As is seen, the model only predicts "Both lines" detection, without predicting any "No lines" detection or "One line" detection. This is attributed to the dominance of the "Both lines" state in the detected states data. The estimated fixed coefficients for “Both lines” detected, with “No lines” as reference category, are presented in Table 6.9.

Table 6.8: Observed vs Predicted Detection states - GLMM

Observed	Predicted		
	One_line	Both_lines	No_detection
One_line	0.0%	100.0%	0.0%
Both_lines	0.0%	100.0%	0.0%
No_detection	0.0%	100.0%	0.0%

Table 6.9: Fixed Coefficient estimates for Both Lines detection - GLMM

Model term	Coefficient estimate	Standard Error	95% CI	p value
Intercept	3.818	0.423	[2.989, 4.648]	<0.001
Clear Visibility	-0.377	0.056	[-0.487, -0.267]	<0.001
Cloudy Visibility	-0.260	0.056	[-0.370, -0.151]	<0.001
Rainy Visibility	0.190	0.093	[0.008, 0.372]	0.041
Dark_Rainy Visibility	-0.544	0.063	[-0.668, -0.421]	<0.001
SL Visibility	-0.383	0.055	[-0.492, -0.275]	<0.001
SL_Rainy Visibility	-1.750	0.067	[-1.881, -1.619]	<0.001
Dark Visibility		*(Reference value)*		
60-70	-1.542	0.045	[-1.630, -1.454]	<0.001
70-80	-0.006	0.047	[-0.099, 0.087]	0.907
>90	-0.590	0.072	[-0.730, -0.449]	<0.001
80-90		*(Reference value)*		

For the Visibility conditions, all the estimates are significant at 95% and therefore also significantly different from the reference condition (Visibility = 6, or “Dark” condition). The estimates are all negative, except for the Visibility 2 (“Rainy”) condition. The interpretation is that as compared to the “Dark” condition, all other visibility conditions, except for the “Rainy” condition, have a lesser probability of “Both lines” detected. So, when driving in “Rainy” condition as compared to “Dark” condition, there is a higher probability of “Both lines” detection. This may be counterintuitive but explained by almost all the “Rainy” conditions logged in the test being “Light Rain”. The visibility conditions can also be ranked (as compared to “Dark” condition), in decreasing order of probability of “Both lines” detected. The order is as follows: “Rainy”, “Cloudy”, “Clear”, “Streetlights”, “Dark and Rainy”, and “Streetlights and Rainy”. The rainy night conditions are the “worst-performing”, but the day rainy condition “best performing”. This result, however, this must be considered with the distribution of rainy conditions during the test, as it was mostly light rain (refer Figure 5.1).

For Speed categories, except for the 70-80 kmph category (Speed = 1), the other categories have significant estimates at 95% and therefore also significantly different from the 80-90 kmph category (Speed = 3). It also means that the 70-80 kmph category is not significantly different from the 80-90 kmph category. Driving at 60-70 kmph or >90 kmph, as compared to at 80-90 kmph, has a lower probability of having “Both lines” detection. The chance of “Both lines” detection is more than twice at >90 kmph than at 60-70 kmph, with respect to 80-90.

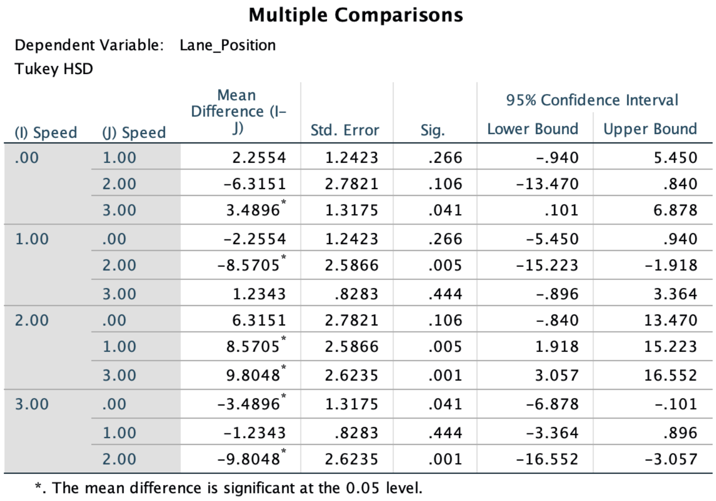
6.2.2. Lane Keeping Performance model

The regression model for lane-keeping performance has the predicted variable identified as the Lane Position. The commonly adopted norm is to use Mean Lateral Position as the indicator as it is useful to evaluate the lane-keeping performance on specific stretches of road that are of a fixed length. This research, however, looks to evaluate performance on a temporal level, as the objective is to evaluate the performance while driving in different environmental conditions. Therefore, it is decided to use the Lane Position as the predicted variable. The predicting variables are Speed category, Lane Width, and Type of Curves. The model does not include Visibility conditions as there were no visibility changes for the one test drive.

Figure 6.8 shows the Lane Position distribution, distribution of the Speed categories, Lane Width categories, and Type of Curves during this test session. As the predicting variables are all categorical, ANOVA test is used to see which variables have an association with the Lane Position. Moreover, a multiple comparisons test is done to see if there are significant differences in Lane Position between the categories of the variables.

The Multiple comparisons table for Speed Category is presented in Table 6.10. As can be seen, there are significant differences in Lane Position between the 60-70 category (Code 0) with 70-80 category (Code 3), and between 70-80 (Code 1) with >90 (Code 2) and between 80-90 (Code 3) with >90 (Code 2). Therefore, it can be said that there is a significant effect that Speed has on Lane Position.

Table 6.10: Multiple Differences table of Lane Position and Speed category



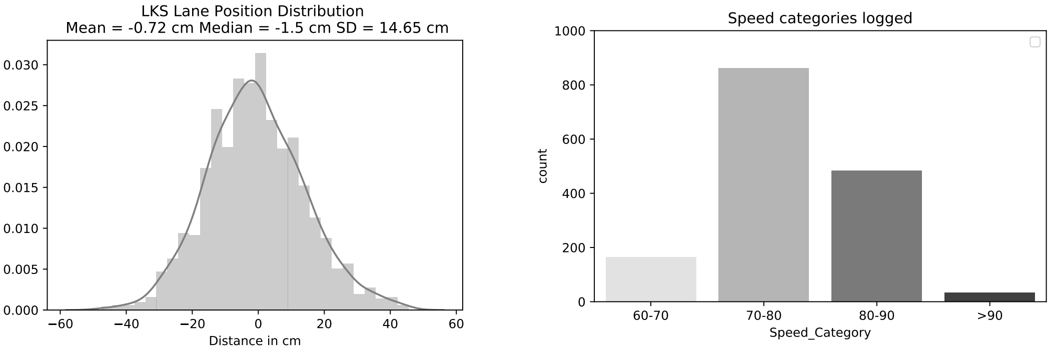
Multiple Comparisons

Dependent Variable: Lane_Position
Tukey HSD

(I) Speed	(J) Speed	Mean Difference (I–J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
.00	1.00	2.2554	1.2423	.266	-.940	5.450
	2.00	-6.3151	2.7821	.106	-13.470	.840
	3.00	3.4896*	1.3175	.041	.101	6.878
1.00	.00	-2.2554	1.2423	.266	-5.450	.940
	2.00	-8.5705*	2.5866	.005	-15.223	-1.918
	3.00	1.2343	.8283	.444	-.896	3.364
2.00	.00	6.3151	2.7821	.106	-.840	13.470
	1.00	8.5705*	2.5866	.005	1.918	15.223
	3.00	9.8048*	2.6235	.001	3.057	16.552
3.00	.00	-3.4896*	1.3175	.041	-6.878	-.101
	1.00	-1.2343	.8283	.444	-3.364	.896
	2.00	-9.8048*	2.6235	.001	-16.552	-3.057

*. The mean difference is significant at the 0.05 level.

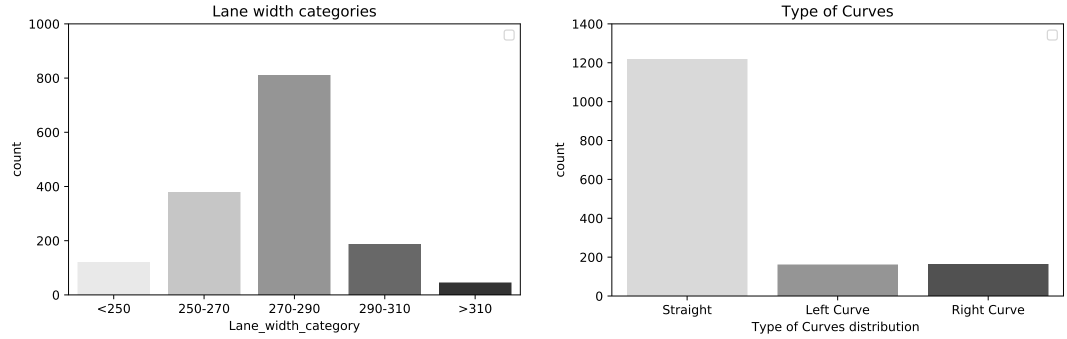
The Multiple comparisons table for Lane width Category is presented in Table 6.11. It can be observed that the only significant differences are between the <250 category (Code 0) and all other Lane width categories. There is no significant difference of Lane Position between the other Lane width categories. Therefore, it can be said that there is a significant effect that Lane width has on Lane Position. Moreover, given the high insignificance of differences



(a) Lane position distribution

(b) Distribution of Speed categories on the test session

Figure 6.8: Variables Distributions on the test session



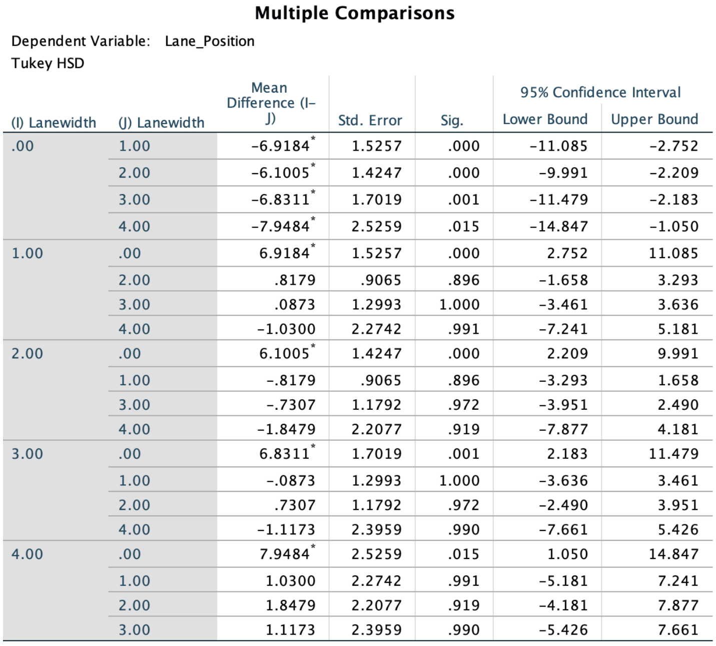
(c) Distribution of Lane widths on the test session

(d) Distribution of Type of Curves on the test session

Figure 6.8: Variables Distributions on the test session (contd.)

between the other categories, it is better to re-code the Lane width category as a binary variable (either <250 (Code 1), or otherwise (Code 0)).

Table 6.11: Multiple Differences table of Lane Position and Lane width category



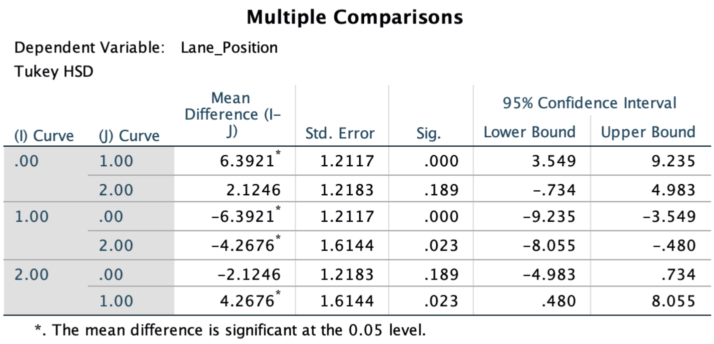
Multiple Comparisons

Dependent Variable: Lane_Position
Tukey HSD

(I) Lanewidth	(J) Lanewidth	Mean Difference (I–J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
.00	1.00	−6.9184*	1.5257	.000	−11.085	−2.752
	2.00	−6.1005*	1.4247	.000	−9.991	−2.209
	3.00	−6.8311*	1.7019	.001	−11.479	−2.183
	4.00	−7.9484*	2.5259	.015	−14.847	−1.050
1.00	.00	6.9184*	1.5257	.000	2.752	11.085
	2.00	.8179	.9065	.896	−1.658	3.293
	3.00	.0873	1.2993	1.000	−3.461	3.636
	4.00	−1.0300	2.2742	.991	−7.241	5.181
2.00	.00	6.1005*	1.4247	.000	2.209	9.991
	1.00	−.8179	.9065	.896	−3.293	1.658
	3.00	−.7307	1.1792	.972	−3.951	2.490
	4.00	−1.8479	2.2077	.919	−7.877	4.181
3.00	.00	6.8311*	1.7019	.001	2.183	11.479
	1.00	−.0873	1.2993	1.000	−3.636	3.461
	2.00	.7307	1.1792	.972	−2.490	3.951
	4.00	−1.1173	2.3959	.990	−7.661	5.426
4.00	.00	7.9484*	2.5259	.015	1.050	14.847
	1.00	1.0300	2.2742	.991	−5.181	7.241
	2.00	1.8479	2.2077	.919	−4.181	7.877
	3.00	1.1173	2.3959	.990	−5.426	7.661

The Multiple comparisons table for Type of Curve is presented in Table 6.12. There are significant differences in Lane Position between the Left curves and Right curves, as well as between Left and Straight sections. Therefore, there is a significant effect that the type of curve has on Lane Position.

Table 6.12: Multiple Differences table of Lane Position and Type of curve



Multiple Comparisons

Dependent Variable: Lane_Position
Tukey HSD

(I) Curve	(J) Curve	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
.00	1.00	6.3921*	1.2117	.000	3.549	9.235
	2.00	2.1246	1.2183	.189	-.734	4.983
1.00	.00	-6.3921*	1.2117	.000	-9.235	-3.549
	2.00	-4.2676*	1.6144	.023	-8.055	-.480
2.00	.00	-2.1246	1.2183	.189	-4.983	.734
	1.00	4.2676*	1.6144	.023	.480	8.055

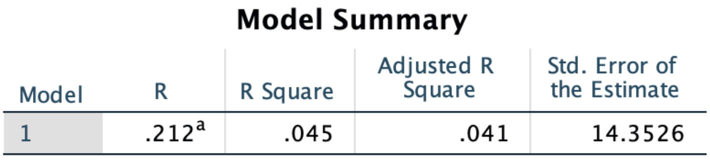
*. The mean difference is significant at the 0.05 level.

In order to now estimate a model that predicts the Lane Position using the Speed category, Lane width category, and Type of Curve, selecting the model type is needed. As the predicted variable is continuous, and the predicting variables are categorical, a Multiple Linear Regression model is chosen. The SPSS tool is used to build the regression model. The variables are dummy coded for each of its values. The next section presents and discusses the results.

Results

The Model Summary is presented in Table 6.13. The low R-square value means that there is a large amount of unexplained variations of the data from the fit regression line. There is, therefore, a need for more explanatory variables (such as steering wheel measurements, type of lane marking, quality of lane marking) which this dataset lacks. It may also be noted that the Random intercept effects were found to be insignificant (Significance of 0.480).

Table 6.13: Multiple Linear Regression model summary

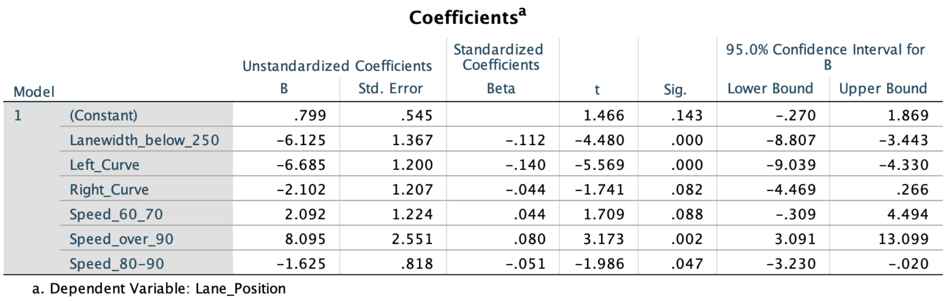


Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.212[a]	.045	.041	14.3526

The estimated coefficients are tabulated in Table 6.14. There is one value missing for each of the variables. Those are the reference categories. For example, the table shows the Left and Right curves coefficient estimates. The model captures the effect of the reference value (Straight section) in the constant term, when (Left curve = 0) and (Right curve = 0).

Table 6.14: Multiple Linear Regression model coefficient estimates



Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	.799	.545		1.466	.143	-.270	1.869
	Lanewidth_below_250	-6.125	1.367	-.112	-4.480	.000	-8.807	-3.443
	Left_Curve	-6.685	1.200	-.140	-5.569	.000	-9.039	-4.330
	Right_Curve	-2.102	1.207	-.044	-1.741	.082	-4.469	.266
	Speed_60_70	2.092	1.224	.044	1.709	.088	-.309	4.494
	Speed_over_90	8.095	2.551	.080	3.173	.002	3.091	13.099
	Speed_80-90	-1.625	.818	-.051	-1.986	.047	-3.230	-.020

a. Dependent Variable: Lane_Position

The significant effects are only from Lane width_below_250 dummy variable, the Left_curve dummy variable, the Speed_over_90 dummy variable, and the Speed_80-90 variable. Lane widths below 250 cm tend to make the vehicle steer in such a way that the Lane Position is about 6 cm more left than on roads having Lane widths over 250 cms. Also, driving on left curves makes the LKS to keep about 6.7 cms more left than on straight sections. Driving over 90 kmph tends the LKS to keep about 8 cm more right than 70-80 kmph (although, the amount of driving above 90 is very less, see Figure 6.5), and driving at 80-90 kmph tends the LKS to keep about 1.6 cm more left than 70-80 kmph.

6.3. Performance Evaluation Results

This section presents an overview of the performance indicators measured during the field test, with respect to the factors that this research studied.

First, Table 6.15 presents the performance thresholds of the indicators that were initially based on Literature, but adopted to the field test results. The performance indicators are evaluated according to these thresholds in different driving conditions.

Table 6.15: Performance evaluation thresholds for the Indicators

Indicator	**High Performance**	**Medium Performance**	**Low Performance**
Percentage No Lines Detection	<= 5%	>5%, <=10%	>10%
Percentage Both Line Detection	>90%	<=90%, >85%	<=85%
MLP[1]	<= +-2 cm	> +-2 cm, <= +-4 cm	> +-4 cm
SDLP	<= 15 cm	> 15 cm, <=30 cm	>30 cm

[1] Mean and Median Lateral Position

6.3.1. Detection Indicators

This research proposed two indicators for detection: Percentage Both Lines Detection, and Percentage No Lines Detection. These indicators are evaluated for both the LKS and LDW in different conditions. Tables 6.16 and 6.17 present the results of these indicator measurements in different visibility conditions and speed categories, respectively. Using the evaluation thresholds defined in Table 6.15 for the “Percentage Both Lines Detection” indicator, Clear, Cloudy, Rainy, and Dark are the “High Performance” driving conditions. Dark_Rainy ad Streetlights are the “Medium Performance” driving conditions, and Streetlights_Rainy is the “Low Performance”driving condition. Previous discussion showed that all conditions are significantly different from the Dark condition in terms of Percentage Both Lines Detection. Concerning the speed categories, 60-70 kmph has “Low Performance”, 70-80 kmph and 80-90 kmph have “High Performance”, and >90 kmph has “Medium Performance” for both the detection indicators. Previous discussion showed that only 70-80 kmph was not significantly different from the 80-90 kmph in terms of Both Lines Detection.

Table 6.16: Detection evaluation in visibility conditions

Visibility category	**Percentage Both Lines Detection**	**Percentage No Lines Detection**
Clear	90.3%	5.6%
Cloudy	92.4%	5.4%
Rainy	92.9%	4.6%
Dark	94.7%	3.3%
Dark_Rainy	82.0%	6.3%
Streetlights	90.0%	6.6%
Streetlights_Rainy	61.6%	15.4%

Table 6.17: Detection evaluation with speed categories

Speed category (kmph)	Percentage Both Lines Detection	Percentage No Lines Detection
60-70	80.4%	13.5%
70-80	92.1%	3.3%
80-90	94.2%	3.3%
>90	88.4%	5.8%

6.3.2. Lane-Keeping Indicators

The analysis considered three factors that affect lane-keeping performance: Lane width, Type of Curve, and Speed category. This research uses three indicators for evaluating lane-keeping performance: Mean Lane Position, Median Lane Position, and Standard Deviation of Lane Position. Tables present the indicators measured in different Lane widths, Curve types, and Speed categories, respectively. Lane width less than or equal to 2.5 m cause the LKS to have “Low Performance”, and lane width above 2.5 m cause the LKS to have “High Performance”. While the Mean (and Median) Lane Position is significantly more Left on lane widths less than or equal to 2.5 m, the SDLP is lower than the SDLP on lane widths greater than 2.5 m. This suggests that the vehicle manufacturer intended this kind of lane-keeping performance. As for curves, the MLP on Left curves is significantly more left than on Straight sections and Right curves, and is classified as “Low Performance”. The MLP for right curves is not significantly different from Straight curves as previously discussed. Concerning the speed categories, only the >90 kmph sees “Low Performance”. Earlier discussion already indicated the low duration of driving at >90, and hence may be due to other specific situational factors. All other speed categories see “High Performance” in terms of MLP.

Table 6.18: Lane-keeping performance evaluation with Lane width

Lane width	Mean Lateral Position (cm)	Median Lateral Position (cm)	SDLP (cm)
Less than or equal to 2.5 m	-6.69 (Left)	-6.50 (Left)	10.97
Greater than 2.5 m	-0.21 (Left)	-0.50 (Left)	14.82

Table 6.19: Lane-keeping performance evaluation with Type of Curve

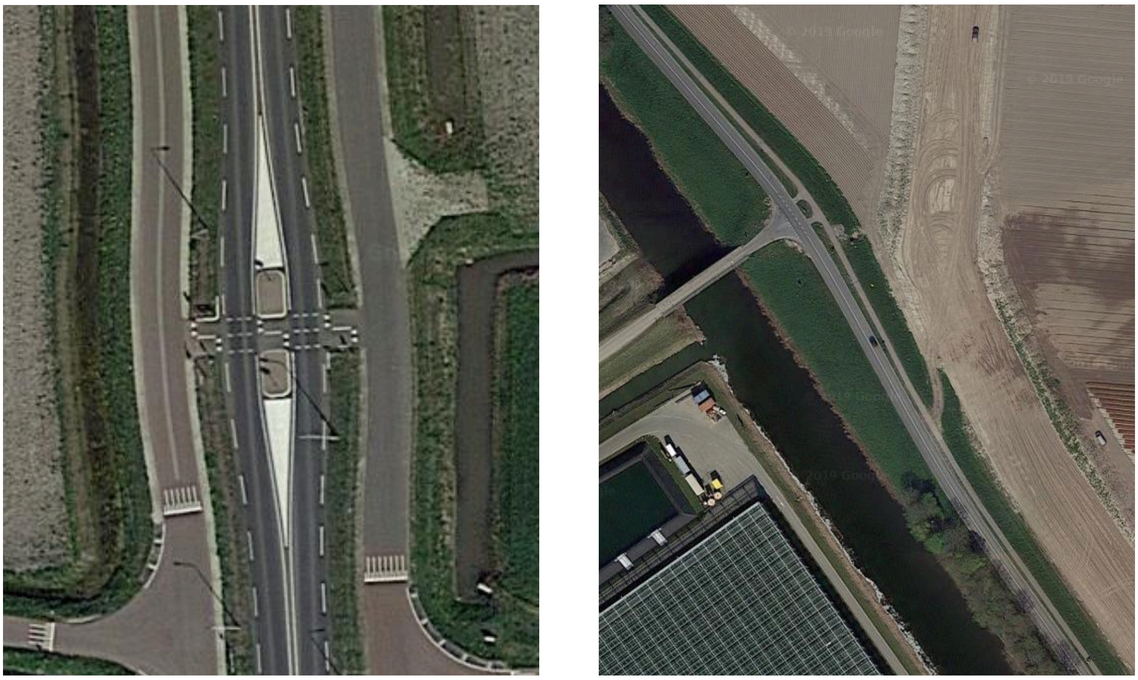
Curve Type	Mean Lateral Position (cm)	Median Lateral Position (cm)	SDLP (cm)
Straight	0.18 (Right)	-0.50 (Left)	13.72
Left Curve	-6.21 (Left)	-6.00 (Left)	16.38
Right Curve	-1.94 (Left)	-3.00 (Left)	18.11

Table 6.20: Lane-keeping performance evaluation with Speed category

Speed category (kmph)	Mean Lateral Position (cm)	Median Lateral Position (cm)	SDLP (cm)
60-70	1.50 (Right)	0.50 (Right)	14.92
70-80	-0.75 (Left)	-1.50 (Left)	15.09
80-90	-1.99 (Left)	-2.25 (Left)	13.13
>90	7.82 (Right)	5.00 (Right)	18.98

6.4. Field Test Observations

In addition to the insights obtained from the data analysis, this study saw some other insights during the conduction of the field test, which were not scientifically measured nor statistically tested. However, these observations are still interesting and useful. Experience from the field test showed that at medians for bicycle crossings, the LKS is unable to steer well enough. Figure 6.9a shows a top view of such a median. Another instance was on sharp reverse curves (see Figure 6.9b). The LKS failed at keeping the vehicle off the lane edge in these situations. Therefore, the combination of the speed limit of the road and the radius of the curve is essential to design for a safe driving experience.



(a) Sharp median crossing - Top view

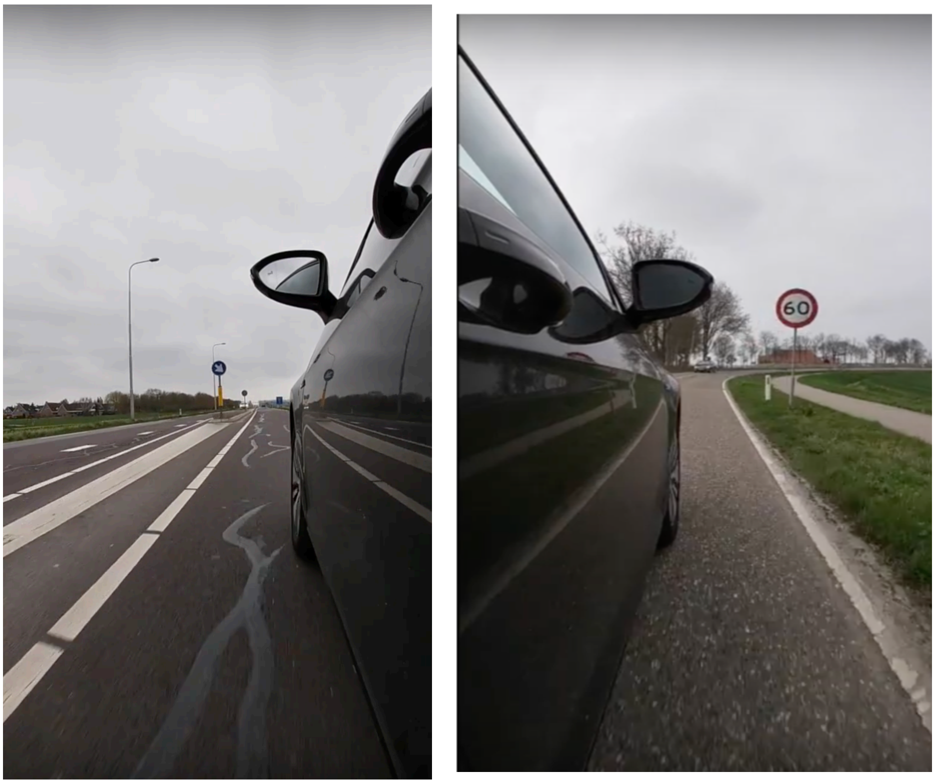
(b) Sharp reverse curve - Top view

Figure 6.9: Example situations of curves on the road where the LKS failed

Te field test also revealed that reconstructed roads have marks remaining from the old roads that are still visible on the pavement of the new roads (Figure 6.10a shows an example). The LKS starts following the old road marking thus deviating from the lane. Therefore, reconstructed roads must be adequately checked to remove such old road visibility. Similarly, asphalt repair patches, as shown in Figure 6.10b tend to confuse the Lane Assistance Systems that may cause them to identify these patches as the lane markings, leading to unsafe driving. Therefore, patchworks must not be visible.

Experience from the field test reinstated the importance of curves in many instances. On some very sharp curves during the field test, speed limit signs indicated slowing down from 80 kmph (the standard speed limit on provincial roads) to 60 kmph (see Figure 6.10c). However, the sign placement was too close to the curve, not providing enough time for the driver to take control of the LKS. Therefore, the Road Authority should first design the curves with a radius on which LKS systems can operate. Otherwise, it is advisable to have speed reduction signs well ahead of the curves providing drivers sufficient time to take control. It can also be useful to provide Infrastructure to Vehicle communication at curves to let the vehicles with LKS know to slow down or to ask the driver to take control.

(a) Visible marks from reconstructed roads



(b) Asphalt repair marks

(c) Speed limit signs placed too late

Figure 6.10: Example Infrastructure Issues

This Chapter discussed the performance of the LKS and LDW with different factors. Regression models were also developed to estimate the effect of the factors on the performance. Finally, some experiences from the field test were also discussed. From the field test results and the regression models, Levels of Service of the driving environment can be determined.

7

Conclusions and Discussion

7.1. Research Overview

While ADAS systems are becoming increasingly popular on the roads, this is being driven not only by the market but also by the authorities on the presumption that more ADAS in cars will lead to safer roads. As of 2022, the new EU regulation makes it mandatory that all vehicles sold in the EU will have a set of automated safety systems to increase safety on roads. These include Lane Assistance systems. There are various automated vehicles already operational in several places, especially in the USA. So, automated vehicles (though, at lower levels of automation) are no more only whims of the market, they are being and going to be increasingly promoted and introduced by the governments to the citizens. While the intention of ADAS is undoubtedly to improve the safe driving behaviour, the limitations of these technologies is a matter that all parties need to address seriously. Therefore, this research investigated the performance of commercially available Lane Assistance Systems (LKS and LDW) and aimed to formulate road infrastructural recommendations to the road authority - the Province of North-Holland (PNH) - to increase the safe performance of these systems.

This research adopted a two-level approach. First, a Systems theoretical perspective was adopted to conduct an extensive risk analysis of the Lane Assistance System - Driving environment interaction process. Second, a field test was conducted to collect empirical data of these systems driving on provincial roads and the performance was evaluated using specific metrics. This Chapter discusses the results and conclusions of these two approaches, and reflects on the methodology and also Literature findings. This Chapter concludes with the limitations of this research.

7.2. Road Infrastructure Requirements

The main research question was ***"What changes need to be made to the road infrastructure to increase the safe performance of Level 1 Automated Vehicles with Lane Assistance Systems?"***. This section discusses the results of the STPA and the field test to answer this research question.

Firstly, Table 7.1 presents the results of the STPA in the form of Infrastructure requirements. The RSRs (4.3) and the Additional RSRs (4.4) derived and presented in Chapter 2.4 are combined to form the final Infrastructure Requirements in Table 7.1. In addition to these requirements, insights obtained from the field test are translated into Infrastructure Recommendations.

Table 7.1: Infrastructure Requirements

Infrastructure Requirements from STPA
- Roads must have a pavement design and drainage system well enough to prevent slippery roads for vehicles.
- There must be a sufficient transition section between two simultaneous reverse curves, taking into account the max steering torque of the vehicle, the speed limit of that road stretch, the width of the lane, the radius of the curves, and reaction time of the LKS.
- Reduced speed limit signs must be placed well before sharp curves to enable safe manual takeover by the driver.
- There must be a sufficient transition section between two simultaneous curves, taking into account the max steering torque of the vehicle, the speed limit of that road stretch, the width of the lane, the radius of the curves, and reaction time of the LKS.
- Lane markings must be sufficiently distinct and recognisable, offering high contrast with the pavement.
- There must not be high contrast differences between pavement and immediate shoulder of the road that might be recognised as the lane edge.
- Lane markings must be consistent with respect to the function of the road they are on, to ensure that LKS cameras can be better trained to detect them.
- The radius of the curves must be such that the vehicles can navigate them taking into account the max steering torque, the width of the lane, the speed limit of that road stretch, and reaction time of the LKS.
- The road and roadside infrastructure must be designed to assist the detection of the lane markings to prevent high contrast differences with objects other than lane markings, but also to prevent contrast reduction between lane markings and the pavement in different visibility conditions.
- There must be no marks remaining from reconstructed roads that might indicate lane boundaries different from the new actual lane boundaries.
- The road design must be done taking into account the Sight Distance of the cameras of these automated systems and Reaction Time needed for execution of LKS steering correction.
- There must not be roadside objects that cast shadows resembling lines (such as crash barriers, from roadside buildings or other infrastructure, or from trees that have a particularly long bark).
- There must be no asphalt repair patches on the road that might be recognised as a lane marking.
- The width of the lanes must be designed to safely accommodate the safe lane position limit of the LKS vehicles.

The presented Infrastructure Requirements assume a certain level of basic infrastructure. These assumptions are:

- The road pavement is smooth without deterioration and/or potholes.
- At least some kind of lane markings exist on the road.
- Speed limit of the road allows the Lane Assistance Systems to be active.
- The lane width is at least as wide as the vehicle.

For Lane Assistance Systems, detection is the first and crucial part of the process that determines performance. The Road Authority must make road infrastructure changes from the perspective of visibility. Therefore, changes in the road infrastructure are not independent of the visibility conditions. For instance, detection performance is most poor in the dark under streetlights, especially when it is raining. The detection performance is poor also when it is not raining, under streetlights in the dark. Therefore, different types of lane markings can be adopted in the stretches where streetlights are present that can maintain a high contrast with the pavement even with the streetlight reflection on them.

The additional step in the STPA provided some recommendations in addition to the set of Infrastructure requirements by the entire STPA. These recommendations are:

- Digital I2V communication could be provided before curves to advise if manual takeover needs to be done.
- In situations of relatively high risk such as curves, rumble strips could be useful as lane markings to alert the driver when going over or beyond the lane marking boundary.
- High-friction road surfacing on relatively risky sections such as on curves
- Warning signs for drivers to be more alert and ready to take over control could be placed at critical sections.
- Speed limits could be reduced at critical sections such as sharp curves to mandate manual driving.

These infrastructure requirements and recommendations must be incorporated in combination with conventional road design guidelines and practices.

The operationalisation of the Refined Safety Requirements is demonstrated by classifying the field test results using performance thresholds. For instance, a Refined Safety Requirement was “The sensors must have an acceptable level of detection performance in different visibility conditions that could occur”. In order to evaluate the detection performance of the sensors, the classification shown in Table 7.2 is used. Thus, the sensors of this study have an acceptable level of performance in Clear, Cloudy, Rainy, Dark, and Dark_Rainy conditions (assuming only “High Performance” is acceptable for the “Percentage Both Lines Detection indicator). If the ”Percentage No Lines Detection“ indicator is used, then only the Rainy and Dark conditions have an acceptable level of performance. Thus, it is important to define the acceptable level of performance for the decided indicators.

Table 7.2: Detection evaluation in visibility conditions

Visibility category	**Percentage Both Lines Detection**	**Percentage No Lines Detection**
Clear	90.3%	5.6%
Cloudy	92.4%	5.4%
Rainy	92.9%	4.6%
Dark	94.7%	3.3%
Dark_Rainy	82.0%	6.3%
Streetlights	90.0%	6.6%
Streetlights_Rainy	61.6%	15.4%

Another Refined Safety Requirement was that ”The width of the lane must be designed to safely accommodate the safe lane position limit of the LKS vehicle“. The field test results showed the lane-keeping performance with lane width changes (presented in Table 7.3). Thus, the lane widths above 2.5 m can safely accommodate the LKS, but not lesser lane widths (assuming MLP as the indicator). The Road Authority, when considering to implement this Refined Safety Requirement, must conduct field tests to determine the performance of the vehicles on different lane widths, and then decide on the acceptable lane widths by looking at the acceptable performance level.

Table 7.3: Lane-keeping performance evaluation with Lane width

Lane width	Mean Lateral Position (cm)	Median Lateral Position (cm)	SDLP (cm)
Less than or equal to 2.5 m	-6.69 (Left)	-6.50 (Left)	10.97
Greater than 2.5 m	-0.21 (Left)	-0.50 (Left)	14.82

As discussed, this study conducted a performance evaluation of the LKS andLDW systems in different driving conditions, and classified the performance in well-defined thresholds. This classification forms the Levels of Service of the driving environment for those systems. Table 7.4 presents the Levels of Service of the ODD from the described classification.

Table 7.4: ODD Levels of Service

Level of Service	Visibility condition	Speed category	Lane width	Type of curve
High Performance	Dark, Rainy, Cloudy, Clear	70-80, 80-90	>= 2.5 m	Straight section, Right curve
Medium Performance	Streetlights, Dark_Rainy	>90		
Low Performance	Streetlights_Rainy	60-70	< 2.5 m	Left Curve

Figures 7.1a and 7.1b show the ”Highest“ Performing ODD and the ”Lowest“ Performing ODD, respectively, as derived from the results of the analysis.

(a) Highest Level of Service ODD

(b) Lowest Level of Service ODD

Figure 7.1: Highest and Lowest Levels of Service of ODD

Thus, this research systematically derived a set of Infrastructure Requirements and recommendations for Lane Assistance Systems. It also evaluated the performance of LKS andLDW systems in different driving conditions and estimated the effect of these conditions on the performance. This study also demonstrated the operationalisation of the Infrastructure Requirements by using performance thresholds from the field test results. Finally, ODD Levels of Service were derived to connect the driving environment to the expected performance of these Lane Assistance Systems. Thus, the Road Authority can adopt the Infrastructure Requirements using the operationalised ODD Levels of Service, and can also use the developed methodology to gain similar insights for other driving environment conditions and other Lane Assistance Systems.

7.3. Synergy of STAMP and Field test

As mentioned, this research conducted a thorough risk analysis of the System capturing the interactions between the Lane Assistance Systems and their driving environment using the STAMP framework and the STPA tool. This resulted in a final set of Refined Safety Requirements (Refer Appendix Tables A.7, A.8, A.9, and A.10). The test drive also gave rise to useful results (refer to Chapter 6). This section discusses the strength of the combination of these two methods.

One of the Refined Safety Requirements concerning infrastructure was ’■Lane markings must be sufficiently distinct and recognisable, offering high contrast with the pavement”. The results from the field test of the detection performance analysis for different visibility conditions show that the poorest performing visibility conditions are Streetlights with Rain, Dark and Rainy, and Streetlights. These two results fit together well as the contrast difference between the lane markings and the pavement decreases in the presence of Streetlights. Moreover, detection is better in the “Dark” condition than in “Clear” or “Cloudy” condition (Contrast difference between lane markings and the pavement is lesser during the day than during the night). This also warrants that the LKS systems must be improved to perform detection in these conditions better, which is what the Refined Safety Requirements’ Hardware Requirements (Refer Appendix Table A.10) prescribed.

There were some Refined Safety Requirements focused on curves. The RSRs stated that curves could have a significant effect on performance. For instance, it was prescribed (see Table 4.3) that *“The radius of the curves must be such that the vehicles can navigate them taking into account the max steering torque, the width of the lane, the speed limit of that road stretch, and reaction time of the LKS”.* The performance evaluation of Lane Position showed that there is a significant difference in Lane Position on Left curves than on straight stretches, where the vehicle keeps significantly more left. Therefore, this again supports the result from the STPA analysis.

One of the Additional Infrastructure Requirements includes that “The width of the lanes must be designed to safely accommodate the safe lane position limit of the LKS vehicle” suggesting that the width of the lane affects the performance. The results from the analysis also show that lane widths below 250 cm make the LKS to steer significantly more left than larger lane widths, but no significant difference between the wider lane width categories. Hence, there is perhaps a lane width threshold where the LKS has a different mode of operation below and above that threshold. This threshold for the particular system studied lies around 250 cms.

While the STPA was able to provide useful prescriptions, it certainly is not exhaustive. For instance, the analysis of the data from the field test shows that speed has a significant effect on LKS performance. However, the STPA completely missed this effect. This is due to the limited insight into the operation of the LKS algorithm itself. On the other hand, the STPA provided many recommendations such as those concerning the torque steering corrections, that the field test could not capture. Thus, System dynamics cannot be described entirely only by STPA or only the field test. Their combination enables a complete problem analysis.

7.4. Reflection on methodology

The methodology adopted in this research study provided two-fold learnings. Firstly, its ability to answer the research questions themselves is one aspect. The other aspect is the potential of this methodology to be reused not only to answer new questions stemming from this research but also in applications to evaluate other ADAS systems. This section critically reflects on the methodology adopted by this research and discusses its strengths and limitations.

The Systems Theoretic Accident Modelling and Processes (STAMP) model and the Systems Theoretic Process Analysis (STPA) tool proved to be a powerful tool to discover the complexities of the LKS operation, which itself is only at the initial levels of automation. The step-wise approach maintains a strong logic and connection between the entire process right until the end. Moreover, the analysis consistently focuses on the scope defined at the beginning where the System, Losses, and Hazards are defined. The method allows for a very well structured and guided analysis, yet enables the incorporation of aspects that require knowledge of the System and experience in the analysis. The STPA offered a well-structured taxonomy for identifying potential failures, and at the same time provided for experience and creativity to contribute to it. Defining the System as a Control problem provides a new perspective that makes the interactions in the System more clear. Another benefit of the STPA is its almost unlimited potential for analyses of a System. The extent of analysis is limited only by the depth of knowledge and information regarding the System operation. This also means that the System can be analysed at multiple levels, from a broad functional level to a detailed sub-component level analysis.

While the STAMP and the STPA certainly proved to be very useful, using this method has some limitations. Firstly, although the method maintains a good connection from the definition of the Hazards to the end, there is a weak link to the possible Losses resulting from a Hazard. The method lacks a probabilistic approach to classify the Unsafe Control Action (UCA)s and Hazards to the Losses. For instance, the probability of a fatal crash when the vehicle deviating from the safe lane threshold on a straight section is lesser than on a curve. The method misses this link from the failure scenario to the probability of a Loss. Providing a link between the UCAs and the Losses through the probability of Loss occurrence would increase its effectiveness. Another “limitation” of the method is that although it provides a useful taxonomy of possible failures to guide the analysis, there is a significant dependency on the knowledge about the System and the components. The method depends on the amount of information about the System that is input.

Additionally, the method can be a rather time-consuming process to work from the definitions step, drawing the control structure, formulating UCAs, identifying Loss Scenarios and finally to arrive at the Refined Safety Requirements. While it is an advantage of this method to allow focus on the defined scope, it is difficult to scope the depth of the analysis. This could also be an advantage that it offers a potentially vast depth of analysis. Nevertheless, the effort multiplies exponentially for every level deeper into the operations.

The field test proved to be invaluably useful. Field tests are probably the best way to test the performance of a System (structured experiments are useful as well) as it results in getting the “ground truth”. Driving with the two vehicles on the road gave rise to a lot more insights into their functioning. This was useful in performing iterations of the STPA analysis to incorporate additional failure scenarios and also to increase the extent of specificity of the analysis. The field test analysis showed the effect of speed on detection performance. The STAMP analysis could not predict this effect due to the limitation of the insights into the functioning of the system. Furthermore, as already stated, it is possible to capture the actual effect of the driving environment on the performance of the systems. While the field test was useful, there are limitations also with this method for performance evaluation. It may not be able to capture all the different possible scenarios that can be encountered by the systems. There is also obviously a heavy dependence on the extent and quality of the data collected. Besides, the results are valid for those specific scenarios and limited to the observations. Thus there is little opportunity to gain a macroscopic understanding of the relationships existing between the components of the System and to extend it to other Advanced Driver Assistance Systems (ADAS).

7.5. Reflection on State of the Art

It is essential to reflect the findings of this research in the light of state of the art on infrastructure for lane assistance systems that Chapter 2 discussed.

The first point of discussion is the inconsistency between the expectations of research from Lane Assistance Systems and the present scenario of these systems. The vast majority of studies that look at the infrastructure requirements for Lane Assistance Systems expect that these systems are high performing as the studies consider higher levels of automation (Level 4 and 5), as well as complete, or near-complete market penetration. At the current state of development, full automation is a distant reality expected by some studies only around 2075 (Lu 2018). Until then, there would be dynamic changes in the development of automated vehicles, towards increasing levels of automation, simultaneously increasing the performance of their Advanced Driver Assistance Systems (ADAS). Therefore, it is only natural to expect that these intermediate levels of automation will not be perfect. Road authorities must acknowledge this and take appropriate measures in the road infrastructure to increase safety not only for these vehicles equipped with ADAS but also for other human traffic that participates on the road and interact with these automated systems.

One of the most common change in road infrastructure expected is that lane widths can be reduced as Lane Assistance Systems are able to keep consistently to a specific position in the lane without deviations (Morsink et al. 2016, Farah et al. 2018, Huggins et al. 2017, Johnson et al. 2016). The field test showed that the position of the vehicle on the lane is inconsistent. The position depends on different factors such as speed, type of curve, and width of the lane. It also depends on other possible factors that this research did not study (such as lane marking configuration, type, quality, pavement characteristics, shoulder type, median type). This research also saw that the LKS fails to navigate sharp curves safely. Moreover, different manufacturers have different algorithms that run the LKS, and they currently have no standard guidelines on what is an acceptable good performance in terms of maintaining a position on the lane. Therefore, reduction in lane widths must be considered carefully after extensive study on the capabilities of the LKS, and certainly is not a measure that road authorities must implement immediately.

Aigner et al. (2017) predicted the ODD for a Level-4 autopilot system. It is interesting to compare this with the findings of this research to see the current status of these ADAS systems. It focused on the lane marking being of at least a certain quality, assuming that the camera detects the location of the lane border. This indicates that the detection is done by recognising line borders on the road. The recommendation of this research to avoid other “lines” in the environment can be incorporated in the findings of Aigner et al. (2017). When expecting the ODD in terms of weather conditions, Aigner et al. (2017) did not identify street lighting to have a role. This research finds that street lights cause a significant deterioration in detection performance, especially in rainy conditions.

García (2019) conducted a pilot test with a Lane Keeping System to study the effect of lane width on the share of control between the human driver and the Lane Keeping System. It was found that the Lane Keeping System cannot operate on lane widths less than or equal to 2.5 m, and it always can operate on lane widths greater than or equal to 2.75 m. It was argued that lane widths could not be reduced at the current level of automated vehicle development. The field test conducted in this research reveals that the LKS is able to operate in lane widths less than 2.5 m as well. However, the performance reduces from “High Performance” at lane widths greater than 2.5 m to “Low Performance” at lane widths of 2.5 m and lesser. Thus, field tests done using different automated systems result in different results. Johnson et al. (2016) found that as the lane width decreases, drivers tend to depart further away from the lane centre. This is similar to the LKS driving behaviour on lane widths smaller than 2.5 m. Thus, there is a similarity between human driving behaviour and the LKS driving behaviour with respect to lane widths.

Nitsche et al. (2014) qualitative results on the most influencing factors for Lane Assistance Systems based on literature review and experts’ and stakeholders’ opinion predicted that the factors having a “High” influence were “Complex Road Environments”, “Quality of lane markings”, “Poor visibility due to bad weather”, “Temporary work zones”, and “Discontinuous or damaged road edges or kerbs”. Weather (or visibility condition) significantly affects the performance of the Lane Assistance Systems as seen in this research. Das et al. (2019) found that lane-keeping performance of drivers deteriorated in poor visibility conditions as compared to good visibility conditions. This shows that visibility conditions also affect human lane-keeping performance. Road works can be an essential aspect as the test showed that the LKS sometimes recognises the edge of the road, or asphalt repair patches as the lane marking. Therefore, it is very likely that it would struggle to perform well in the presence of temporary lane markings at road works. As the test drive in this research was on provincial roads, the speed limit at road works was 50 kmph, which was lesser than the threshold required for activation of the LKS; hence it could not be tested. Nevertheless, it is undoubtedly a significant scenario that needs to be studied.

Nitsche et al. (2014) also classified “Poor visibility due to darkness”, “Low curve radii”, and “Quality of streetlights” as factors having a “medium” influence on the performance of lane-keeping systems. The results of this research show that the detection performance is better in darkness, due to the high contrast between the pavement and the lane markings. Therefore, darkness by itself does not necessarily lead to the poor performance of lane detection. In the absence of streetlights, the detection will depend on other factors such as the type of vehicle headlights and the look-ahead distance for detection. Quality of streetlights play an essential role as shown by the test drive as the presence of streetlights decreases the contrast between the lane markings and the pavement. Low curve radii turned out to be a factor of primary importance, both from the STAMP model results, as well as the test drive. Therefore, it might be appropriate to classify it as a factor of “High” influence on performance. Nitsche et al. (2014) also suggested “Well-removed old lane marking remnants” as an important infrastructure requirement. Both the STAMP results and the experience from the test drive support this.

Morsink et al. 2016, in addition to proposing a reduction in lane widths, also proposed that the radius of curves could become smaller with automated vehicles. This is because they are expected to perform better and drive on curves at higher speeds. Morsink et al. 2016 also recommended to improve the quality and uniformity of lane markings and reduce the intensities of lights at intersections. As already discussed, the reduction of lane widths and the reduction of the radius of curves are not applicable until the performance of the systems is perfect, which is not the case currently. Reduction of the intensity of lights at intersections is an interesting recommendation. It could be extended to streetlights in general along the road, as high-intensity streetlights reduce contrast differences between the pavement and the lane marking.

Johnson et al. (2016) found that as the sharpness of curves increases, human drivers tend to move closer to the lane boundary (so, away from the lane centre). The results of this research show that the LKS moves significantly away from the lane centre on Left curves than on straight sections. This suggests that LKS driving behaviour similar to human drivers. This is an interesting observation for studies on human drivers’ trust in these automated systems.

There is a lot of focus on lane markings with respect to its quality and type (Catapult Transport Systems UK 2017, Huggins et al. 2017). It is suggested that lane markings must be consistent and of good quality as inconsistent lane markings could confuse the Lane Assistance Systems. This is not very conclusive from this research, as the detection relies on finding a “line” on the road, as opposed to identification of a “lane marking”. Lane markings that are different in configuration are not expected to have a significant effect as long as they can offer a “line” as required. Huggins et al.’s (2017) suggestion to provide different types of lane markings to cause different driving behaviours based on the lane markings may take time. However, as detection methods advance to include identification of lane markings and corresponding changes to the algorithm of these systems, the configuration of lane markings and its effect on performance becomes important.

7.6. Research Limitations

As with any research, there are limitations to this research. They are discussed below.

- Firstly, concerning the whole research, the scope of the System is limited to the Lane-Keeping System and the driving environment components. An important component is the human driver. The driver plays a crucial role in the performance of Lane Assistance Systems, especially Lane Keeping Systems. The interaction between the driver and the Lane Assistance Systems is beyond the scope of this research.
- Concerning the STAMP model, a crucial step is the drawing of the Control Structure. That is constructed based on the level of information known at the point of conduction

of this research. Detailed information such as the algorithm of the LKS is not known. Hence, that is a black box. Moreover, the assumptions on the LKS functioning are limited by the information available through accessible patents, resources, and experience from the test drive.

- The Unsafe Control Action (UCA)s, the Loss Scenarios, and the Refined Safety Requirement (RSR)s of the STAMP are not exhaustive. The STAMP model, in the form of the STPA analysis provides a good taxonomy to make an extensive analysis. However, there is still a dependence on the information and experience available with the System under consideration. Therefore, there could be even more UCAs, Loss Scenarios, and RSRs with the availability of deeper insights into the working of the System.
- The STPA results assume that all the Refined Safety Requirements are equally important. This is because of its inability to incorporate the probability of the occurrence of a Loss in case of a requirement not being met. This research attempted to develop a ranking system by conducting a survey to rank the Losses. However, the link between the Losses and UCAs was still not based on probability or any order of importance.
- The data collected in the field test on the visibility conditions were subjective. Data collection only noted if there was clear weather, rainy weather, or street lights. However, there was no data collection done for the objective visibility, such as lighting intensity of the street lights. Thus, the results are suggestive of the effect that visibility conditions have on the performance but unable to precisely estimate the effect of the variability of the conditions themselves (such as different intensities of street lights) on the performance.
- There was no data collected concerning the steering wheel, which could have been an important aspect. Thus there was no data on the time of application of steering correction or the extent of steering correction. The differentiating between the human driver steering and the LKS steering is done by manual logging by the co-driver. So, there is bound to be some errors. However, the delays in logging change of steering control have been corrected.
- Due to no data available on the lane marking type and quality, it was not possible to evaluate the effect that they have on the performance of the Lane Assistance Systems.
- There was also no data available concerning the specifications of the cameras that the LKS and LDW systems use. Therefore, this limited the insights into the effect of the sensor specification on the detection performance.
- The detection performance is measured from the dashboard of the vehicles. However, this indicates what the vehicles “think” they see. There is not necessarily an implication on the quality of infrastructure that they are driving on. However, there were only a few instances when there was an actual mismatch between the detection state and the actual presence of lane markings, as determined by a manual check.
- As the human driver is out of the research scope, the driving share between the human driver and LKS is excluded from the analysis. Different people may decide to take control at different points in various scenarios based on trust and other factors. This research did not explore this aspect.
- The data on the position of the vehicle on the lane was available only for one test session due to time and resource constraints. Therefore there could not be any insights into the effect of visibility conditions on the lane position. Also, the dataset was limited in size due to it being only one test session. Additional data could have resulted in more reliable results.
- This research does not accommodate for limitations with respect to budget constraints or other constraints on the feasibility of infrastructure changes.

8

Recommendations

Road authorities need to be aware of the nature of the interactions between the Lane Assistance Systems with the driving environment, and also the resulting risks. The STAMP model analysis provided an extensive and detailed overview of these interactions and their risks. It also specified certain safety requirements to meet in order to expect the safe operation of these systems on the roads. This, in combination with the results and experience from the test drive, resulted in infrastructure requirements and recommendations. In addition to this, this Chapter also discusses some recommendations stemming from this research.

8.1. Scientific Recommendations

8.1.1. STAMP

This research adopted a combined two-fold methodology in the form of the Systems Theoretic Accident Modelling and Processes (STAMP) model followed by the field test. For the STAMP model and Systems Theoretic Process Analysis (STPA) analysis performed, some aspects could lead to an even better and more extensive analysis:

- First, there should be a “probabilistic link” between the Unsafe Control Action (UCA) and the defined losses. Presently, there is a sort of “all-or-nothing” link between the two. That is, if an UCA occurs, then it is regarded that all the Losses associated with it occur; and if the UCA does not occur, then no losses associated with it occur. Incorporation of the probability of a Loss, given an UCA would provide a much better insight into the risk associated with that UCA.
- Similarly, there must be a link between the Loss Scenarios and the UCAs as the occurrence of a specific Loss Scenario could increase the probability of the corresponding UCA. Providing these probabilistic links would make the STPA analysis even more intensive and cumbersome. However, the added value in terms of operationalisation from conceptual to a more realistic analysis would be invaluable. Adding these probabilistic links, however, needs a much more detailed insight into the operation of the entire System that could be difficult to acquire.
- For the obtained Refined Safety Requirements (RSRs) at the end of the STPA, it is recommended to perform an appropriate classification for enhanced insights and usefulness of the results, as was done in this research by classifying them into Infrastructure related, In-vehicle Communication related, Algorithm related, and Hardware related requirements.
- After the deriving of Refined Safety Requirements (RSRs), this research also derived the Additional Refined Safety Requirements. This proved to be very effective, and future

use of this is recommended. Taking the example of the RSRs of this research, they were classified as Infrastructure related, In-vehicle Communication related, Algorithm related, and Hardware related. As this research was focused on Infrastructure, an additional step was done that looked at what role could Infrastructure play to support the RSRs of other categories. These "Additional Infrastructure Requirements" could be added to the list of Infrastructure related RSRs. This could similarly be done from the standpoint of other categories.

- After the deriving of the RSRs, in order to make the results more easy to use, it is recommended that appropriate indicators be identified to evaluate the extent of adherence to the requirements by the relevant System components. For instance, *"Lane markings must be sufficiently distinct and recognisable, offering high contrast with the pavement"* was one of the RSRs. Two indicators can be identified here: the visibility of the lane marking, and the contrast with the pavement. This assists in the operationalisation of the RSRs.

8.1.2. Field test

Several learnings from the field test would be useful to incorporate in future field tests with similar objectives:

- Firstly, understanding the actual mode of operation of the ADAS would be invaluable. However, the algorithms implemented in these systems are not publicly available. Therefore, it would be beneficial to collaborate with vehicle manufacturers. The insights would then make the results much more valuable.
- The specifications of the detection cameras/sensors used in these vehicles are also useful to know as it provides a better insight into the operations and assists in the selection of the systems used in the field test to ensure different sensors are tested if that is the objective.
- It is recommended to use more precise and reliable devices for measurements, such as CAN bus or LiDAR, as opposed to video cameras for measurements (that this research used for measuring the distance to the lane marking).
- In terms of data collected, it is recommended to collect lane marking quality and lane marking configuration data. This data would have added much value by providing much more insights into the factors that affect the performance of the ADAS.
- Steering wheel data is also highly recommended to be collected for evaluating ADAS such as LKS and LDW. This data would be useful in measuring indicators such as Steering Reversal Rate, Steering response time, and Number of steering reversals. These indicators are expected to add much more explanation to how the vehicle is driving.
- Future studies could find data on the roadside infrastructure useful as components along the road could affect the performance of the LKS and LDW systems.
- Finally, it is recommended to perform field tests with vehicles from different manufacturers, as done in this research, to account for market variability.

8.1.3. Recommendations for Further Research

In addition to the recommendations discussed above, there are also some recommendations for the research questions itself. Further research could focus on including additional ADAS, such as Adaptive Cruise Control (ACC), therefore also going from Level 1 to higher levels of automation. It would be interesting to see how the vehicle drives when these ADAS are used individually and also in combination. It is also crucial to study the interaction between the human driver and the ADAS, and how that affects the performance of the vehicle in different road environments. Furthermore, the effect that surrounding traffic has on the performance of the ADAS-equipped vehicle and also vice-versa are very interesting research questions. It is also recommended to look at other indicators of measurement, going from more traditional driving task related indicators to indicators connecting the driving environment such as the risk of the vehicle on the road caused due to components of the road infrastructure. Finally, it is also useful to perform similar studies not only on provincial roads but also on the national motorways.

8.2. Practical Recommendations

Apart from the specific infrastructure requirements derived from this research, some other practical recommendations stemming from this research are:

- Firstly, the road authority must adopt a new perspective of looking at infrastructure for ADAS-equipped vehicles. The traditional methods of design will no more be applicable. For this, the road authority must have an extensive understanding of the relationships that occur between the various components of the driving environment when such a vehicle drives in it. Therefore, it is recommended to maintain a detailed report on this to assist in road design, maintenance, and policy.
- The road authority must maintain an up-to-date digital database of the infrastructure that it manages. The resolution of this database would be useful when it covers components such as type of lane markings, their configuration, pavement type, and roadside infrastructure. It is advised to connect these components to the respective hectometer for easy reference.
- Additionally, a database for maintenance-related information is important. This could, for instance, contain the quality of the lane markings and pavement quality in addition to other aspects of the road. This database needs to be updated regularly after maintenance that must be periodic. A maintenance plan needs to be prepared to ensure that the Road Authority checks the components of the road infrastructure at the right time in order to take corrective action. Such a maintenance plan must contain the frequency of inspection, in addition to the inspection tasks such as what indicators to measure for the respective infrastructure components, and also a procedure for identifying and prioritising critically worn-out infrastructure.
- The basis of designing a road could need updating, in terms of the definition of the target user. The target user conventionally was a human-driven car, and therefore road design was done based on the characteristics of a human driver. With the advent of ADAS enabled vehicle, this might need a re-look. Basic parameters and definitions such as Sight Distance and Reaction Time might need to be updated, and consequently, the implications on road design must be discussed.
- Using a methodology like in this research, an evaluation of all the roads under the jurisdiction of the Road Authority can be made. From this, the Road Authority can identify the critical roads that are expected to see the worst performance of ADAS enabled vehicles, and set-up a prioritisation system to make improvements to these roads.
- There must be a collaboration among the road authorities to share knowledge and experience to ensure consistency in terms of road design standards, and also in terms of outlook towards ADAS enabled vehicles. Furthermore, a collaboration with the vehicle authority and also the vehicle manufacturers needs to be made to agree on the accepted performance standards for driving on the roads with mixed traffic. Such collaboration will result in a much clearer picture of what the road authorities can expect from these vehicles.
- Road authority can increase the awareness of drivers that use these vehicles by informing them of the limitations of these vehicles, especially at a scenario-specific level (for example, informing users that their ADAS systems might not work safely on curves or crossings, so they have to take precaution to stay alert)

There is an important role for the road authorities to fully understand and take proactive action to become ready for the incoming wave of automated driving. Car manufacturers also need to ensure that their systems are properly tested. The vehicle manuals must inform drivers better by clearly explaining the conditions and limitations of using the ADAS. A special driving license examination may be needed for those using ADAS as the tasks of drivers in such vehicles are increasingly becoming different from conventional driving tasks. Ideally, a close collaboration between road authorities and car manufacturers is required to ensure safer driving conditions. In any case, the automated vehicles wave is a reality, and the road authority must take a proactive stance to provide a safe driving experience for all the citizens.

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A

Appendix

Table A.1: Unsafe Control Actions and their corresponding Safety Requirements

UCA	**Corresponding SR**
UCA-1: In case of both lines detected, LKS does not steer back when vehicle deviates from lane centre beyond safe threshold [H1]	SR-1: In case of both lines detected, LKS must steer back when vehicle deviates from lane centre beyond safe threshold [UCA-1]
UCA-2: LKS provides unrequired steering correction when already within safe lane position threshold [H1]	SR-2: LKS must not provide steering correction when not required on a straight stretch [UCA-2]
UCA-3: LKS steering overcorrection due to steering applied too early ahead of the location where needed [H1]	SR-3: LKS must apply steering correction at the appropriate location where needed [UCA-3]
UCA-4: LKS steering correction stopped too soon, when longer duration was needed [H1]	SR-4: LKS steering correction must not be stopped before a certain duration [UCA-4]
UCA-5: In case of one-line detection, LKS does not steer back when vehicle deviates from lane edge beyond safe threshold [H1]	SR-5: In case of one-line detection, LKS must steer back when vehicle deviates from lane edge beyond safe threshold [UCA-5]
UCA-6: LKS provides too less steering correction [H1]	SR-6: LKS must not provide too less steering correction [UCA-6]
UCA-7: LKS steering correction applied too late, after the location where needed [H1]	SR-7: LKS must apply steering correction at the appropriate location where needed [UCA-7]
UCA-8: LKS steering correction applied too long, when shorter duration needed [H1]	SR-8: LKS steering correction must not be applied after a certain duration [UCA-8]
UCA-9: LKS provides excessive steering correction [H1]	SR-9: LKS must not provide excessive steering correction [UCA-9]
UCA-10: LKS provides steering correction towards the opposite (or wrong) direction [H1]	SR-10: LKS must provide steering correction in the required direction [UCA-10]
UCA-11: Road authority does not provide any lane markings on LKS-enabled vehicles plying roads [H2]	SR-11: Road authority must provide lane markings on LKS-enabled vehicles plying roads [UCA-11]
UCA-12: Road authority provides deteriorated lane markings on LKS-enabled vehicles plying roads [H2]	SR-12: Road authority must not provide deteriorated lane markings on LKS-enabled vehicles plying roads [UCA-12]
UCA-13: Road authority, on consecutive curves, designs the second curve to start too early in the section [H1]	SR-13: Road authority, on consecutive curves, must design the second curve to start at least after a certain distance after the first curve [UCA-13]
UCA-14: Road authority does not provide transition section/ relaxing section after a curve before encountering the straight section [H1]	SR-14: Road authority must provide transition section/ relaxing section after a curve before encountering the straight section [UCA-14]
UCA-15: Road authority provides lane markings of less width on LKS-enabled vehicles plying roads [H2]	SR-15: Road authority must provide lane markings of at least a certain width on LKS-enabled vehicles plying roads [UCA-15]
UCA-16: The road authority provides reduced speed limits too close to sharp curves [H1]	SR-16: Road authority must provide reduced speed limits at least at a certain distance before sharp curves [UCA-16]
UCA-17: Road authority designs curves of radius too sharp for LKS on LKS-enabled vehicles plying roads [H1]	SR-17: Road authority must design curves of at least a certain radius on LKS-enabled vehicles plying roads [UCA-17]
UCA-18: Road authority, takes too long to make a correction to any wrong existing infrastructure component [H1, H2]	SR-18: Road authority, must make corrections to wrong existing infrastructure components within a certain time period) [UCA-18]
UCA-19: Road authority provides lane markings that are confusing to LKS, on LKS-enabled vehicles plying roads [H1, H2]	SR-19: Road authority must not provide lane markings that are confusing to LKS, on LKS-enabled vehicles plying roads [UCA-19]
UCA-20: Road authority enforces speed limit lower than what is needed for LKS to be active, on LKS-enabled vehicles plying roads [H2]	SR-20: Road authority must not enforce speed limit lower than what is needed for LKS to be active, on LKS-enabled vehicles plying roads [UCA-20]
UCA-21: Road authority provides lane markings covered with dirt [H2]	SR-21: Road authority must not provide lane markings with dirt [UCA-21]
UCA-22: Road authority, when reconstructing a road, does not remove visibility of old road marks [H1]	SR-22: Road authority, when reconstructing a road, must remove the visibility of old road marks [UCA-22]
UCA-23: Road authority provides trees too close to the lane edge [H1]	SR-23: Road authority must provide trees at least at a certain distance away from the lane edge [UCA-23]

Table A.2: Loss Scenarios for UCA 1 and 2

UCA	*Why UCAs occur?*		*Why would CAs be improperly/not executed?*	
	Unsafe Controller Behaviour	**Causes of inadequate feedback/information**	**Involving control path**	**Involving control process**
UCA-1: In case of both lines detected, LKS does not steer back when vehicle deviates from lane center beyond the safe threshold [H1]	The power to the LKS controller fails, leading it not function [UCA-1], causing the vehicle to deviate from lane center beyond the safe threshold [H1]	Signal disconnection between the sensors and the LKS controller maybe due to wire disconnect or power failure, causing the detected lines not being communicated to the controller, leading to no action taken by the LKS controller [UCA-1], causing deviation from lane center beyond the safe threshold [H1]	Human driver is in steering control, which overrides the LKS controller enabling it ineffective [UCA-1], causing vehicle to deviate from lane center beyond the safe threshold [H1]	LKS infact, is inactive, but the display has a time lag, thereby showing that both lines are detected, whereas infact LKS is not controlling steering action [UCA-1], leading to deviation beyond the safe threshold from the lane center [H1]
	LKS control algorithm has a different safe lane position limit, causing LKS to not steer back [UCA-1] causing the vehicle to be deviated from the lane center beyond the safe threshold [H1]	Dirt on sensor degrades sensor detection capability leading to inadequate detection of lane markings, therefore not executing steering correction [UCA-1] causing the vehicle to be deviated from the "real" lane center beyond the safe threshold [H1]	Signal disconnect between LKS controller and steering mechanism (actuator), causing calculated steering correction not being executed [UCA-1], leading to deviation from lane center beyond the safe threshold [H1]	The steering correction is executed by the steering mechanism, however, the vehicle does not move accordingly due to slippery road surface (due to rain), causing the vehicle to not steer back [UCA-1], leading to it deviating from the lane center beyond the safe threshold [H1]
	Human driver lets the LKS steer the instant when both lines are detected, whereas the LKS controller needs a certain time period to start steering control, resulting in the LKS controller not operating [UCA-1], causing the vehicle to deviate from lane center beyond the safe threshold [H1]	In bad weather conditions, sensors detection capability degrades, leading to inadequate detection of lane markings, causing the LKS not to steer back [UCA-1] causing the vehicle to be deviated from the lane center beyond the safe threshold [H1]		
	LKS control algorithm determines the vehicle position incorrectly with respect to the lane markings, causing LKS to not steer back [UCA-1] when the vehicle deviates the lane center beyond the safe threshold [H1]			
	The LKS controller has detected another object, such as the edge of the road instead of the lane marking, therefore not executing steering correction [UCA-1] when the vehicle deviates the "real" lane center beyond the safe threshold [H1]			
UCA-2: LKS provides unrequired steering correction when already within safe lane position threshold [H1]	When both lines detected, LKS control algorithm has a different safe lane position limit, causing LKS to steer [UCA-2] even when the vehicle is within safe lane position threshold, causing deviation from lane center beyond the safe threshold [H1]	Signal disconnection between the sensors and the LKS controller maybe due to wire disconnect or power failure just before the vehicle reaching the safe position, causing the new state not being communicated to the controller, leading to the LKS controller continuining the previous steering [UCA-2], causing deviation from lane center beyond the safe threshold [H1]	Human driver is in steering control, which overrides the LKS controller enabling it ineffective although it tries to execute no steering correction [UCA-2], causing vehicle to deviate from lane center beyond the safe threshold [H1]	No steering correction is provided by the LKS controller, however, the vehicles still "steers" due to slippery road surface (due to rain) [UCA-2], leading to it deviating from the lane center beyond the safe threshold [H1]
	When only one line detected, LKS control algorithm has a different "safe distance from lane" parameter causing LKS to steer [UCA-2] even when the vehicle is within safe lane position threshold, causing deviation from lane center beyond the safe threshold [H1]	Dirt on sensor confuses the LKS to detect a line (in reality, not the lane marking), therefore executing steering correction [UCA-2] when the vehicle is already in safe lane position threshold, causing deviation from "real" lane center beyond the safe threshold [H1]	The actuator does not receive a "stop steering" command after the vehicle has entered safe lane position limit due to communication breakdown with the LKS controller, therefore continuinig the steering [UCA-2], causing the vehicle to deviate from lane center beyond the safe threshold [H1]	
	LKS control algorithm determines the vehicle position incorrectly with respect to the lane markings, causing LKS to steer [UCA-2] even when the vehicle is within safe lane position threshold, causing deviation from lane center beyond the safe threshold [H1]	In bad weather conditions, sensors detection capability degrades, leading to inadequate detection of lane markings, causing the LKS to steer back even when not needed [UCA-2] causing deviation from lane center beyond the safe threshold [H1]		
	The LKS controller has detected another object, such as the edge of the road instead of the lane marking, therefore executing steering correction [UCA-2] when vehicle already within safe lane position threshold, causing deviation from lane center beyond the safe threshold [H1]			

Table A.3: Loss Scenarios for UCA 3 and 4

UCA	*Why UCAs occur?*		*Why would CAs be improperly/not executed?*	
	Unsafe Controller Behaviour	**Causes of inadequate feedback/information**	**Involving control path**	**Involving control process**
UCA-3: LKS steering overcorrection due to steering applied too early ahead of the location where needed [H1]	LKS controller algorithm looks too far ahead, resulting in steering corrections being applied too quickly causing steering overcorrection [UCA-3], causing deviation from lane center beyond the safe threshold [H1]	Dirt on sensor confuses the LKS to detect incorrect lines executing steering correction too early than needed [UCA-3], causing deviation from lane center beyond the safe threshold [H1]	Human driver takes steering control, which overrides the LKS controller enabling it ineffective, and steers earlier than needed [UCA-3], causing vehicle to deviate from lane center beyond the safe threshold [H1]	
	LKS controller detects the objects closer than they actually are, causing it to take steering correction action earlier than when needed [UCA-3], causing deviation from lane center beyond the safe threshold [H1]	In bad weather conditions, sensors detection capability degrades, confusing the LKS controller to steer earlier than needed [UCA-3], causing the vehicle to deviate the lane center beyond the safe threshold [H1]		
	LKS controller does not have a prediction component where it takes into account the time needed to reach the location where steering correction is needed, leading to it steering instantaneously. This makes it steer immediately even before the location where the steering is actualy needed [UCA-3], causing deviation from lane center beyond the safe threshold [H1]	The camera has a long look ahead distance, without covering the more immediate scenario, leading to the LKS controller only receiving input of the road much farther ahead, leading to steering correction applied too early [UCA-3], causing deviation from the lane center beyond the safe threshold [H1]		
UCA-4: LKS steering correction stopped too soon, when longer duration was needed [H1]	The power to the LKS controller fails after steering correction has begun but the vehicle has not yet entered safe lane position limit, therefore stopping steering correction earlier than needed [UCA-4], causing the vehicle to be deviated from lane center beyond the safe threshold [H1]	Signal disconnection between the sensors and the LKS controller maybe due to wire disconnect or power failure, causing the detected lines not being communicated aynymore to the controller, leading to the LKS controller stopping steering correction [UCA-4], causing deviation from lane center beyond the safe threshold [H1]	Human driver is in steering control, which overrides the LKS controller enabling it ineffective to continue steering until needed [UCA-4], causing vehicle to deviate from lane center beyond the safe threshold [H1]	
	LKS controller executes too low steering correction for the duration of the execution, and hence stopping the steering correction before reaching safe lane position limit [UCA-4], causing the vehicle to be deviated from the lane center beyond the safe threshold [H1]	Power failure to the sensor causing the steering correction to stop before reaching the safe lane position limit [UCA-4], leading to deviation from lane center beyond the safe threshold [H1]	Signal disconnect between LKS controller and steering mechanism (actuator), stopping the steering correction from being executed [UCA-4], causing deviation from the detected lane edge beyond the safe threshold [H1]	
	LKS control algorithm determines the vehicle position incorrectly with respect to the lane markings, causing LKS to assume it is already in safe position limit. Thereby stopping steering before reaching the safe lane position limit [UCA-4] even when the vehicle is within safe lane position threshold, causing deviation from lane center beyond the safe threshold [H1]	Dirt on sensor causes the LKS controller to stop steering earlier than needed [UCA-4], causing deviation from lane center beyond the safe threshold [H1]		
	When both lines detected, LKS control algorithm has a different safe lane position limit, causing LKS to stop steering before reaching the "real safe lane position limit" [UCA-4], causing deviation from lane center beyond the safe threshold [H1]	In bad weather conditions, sensors detection capability degrades, confusing the LKS controller to stop steering earlier than needed [UCA-4], causing the vehicle to deviate the lane center beyond the safe threshold [H1]		
	When only one line detected, LKS control algorithm has a different "safe distance from lane" parameter causing LKS to stop steering before reaching the "real safe lane position limit" [UCA-4], causing deviation from lane center beyond the safe threshold [H1]			

Table A.4: Loss Scenarios for UCA 5 and 6

UCA	*Why UCAs occur?*		*Why would CAs be improperly/not executed?*	
	Unsafe Controller Behaviour	**Causes of inadequate feedback/information**	**Involving control path**	**Involving control process**
UCA-5: In case of one-line detection, LKS does not steer back when vehicle deviates from lane edge beyond the safe threshold [H1]	The power to the LKS controller fails, leading it not function [UCA-5], causing the vehicle to deviate from lane edge beyond the safe threshold [H1]	Signal disconnection between the sensors and the LKS controller maybe due to wire disconnect or power failure, causing the detected line not being communicated to the controller, leading to no action taken by the LKS controller [UCA-5], causing deviation from the detected lane edge beyond the safe threshold [H1]	Human driver is in steering control, which overrides the LKS controller enabling it ineffective [UCA-5], causing deviation from the detected lane edge beyond the safe threshold [H1]	LKS infact, is inactive, but the display has a time lag, thereby showing that one line is detected, whereas infact LKS is not controlling steering action [UCA-5], causing deviation from the detected lane edge beyond the safe threshold [H1]
	LKS control algorithm has a different safe distance from lane limit causing LKS to not steer back [UCA-5] when the vehicle deviates the detected lane edge beyond the safe threshold [H1]	Dirt on sensor degrades sensor detection capability leading to inadequate detection of the lane marking, therefore not executing steering correction [UCA-5], causing deviation from the detected lane edge beyond the safe threshold [H1]	Signal disconnect between LKS controller and steering mechanism (actuator), causing calculated steering correction not being executed [UCA-5], causing deviation from the detected lane edge beyond the safe threshold [H1]	The steering correction is executed by the steering mechanism, however, the vehicle does not move accordingly due to slippery road surface (due to rain), causing the vehicle to not steer back [UCA-5], causing deviation from the detected lane edge beyond the safe threshold [H1]
	Human driver lets the LKS steer the instant when one line is detected, whereas the LKS controller needs a certain time period to start steering control, resulting in the LKS controller not operating [UCA-5], causing the vehicle to deviate from the detected lane edge beyond the safe threshold [H1]	In bad weather conditions, sensors detection capability degrades, leading to inadequate detection of the lane marking, causing the LKS not to steer back [UCA-5], causing deviation from the detected lane edge beyond the safe threshold [H1]		
	LKS control algorithm determines the vehicle position incorrectly with respect to the lane edge causing LKS to not steer back [UCA-5] when the vehicle deviates from the detected lane edge beyond the safe threshold [H1]			
	The LKS controller has detected another object, such as the edge of the road instead of the lane marking, therefore not executing steering correction [UCA-5] when the vehicle deviates from the "real" lane edge beyond the safe threshold [H1]			
UCA-6: LKS provides too less steering correction [H1]	LKS control algorithm has a larger safe position limit causing LKS to not steer enough [UCA-6] causing the vehicle to be outside the lane center beyond the safe threshold [H1]	Dirt on sensor degrades sensor detection capability leading to inadequate detection of the lane marking, therefore not executing sufficient steering correction [UCA-6], causing deviation from the lane center beyond the safe threshold [H1]	Human driver interferes constantly with the steering task and reduces the steering torque intensity, resulting in the LKS providing too less steering correction [UCA-6], causing the vehicle to deviate from the detected lane edge beyond the safe threshold [H1]	On curves, the radius of the curves are very sharp such that the LKS cannot steer sufficiently even with the max torque, resulting in insufficient steering by LKS to negotiate the curve [UCA-6], causing deviation from lane center beyond the safe threshold [H1]
	LKS control algorithm has a small max torque limit causing LKS to not steer enough [UCA-6] causing the vehicle to be outside the lane center beyond the safe threshold [H1]	In bad weather conditions, sensors detection capability degrades, leading to inadequate detection of the lane marking, causing the insufficient steering correction [UCA-6], causing deviation from the lane center beyond the safe threshold [H1]	Sensitivity of the steering mechanism is reduced due to wearing out, causing steering correction of lesser intensity to be applied than needed [UCA-6], resulting in the vehicle still being outside the lane center beyond the safe threshold [H1]	On S-shaped curves (reverse curves) without transition sections, the vehicle which has just negotiated a previous curve starts entering the new curve with the previous steering correction (which is in the opposite direction as needed next). This results in steering correction that is insufficient within the time limit [UCA-6], leading to deviation from the lane center beyond the safe threshold [H1]
	LKS control algorithm determines the vehicle position incorrectly with respect to the lane markings, and thefore applying insufficient steering [UCA-6] causing still a deviation from lane center beyond the safe threshold [H1]	The camera has a small look ahead distance, leading to the LKS controller not receiving input of the road ahead, thus for instance not anticipating sharp curves, leading to insufficient steering correction [UCA-6], causing deviation from the lane center beyond the safe threshold [H1]		On double curves of different radius without transition sections, the vehicle which has just negotiated a previous curve of larger radius starts entering the new curve of smaller radius with the previous steering correction (which is lesser than needed next). This results in steering correction that is insufficient within the time limit [UCA-6], leading to deviation from the lane center beyond the safe threshold [H1]
	The LKS controller has detected another object, such as the edge of the road instead of the lane marking, therefore executing insufficient steering correction with respect to the real lane markings [UCA-6]. causing the vehicle to be deviated from the "real" lane center beyond the safe threshold [H1]			
	LKS algorithm uses only a very short lookahead distance to calculate the steering correction, therefore not being able to execute sufficient steering correction [UCA-6], leading to deviation from the lane center beyond the safe threshold [H1]			

Table A.5: Loss Scenarios for UCA 7 and 8

UCA	*Why UCAs occur?*		*Why would CAs be improperly/not executed?*	
	Unsafe Controller Behaviour	**Causes of inadequate feedback/information**	**Involving control path**	**Involving control process**
UCA-7: LKS steering correction applied too late, after the location where needed [H1]	LKS controller algorithm looks only at the immediate road, resulting in steering corrections being applied too late causing delayed steering correction [UCA-7], causing deviation from lane center beyond the safe threshold [H1]	Dirt on sensor confuses the LKS to detect incorrect lines executing steering correction too late than needed [UCA-7], causing deviation from lane center beyond the safe threshold [H1]	Human driver takes steering control, which overrides the LKS controller enabling it ineffective, and steers later than needed [UCA-7], causing vehicle to deviate from lane center beyond the safe threshold [H1]	On S-shaped curves (reverse curves) without a transition section between these two curves, the vehicle which has just negotiated a previous curve immediately enters the new curve with the previous steering correction. Thus, it takes some time to execute steering correction causing it to be applied late [UCA-7], leading to deviation from the lane center beyond the safe threshold [H1]
	LKS controller detects the objects further than they actually are, causing it to take steering correction action later than when needed [UCA-7], causing deviation from lane center beyond the safe threshold [H1]	In bad weather conditions, sensors detection capability degrades, confusing the LKS controller to steer later than needed [UCA-7], causing the vehicle to deviate the lane center beyond the safe threshold [H1]		
	LKS controller's time-to-object prediction component incorrectly calibrated, making it to steer later than needed [UCA-7], causing deviation from lane center beyond the safe threshold [H1]	The camera has a short look ahead distance, covering only the immediate road, leading to the LKS controller only receiving input of the road immediately ahead, leading to steering correction applied too late [UCA-7], causing deviation from the lane center beyond the safe threshold [H1]		
	LKS control algorithm determines the vehicle position incorrectly with respect to the lane markings, causing LKS to not steer even when the vehicle is outside safe lane position threshold [UCA-7] , causing deviation from lane center beyond the safe threshold [H1]			
	LKS control algorithm takes a long time to calculate steering correction, leading to steering later than needed [UCA-7], causing deviation from lane center beyond the safe threshold [H1]			
UCA-8: LKS steering correction applied too long, when shorter duration needed [H1]	The power to the LKS controller fails after steering correction has begun and the vehicle has just entered the safe lane position limit, therefore unable to send a stop steering correction signal, causing steering correction to be applied longer than needed [UCA-8], causing the vehicle to be deviated from lane center beyond the safe threshold [H1]	Dirt on sensor causes the LKS controller to continue steering even later than needed [UCA-8], causing deviation from lane center beyond the safe threshold [H1]	Human driver is in steering control, which overrides the LKS controller enabling it ineffective to stop steering after sufficient [UCA-8], causing vehicle to deviate from lane center beyond the safe threshold [H1]	On S-shaped curves (reverse curves) without a sufficient transition section between these two curves, the vehicle which has just negotiated a previous curve immediately enters the new curve with the previous steering correction. Thus,the previous steering correction is continued even when not needed [UCA-8], leading to deviation from the lane center beyond the safe threshold [H1]
	LKS controller executes too high steering correction for the duration of the execution, and hence continuing the steering correction even after reaching safe lane position limit [UCA-8], causing the vehicle to be deviated from the lane center beyond the safe threshold [H1]	In bad weather conditions, sensors detection capability degrades, confusing the LKS controller to continue steering even later than needed [UCA-8], causing the vehicle to deviate the lane center beyond the safe threshold [H1]	Signal disconnect between LKS controller and steering mechanism (actuator), causing the "stop steering" signal not being sent and therefore steering continued [UCA-8], causing deviation from the detected lane edge beyond the safe threshold [H1]	
	LKS control algorithm determines the vehicle position incorrectly with respect to the lane markings, causing LKS to assume it is not yet in safe position limit. Thereby continuing steering even after reaching the safe lane position limit [UCA-8] causing deviation from lane center beyond the safe threshold [H1]			
	When both lines detected, LKS control algorithm has a different safe lane position limit, causing LKS to continuing steering even after reaching the "real safe lane position limit" [UCA-8], causing deviation from lane center beyond the safe threshold [H1]			
	When only one line detected, LKS control algorithm has a different "safe distance from lane" parameter causing LKS to continue steering even after reaching the "real safe lane position limit" [UCA-8], causing deviation from lane center beyond the safe threshold [H1]			

Table A.6: Loss Scenarios for UCA 9 and 10

UCA	*Why UCAs occur?*		*Why would CAs be improperly/not executed?*	
	Unsafe Controller Behaviour	**Causes of inadequate feedback/information**	**Involving control path**	**Involving control process**
UCA-9: LKS provides excessive steering correction [H1]	LKS control algorithm determines the vehicle position incorrectly with respect to the lane markings, and thefore applying excessive steering [UCA-9] causing still a deviation from lane center beyond the safe threshold [H1]	Dirt on sensor degrades sensor detection capability leading to inadequate detection of the lane marking, therefore executing excessive steering correction [UCA-9], causing deviation from the lane center beyond the safe threshold [H1]	Human driver interferes constantly with the steering task and increases the steering torque intensity, resulting in the LKS providing excessive steering correction [UCA-9], causing the vehicle to deviate from the detected lane edge beyond the safe threshold [H1]	The steering correction is executed by the steering mechanism, however, slippery road surface (due to rain) cause the vehicle to excessively steer [UCA-9], causing deviation from the detected lane edge beyond the safe threshold [H1]
	The LKS controller has detected another object, such as the edge of the road instead of the lane marking, therefore executing excessive steering correction with respect to the real lane markings [UCA-9],causing the vehicle to be deviated from the "real" lane center beyond the safe threshold [H1]	In bad weather conditions, sensors detection capability degrades, leading to inadequate detection of the lane marking, therefore executing excessive steering correction [UCA-9], causing deviation from the lane center beyond the safe threshold [H1]		On double curves of different radius without transition sections, the vehicle which has just negotiated a previous curve of smaller radius starts entering the new curve of larger radius with the previous steering correction (which is more than needed next). This results in excessive steering correction [UCA-9], leading to deviation from the lane center
	LKS algorithm uses only a very long lookahead distance to calculate the steering correction, therefore execute excessive steering correction [UCA-9], leading to deviation from the lane center beyond the safe threshold [H1]	The camera has a long look ahead distance, leading to the LKS controller reacting to changes in the road earlier, leading to excessive steering correction [UCA-9], causing deviation from the lane center beyond the safe threshold [H1]		
UCA-10: LKS provides steering correction towards the opposite (or wrong) direction [H1]	LKS control algorithm determines the vehicle position incorrectly with respect to the lane markings, and thefore applying opposite steering [UCA-10] causing still a deviation from lane center beyond the safe threshold [H1]	Dirt on sensor degrades sensor detection capability leading to inadequate detection of the lane marking, therefore executing opposite steering correction [UCA-10], causing deviation from the lane center beyond the safe threshold [H1]		On S-shaped curves (reverse curves) without transition sections, the vehicle which has just negotiated a previous curve starts entering the new curve with the previous steering correction, which is in the opposite direction as needed [UCA-10], leading to deviation from the lane center beyond the safe threshold [H1]
	The LKS controller has detected another object, such as the edge of the road instead of the lane marking, therefore executing opppsite steering correction with respect to the real lane markings [UCA-10],causing the vehicle to be deviated from the "real" lane center beyond the safe threshold [H1]	In bad weather conditions, sensors detection capability degrades, leading to inadequate detection of the lane marking, therefore executing opposite steering correction [UCA-10], causing deviation from the lane center beyond the safe threshold [H1]		

Table A.7: Refined Safety Requirements: Infrastructure Requirements

Infrastructure Requirements	
Roads must have a pavement design and drainage system well enough to prevent slippery roads for vehicles.	The radius of the curves must be such that the vehicles are able to navigate them taking into account the max steering torque, the width of the lane, the speed limit of that road stretch, and reaction time of the LKS.
There must be a sufficient transition section between two simultaneous reverse curves, taking into account the max steering torque of the vehicle, the speed limit of that road stretch, the width of the lane, the radius of the curves, and reaction time of the LKS.	There must be no marks remaining from reconstructed roads that might indicate lane boundaries different from the new actual lane boundaries.
There must be a sufficient transition section between two simultaneous curves, taking into account the max steering torque of the vehicle, the speed limit of that road stretch, the width of the lane, the radius of the curves, and reaction time of the LKS.	There must not be roadside objects that cast shadows resembling lines (such as crash barriers, from roadside buildings or other infrastructure, or from trees that have a particularly long bark).
There must not be high contrast differences between pavement and immediate shoulder of the road that might be recognised as the lane edge.	There must be no asphalt repair patches on the road that might be recognised as a lane marking.

Table A.8: Refined Safety Requirements: In-vehicle Communication Requirements

In-vehicle Communication Requirements	
The human driver must be notified to not let go manual control until the decided time period has passed after detection of both lines.	There must be constant connection between the LKS controller and the sensors, with a system to detect communication failures and alert the driver to take action.
There must be a constant communication between sensors and the LKS controller, with a system to detect communication failures and alert the driver to take action.	There must be constant connection between the LKS controller and the actuator (Steering mechanism) with a system to detect communication failures and alert the driver to take action.
In case of human driver override, a subtle notification to the driver indicating deviation from the safe lane position limit must be provided to alert the driver of the potentially dangerous situation.	The human driver must be notified to not let go manual control until the decided time period has passed after detection of at least one line.
There must be a constant communication between LKS controller and the steering mechanism, with a system to detect communication failures and alert the driver to take action.	When there is a communication failure, no steering command must be sent by the LKS controller by default, in addition to the driver being informed.

Table A.9: Refined Safety Requirements: Algorithm Requirements

Algorithm Requirements	
The safe lane position limit hard-coded in the LKS controller must be within the threshold as agreed by authority/OEMs by research.	LKS controller algorithm must have a prediction component to take into account the time needed to reach the location where steering correction is needed, before executing it.
The LKS control algorithm must be properly tested to ensure that it determines the position of the vehicle in the lane accurately, within an acceptable error range.	LKS controller algorithm must be calibrated to accurately estimate the torque to reach the safe lane position where the correction must be stopped.
The safe distance from lane edge hard-coded in the LKS controller must be within the threshold as agreed by authority/OEMs by research.	The max torque limit of the LKS controller must be high enough to ensure it can safely respond to road situations, but also not exceeding the driver and passenger comfort and safety.
LKS controller algorithm must be designed to respond to the road upto a long enough distance that is calculated using the time needed to reach that location and the time needed to fully complete executing the steering correction.	LKS controller algorithm's time-to-object prediction component must be calibrated to a sufficient degree of accuracy.
LKS controller needs to be calibrated to estimate distance to objects in the driving environment up to an acceptable degree of accuracy.	

Table A.10: Refined Safety Requirements: Hardware Requirements

Hardware Requirements	
There must be constant power supply to the LKS controller, with a system to detect power failures and alert the driver to take action.	There must be constant power supply to the sensor with a system to detect power failures and alert the driver to take action.
The sensors must be calibrated to recognise lane markings (including their various types), and be able to differentiate them with "lines" occurring in the environment.	Steering mechanism sensitivity must be monitored by the LKS regularly by, for example, comparing expected and actual lane position before and after the steering correction execution. Deterioration of sensitivity below acceptable levels must result in automatic deactivation of the LKS, and alerting the driver.
The sensors must be cleaned frequently, and its detection performance checked regularly, with even a regular reminder to the driver to clean the sensor after certain duration or certain distance of driving if needed.	The steering torque calculation and processing time must be negligible to ensure an adequate and safe response.
The sensors must have an acceptable level of detection performance in different visibility conditions that could occur.	In case of human driver override and extreme deviation from safe lane position limit, gentle and non-dominating haptic feedback could be provided to the driver.
There must be negligible time lag between sensor detection and the display, to ensure accurate information display to human driver.	The vehicle tyres must be resistant enough to function with precision even in slippery road conditions.
The camera must cover the road environment downstream upto a distance that is calculated incorporating the minimum and maximum speed of the vehicle (consequently the time needed to travel that distance), and the time needed for executing steering action.	When there is a power failure, no steering command must be executed by the steering mechanism by default, in addition to the driver being informed.