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Master's Thesis

Investigating the Impact of In-Vehicle Distraction on Driving Performance during Safety Critical Events Using Visual Tracking in a Context-Aware Driving Simulator Environment

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Declaration Concerning the Master's Thesis

I hereby confirm that this thesis was written independently by myself without the use of any sources beyond those cited, and all passages and ideas taken from other sources are cited accordingly. This thesis has never been previously submitted anywhere for assessment.

Munich, 13th November, 2021
Debapreet Batabyal

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Abstract

In recent times, in-vehicle technologies like cell phones and Advance Driver Assistance Systems have proliferated the market. These devices compete for the driver's cognitive attention during the driving task. Texting in particular has found to be a critical factor in degrading driving performance during safety critical events. Although many studies have investigated the impact of texting on driving performance, few have done so in a context-aware environment where the driver would be exposed to potentially dangerous driving conditions in the presence of a real-time intervention system. The aim of this research is to do this with the help of visual tracking in a driving simulator environment. Driving simulator trials, as part of stage 1 of the i-DREAMS project, were conducted at the Chair of Transportation Systems Engineering at the Technical University of Munich to measure driving performance. Additionally, drivers' gaze data was collected using an eye tracker. This was analyzed using descriptive and inferential statistical methods as well as visualization techniques. Findings suggested that distraction during safety critical events had a significant impact on deteriorating longitudinal and lateral performance control, while having a compensatory effect on the reaction time across diverse safety critical events and traffic environments. Additionally, based on gaze data, drivers were found to be interacting with in-vehicle devices such as cell phones and the i-DREAMS intervention system even during potentially dangerous driving situations. It was assessed that during possible Vulnerable Road User collisions, distracted drivers tended to look up to ten times more at the i-DREAMS interface as compared to the baseline scenario. The summarized findings help in supplementing naturalistic studies investigating distraction using eye trackers. Additionally, they provide an in-depth insight with recommendations for future research in this direction.

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List of Abbreviations

ADAS	Advanced Driver-Assistance Systems
AOI	Area of Interest
CE	Critical Event
ETA	Eye Tracking Analysis
ET	Eye Tracker
FC	Fixation Count
HMI	Human Machine Interface
i-DREAMS	smart Driver and Road Environment Assessment and Monitoring System
IVIS	In-Vehicle Information Systems
NE	Non-Event
OEM	Original Equipment Manufacturer
PE	Pre-Cursor Event
STZ	Safety Tolerance Zone
TFD	Total Fixation Duration
TOI	Time of Interest
VRU	Vulnerable Road User

Chapter 1. Introduction

The first chapter introduces the thesis topic by giving a foundational overview, establishes the research motivation, lays down the research objectives and questions, states the expected theoretical, methodological, and practical contributions, and finally defines the framework of the thesis and consequently the structure of the report.

1.1. Introduction

According to the National Safety Council, there are approximately 1.6 million vehicle crashes annually while using a cell phone (Snyder, 2021). About 390,000 annual injuries and fatalities result from accidents due to the driver being distracted while texting (Ornelas, 2021). These numbers are increasing every year (EC, 2018; WHO, 2011).

The primary driving task is complex. This requires the coordination of the driver's mental, physiological, sensory and psychomotor faculties (Beirness et al., 2002; Peters & Peters, 2001). Thus, a high degree of concentration is needed on the part of the driver for safe driving. However, it is not entirely uncommon to see drivers being distracted during the primary driving task. According to Streff et al. (2000), driver distraction is defined as: "a shift in attention away from stimuli critical to safe driving toward stimuli that are not related to safe driving". This can engage a driver visually, aurally, physically, and cognitively (Ariza, 2021). The World Health Organization has identified distracted driving as a reason behind millions of injuries and fatalities each year (WHO, 2018). Thus, distracted driving is a global safety hazard that needs to be tackled.

Texting while driving is the most critical form of in-vehicle distraction (NHTSA, 2021). Drivers using mobile phones are four times at risk of being involved in a collision than drivers who are not distracted (WHO, 2021). In addition to this, according to WHO (2021), texting while driving has negative repercussions on braking reaction time, lateral position keeping and headway maintenance. Research has shown the distraction caused by texting while driving affects a driver's gaze patterns, decision-making times, and speed and acceleration control (Green et al., 1993; Reed & Green, 1999). In fact, this is six times more probable to cause a collision than drunk driving (NHTSA, 2021). Answering a text message while driving diverts the attention from the primary driving task for approximately five seconds. If a driver is traveling at 55 mph, five seconds is enough to traverse the length of a football field (Snyder, 2021). This also causes a 400 percent increase in time spent with driver gaze not focusing on the road ahead.

From the aforementioned paragraphs, we can conclude that texting while driving was a critical reason behind in-vehicle distractions. Diverse methods have been formulated using state of the art technologies for measuring distraction. These include driving simulator studies, naturalistic driving studies and visual gaze monitoring studies (Young et al., 2003). All of them are effective in Human-Machine Interface (HMI) evaluation.

High-fidelity driving simulators offer a realistic, safe and controlled environment to study distraction due to texting while driving (Godley et al., 2001; Reed & Green, 1999). They can be further configured with devices like Advanced Driver Assistance Systems (ADAS) and eye trackers to get a more nuanced view on the impact of texting on the primary driving task. Previous studies (Yannis et al., 2014; Thapa et al., 2015) have proved the effectivity of high-fidelity driving simulators in studying distraction and its impacts on driving performance. As opposed to this, naturalistic studies are more dangerous and less controlled in studying critical safety events such as tailgating and Vulnerable Road User (VRU) collisions (Goodman et al., 1997).

Although simulators have been used for years in studying in-vehicle distraction, they are more effective when paired with newer technologies like eye trackers. This aids in the collection of data from two independent sources and its consequent analysis. Eye trackers help in monitoring eye movement parameters like gaze and fixation and their changes with respect to different driving conditions (Le et al., 2020). These devices can help gain an insight into a driver's cognitive processes, since they are triggered by eye movements (König et al., 2016). The latter is important in analyzing how a driver reacts to distraction stimuli like text messages while driving. Eye tracking devices have also been used in the past to investigate visual attention feedback in order to obtain more information about attentional resource allocation (Toreini et al., 2020).

Cell phones are not the only in-vehicle technologies available that play an important role in distracting drivers. The usage of ADAS is playing an increasingly crucial role in compensating distractions during safety critical events when the driver is engaged in secondary or tertiary driving tasks. However, there have been conflicting results between studies and in general, this topic has low consensus amongst different traffic scientists (Dunn et al., 2019; Cades et al., 2017). On one hand, ADAS and similar route guidance systems have found to reduce distraction and improve road safety as opposed to systems that require visual-manual input of route information (Tijerina et al., 1998; Dingus et al., 1995). On the other hand, there have been concerns about ADAS systems endangering the very task that it was supposed to protect against, i.e., by being a source of distraction for the driver (Regan et al., 2001). It has been found that these devices can distract drivers physically, visually, aurally, and cognitively (Young et al., 2003). Thus, they share traits which are very similar to cell phones in distracting the driver (at least partially) during the primary driving task.

Thus, in-vehicle distraction sources are competing with the primary driving task for the driver's attention and is therefore a growing concern for driver safety (Strayer et al., 2015). The number of distraction-related fatalities will be on the rise as a result (Stutts et al., 2001). According to the WHO (2011), by 2030, road traffic injuries will be the fifth leading cause of fatalities globally. It is presently the ninth. Thus, there is an urgent need to develop "objective, standardised, measures of distraction" (NHTSA, 2002) in order to mitigate its impacts on road safety. Extensive research is required to comprehend drivers' behaviour to engage in potentially distracting tasks, the factors that affect this behaviour, and the conditions that bring about this engagement in distracting tasks.

This is where the i-DREAMS project becomes significant in this context. It seeks to "establish a framework to define, develop, test and validate a context-aware safety envelope for driving in a 'Safety Tolerance Zone' (STZ)" (Pilkington-Cheney et al., 2020). Stage one of the project deals with simulator trials to study driving performance under a wide range of conditions, including safety critical events. In addition to the statutes laid down by the i-DREAMS consortium, the Technical University of Munich (TUM) decided to study distraction via texting with the help of eye trackers in a driving simulator. Although past studies have investigated the impacts of distraction by using visual tracking, there is limited research studying the impact of distraction via texting in the presence of a real-time intervention-based system like i-DREAMS on the driving performance during safety critical events. The consequences of such a research would align itself with the European Union's plans to have zero serious injuries or fatalities on roadways by 2050 (EC, 2021). This is also in line with the United Nations General Assembly's plan to halve the number of global fatalities and injuries from road traffic accidents by 2030 (WHO, 2011).

1.2. Research Motivation

Thus, distraction caused by in-vehicle devices are a growing concern for driver safety. In a recent survey (Snyder, 2021), forty-eight percent of drivers admitted to answering phone calls while driving. Fifty-eight percent of these drivers continued driving while conversing on the phone. Ten percent of all surveyed drivers admitted to sending text messages while driving. Fourteen percent of drivers responded by saying they read text messages while driving. As the market for in-vehicle technologies grows rapidly year after year, the probability of distraction-related accidents will increase proportionately (Stutts et al., 2001). Thus, this is an area of road safety investigation that needs urgent attention.

There is strong evidence that the impact of technology-based distraction is dependent on the frequency of exposure to the distraction stimuli (Young et al., 2003). However, very little known about the relative frequency with which drivers interact with in-vehicle distraction sources. There have been a wide range of methodologies used to measure the impact of texting on driving performance (ex: epidemiological, naturalistic, closed course, and simulator studies). However, owing to the level of complexity and variables involved associated with cell phone usage, there has been little agreement amongst road safety experts regarding the exact effects of texting on specific areas of driving performance (Nowakowski et al., 2001; STTG, 2002).

The entry of driving performance measurement technologies like driving simulators and distraction-compensating devices like ADAS have improved our insights into this topic. However, most past simulator studies dealing with the topic of in-vehicle distraction via texting have two major deficiencies. They measured driver distraction preliminarily via distraction driving surveys (Gliklich et al., 2016; Bergmark et al., 2016; NHTSA, 2015). This added a layer of subjectivity to driving performance based on how the driver perceived his driving behaviour. Little insight has been gained into cognitive processes, for example, with the help of visual tracking that help us investigate actual driver behavioural characteristics during safety critical events. Secondly, where simulator or naturalistic driving studies have incorporated ancillary technologies like eye trackers, there has been limited research studying the impact of distraction via texting in the presence of a real-time intervention-based system like i-DREAMS on the driving performance, especially during potentially dangerous events like tailgating and Vulnerable Road User (VRU) collisions. There is very little information available regarding how drivers interact with in-vehicle Technologies. It is unclear whether they use them in the manner intended by Original Equipment Manufacturers (OEM); and at what threshold they become a distraction.

An integrated simulator environment along with the presence of in-vehicle technologies (including systems that simulate distraction, mimicking naturalistic on-road driving conditions) and the consequent measurement of distraction and its impact on the driving performance would help gain an insight into the driver gaze behaviour and its implications on road safety during safety critical events. The use of visual tracking analysis can help understand how drivers interact with in-vehicle technologies, which can be either distracting (mobile phones) or intervening in nature (as in the case of the i-DREAMS system), based on their gaze data. This, therefore, acts as a motivation to conduct this research.

1.3. Objectives and Research Questions

The main objective of this research is to investigate the impacts of in-vehicle distraction (texting using a hand-held mobile phone) on driving performance in the presence of an intervention-based Advanced Driver Assistance System (i-DREAMS device) using visual tracking in a driving simulator environment.

Probing the research objectives would help Original Equipment Manufacturers (OEMs), users of in-vehicle technologies and policy makes identify the driving performance parameters that degrade the most during safety critical events due to the presence of in-vehicle distraction. An assessment of the impact texting on the driving task would help legislators enact policies in line with road safety projects like Vision Null of the European Commission, which would consequently reduce the number of on-road fatalities and serious injuries due to distraction. Using eye tracking analysis to study driver gaze behaviour and its relation to driving performance parameters can also help in the design of better HMIs.

In order to analyze driving performance using a driving simulator and an eye tracker, the necessary simulator trials must be run for data collection. Thus, in order to accomplish the primary objective, simulation experiments must be conducted and information about driving performance variables and eye tracking metrics must be collected. This forms the backbone on which the analysis is based, and hence an important objective. The analysis of the simulator and eye-tracking data would follow the i-DREAMS simulator trials, which forms stage one of the complete i-DREAMS project.

Achieving the research objectives will be done by answering the following research questions:

1. What impact does in-vehicle distraction in the form of texting have on the primary driving task?
2. Do driving performance parameters degrade significantly when the driver encounters safety critical events in the presence of in-vehicle distraction in a simulated driving environment (when compared to the baseline scenario with no distraction)?
3. If yes, which driving performance variables are affected the most during safety critical events?
4. Can Eye Tracking Analysis (ETA) be used to analyse driving performance satisfactorily and reliably?
5. Is there an association between gaze behaviour of drivers during safety critical events like tailgating and possible Vulnerable Road User (VRU) collisions and the deterioration of driving performance?
6. Does a context aware system like the i-DREAMS intervention system help in mitigating distraction during safety critical events?

The aforementioned research questions in addition to the main objectives converge to help answer the main research question associated with this thesis: what impact does in-vehicle distraction have on the driving performance in the presence of a real-time ADAS in a simulated driving environment?

1.4. Expected Contributions

To meet the research objectives and to answer the research questions, the thesis is expected to have the following contributions:

Theoretical Contributions

- Providing theoretical insights into the relationship between driver gaze behaviour and driving performance parameters in the context of distracted driving.

There have been experiments in the past that investigated the impacts of texting on the primary driving task in simulated environments (Yannis et al., 2021; McKeever et al., 2013; Thapa et al., 2015). In addition to this, there have also been investigations using eye trackers to study the effects of cognitive or visual distraction on the driving performance (Groner et al., 1989; Pashler & Sutherland, 1998; Pashler, 2016). However, to the author's best knowledge, there have been no studies that explore the association between driver gaze behaviour and driving performance during safety critical events in the presence of in-vehicle distraction in a simulated environment.

- Identifying driving performance parameters with a high degree of deterioration in the course of distracted driving during safety-critical events.

Methodological Contributions

- Collection of driving performance and visual tracking data as part of stage one of the i-DREAMS study.
- Identification of the critical driving performance and visual tracking parameters that are most sensitive to changes during unsafe driving conditions, via a comprehensive literature review.
- Using Tobii Pro Lab (V1.162) to analyze the collected eye tracking metrics.
- Using descriptive statistics to quantitatively analyse the impact of distraction on driving performance.

- Using inferential statistics to assess identified driving performance data using unpaired (two sample) t-tests to explore how driving performance changes between baseline and distracted driving scenarios.
- Identifying changes in the gaze pattern between different Areas of Interest (AOI) between baseline (intervention) and distraction scenarios of the drive.
- Recommending a framework for future work (regression analysis) to find the nature and strength of the relationship between driving performance variables and eye tracking metrics.

Practical Contributions

- Providing insights into the simulator experiment design and useful recommendations for improvement of the same.
- Recommendations on possible future eye tracking studies to investigate the impact of distraction during safety critical events based on the thesis outcomes.

1.5. Thesis Framework

The thesis framework is shown in figure 1.1.

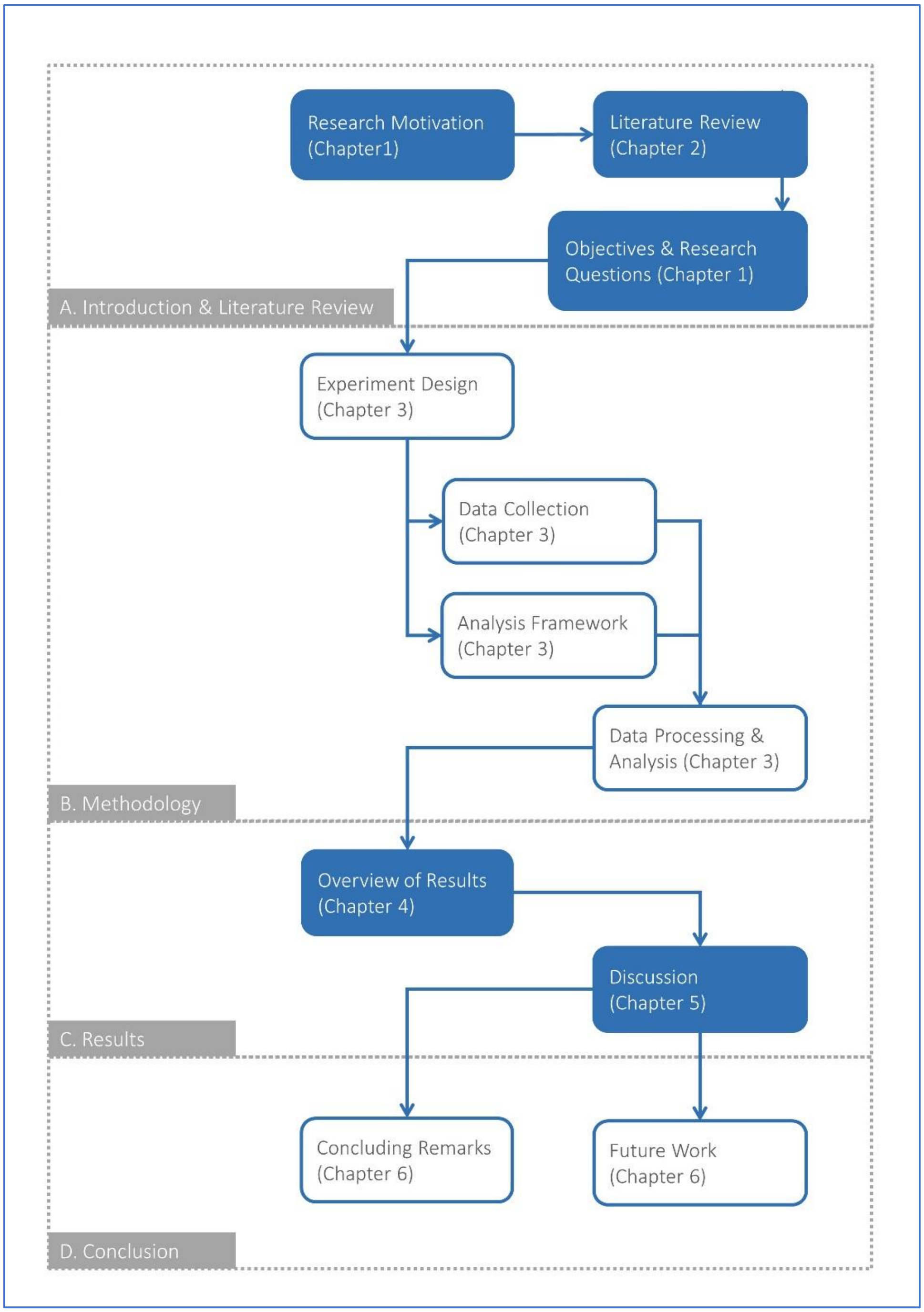

Figure 1.1. - Thesis Framework (source: own illustration)

1.6. Report Structure

In order to meet the objectives and to answer the research questions, this thesis is divided into six main chapters. This is based on the thesis framework. The first chapter introduces the topic and lays down the research objective, motivation, and questions. The second chapter deals with the literature review. This has seven subsections. This chapter explores the role of driving simulator studies in exploring driver distraction, driving performance variables most sensitive to in-vehicle distraction, the role of safety critical events on safe driving, impact of distraction on the primary driving task via the usage of hand-held mobile phones, utilization of eye trackers to monitor driver glance behaviour, the effects of intervention-based devices such as ADAS on driving performance, and finally analytical methods that have been used to quantitatively and qualitatively assess driving performance in past studies. The third chapter explains the driving simulator experiment design. methods of data collection, analysis of the same for both driving simulator as well as eye tracking data and specifies the hypotheses to be tested. The fourth chapter presents an overview of results, which would help answer the research questions objectively. The penultimate chapter carries out a discussion of the research results and findings and their implications on different levels. The final and sixth chapter concludes this thesis with the presentation of recommendations, future work and limitations.

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Chapter 2. Literature Review

This chapter forms the basis for the conceptualization of this research design. It includes information about areas that would be explored to help answer the research objectives and questions. The literature review has been divided into seven segments. The first and second parts explore the impact of in-vehicle devices on the primary driving task. The third part deals with the role of driving simulator studies in exploring the impacts of distraction on driving performance. The fourth sub-section examines the usage of visual tracking in analyzing the effects of cognitive and visual distraction. The fifth segment gives an overview of driving performance variables and their sensitivity to in-vehicle distraction. The following part explains the influence of safety critical events on driving performance. For the purpose of this thesis, safety critical events have been bifurcated into possible Vulnerable Road User (VRU) collisions and tailgating scenarios. The final element of the literature review takes a look at analysis methods used in previous studies to measure driving performance.

2.1. The Impact of Texting on the Primary Driving Task

2.1.1. Driver Distraction

The driving task can be trifurcated into three parts: primary, secondary, and tertiary (Chukwuemeka et al., 2021). Primary tasks involve steering and accelerating, i.e., controlling the position and speed of the vehicle during driving. Secondary tasks have a supportive function to the primary driving task. Finally, tertiary tasks are carried out to control in-vehicle systems such as GPS and navigation (Murali et al., 2021). For the purpose of future reference, we combine the secondary and tertiary categories into one: the supplementary driving task.

Driver distraction is the temporary shifting of attention from the primary driving task to a supplementary one (Zatmeh-Kanj et al., 2021). This compromises the safety of the driver. Distraction sources can be in-vehicle or external. Depending on the type of distraction present, this can engage a driver in four ways: 1) visually by affecting the driver's attention allocation, 2) aurally through notifications, 3) physically, and 4) cognitively (Ariza, 2021).

2.1.2. The Impact of Texting on Driving Performance

Caird et al. (2014) conducted a meta-analysis of twenty-eight studies investigating the impact of texting on driving performance. The authors coded text messaging tasks as independent variables and considered driver gaze data, reaction times, longitudinal and lateral lane position, Time to Collision (TTC), velocity and headway as dependent variables. They found that typing text messages during the driving task negatively influenced gaze behaviour (off-road), stimulus detection, lane positions, velocities and headways. Reading and replying to a text message was found to require a greater cognitive workload than simply reading a message. A study found that drivers were twenty-three times more likely to crash while texting as compared to the baseline condition without distraction (Ritchell, 2009). Drivers who looked away from the road ahead for substantial periods of time while typing responses to text messages were found to be involved in a higher number of crashes and had a slower response to safety critical events (Hosking et al., 2009; Owens et al., 2011). Drivers who read and answered text messages during tailgating situations were found to decrease their longitudinal velocity and increase their distance to leading vehicles (Caird et al., 2014).

A study by Owens et al. (2011) noted that typing a simple text message with fourteen characters such as “I’m on my way home” took drivers an average of thirty-seven seconds to type while driving simultaneously. Out of this time, the driver fixated twenty-six seconds off the roadway and looked at their phone screens an average of 17.5 times. The study also found that the longest average fixation duration off the roadway was 2.7 s. Off-road fixations of durations 1.6 s and above have been known to increase collision risk (Horrey et al., 2007; Klauer et al., 2006; Simons-Morton et al., 2014).

In addition to simulator studies in a controlled environment, on-road naturalistic studies have confirmed the notion that crash risk increased when texting during driving (Klauer et al., 2014; Olson et al., 2009). The acuteness of the impact of texting on the driving task has been found to be worse than dialling on a cell phone (Ranney et al., 2011) or talking on it (Caird et al., 2008; McEvoy et al., 2005; Redelmeier et al., 1997).

Besides visual and cognitive distraction, texting also caused physical distraction in drivers. One or both hands were used to answer or type a text message. During answering, normally the hands were pinned to the steering wheel or the cell phone was held in one hand and the steering wheel controlled with the other. This had an impact on the lateral position of the vehicle and caused the frequency of steering wheel corrections to result in erratic vehicle movement (Owens et al., 2011).

What is surprising is that most drivers were unable to perceive the risk of a crash accurately when texting and driving simultaneously (Matthews et al., 1986). According to a comprehensive literature review synthesis by Papantoniou et al., (2017) based on over forty driving simulator studies investigating the effect of in-vehicle distraction on driving performance, texting and cell phone use were the most common sources of distraction that were explored. Thus, we can conclude that texting during the driving task results in visual, physical, and cognitive distraction. Drivers under the influence of this condition are an active safety threat and its impact on driving performance and consequently road safety needs to be investigated.

2.2. Intervention-Based Systems and their Influence on Driving Performance

ADAS systems have been found to play an increasingly important role in mitigating the impacts of distraction during safety critical events (such as tailgating scenarios or possible VRU collisions) when the driver is engaged in secondary or tertiary driving tasks (Dumitru et al., 2018). However, there have been conflicting results between researchers and it is a contentious topic with low consensus (Dunn et al., 2019; Cades et al., 2017).

On one hand, ADAS and other similar navigation systems had a mitigating and compensatory effect on visual and cognitive distraction (Tijerina et al., 1998; Dingus et al., 1995). This consequently assisted the driver when she was distracted, as opposed to systems that require visual-manual input of route information. An experiment incorporating an ADAS and a driving simulator investigated the influence of social media applications in distracting the driver (Dumitru et al., 2018). Multiple scenarios involved simulator runs with and without distraction and ADAS interventions. The authors concluded that ADAS warnings helped in reducing dangerous driving conditions by over forty percent when the driver was distracted, compared to the baseline situation in which the driver was distracted but there were no warnings.

On the other hand, there have been concerns about ADAS systems being an in-vehicle source of distraction for the driver akin to hand-held mobile devices (Regan et al., 2001). It has been found that these devices distracted drivers physically, visually, aurally, and cognitively (Young et al., 2003). Thus, it can be inferred that ADAS devices distract the driver at least partially during the primary driving task.

Hungund et al. (2021) reviewed 29 papers to examine the relationship between the frequency of ADAS use and driver distraction. They concluded that there is an overwhelming association between ADAS and an increased secondary task engagement, as well as an improved secondary task performance. According to their research, drivers tended to divert their attention to secondary tasks and away from driving tasks while using an ADAS, thus endangering safety. It was concluded that ADAS is not yet a full-proof substitute for driving.

Wierwille (1993) estimated that 90% of information that is cognitively processed by the driver is visual in nature. This visual resource was limited and multiple in-vehicle technologies like ADAS competing for the driver's attention simultaneously made the situation more precarious. As a result, the driving performance was found to be inversely proportional to the visual demand (Tsimhoni & Green, 2001). Lansdown et al. (2004) stated that during multiple secondary tasks, simultaneous distractions led to higher cognitive workloads on the part of the driver.

In order to minimize cognitive distraction, it has been suggested to change the duration and nature of interaction between the ADAS and the driver, in addition to using a context aware ADAS (Brooks et al., 2007). The i-DREAMS system is a context aware ADAS that seeks to implement this. According to Pilkington-Cheney et al. (2020), "the i-DREAMS project aims to establish a framework to define, develop, test and validate a context-aware safety envelope for driving in a 'Safety Tolerance Zone' (STZ). Safety-oriented interventions will be used to warn or inform the driver in real-time, and on an aggregated level after driving. The main output of the i-DREAMS project will be an integrated set of monitoring and communication tools for intervention and support, including in-vehicle assistance, feedback, and notification tools, as well as a gamified platform for self-determined goal setting."

To conclude this sub-section, previous studies have found ADAS and similar route navigation technologies to be beneficial in their function to mitigate distraction during the primary driving task. However, this comes with some caveats. There is evidence that such devices increase the cognitive workload during secondary tasks. However, very little research exists on the combined influence of multiple in-vehicle devices (such as a combination of a cell phone and a context aware ADAS like the i-DREAMS system) during driving.

2.3. The Role of Driving Simulator Studies in Exploring the Impact of Distraction on the Primary Driving Task

Driving simulators have been used extensively in studying the effect of distraction on driving performance (Elsa et al., 2010). They have been utilized in the investigation of in-vehicle and external distraction, incorporating different participant sample characteristics (gender, demographics, etc.), experimental designs (simulated traffic, road environment, driving tasks, etc.), as well as different distraction sources (cell phones, ADAS, etc.) (Papantoniou et al., 2013).

These devices have several advantages over naturalistic studies. They provide a safe and controlled driving environment for participants under the influence of in-vehicle and external distraction (de Winter et al., 2012). They can be used in the study of distraction involving multiple-vehicle scenarios, a wide range of test conditions (e.g.: time of day, weather conditions, driving environments, hazardous driving situations with distraction present, etc.) (Papantoniou et al., 2013). Finally, they are more economical than modifying a vehicle for on-road trials and allow for the evaluation of new in-vehicle systems and distraction scenarios (Papantoniou et al., 2013).

Several studies have confirmed that in-vehicle sources of distraction like cell phones and ADAS had a more prominent effect on the driving performance than external ones (Horberry et al., 2009; Strayer et al., 2003; Johnson et al., 2004; Lesch et al., 2004; Neyens et al., 2008; Bellinger et al., 2008; Yannis et al., 2010). Driving behaviour was affected in terms of velocity, lateral position, headways and reaction times (Papantoniou et al., 2013).

According to Papantoniou et al. (2013), the most common source of in-vehicle distraction studied in driving simulator experiments was cell phone use. This was based on a comprehensive literature review of over forty scientific papers dealing with the study of distraction in simulated environments. Strayer et al. (2003) found that using a hands-free cellular device while driving in a driving simulator increased the headway distance from lead vehicles, especially in zones with high traffic density. Rakauskas et al. (2004) noted that cell phone conversations while driving caused higher variations in speed, accelerator pedal position, and higher mental workloads. Thapa et al. (2015) studied the effect of texting and cell phone conversations on the primary driving task at varying complexity levels. Results suggested that driving performance in terms of the longitudinal and lateral positions and speeds of the vehicle deteriorated during texting while driving. However, cell phone conversations tended to show no large deviations from the baseline scenario.

According to Rumschlag et al. (2015), texting while driving in a simulator had a major role in increasing the frequency and severity of lane deviations. The magnitude of excursions in terms of frequency and severity was highly correlated with the duration of the texting task undertaken. Yannis et al. (2014) investigated the impact of distraction due to texting on young adults using a driving simulator. The drive consisted of different driving conditions (rural and urban segments, varying weather conditions, etc.). Results highlighted the increased reaction times to unsafe driving conditions and the increased crash risk when a driver was encountering such situations while texting in the driving simulator. McKeever et al. (2013) contrasted the driving performance while texting between a baseline scenario with distraction absent and a test scenario with distraction in a driving simulator. The authors concluded that texting had a significant negative effect on lane keeping, velocity maintenance, and attention allocation.

In-Vehicle Information Systems (IVIS) such ADAS have been found to be competing for the driver's attention during the driving task (Regan et al., 2001; Young et al., 2003). To study this, Jamson et al. (2005) examined the relation between primary and supplementary task complexity in a driving simulator environment. They noted that participants were unable to fully prioritise the primary driving task under increased attentional allocation demand because of interventions from the in-vehicle ADAS. This also had a marked effect on the driving performance in terms of reduced braking capabilities and shorter time-to-collision. Domnez et al. (2006) assessed the driver's interaction with IVIS. This included real-time warnings that alerted drivers based on the percentage of eye glances that are off-road. The authors concluded that this interaction in the simulator environment delayed response times, braking in cases of tailgating scenarios, and delayed accelerator releases. Reyes and Lee (2008) explored the impact of mental workload on driving behaviour for interactions with an IVIS. They inferred that competition between in-vehicle technologies for the driver's attention allocation had a marked impact on the decrements in driving performance.

However, ADAS systems have also found to have beneficial effects on the distraction task in simulator studies. Dumitru et al. (2018) assessed the influence of distraction via social media applications in a simulator study. There were three design scenarios with varying levels of complexity. This included driving with and without distraction and real-time IVIS warnings in times of unsafe driving. The results highlighted that the IVIS helped in reducing unsafe driving behaviour and excursions by over forty percent as compared to the baseline scenario in which there was distraction but no warnings. Context-aware intervention systems have also been found to have a beneficial effect on the driving performance as compared to systems where route information has to be entered manually (Brooks et al., 2007).

On the whole, there is a need to research the impacts of context-aware ADAS in decreasing the in-vehicle distraction with the help of controlled and simulated driving environments under varying cognitive workloads and driving conditions. A driving simulator can be helpful in such cases. According to Papantoniou et al. (2013), based on a comprehensive literature review of over forty scientific papers on simulator studies to investigate distraction, there are several gaps that need to be filled. The majority of studies do not use enriched datasets that are representative of the demography. They mostly focus on the 18-55 years old demographic group, with only 17.4% of the drivers aged 55 years or older. This caused a skewing of the dataset. The simulated road environments were mostly monotonous in nature, with the majority of them being on rural simulated stretches. 30% of such studies excluded ambient traffic on the simulated road network. This leads to learning on the part of the driver and biased simulation results. To the best knowledge of the driver, there were no studies that incorporated the usage of a context-aware ADAS in a driving simulator to study distraction due to texting with the help of visual tracking.

2.4. Using Visual Tracking to Study Driver Distraction

The concept of visual tracking to study how we gather information via glancing at specific objects has been around since the 1800s (tobiipro, 2021). Eye tracking can be defined as the process of monitoring eye movements to assess where an individual is gazing at and associated information like the object of interest the subject is looking at and the gaze duration (Franchak, 2020).

An eye tracking device makes use of invisible near-infrared rays and high definition cameras to project incident light onto the eye and assess the direction of the reflected ray off the eye's cornea (tobiipro, 2021). Analyzer modules with the appropriate algorithms are then made use of to assess the eye position and its gaze. The aim is to visually map the subject's gaze behaviour. This functioning of an eye tracker has been depicted in figure 2.1.

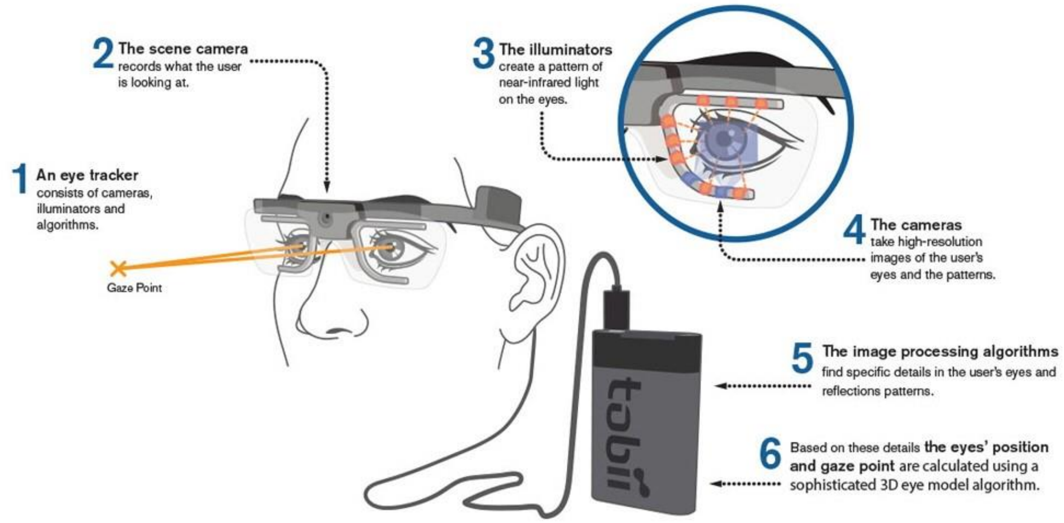


Figure 2.1. - The functioning of an eye tracker, specifically Tobii Pro Glasses (source: tobiipro, 2021)

2.4.1. Introduction to Eye Tracking Parameters

To understand the role of eye trackers in studying driver distraction, we must first understand the eye-mind hypothesis. It states that what the eyes fixate on and what the mind processes occurs simultaneously (Just et al., 1980). Cognitive processes are generally indicated by eye movements. Hence, tracking eye movements can lead to inferences on different cognitive processes occurring in the brain (tobiipro, 2020). There have been several studies in the past to investigate the effect of distraction on the primary driving task using specific methods. The usage of eyetracking analysis (ETA) has evolved to be a become a popular means to collect information based on eye movements of the driver. This gives us parameters of interest to study the effects of distraction. These parameters can include eye movement patterns, gaze behaviour, fixation, and attention allocation to different objects while driving (tobiipro, 2014).

In the static context, eye movements may be classified as fixations and saccades (tobiipro, 2014). Fixations limit the foveal gaze on an object. This is done to acquire information and hence, the length of a fixation usually indicates the complexity of the information processing task (Beraneck, 2014). As opposed to this, saccades are jumps in between fixations. These are one of the fastest movements in the human body and last for about 30 ms (Vetturi, 2020).

Eye movements in the dynamic context include vergence, smooth pursuit and Vestibular Ocular Reflex (tobiipro, 2014). The Vestibular Ocular Reflex (VOR) is responsible for stabilizing the gaze via compensatory eye movements in the opposite direction of the head movement (Beraneck, 2014). During a smooth pursuit, the driver is following an object with their gaze. It isn't essentially a fixation or saccade. However, the driver is moving the foveal area along with the object. Essentially, the effectivity of an eye tracking study depends on the eye movements and attention characteristics of the driver. Two mechanisms are mainly used by the eyes: capturing an object via fixation and smooth pursuit depending on the dynamicity and stabilizing the image via VOR (tobiipro, 2020).

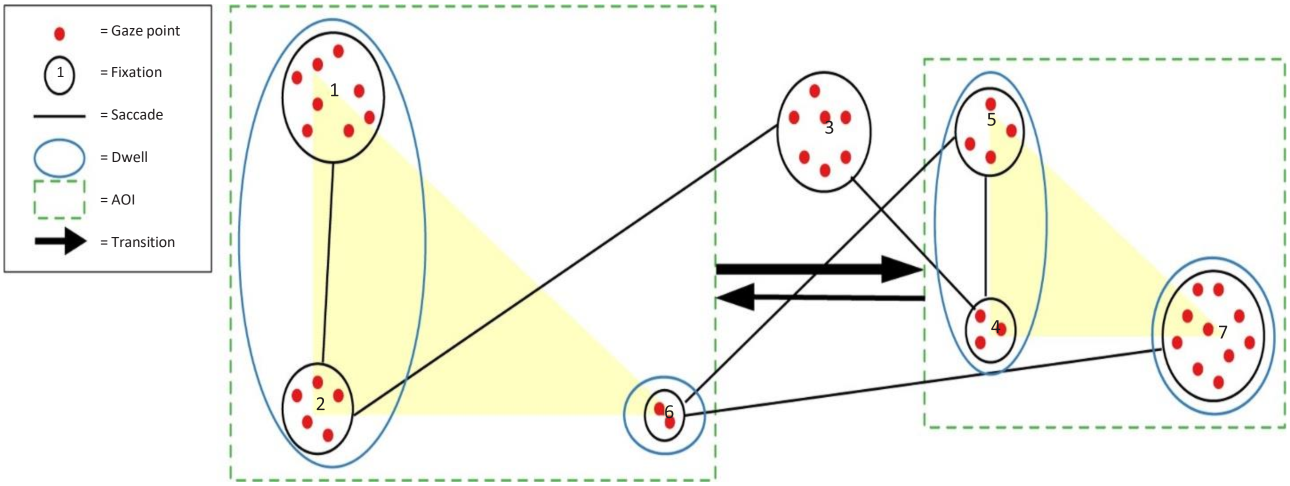


Figure 2.2. – Eye tracking trajectories (source: Blascheck et al., 2017)

2.4.2. Studying the Effects of Distraction on the Driving Task with the Help of Eye Trackers

Researchers have investigated the relationship between cognitive attention and eye movements for over three decades (Groner et al., 1989; Pashler et al., 1998; Pashler, 2016). Previous studies have been successful in using eye-trackers to study the effects of distraction on the primary driving task. This has been done by monitoring eye movement parameters like gaze and fixation and their changes with respect to different driving conditions (Le et al., 2020). Le et al. (2020) studied driver distraction by using visual tracking under simulated and naturalistic conditions. The involuntary eye movements were stimulated by studying the optokinetic response using the vestibulo-ocular reflex model due to cognitive loading. They concluded that the difference between actual eye movements of the driver and eye movements that were simulated via the presence of diversions is a measure of cognitive distraction. König et al. (2016) found that regions of the oculomotor system formed networks within specific regions of the brain under repeated distraction loading. This can help gain an insight into a driver's cognitive processes, since they are triggered by eye movements.

Previously, it was mentioned that the driving task can be divided into three main components: primary, secondary and tertiary tasks (Kern et al., 2009). Studies have shown that people who say they are proficient in multitasking are actually switching their attention between tasks (APA, 2006). In addition to this, studies have confirmed drivers to have access to one visual resource which was usually shared between different tasks while driving (including the primary and secondary driving tasks) (Smith et al., 2004). Thus, attentional resources were found to be limited. Eye tracking devices have also been used in the past to investigate visual attention feedback in order to obtain more information about attentional resource allocation (Toreini et al., 2020).

Eye trackers have been used in conjunction with mobile devices to evaluate how drivers reacted to distraction stimuli via increased workloads. This was important since one of the major causes of distraction in traffic was the usage of phones (Desmet, 2019). For example, Kim and Yang (2018) reproduced varying environmental conditions and studied the effects of the incremental distraction loads using mobile phones and in-vehicle devices on the driving task with the help of an eye tracker. The environmental conditions included normal driving in a baseline scenario, the presence of visual-manual loads, and finally, a cognitive overload. The authors found that the reduction of the driver's gaze ratio on the road ahead during the presence of the visual-manual load was actually less when compared to the baseline scenario when the driver was driving normally. However, during the overload task phase, when the driver's cognitive capabilities were the most stressed, his gaze ratio on the road ahead was more than when driving under no load. Experiments conducted by Nabatilan et al. (2012) seemed to confirm this. The authors assessed the visual behavior of drivers using visual tracking in a simulated environment. This also took into account driving error and a subjective workload assessment tool. All drivers reported higher workloads while driving and using mobile devices simultaneously. Consequently, this led to more driving errors and the decline in driving performance. Thus, eye trackers formed an integral part of investigating the effects of workload due to mobile phones on driving performance.

Eye tracking devices have been used extensively in the past to study driver visual attention while driving in traffic. Desmet et al. (2019) compared the changes in visual attention during trips where hands-free phone calls were made vs trips without any telephonic conversations. The researchers found that participants fixate less on road signs, other vehicles in the traffic and the dashboard during hands-free phoning. It was also found that the eye fixations had a wider distribution spatially. The authors concluded with the help of eye tracking data that during hands-free phoning, the drivers fixated less on traffic related information. Beijer et al. (2004) investigated the glance behavior of drivers with respect to roadside advertising signs. The fixation metrics of drivers suggested that sign placements in the visual traffic field affected glance behaviour and consequently driving performance.

There have been several studies using eye trackers to inspect the effects of different devices on the primary driving task. Brodeur et al. (2020) analyzed the distracting effects of smartwatches in comparison to smartphones and their impact on the driving performance. It was found that a driver's gaze distribution is less focused on the task with a smartwatch than a smartphone. Additionally, vocal assistants were found to have the least impact on the driving task, irrespective of using a smartphone or a smartwatch. In addition to this, Hashash et al. (2019) examined the decrements in visual attention allocation and consequently driving performance while texting during the primary driving task. They concluded that the effects of texting and social media browsing have similar effects in deteriorating the driving performance.

2.4.3. Analysis of Eye Tracking Metrics

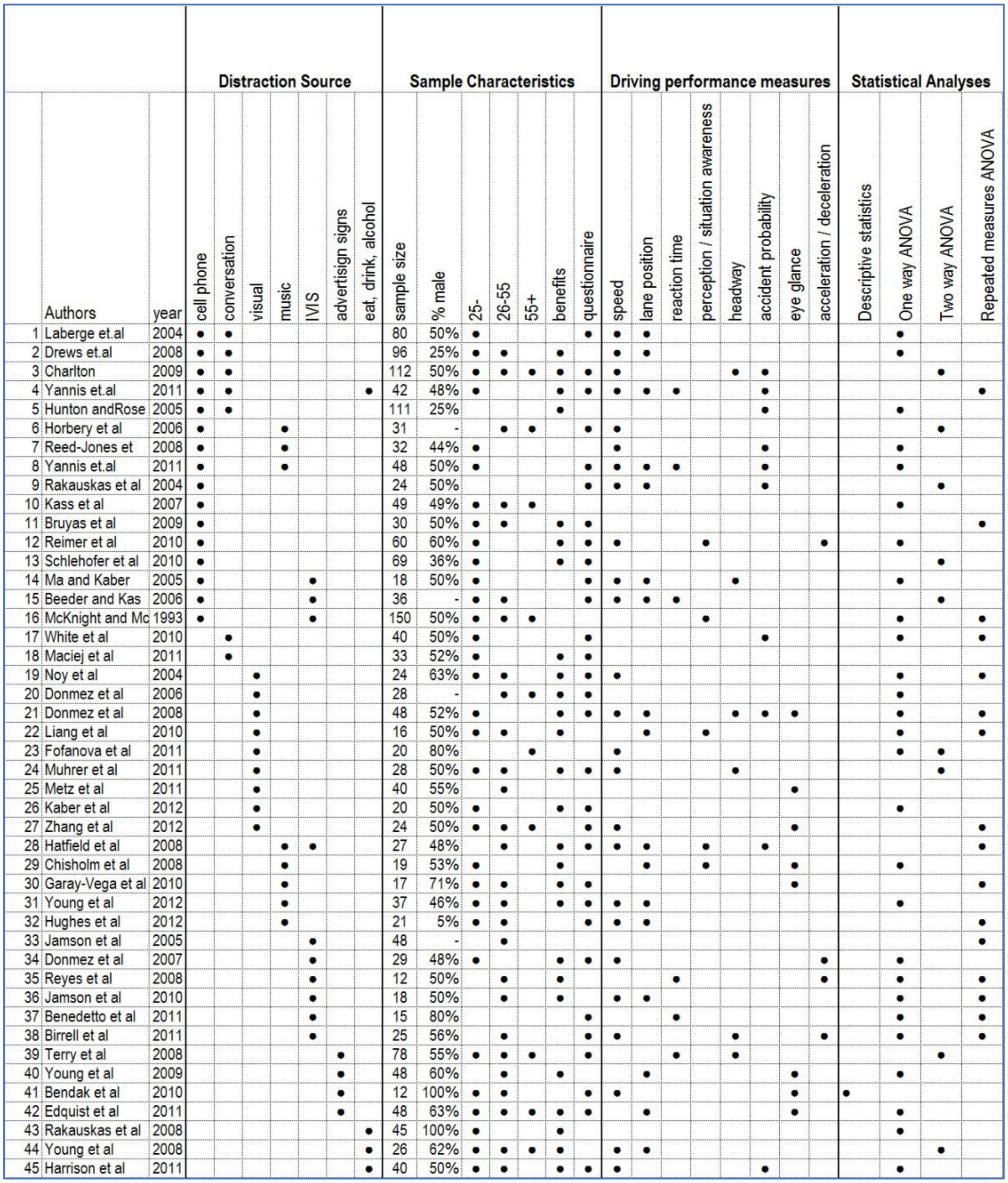
Please see section **2.7.2.**

To conclude this sub-section, we touched upon the eye-mind hypothesis, which states that the cognitive processes inside the brain are dependent on the gaze behaviour of an individual. ETA has been used successfully in the study of distraction behaviour of drivers during the primary driving task in both simulator as well as naturalistic studies. However, the author found no mention of previous eye tracking studies based on driver gaze behaviour that analyzed the combined effect of in-vehicle distraction via texting and the possible compensatory effect of a context aware real-time, intervention-based system like i-DREAMS on driving performance.

2.5. Critical Driving Performance Parameters and their Sensitivity to Distraction

According to Paas et al. (1993), "Performance may be roughly defined as the effectiveness in accomplishing a particular task". Driver distraction can be measured quantitatively or qualitatively in terms of its impact on driver attentional allocation, behaviour, and accident risk (Papantoniou et al., 2017). It is a complex and multifaceted phenomenon which can't be analyzed effectively using a single variable (Papantoniou et al., 2017). The decision regarding selection of metrics should be based on the specific research questions (Regan et al., 2008).

Papantoniou et al. (2017) synthesized over forty simulator studies involving the impact of distraction on the driving performance and found that the most important driving performance parameters critical for distracted driving research were (in terms of frequency): speed, lane position of vehicle, steering wheel angle, number of eye glances, headway, reaction time, overtaking, and acceleration and deceleration amongst other variables. Table 2.1. summarizes the results.



			Distraction Source							Sample Characteristics							Driving performance measures								Statistical Analyses			
	Authors	year	cell phone	conversation	visual	music	IVIS	advertisign signs	eat, drink, alcohol	sample size	% male	25-	26-55	55+	benefits	questionnaire	speed	lane position	reaction time	perception / situation awareness	headway	accident probability	eye glance	acceleration / deceleration	Descriptive statistics	One way ANOVA	Two way ANOVA	Repeated measures ANOVA
1	Laberge et.al	2004	●	●						80	50%	●				●	●	●								●		
2	Drews et.al	2008	●	●						96	25%	●	●		●		●	●								●		
3	Charlton	2009	●	●						112	50%	●	●	●	●	●	●				●	●					●	
4	Yannis et.al	2011	●	●					●	42	48%	●			●	●	●	●	●			●						●
5	Hunton andRose	2005	●	●						111	25%				●							●				●		
6	Horbery et al	2006	●			●				31	-		●	●		●	●										●	
7	Reed-Jones et	2008	●			●				32	44%	●					●					●				●		
8	Yannis et.al	2011	●			●				48	50%	●				●	●	●	●			●				●		
9	Rakauskas et al	2004	●							24	50%					●	●	●				●					●	
10	Kass et al	2007	●							49	49%	●	●	●												●		
11	Bruyas et al	2009	●							30	50%	●	●		●	●												●
12	Reimer et al	2010	●							60	60%	●			●	●	●			●				●		●		
13	Schlehofer et al	2010	●							69	36%	●			●	●											●	
14	Ma and Kaber	2005	●				●			18	50%	●				●	●	●			●					●		
15	Beeder and Kas	2006	●				●			36	-	●	●			●	●	●	●								●	
16	McKnight and Mc	1993	●				●			150	50%	●	●	●						●						●		●
17	White et al	2010		●						40	50%	●				●						●				●		●
18	Maciej et al	2011		●						33	52%	●			●	●												
19	Noy et al	2004			●					24	63%	●	●		●	●	●									●		●
20	Donmez et al	2006			●					28	-		●	●	●	●										●		
21	Donmez et al	2008			●					48	52%	●			●	●	●	●			●	●	●			●		●
22	Liang et al	2010			●					16	50%	●	●		●			●		●						●		●
23	Fofanova et al	2011			●					20	80%			●			●									●	●	
24	Muhrer et al	2011			●					28	50%	●	●		●	●	●				●						●	
25	Metz et al	2011			●					40	55%		●										●					
26	Kaber et al	2012			●					20	50%	●			●	●										●		
27	Zhang et al	2012			●					24	50%	●	●	●		●	●						●					●
28	Hatfield et al	2008				●	●			27	48%		●		●	●	●	●		●		●						●
29	Chisholm et al	2008				●				19	53%	●			●			●		●			●			●		
30	Garay-Vega et al	2010				●				17	71%	●	●		●	●							●					●
31	Young et al	2012				●				37	46%	●	●		●	●	●	●								●		
32	Hughes et al	2012				●				21	5%	●	●			●	●	●										●
33	Jamson et al	2005					●			48	-		●															●
34	Donmez et al	2007					●			29	48%	●			●	●	●							●		●		
35	Reyes et al	2008					●			12	50%		●		●				●					●		●		●
36	Jamson et al	2010					●			18	50%		●		●		●	●								●		●
37	Benedetto et al	2011					●			15	80%					●			●							●		●
38	Birrell et al	2011					●			25	56%		●			●	●				●			●		●		●
39	Terry et al	2008						●		78	55%	●	●	●		●			●		●						●	
40	Young et al	2009						●		48	60%		●		●			●					●			●		
41	Bendak et al	2010						●		12	100%	●	●			●	●						●		●			
42	Edquist et al	2011						●		48	63%	●	●	●	●	●		●					●			●		
43	Rakauskas et al	2008							●	45	100%	●			●											●		
44	Young et al	2008							●	26	62%	●	●	●	●		●	●									●	
45	Harrison et al	2011							●	40	50%	●	●		●	●	●					●				●		

Table 2.1. - Most frequently used driving performance parameters based on forty-five high-fidelity simulator studies investigating the impact of distraction on driving performance (source: reproduced from Papantoniou et al., 2017)

The aforementioned driving simulator dependent variables were categorized as follows:

1. **Longitudinal control parameters**: the most common metrics under this category were speed and headway (Papantoniou et al., 2017).

    - **Speed**: Speed was a very commonly used dependent variable in driver distraction studies (Papantoniou et al., 2017). Associated measures included mean speed, speed variability, maximum speed, etc. depending on the research objectives to be investigated (Hogema and van der Horst, 1994; Manser et al., 2007). During distracted driving, the most commonly adopted measure by drivers was to slow down their speeds to increase available reaction time (Chu, 1994). Past studies by Haigney et al. (2000) have shown that that drivers exhibited higher speed variability and throttle control while using a mobile device while driving.

    - **Headway**: The most commonly used metrics under headway included mean headway (distance or time based) and minimum headway. Shorter headways indicated a deterioration of driving performance and a measure of increased cognitive load (Regan et al., 2008). Some studies have shown that drivers tend to implement increased headways when interacting with secondary tasks (Greenberg et al., 2003; Östlund et al., 2004). However, time and space headways were highly sensitive to simulated ambient traffic and therefore maybe a less reliable measure of driving performance across multiple simulator studies with varying levels of ambient traffic (Papantoniou et al., 2017).

2. **Lateral control parameters**: The most commonly used metrics under this category were lateral position and steering wheel control. These variables were especially sensitive to cognitive workloads and off-road gaze patterns owing to distractions.

    - **Lateral position**: The position of the vehicle with respect to the centre of the lane can be quantified with the help of this variable. Most important measures included standard deviation and mean of vehicle lateral position (Papantoniou et al., 2017). Decrements in its control was used as a measure of the impact of cognitive task load on driving performance when the driver was distracted by in-vehicle sources (Greenberg et al., 2003; Green et al., 2004). Horrey et al. (2006) and Caird et al. (2008) noted that cell phone conversations while driving didn't have a marked impact on lane keeping. Liang et al. (2010) concluded that visual, induced and cognitive distraction had different effects on lateral position performance.

- **Steering wheel control**: The most frequently used parameter was the steering wheel angle. According to Regan et al. (2008) and McGehee et al. (2004), drivers made minimal corrective steering wheel movements when driving in the absence of distraction. However, when distracted driving took place, the driver compensated errors by making large and sudden steering wheel movements to maintain lateral position.

Other important variables studied were the longitudinal acceleration and deceleration (Papantoniou et al., 2017) and the Time to Collision (TTC). The former was related to the longitudinal velocity and analyzed in four out of over forty papers. The TTC has been used in past studies to measure the severity of traffic conflicts and for separating aggressive driving from normal behaviour (van der Horst et al., 1994). The authors concluded that a TTC in the range of 4.5 to 5 s in the visibility range of 40 and 120 m is critical for investigation in order to activate a Collision Avoidance System (CAS). Based on the literature review conducted, critical driving performance variables which have been identified due to their sensitivity to distraction have been summarized in table 2.2.

Category	**Variable Name**	**Based on Literature Review from Source**	**Unit**
Longitudinal Control	Longitudinal Velocity	Papantoniou et al., 2017; van der Horst et al., 1994; Manser and Hancock, 2007; Chu, 1994 and Haigney et al., 2000	m/s
	Headway	Regan et al., 2008; Greenberg et al., 2003; Östlund et al., 2004 and Papantoniou et al., 2017	s
Lateral Control	Lateral Position	Greenberg et al., 2003; Green et al., 2004; Horrey et al., 2006; Caird et al., 2008 and Liang et al., 2010	m
	Steering Wheel Angle	Regan et al., 2008 and McGehee et al., 2004	Degrees
Reaction Time	TTC	van der Horst et al., 1994 and Papantoniou et al., 2017	s
Others[a]	Lateral Velocity	-	m/s
	Longitudinal Acceleration	Papantoniou et al., 2017	m/s^2
	Lateral Acceleration	-	m/s^2

Table 2.2. - Summary of critical driving performance parameters most sensitive to in-vehicle distraction (source: own)

2.6. Driving Performance During Safety Critical Events

As part of stage one of the i-DREAMS project, the chair of Transportation Systems Engineering at the Technical University of Munich was given the responsibility to conduct simulator trials with the experiment design focusing on two risk scenarios: tailgating and Vulnerable Road User collisions (Ezzati Amini et al., 2021).

Based on section **2.5.**, we now have the most important driving performance parameters. We would like to see how the behaviour of longitudinal control measures (speed and headway), lateral control measures (lateral position and steering wheel angle), reaction time measure (Time to Collision) and other associated measures (acceleration and deceleration) change during the aforementioned safety critical events, especially when the driver is being distracted during the driving task. The results for the tailgating scenario have been summarized in table 2.3.

a – Although the variables under 'Others' were not categorized into groups by Papantoniou et al. (2017), it can be said that lateral velocity and lateral acceleration are measures of lateral control and longitudinal acceleration is a measure of longitudinal control.

Safety critical event: tailgating		
Longitudinal control parameters	Speed	1] Distracted following vehicles maintained their previous mean speeds rather than reacting to leading vehicles (Przybyla et al., 2014). 2] Average speeds were lower, on the other hand Coefficient of Variations of speeds were much higher when testing the impact of texting during tailgating scenarios using the microscopic traffic simulation model TRANSMODELER (Zatmeh-Kanj et al., 2021).
	Headway	1] Drivers busy on cell phone conversations while driving maintained larger headway distances as compared to the baseline condition (absence of distraction) during car-following situations (Strayer et al., 2003; Strayer and Drews, 2004). 2] In many cases, increases in headway to compensate for the increase in cognitive workload due to processing speech-based emails while in a tailgating scenario wasn't enough to avoid collisions (Jamson et al., 2004).
Lateral control parameters	Lateral position	1] As headways became smaller in congested networks due to the Level of Service worsening, drivers appeared to compensate by increasing their lateral position to other drivers. However, they were not driving under the influence of distraction. When the stretch became more congested, the standard deviations in lateral positions decreased (Bunker et al., 2005).
	Steering wheel angle	-
Reaction time parameter	Time to Collision	1] Drivers had minimum adjusted TTC of approximately 1 s as opposed to 3.5 s for drivers who used a Rear-end collision avoidance system (RECAS) to get warnings in a high-fidelity driving simulator. Thus, the TTC shows a decrease of about 72 percent (Lee et al., 2002).
Other parameters	Acceleration and deceleration	1] In a survey aimed at people who had experienced rear-end collisions, it was found that delay on the part of the drivers surveyed in recognizing unexpected deceleration by the other vehicle accounted for half of the crashes. However, it was unclear what percentage of drivers surveyed were under the influence of distraction (Kodaka et al., 2003). 2] Figures 2.3. and 2.4. exhibit how calculated coefficients of headway were positive for car-following deceleration and negative for car-following acceleration. The impact of both was the smallest in the texting condition. This was estimated using a GM car-following model. Thus, driver acceleration and deceleration were not very responsive to headway gaps (Zatmeh-Kanj et al., 2021). 3] It was also found that drivers accelerate at a lower rate when their speed was higher. The sensitivity of the acceleration to the driver's speed was lower in the scenario where she was distracted by text messages (Zatmeh-Kanj et al., 2021).

Table 2.3. - Synthesis of studies investigating the impact of car-following on driving performance variables in the presence of in-vehicle distraction (source: own)

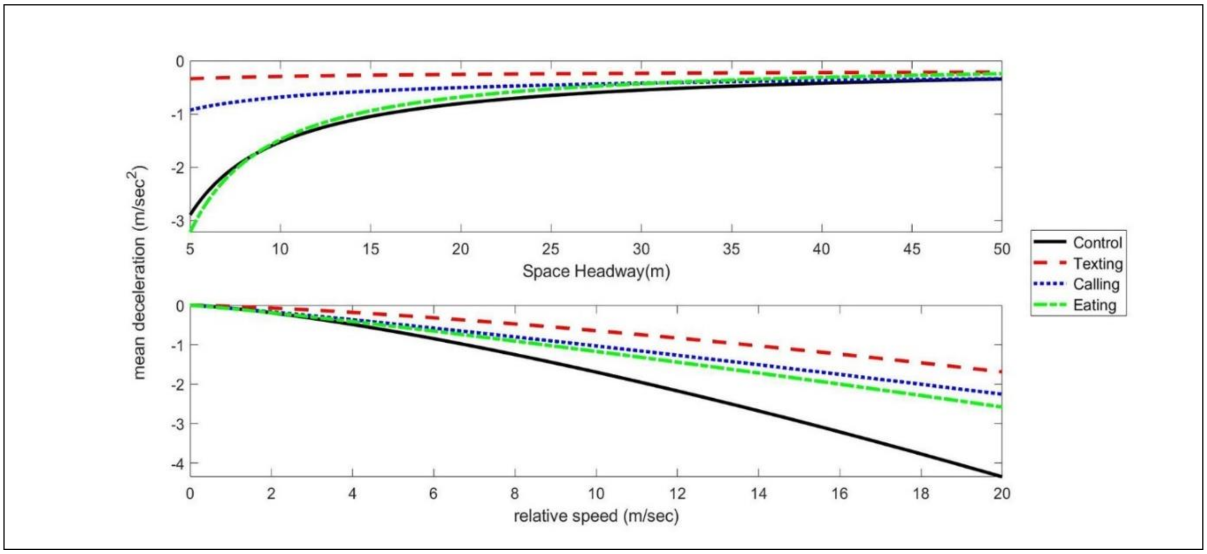


Figure 2.3. - Impact of space headway and relative speed on average deceleration during car-following in Gipps' model (GM) based on different levels of distraction (source: Zatmeh-Kanj et al., 2021)

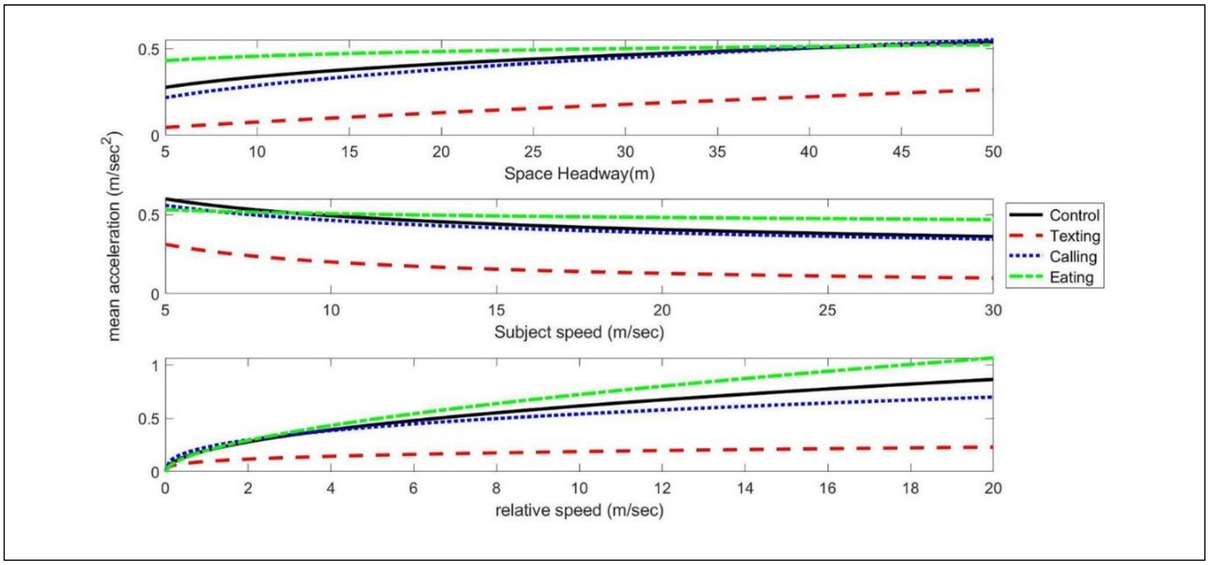


Figure 2.4. - Impact of space headway, subject speed, and relative speed on average acceleration during car-following in Gipps' model (GM) based on different levels of distraction (source: Zatmeh-Kanj et al., 2021)

Even though information about the most critical driving performance variables were available for the car-following scenario, this wasn't the case for pedestrian collisions. Data was sparsely available. However, according to Ezzati Amini et al. (2021), the most relevant metrics for studying VRU collisions were reaction time, steering variability and brake reaction. From section **2.5.** we know that this overlaps with two parameters: TTC and the steering wheel angle that were found as a result of a comprehensive literature review.

2.7. Analysis Methods Used to Measure Driving Performance

2.7.1. Analysis of Simulator Variables

Researchers have used descriptive and inferential statistics extensively to analyze driving performance parameters during multiple simulator studies (Bendak et al., 2010; Beede et al., 2006; Reimer et al., 2010) in the presence of in-vehicle as well as external distraction. The most common source of in-vehicle distraction was texting, with over 35 percent of studies evaluated during a comprehensive literature review by Papantoniou et al. (2017) using cell phones to trigger text messages in order to distract participants during the driving task. This fact and the aforementioned analysis methods suit our research objectives since we would be investigating the impact of in-vehicle distraction via texting on driving performance with the help of simulator trials.

Descriptive statistics along with graphic analysis have been used by Yannis et al. (2014) to quantitatively describe the features of the data being obtained from a driving simulator, driving behaviour, and self-assessment questionnaires. The authors initially used box plots to quantitatively exploit the datasets and to show statistically significant values like mean, standard deviation, maximum and minimum values of longitudinal control, lateral control, reaction time, gap acceptance, eye movement and workload measures. This was done to explore the effect of specific driver, environment and traffic parameters as well as distraction on driving performance. According to Yannis et al. (2014), this was especially beneficial in identifying outliers, degree of dispersion and skewness in the large dataset having many variables.

According to table 2.1., based on a synthesis of forty-five simulator studies investigating the impacts of distraction on the driving performance, it was found that an overwhelming majority of studies used inferential statistical methods (Papantoniou et al., 2017). The most common method implemented was ANOVA. The one-way

ANOVA was used (either solitarily or in combination with another method) approximately 60 percent of the time. Table 2.4. represents the breakdown of the methods used.

Method used	**Percentage of studies**
Descriptive statistics	2.2 percent
Only one-way ANOVA	40 percent
Only two-way ANOVA	20 percent
Only repeated measures ANOVA	17.8 percent
Combination of two or more methods	20 percent

Table 2.4. - Frequency of statistical methods in forty-five simulator studies investigating the impacts of distraction on driving performance (source: data extracted from Papantoniou et al., 2017)

However, it is worth bearing in mind that the ANOVA method is used when we want to determine whether three or more populations are statistically different from each other subject to certain criteria (Mishra et al., 2019). On the other hand, a two-sample *t*-test can be used for two populations effectively. It must be noted that the ANOVA is an extension of the independent samples *t*-test, where the mean between two independent populations are compared (Mishra et al., 2019).

During the i-DREAMS simulator trials, the participant had to partake in a practice drive, a monitoring scenario where the driver drove without an IVIS, an intervention scenario where she drove with the i-DREAMS IVIS and received real-time interventions based on driving conditions, and finally the distraction scenario, where she drove with an IVIS along with the presence of in-vehicle distractions via texting (Pilkington-Cheney et al., 2020). Under such a scenario, where three independent populations are being analyzed, a one-way ANOVA would be appropriate. However, this thesis deals with the last two scenarios, namely intervention and distraction. This makes it ideal for a two-samples *t*-test. Owing to the less number of groups, the magnitude of the type I error would also be negligible.

Bendak et al. (2010) used a paired t-test to investigate the role of road-side signs in distracting drivers with the help of a driving simulator. The authors used the following hypothesis to test five performance indicators (number of tailgating and over-speeding occurrences, number of times the vehicle had a lane excursion, occurrences of not signaling when passing other cars or turning, and number of times of crossing dangerous intersections unsafely) between the baseline and distraction scenarios:

H_0: $\mu_1 = \mu_1$
H_1: $\mu_1 > \mu_2$

Where H_0 was the null hypothesis to be tested; μ_1 was the average performance indicator in the segment with on-road advertisement signs (test scenario); μ_2 was the average performance indicator on the roadway stretch without on-road advertisement signs (baseline scenario). A significance level of $\alpha = 0.05$ was used. On the other hand, Yannis et al. (2014) used a ninety percent confidence interval, with a *t*-value higher than 1.64, and a *p*-value lower than 0.100.

In addition to descriptive statistics, Yannis et al. (2014) utilized regression models (general linear models and general linear mixed models) for critical driving performance metrics. They were used to explore the direct effect of distraction on the driving task and indirectly on safe driving behaviour. Washington et al. (2011) remarked, however, that under certain conditions, the assumptions of linear regression are not strictly fulfilled, and suitable alternatives are not known, comprehended, or implemented. Both general linear models and general linear mixed models are beyond the scope of this thesis, but will be taken up in future research.

2.7.2. Analysis of Eye Tracking Metrics

According to Papantoniou et al. (2017), fixation was the most important eye tracking parameter used to identify cognitive distraction. This was based on a synthesis of over forty driving simulator studies involving the investigation of distraction on the driving performance. A comprehensive literature review of over twenty-two visual tracking studies (Sharafi et al., 2015) revealed that eye tracking metrics used for the purpose of analysis can be divided into two main categories:

1. Metrics based on the number of fixations
2. Metrics based on the duration of fixations

The former category measures gaze behaviour depending on the number of fixations on a specified Area of Interest (AOI). Sharafi et al. (2015) revealed that there were four commonly used metrics under this category. This included Fixation Count (FC), Fixation Rate, Fixation Spatial Density, and Convex Hull Area (Goldberg et al., 1999; De Smet et al., 2014; Cepeda et al., 2010; Binkley et al., 2013; Sharif et al., 2012).

Gaze metrics based on the duration of fixations gave a measure of the time required to analyze a stimulus (Goldberg & Kotval, 1999). The most commonly used variables under this category included Average Fixation Duration (AFD), Ratio of On-Target to All-Target Fixation Time, Total Fixation Time, Average Duration of Relevant Fixations and Normalized Rate of Relevant Fixations (Goldberg et al., 1999; Binkley et al., 2013; Sharif et al., 2012; Petrusel et al., 2012; Jeanmart et al., 2009; Busjahn et al., 2011; Busjahn et al., 2014; Bednarik et al., 2012; Ali et al., 2015; Bednarik et al., 2005). In such studies, it was imperative to study both categories because a particular area of interest may have a low count but a high duration and vice versa (Sharafi et al., 2015).

The analysis of eye tracking variables would be done via Tobii Pro Lab for this research. Owing to technical limitations, the analyzer software provides Fixation Count (FC), Average Fixation Duration, and Total Fixation Duration as outputs out of all the metrics mentioned previously.

Fixation Count (FC) is the total number of fixations present in a particular AOI (Sharafi et al., 2015; tobiipro, 2020). Goldberg et al. (1999) noted that higher number of fixations on a specific AOI due to an induced stimulus meant that the subject wasn't able to cognitively gather relevant information he was looking for efficiently. Previous eye- tracking studies used this variable to single out AOIs that attracted more visual attention/gaze. A higher value for this metric was also used to imply that more visual effort was required to perform a specified task.

Average Fixation Duration (AFD) is the sum of all fixation durations divided by the number of fixations on a particular AOI (Goldberg et al., 1999; tobiipro, 2020; Busjahn et al., 2011; Bednarik et al., 2005). This was denoted by equation 1, where ET(F_i) and ST(F_i) are the end time and start time for a fixation F_i and n is the total number of fixations in a specified AOI (Sharafi et al., 2015).

$$AFD\ (AOI) = \frac{\sum_{i=1}^{n}\big(ET(Fi) - ST(Fi)\big)\ in\ AOI}{n}$$

Equation 1 - Average Fixation Duration (Sharafi et al., 2015)

Total Fixation Duration (TFD) has been defined as the sum of the durations of all fixations in an AOI during a specified task (Busjahn et al., 2014; Busjahn et al., 2011). This metric can also be obtained as the summation of all dwell times by a subject on a particular AOI during the entire duration of a task (Busjahn et al., 2014). Table 2.5. depicts the critical driving performance variables obtained from eye tracker studies selected on the basis of relevance in literature.

Sharafi et al. (2015) presented two tables[c] (2.6. and 2.7.) with the metrics based on the number and duration of fixations used in past studies along with their interpretations.

Category	**Variable Name**	**Based on Review of Relevant Literature**	**Unit**
Metrics based on the number of fixations[b]	Fixation Count	Papantoniou et al., 2017; Sharafi et al., 2015; Goldberg et al., 1999; De Smet et al., 2014; Cepeda et al., 2010; Binkley et al., 2013; Sharif et al., 2012	Count
Metrics based on the duration of fixations	Total Fixation Duration	Goldberg et al., 1999; Binkley et al., 2013; Sharif et al., 2012; Petrusel et al., 2012; Jeanmart et al., 2009; Busjahn et al., 2011; Busjahn et al., 2014; Bednarik et al., 2012; Ali et al., 2015; Bednarik et al., 2005	s
	Average Fixation Duration	Goldberg et al., 1999; Binkley et al., 2013; Sharif et al., 2012; Petrusel et al., 2012; Jeanmart et al., 2009; Busjahn et al., 2011; Busjahn et al., 2014; Bednarik et al., 2012; Ali et al., 2015; Bednarik et al., 2005	s

Table 2.5. - Synthesis of critical eye tracking variables relevant based on utilization in past studies to investigate distracted driving (source: own)

b - As part of the literature review, not much information was found on visits. However, we consider them in the analysis as they are a measure of the noise present in the glance behaviour (tobiipro, 2014). This is critical during distraction scenarios since noise essentially means that the driver is staring at a particular AOI, but not cognitively gathering any information.

c - The tables 2.6. and 2.7. are subsets of more extensive ones containing Fixation Count (FC), Fixation Rate, Fixation Spatial Density, and Convex Hull Area under metrics based on number of fixations and Average Fixation Duration (AFD), Ratio of On-Target to All-Target Fixation Time, Total Fixation Time, Average Duration of Relevant Fixations, and Normalized Rate of Relevant Fixations under metrics based on duration of fixations.

Metric	**Study**	**Interpretation**
Fixation Count (FC)	(Crosby, 1990)	Higher number indicates beacons (key lines) for comprehension.
	(Crosby, 2002)	Higher number shows more devoted attention to AOI.
	(Uwano, 2006)	Higher number on the whole stimulus while reading and scanning the code leads to finding defects faster.
	(Yusuf, 2007)	Higher number indicates poor arrangements of elements in a stimulus which means that more effort is required to explore and navigate.
	(Sharif, 2010)	Higher number indicates more visual effort to find defects.
	(Sharif, 2012)	Higher number indicates more visual effort to perform the task.
	(Sharif, 2013)	Higher number indicates longer processing time to understand source-code phrases.
	(Sharif, 2013)	Higher number indicates more visual effort to perform bug fixing task.
	(Sharafi, 2012)	Higher number indicates more visual effort to recall the name of identifiers.

Table 2.6. - Metric (Fixation Count) based on the number of fixations (source: extracted and reproduced from Sharafi et al., 2015)

Name	**Study**	**Interpretation**
Average Fixation Duration (AFD)	(Crosby, 1990)	Longer fixations indicate beacons (key lines) for comprehension.
	(Bednarik, 2005)	The distribution of average fixation duration over different areas of interest is different.
	(Cepeda, 2010)	Longer fixations indicate that participants devote more time and effort analyzing and understanding the visual stimulus. Thus, representations that require shorter fixations are more efficient.
	(Bednarik, 2005)	Longer fixations indicate that more visual effort is required to work with this specific layout.
	(Busjahn, 2011)	Longer fixations indicate a "substantial increase in demands in terms of attentiveness".
	(Soh, 2012)	Longer fixations indicate more overall effort spent by a participant during the task.
	(Binkley, 2013)	Longer fixations indicate more effort to understand source-code phrases.
	(Cagiltay, 2013)	Longer fixations indicate that the difficulty level of the task is higher.
	(Sharafi, 2013)	Longer fixations indicate more effort to complete the task.
Total Fixation Duration (TFD)	(Crosby, 1990)	Higher value indicate more relative attention that is devoted to an AOI.
	(Crosby, 2002)	Higher value shows areas that the participant considers important.
	(Uwano, 2006)	Higher value for code reading and scanning leads to finding defects faster.
	(Bednarik, 2012)	Higher value indicates more effort.
	(Busjahn, 2014)	Higher value indicates higher attention which denotes rich information and–or higher complexity of the element
	(Ali, 2015)	Higher value shows areas that the participant considers important.

Table 2.7. - Metrics (Average Fixation Duration and Total Fixation Duration) based on duration of fixations (source: extracted and reproduced from Sharafi et al., 2015)

One of the main purposes of eye-tracking-based experiments were to provide information about visual attention distribution and its fluctuations for specific stimuli such as distractions in driving simulator studies (Blascheck et al., 2017). Visual tracking devices record gaze co-ordinates as raw data and then aggregates them into fixations and saccades (tobiipro, 2014; tobiipro, 2020). For specific AOIs, this data needed to be visually presentable to provide a quantitative and/or qualitative measure of the attention distribution (Blascheck et al., 2017). Different approaches have been used by researchers to analyse raw visual tracking data. This includes descriptive and inferential statistical assessment (Holmqvist et al., 2011) and visualization methods (Andrienko et al., 2012). Statistical assessment techniques were helpful in providing quantitative outcomes, whereas visualization helped researchers analyze the data in a qualitative way. This included spatio-temporal aspects of the raw data and complex relationships within the eye tracking data set (Blascheck et al., 2017). This could be supplemented with statistical analysis.

The most common statistical analysis tools for visualizing eye tracking data were bar charts, line charts, box plots, scatter plots, and star plots (Blascheck et al., 2017). According to existing literature, their utility in previous visualization exercises are summarized in table 2.8.

Statistical Analysis Tool	**Previous Visualization Exercises**
Bar charts	These were primarily used to display the histogram of an eye tracking metric (Blascheck et al., 2017). Convertino et al. (2003) used bar charts to plot the percentage of total fixation durations for different combinations of visualizations.
Line charts	Line charts were used to depict information about participants and their corresponding fixation metrics across specified AOIs (Blascheck et al., 2017). Line charts have been used to analyze saccadic behaviour (Atkins et al., 2012). Smith et al. (2013) them to put forward mean values of fixation durations and saccadic amplitudes over time, incorporating dynamic as well as static stimuli within specified AOIs.
Box plots	They were mainly used to investigate deviations in horizontal, vertical, or absolute values of eye tracking metrics (Blascheck et al., 2017). Hornof et al. (2002) analyzed statistical deviations of fixations to assess eye tracker calibration deterioration. Dorr et al. (2010) explored the similarity between eye movement patterns of different participants with tasks involving a dynamic environment.
Scatter plots	These were helpful in plotting eye tracking data in a 2D Cartesian diagram that shows the relation between two variables (Blascheck et al., 2017). Berg et al. (2009) compared human gaze behaviour to those of monkeys. Scatter plots having information about the amplitude and velocity assessments of visual saccadic movements for both humans and monkeys were presented.
Star plots	Goldberg et al. (2010) studied the angular characteristics using scanpaths with the help of star plots. In addition to this, Nakayama et al. (2010) applied this statistical tool to get results based on the angular properties of fixation coordinates.

Table 2.8. - Synthesis of common statistical tools for visualizing ET data (source: own)

As mentioned previously, statistical analysis has its limitations. It can help a researcher gain an insight into quantitative datasets. However, for the purpose of quantitative results, visualization techniques such as heat maps and gaze plots have been extensively used in the past decade (Blascheck et al., 2017). This formed the backbone for exploratory analysis of eye tracking data (Berg et al., 2009).

Heat maps use colour distributions to showcase the number of fixations subjects made within a specific AOI in the presence or absence of stimulus, which may further be static or dynamic in nature (tobiipro, 2014). They also give us information about how long a particular participant fixates within a given AOI. The colour distribution ranges from red (represents the highest fixation counts and the longest fixation durations) to green (with the least of the aforementioned values) (tobiipro, 2014). There are variations of colour levels in between. The distribution of values in the vicinity of a fixation point is made possible with the help of a cubic hermite spline polynomial (cspline) (tobiipro, 2014). However, description of the polynomial itself is beyond the scope of this thesis.

On the other hand, gaze plots show the position and order of fixation points. The size of the points is proportional to the duration of fixation and the number of such points within a certain AOI indicates the count (tobiipro, 2014). However, gaze plots are effective visual tools when the time interval is short or the number of participants is restricted to under a certain threshold (tobiipro, 2014).

To conclude this section, reviewing relevant literature gave us the information that descriptive and inferential statistical methods were commonly employed in previous simulator studies to explore the impact of distraction on driving performance. This included box plots and ANOVA respectively. However, an ANOVA can only be conducted on three or more populations. In case of two populations, a t-test would be the alternative analysis method.

Fixation was found to be the most important metric in visual tracking studies. This was further divided into metrics based on fixation count (Fixation Count) and variables based on fixation duration (Total Fixation Duration and Average Fixation Duration). We assessed that analysis of eye tracking information can be done via descriptive and explorative statistical methods (for quantitative data) and visual methods (for qualitative data). For the latter, Tobii Pro is one of the most popular interfaces used (Blascheck et al., 2017). It provides visualization output in the form of heat maps and gaze plots. For large datasets over longer durations, heat maps were found to be a more efficient method to have a spatiotemporal visualization of eye tracking data.

To conclude this chapter, it was assessed that previous studies have investigated the impact of cognitive and visual distraction on the driving task and have even used visual tracking for this purpose. Texting while driving was found to be the most commonly used in-vehicle distraction source in such studies. However, to the best knowledge of the author, there has been limited work done in exploring the effects of real-time intervention-based systems on the driving performance. This is especially true for safety critical events when the driver is exposed to dangerous driving conditions and distraction stimuli simultaneously. This is done to measure any changes in the driving performance arising out of this situation (context aware warnings + distracted driving). This will be investigated in this thesis by analyzing drivers' gaze data during safety critical events in distraction scenarios (where the driver would receive real-time warnings based on the driving performance), and comparing them with the baseline scenario (without context aware warnings during safety critical events).

*

Chapter 3. Methodology

This chapter elucidates the different methods used to answer the research questions. It has been divided into four parts. The first segment deals with the design of the simulator experiment as part of stage one of the i-DREAMS project. The second part demonstrates the data collection process. The third section explains the data processing and analysis methods used to meet the research objectives. The final part of this chapter enumerates the built hypotheses, according to which the research questions are answered.

3.1. Simulator Experiment Design

3.1.1. Stage 1 of the i-DREAMS Project: Simulator Trials

As part of stage 1 of the i-DREAMS project, the Chair of Transportation Systems Engineering at the TUM was entrusted with the responsibility to conduct simulation runs using a car simulator to test the main risk factors defined within the project objectives (Ezzati Amini et al., 2021). The aim was to have an overview of different risk scenarios that car drivers encountered most frequently. This included tailgating scenarios and VRU collisions. In addition, the impact of distraction during safety critical events on the primary driving task was taken into account.

Within the context of the whole i-DREAMS project, simulator runs were conducted in order to test driver background factors, physiological factors and driving environment factors and how they influenced the driving performance. This would be the basis of developing a Safety Tolerance Zone (STZ) and its validation. Additionally, a secondary objective was to test the effectivity of the real-time, intervention based i-DREAMS system and its effectivity in warning drivers during safety critical events. Finally, the project also set out to gather user feedback and an assessment of technological acceptance about the i-DREAMS technology (Pilkington-Cheney et al., 2020).

To fulfill these objectives, three simulation run scenarios were designed:

- Monitoring: driving in the absence of distraction and without a real-time intervention-based ADAS.
- Intervention: driving with an intervention-based system that would warn drivers in case of safety critical events.
- Distraction: driving with a real-time intervention system in the presence of in-vehicle distraction triggered via text messages.

The trials took place in three traffic environments considering different risk factors: rural, highway and urban. This information has been summarized in tables 3.1. and 3.3. In order to introduce randomization in the dataset, the latin square method was used to change the order of the traffic environments associated with a particular configuration of the drive (monitoring, intervention or distraction). This was done to prevent learning and confounding effects (Ezzati Amini et al., 2021). The experiments themselves are designed to be within-participant (Pilkington-Cheney et al., 2020). More details on the structure of the simulator trial has been summarized in table 3.6.

For the purpose of this thesis, we have considered the intervention (baseline) and distraction (test scenarios) since the research deals with studying the impact of distraction on driving performance during safety critical events in the presence of an in-vehicle intervention system.

Roadway Type	**Speed Limit (km/hr)**
Two-lane and four-lane two-way urban area with one parking lane at each direction.	50
Six-lane two-way highway area.	No speed limit
Two-lane and four-lane two-way rural area without parking lane at each direction.	70

Table 3.1.: Roadway types and corresponding speed limit regulations (source: Ezzati Amini et al., 2021)

3.1.2. Equipment Used for Data Collection

In order to meet the research objectives, the sources of data collection were confined to the simulator and the eye tracker. A brief summary of other data collection sources can be found in table 3.5.

Driving Simulator

The driving simulator is based on a Peugeot 206 and includes a dashboard (with speedometer and tacho gauge), adjustable driver seat, steering wheel, accelerator, brake and the i-DREAMS system amongst other components. It was developed by DriveSimSolutions (DSS) and operates on STISIM Drive 3. Three 49’’ 4K monitors with a 135° field of view are used to simulate the driving environment.

In order to trigger real-time warnings, the simulator was configured with the context aware road monitoring system Mobileye. The latter’s purpose was to measures driving performance parameters like headway distance, in addition to triggering interventions like the Forward Collision Warning (FCW) and Pedestrian Collision Warning (PCW), and consequently collecting this information during each drive. The warnings have been summarized in table 3.2.

Real-time Intervention (Mobileye)
Lane departure warning
Time headway warning
Forward collision warning
Pedestrian collision warning
Cell phone usage warning (only during the distraction phase)
Speed limit (although this isn’t a warning. However, it alerts the driver to the existing speed limit on a stretch with an absence of on-road speed signs).

Table 3.2.: Types of warnings triggered by Mobileye (source: Pilkington-Cheney et al., 2020)

Furthermore, accessory equipment can be used with the simulator to supplement the data collection process. This includes the PulseOn wearable to monitor cardiovascular characteristics and Tobii Pro Glasses 2. The latter has been described in the next subsection.

Figure 3.1.: Driving simulator used for stage 1 of the i-DREAMS project at the Chair of Transportation Systems Engineering at TUM (source: own)

Tobii Pro Glasses 2

Driver gaze movement data during dynamic driving scenarios was recorded using Tobii Pro Glasses 2. Six illuminators cause near-infrared light to be incident on the eyes. Two cameras record the movement pattern of the individual's eye in high resolution The functioning of an eye tracker has been depicted in figure 2.1. Its consequent analysis was done using the Analyzer module of Tobii Pro Lab V1.162. For more details on the eye tracking Analysis (ETA), please refer to section **3.4**.

3.1.3. Risk Scenario Design

The experiment took into consideration two main risk scenarios: tailgating and VRU collisions. In addition to this, distraction would be studied via triggering text messages at specific moments of the drive where a participant used a hand-held cell phone.

VRU collisions were explored via three critical events in rural and urban traffic environments. In these events, the probability of crashing of pedestrian and vehicle was high. In all three events, the pedestrian starts crossing at a speed of 1.2 m/sec (Ezzati Amini et al., 2021).

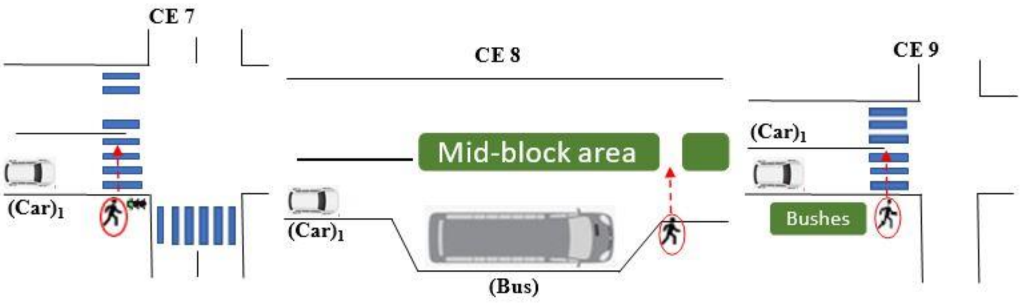


Figure 3.2.: A schematic overview of safety critical events of VRU collisions (source: Ezzati Amini et al., 2021)

For tailgating events, the driver followed a leading vehicle on rural, urban and highway traffic environments with a high probability of forward collisions between the driver and the leading vehicle. Each risk factor was triggered thrice across varying traffic environments in order to ensure adequate validity of observations (Ezzati Amini et al., 2021). The two risk factors are summarized in table 3.3.

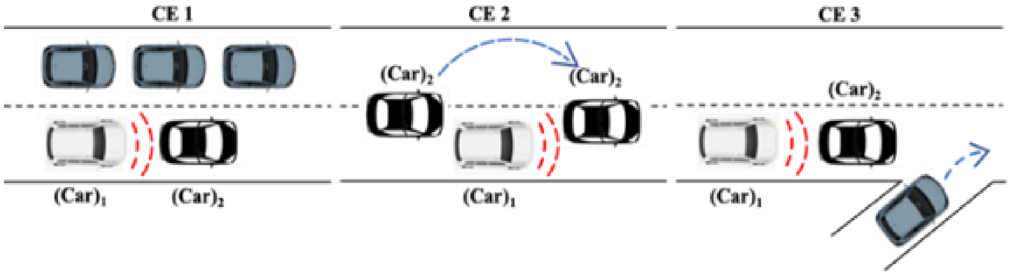


Figure 3.3.: A schematic overview of safety critical events of tailgating scenarios (source: Ezzati et al., 2021)

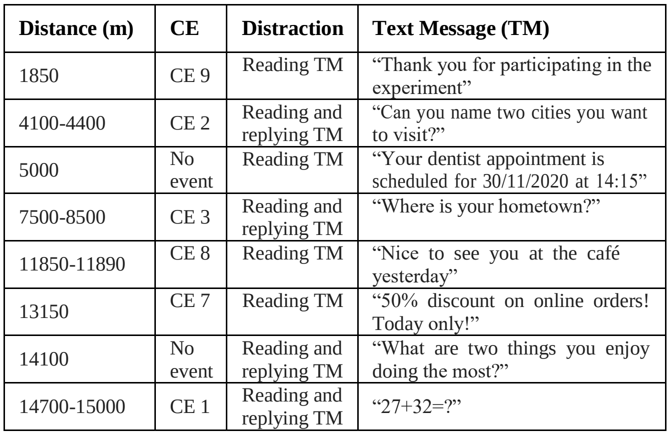
Risk scenario	Event	Road Segment in Simulation Run	Description
Tailgating	CE1-Tail-Rural	Rural	The driver is following a leading vehicle with a low speed, while the gap available in the opposite stream of traffic is not sufficient for overtaking. The tailgating occurs for about 300-350m on the rural stretch.
	CE2-Tail-Highway	Highway	A vehicle enters the highway segment in front of the driver and makes a sudden harsh brake.
	CE3-Tail-Urban	Urban	A vehicle overtakes the driver and abruptly merges into the lane in front of it in the urban segment.
VRU collision	CE1-Pedestrian-Rural	Rural	A pedestrian is obstructed by bushes tries to cross the road at a rural intersection when the driver is approaching.
	CE2-Pedestrian-Urban	Urban	A pedestrian is obstructed by a bus tries to cross the road at an urban intersection when the driver is approaching.
	CE3-Pedestrian-Urban	Urban	A pedestrian jaywalks at a crossing illegally when the traffic light is steel on green phase at the intersection.

Table 3.3.: Overview of risk scenarios (source: Ezzati Amini et al., 2021)

In addition to the six risk scenarios, two special events called non-events have also been incorporated into the experiment design. This was done to introduce some variation in the design, as well as to prevent learning effect (Pilkington-Cheney et al., 2020).

3.1.4. Triggering Distraction

In addition to safety critical events, the impact of in-vehicle distraction via text message on the driving performance was also investigated. Eight text messages were triggered during six critical events and two non-events during the distraction phase of the drive, having varying levels of complexity depending on the task. The task involved either reading the text message or reading and replying to it.



Distance (m)	CE	Distraction	Text Message (TM)
1850	CE 9	Reading TM	"Thank you for participating in the experiment"
4100-4400	CE 2	Reading and replying TM	"Can you name two cities you want to visit?"
5000	No event	Reading TM	"Your dentist appointment is scheduled for 30/11/2020 at 14:15"
7500-8500	CE 3	Reading and replying TM	"Where is your hometown?"
11850-11890	CE 8	Reading TM	"Nice to see you at the café yesterday"
13150	CE 7	Reading TM	"50% discount on online orders! Today only!"
14100	No event	Reading and replying TM	"What are two things you enjoy doing the most?"
14700-15000	CE 1	Reading and replying TM	"27+32=?"

Table 3.4.: Text messages triggered[d] during the distraction scenario (source: reproduced from Ezzati Amini et al., 2021)

3.2. Data Collection

3.2.1. Sources of Data Collection

The i-DREAMS simulator study entailed multiple sources of data collection, each having a specific function. These were Mobileye, PulseOn wearable, CardioGateway, questionnaire data, and finally simulator data via multiple sources (BSAV and Open Module) (Ezzati Amini et al., 2021; Pilkington-Cheney et al., 2020). In addition to the above, the Chair of Transportation Systems Engineering at the TUM decided on collecting visual tracking data using Tobii Glasses 2. This has been summarized in table 3.5. In the context of the thesis, we have considered only the data collected from simulator and the eye tracker. This has been described in detail in subsection **3.3.1.**

d - Note that the order of events changes according to the scenario (A, B or C). In addition, the names of critical events given in the table and in this text differ because the cited paper by Ezzati Amini et al. (2021) takes into consideration all critical events, which includes three involving illegal overtaking. However, TUM was entrusted with the responsibility to only study the safety critical events in subsection 3.1.3.

Data Source	Purpose
Mobileye	Forward Collision Warning (FCW), Lane Departure Warning (LDW), Pedestrian Collision Warning (PCW), etc.
PulseOn wearable	Cardiovascular data such as interbeat interval.
CardioGateway	i-DREAMS real-time interventions such as headway warning.
Questionnaires (one entry questionnaire+two exit questionnaires)	To assess driver background factors, technology acceptance and feedback based on the usage of the i-DREAMS real-time intervention system.
Simulator data (BSAV, OM)	Measurement of driving performance variables. For more details, please see section **3.3.1.**
Tobii Pro Glasses 2	Visual glance data of participants.

Table 3.5.: Data sources used in the i-DREAMS simulator study and their function (source: Ezzati Amini et al., 2021; Pilkington-Cheney et al., 2020)

3.2.2. Participants

3.2.2.1. Selection Criteria

In order to take part in the i-DREAMS simulator study, which was held at the Chair of Transportation Systems Engineering from May-September, 2021, the participants had to meet a few criteria. They were as follows:

1.Valid driver's license in Germany

2.No history of ophthalmic operations or scars on the cornea since this affects the eye tracker's ability to effectively collect gaze data.

3.No spectacles used for the simulation runs since the frame of the spectacle interferes with the sensors present on Tobii Pro Glasses 2.

Participants had to fill an online questionnaire that was available in German and English to input details for this purpose.

3.2.2.1. Recruitment

Recruitment was done via publishing advertisements on the official page of the Chair of Transportation Systems Engineering at TUM, in addition to distribution of flyers around Munich and Garching. There were 111 registrations, 30 of whom met the selection criteria.

3.2.2.3. Enrichment of Sample

In order to have an enriched dataset, participants were chosen to reflect the driver demographics in Munich in terms of age and gender in order to have a representative sample. However, no data was found about vehicle ownership or number of existing driving licenses in Munich and its vicinities. Therefore, an assumption was made that the driving licenses issued or the vehicle ownership numbers would be proportional to the population of a region. The results have been summarized in figures 3.4. and 3.5.

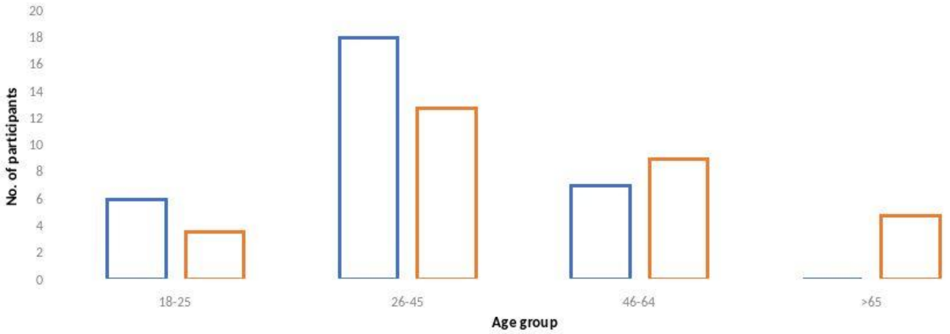


Figure 3.4.: Total participants selected (in blue) vs Munich driver demographics (in orange) for each age group for both genders (source: own)

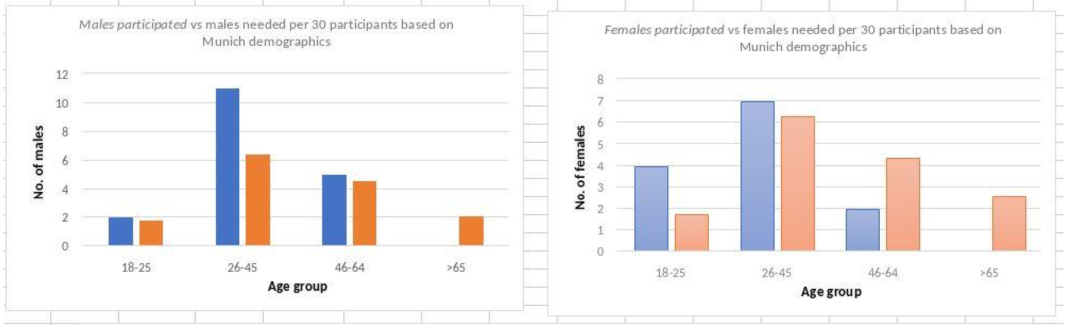


Figure 3.5.: Total participants selected (in blue) vs Munich driver demographics (in orange) for each age group for males (L) and females (R) (source: own)

3.2.2.4. Overview of Trials

Session	**Scenario**	**Duration (m)**	**Description**
Briefing	-	10	A brief description about the i-DREAMS project, including the simulator trials.
Filling of participant info sheet and consent form	-	5	
Filling of entry questionnaire	-	5	To assess information about driver background factors.
Practice simulation run	-	5	In order for the participant to get used to the simulator, including speed limits, braking, lane keeping, etc.
Monitoring configuration	Scenario A/B/C (according to Latin Square Method)	15	Driver drives without an intervention system. 9 events triggered (6 critical events, 2 non-events and 1 precursor event).
Break	-	5	-
Intervention configuration	Scenario A/B/C (according to Latin Square Method)	15	Driver drives with an intervention system that triggers warnings during safety critical events. 9 events triggered.
Filling of exit questionnaire A	-	5	To assess technology acceptance and gather feedback about the i-DREAMS system.
Distraction configuration	Scenario A/B/C (according to Latin Square Method)	15	Driver drives in the presence of in-vehicle distraction triggered via text messages. She does so with the help of the i-DREAMS real-time intervention system. 9 events triggered.
Filling of exit questionnaire B	-	5	To gather feedback about the i-DREAMS system.
Debriefing and remuneration	-	5	Filling of the debriefing form for General Data Protection Regulation purposes. The participants were also compensated with a voucher worth EUR 25.

Table 3.6.: Overview of the i-DREAMS simulator trials (source: own)

3.3. Data Processing and Analysis

The third section of the methodology framework involves the processing of data to make it suitable for usage and its consequent analysis. The subsequent steps are explored in the following subsections.

3.3.1. Sources of Data

The main sources of data used for this research were those collected from the simulator data files and Tobii Pro Glasses 2 (from henceforth used interchangeably with the term ‘eye tracker’). Table 3.7. lists out the distinct variables obtained as a result of the simulator experiments. It must be noted that during the simulator runs, multiple sources of data collection were used for specific purposes. They were Mobileye, PulseOn wearable, CardioGateway, questionnaire data, and finally simulator data via multiple sources (Pilkington-Cheney et al., 2020). This is in addition to the visual tracking data that was obtained from Tobii Pro Glasses 2.

For the purpose of the thesis we consider the data collected from simulator and the eye tracking data. The former was collected via two sources: BSAV and Open Module (OM). However, it should be noted that there was no discrepancy between the values of the variables recorded. The BSAV values were extracted from what the driving simulator wrote to its log file. The (OM) variables were taken from the internal simulator loop. To give an example, internally in the simulation software, the variable “BSAV_ElapsedTime” is a reference to the “Elapsed_Time” from the OM and so forth. For the objective of this thesis, BSAV data was chosen from the simulator data files.

Simulator Variable	**Variable (expanded)**	**Description**	**Unit**
BSAV_ElapsedTime	Elapsed Time	Time since start	s
BSAV_LongAcc	Longitudinal Acceleration	Longitudinal acceleration	m/s^2
BSAV_LatAcc	Lateral Acceleration	Lateral acceleration	m/s^2
BSAV_LongVelocity	Longitudinal Velocity	Longitudinal velocity	m/s
BSAV_LatVelocity	Lateral Velocity	Lateral Velocity	m/s
BSAV_TotalLongDistTravelled	Total Longitudinal Distance Travelled	Total distance driving	m
BSAV_LatPos	Lateral Position	Lateral position with respect to dividing lane (right is positive)	m
BSAV_SteeringWheelAngle	Steering Wheel Angle	Steering wheel input	Degrees
BSAV_RunningCompCrashes		-	-
BSAV_SpeedLimitMS	Speed Limit	Current speed limit in m/s^2	m/s
BSAV_SpeedLimitKPH	Speed Limit	Current speed limit in km/hr	km/h
BSAV_LeftTurnIndicatorState	Left Turn Indicator State	Left turn indicator	-
BSAV_RightTurnIndicatorState	Right Turn Indicator State	Right turn indicator	-
BSAV_MinTimeHeadwayVehicle	Minimum Time Headway of Vehicle	Minimum time to collision (s) between the driver's vehicle and all vehicles in the driver's direction.	s
BSAV_MinTimeHeadwayPedestrian	Minimum Time Headway of Pedestrian	Minimum time to collision between driver and pedestrian	s
BSAV_RunningCompTickets		-	-
BSAV_GasPedalPercentageDisplaced	Gas Pedal Percentage Displaced	Percentage of maximum gas pedal displaced during acceleration	0-1
BSAV_BrakePedalPercentageDisplaced	Brake Pedal Percentage Displaced	Percentage of maximum brake pedal displaced during braking	0-1
BSAV_GasPedalInputCount	Gas Pedal Input Count	Input count of gas pedal	-
BSAV_BrakePedalInputCount	Brake Pedal Input Count	Input count of brake pedal	-

Table 3.7.: Driving simulator metrics extracted from simulator log files (source: own)

For the purpose of visual tracking and its analysis, the corresponding metrics were obtained from the recording files of simulator drives done via Tobii Pro Glasses 2 and its consequent analysis using Tobii Pro Lab. The latter will be touched upon in subsection **3.4.** Table 3.8. gives an overview of the metrics present in the export data file obtained from the Analyzer module of Tobii Pro Lab version 1.162 (x64).

Eye tracker variable name	**Description**	**Unit**
Interval Duration	Interval duration for each safety critical events, with averages, medians, counts, variances, and standard deviations (n-1).	s
Interval Start	Start time of a safety critical event	s
Event Count	Represents number of safety critical events logged per participant according to the defined Times of Interest (TOI)	0-1
Time to First Event	The time when first event starts. This includes custom events and logged live events, for each TOI.	s
Total Fixation Duration	The total duration of the fixations inside an Area of Interest (AOI) during a specified time period.	s
Average Fixation Duration	The average duration of the fixations inside an AOI during a specified time period.	s
Fixation Count	The number of fixations happening in an AOI during a specified time period.	Count
Time to First Fixation	The time to the first fixation inside an AOI during a specified time period.	s
First Fixation Duration	The duration of the first fixation inside an AOI during a specified interval.	s
Total Visit Duration	The total duration of the visits occurring inside an AOI during a specified time period.	s
Average Visit Duration	The average duration of the visits happening inside an AOI during a specified time period.	s
Visit Count	The number of visits occurring inside an AOI during a specified time period	Count

Table 3.8.: Selected eye tracking variables extracted from Tobii Pro Lab Analyzer Edition, v 1.162. (Source: tobiipro, 2014)

For a comprehensive list of all metrics that can be extracted from the analyzer module of Tobii Pro Lab, please refer to chapter 9 of Pro Lab User Manual v1.162 (tobiipro, 2014).

3.3.2. Extraction of Relevant Variables

This step involved filtering relevant metrics based on a comprehensive review of literature involving the study of driver distraction in a driving simulator environment. The synthesis of literature was conducted in sections **2.5.** and **2.7.2.** for driving simulator and visual tracking variables respectively. These were selected based on their sensitivity to distracted driving. The selected parameters for assessing driving performance from the driving simulator and Tobii Pro Lab have been summarized in tables 2.2. and 2.5. respectively.

3.3.3. Extraction of Event-Based Information

Six safety critical events and two non-events were considered for the purpose of analysis. Each recording corresponded to one configuration and scenario of the simulation (e.g.: distraction configuration with scenario B). The necessary events were first logged in the recording of the simulation in the Analyzer module of Tobii Pro Lab. The process of the Eye Tracking Analysis (ETA) will be explained in section **3.4.**

For this purpose, nine Times of Interest (TOI) or events were logged in the recordings, including six critical events, two non-events, and one precursor event. The precursor event was ignored since the participant wasn't under the influence of distraction in this case as she didn't receive text messages. The data file obtained contained information about the starting, ending, and duration of six critical events and two non-events. This data was used to extract the corresponding driving performance variables from the simulator data file based on the starting and ending times of events/TOIs.

3.3.4. Removal of Extraneous Data

The next step was to filter out outlier values. For the simulator dataset, this was done in Excel using the interquartile ranges (the outlier being 1.5 interquartile ranges below the 1st quartile, and 1.5 interquartile ranges above the 3rd quartile). However, this was redundant owing to a few conditions. During the beginning of the simulation the participants were instructed to take into consideration the zonal speed limits, stay on a particular lane and not to overtake during a car-following situations. For this reason, the values of the driving performance parameters were in a particular range (e.g.: for longitudinal velocity the range was 0-the approximate speed limit of the particular road segment the participant was driving on). For the eye tracking metrics, Tobii Pro Lab does the pre-processing and aggregation automatically so there was no need to remove extraneous data manually.

3.3.5. Aggregation of Variables

The simulator variables obtained from the preceding step for each event per participant were aggregated using the AVERAGE function in Excel. Thus, each participant had 8 values for each parameter (e.g.: lateral position), each of which corresponded to a particular event (e.g.: tailgating event in a rural scenario). As for the eye tracker metrics, Tobii Pro Lab pre-processed and aggregated it based on participant, TOI and AOI.

3.3.6. Merging of Simulator and ETA Data

The simulator and eye tracking files were then merged based on the participant ID and event name for correspondence.

3.3.7. Evaluation of Statistically Significant Parameters

The simulator variables selected based on the results of the literature synthesis done in part **2.5.** were then converted to statistically significant parameters, namely the mean, minimum, maximum values and standard deviations. This was done using the AVERAGE, MIN, MAX, and STDEV functions in Excel. The list of relevant variables obtained has been depicted in table 3.9.

Category	Variable name (Unit)	Statistically Significant Parameter Used	Based on Review from Section 2.5.
Longitudinal Control	Longitudinal Velocity	Mean	Papantoniou et al., 2017; van der Horst et al., 1994; Manser and Hancock, 2007; Chu, 1994; Haigney et al., 2000
	Longitudinal Velocity	Maximum	Papantoniou et al., 2017; van der Horst et al., 1994; Manser and Hancock, 2007; Chu, 1994; Haigney et al., 2000
	Headway	Mean	Regan et al., 2008; Greenberg et al., 2003; Östlund et al., 2004; Papantoniou et al., 2017
	Headway	Minimum	Regan et al., 2008; Greenberg et al., 2003; Östlund et al., 2004; Papantoniou et al., 2017
Lateral Control	Lateral Position	Mean	Greenberg et al., 2003; Green et al., 2004; Horrey et al., 2006; Caird et al., 2008; Liang et al., 2010
	Steering Wheel Angle	Mean	Regan et al., 2008; McGehee et al., 2004
Reaction Time	TTC	Mean	van der Horst et al., 1994; Papantoniou et al., 2017
	TTC	Minimum	van der Horst et al., 1994; Papantoniou et al., 2017
Others	Longitudinal Acceleration	Mean	Papantoniou et al., 2017
	Longitudinal Acceleration	Maximum	Papantoniou et al., 2017
	Lateral Acceleration	Mean	-
	Lateral Acceleration	Maximum	-
	Lateral Velocity	Mean	-
	Lateral Velocity	Maximum	-

Table 3.9.: Statistically significant simulator variables according to literature review done in section 2.5. (source: own)

As for the eye tracking metrics, they were kept unchanged from what is depicted in table 2.5. as per information assessed in section **2.7.2.** of the literature review. They were namely Fixation Count, Total Fixation Duration and Average Fixation Duration.

3.4. Data Analysis

3.4.1. Eye Tracking Analysis (ETA)

For this purpose, the recordings of simulation runs containing eye movement data of the participant was imported into the Analyzer module of Tobii Pro Lab V1.162. A single project called "iDREAMS-Experiment" was created containing recording data for 30 participants (30 distraction scenario recordings and 30 intervention scenario recordings amongst others). Each recording had a ".ttgp" file format that could only be read and analyzed using Tobii Pro Lab.

3.4.1.1. Defining Participant Variables

For each recording of a participant, the following multi-option variables were created and defined: configuration (distraction or intervention), scenario (A, B or C), gender, age, and offset. Depending on the type of drive and participant demographic, options could be selected for each sample. Following which a distraction recording was opened in the created project to log the names of 6 critical and 2 non-events which was later used to define Times of Interest (TOI). In addition, information about each individual event included start and end points. This was done only once per project as the changes made were applied to all remaining recordings, irrespective of configuration or scenario.

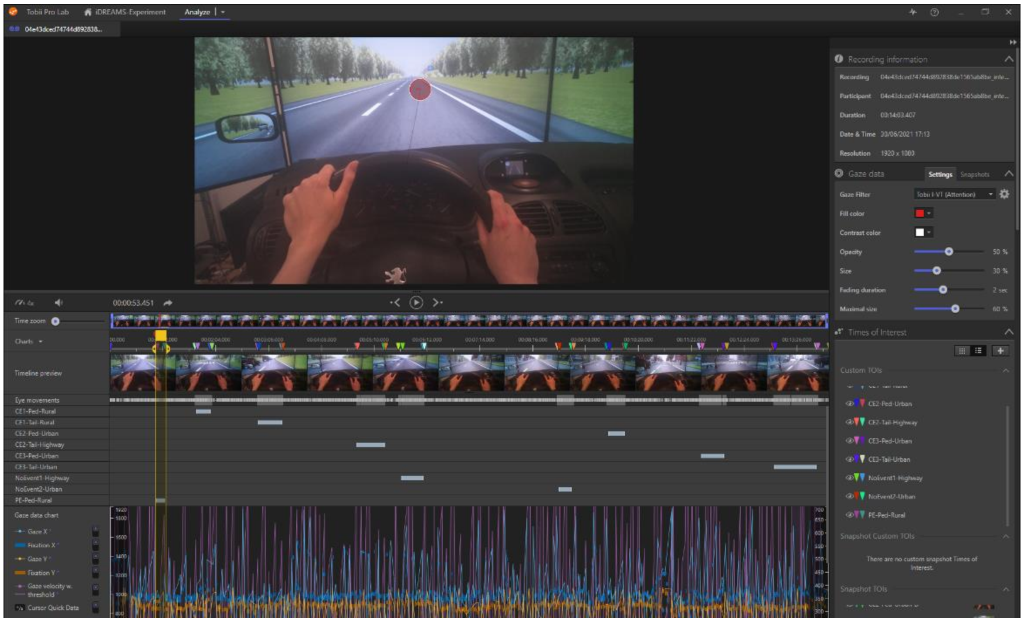
For example, if a recording had the file name "ABCD_distraction_B". Then, the configuration would be distraction with scenario type B being used. The demographic data of the participants were then associated with this data. For a particular event name, it would look like the following: for a tailgating scenario in the rural segment, the event name was defined as 'CE1-Tail-Rural' (the order of events can be found in section III.C. of Ezzati Amini et al., 2021), with the starting and ending points named as 'CE1-Tail-Rural-Start' and 'CE1-Tail-Rural-End'.

The driving simulator run had a lag of about 1-2 s when compared with each eye tracker recording. This occurred because the simulation was started first and then the recording. However, it was important to have synchronized simulator and eye tracker data. Thus, the time offset for each recording was manually extracted and added to Offset Time Option for each recording.

3.4.1.2. Analysis of Eye Tracking Data

It should be noted that for the purpose of ETA, the distraction configuration was the baseline to log all events. This is because the driver receives text messages during the distraction scenario and thus, the specific Times of Interest (TOI) when the driver was distracted could be specified and be used to adjust the recording having an intervention configuration.

The 8 aforementioned events (their starting and ending points) were logged in all recordings and time offset adjusted. This was used to create 8 TOIs by connecting the starting and ending points of each event in the distraction scenario. A TOI in the distraction scenario signified the time interval during which the driver was distracted from the primary driving task. The corresponding TOIs for the intervention configuration were flagged using this information from the distraction scenario.



Recording 04e43dced74744d892838de1565ab8be_inte...
Participant 04e43dced74744d892838de1565ab8be_inte...
Duration 00:14:03.407
Date & Time 30/06/2021 17:13
Resolution 1920 x 1080

Gaze Filter Tobii I-VT (Attention)
Fill color 🟥
Contrast color ⬜
Opacity 50 %
Size 30 %
Fading duration 2 sec
Maximal size 60 %

There are no custom snapshot Times of Interest.

Figure 3.6.: The Time of Interest interface in Tobii Pro Lab V1.162. The 9 grey bars in the bottom half of the picture represent nine events that were logged (6 critical events, 2 non-events and 1 pre-cursor event) (source: own)

An Area of Interest assists in conducting quantitative analyses of glance behavior, including metrics such as Fixation Count, Total Fixation Duration, Average Fixation Duration, etc. in a pre-defined area of the recording interface. For the distraction scenario, five AOIs were created: they for the road ahead, dashboard, i-DREAMS display, mobile phone screen and pedestrian. The first three were kept active all the time, while the mobile phone screen was activated only during the specific TOIs when the driver was engaged in a secondary driving task with the phone. Finally, the pedestrian AOI was only activated during critical events involving VRUs. The intervention recording used all the aforementioned AOIs, except the mobile phone screen. The AOIs position and sizes were constantly adjusted during the drive to provide an accurate representation of glance behaviour.

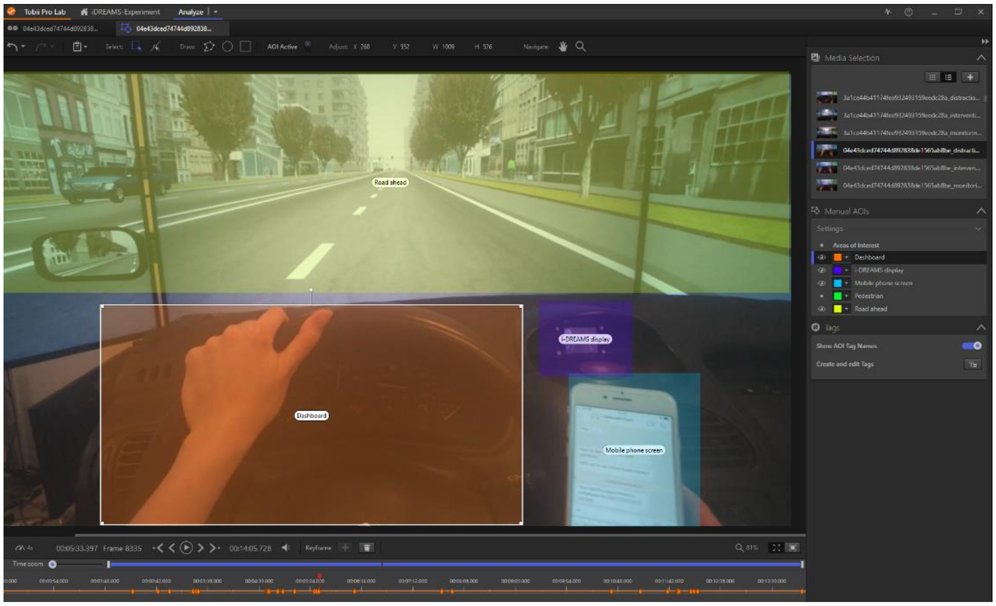


Figure 3.7.: The Area of Interest interface in Tobii Pro Lab V1.162. The AOIs defined for this event include: dashboard (red), road ahead (yellow), i-DREAMS display (violet) and the mobile phone screen (blue) (source: own)

The required metrics from the analyzed recordings were then exported as csv files for the purpose of analysis. The list of variables has been depicted in table 2.5. Heat maps were also obtained as a result of the exports that aggregated gaze behaviour (fixation or count) for all participants for a particular configuration.

3.4.2. Descriptive Analysis of Variables

According to Yannis et al. (2014), descriptive analysis for large datasets becomes essential to quantitatively analyze the data. For the variables selected in tables 2.5. and 3.9., this was done with the help of box plots. They were used to explain the distribution and skewness of data in both distraction and the baseline intervention scenarios. This was done in Excel using the quartile ranges. The box plot was plotted using the 'Box and Whisker Plot' statistic chart function. Owing to the large number of values (8 events times 30 participants for each scenario) and the corresponding plots, it was necessary to filter out the most critical values. This condition was met by considering those cases where the significance criterion was met for a t-test (α =0.05) between the intervention and distraction scenarios for a particular driving performance variable. The mean values obtained from the t-tests were for each variable was considered for the selection criterion. Meeting this condition implied that distraction had a significant impact on that particular driving performance parameter during an event and hence these are values we would be interested in.

In addition to box plots, bar graphs were used to depict which variables had the most fluctuations during specific critical and non-events.

3.4.3. Inferential Analysis of Variables

After descriptive analysis was conducted, inferential statistical methods were used by Yannis et al. (2014) to interpret relationships between driving performance variables. It was seen in section **2.7.1.** that for two populations, a two sample *t*-test is helpful in establishing this relationship since the baseline intervention scenario and the distraction scenario are independent samples. This essentially gave us a measure of evaluation of the effect of distraction on the driving performance when compared to the baseline scenario. This was consequently a measure of the means of the two data populations and if they were statistically significantly different from each other.

According to Bendak et al. (2010) (section **2.7.1.**), the hypothesis to be tested for the distraction and baseline scenarios was as follows:

H_0: $\mu_1 = \mu_1$
H_1: $\mu_1 > \mu_2$

Where H_0 was the null hypothesis to be tested; μ_1 was the average performance indicator during the test scenario; μ_2 was the average performance indicator during the baseline scenario. A significance level of $\alpha = 0.05$ was used. On the other hand, Yannis et al. (2014) used a ninety percent confidence interval, with a t-value higher than 1.64, and a p-value lower than 0.100. However, for the purpose of this analysis, $\alpha = 0.05$ has been considered for greater accuracy.

However, t-tests can usually be performed when certain validation criteria are met (Petritis, 2018). In the case of this research, they were as follows:

Criterion	**Validation**
The samples are independent of each other.	Validated because data collection for intervention and distraction scenarios were conducted independent of each other and so were the resulting values of driving performance variables across drives.
Having (approximately) normal distributions.	Validated in Excel using the NORMDIST function.
High sample size (>30).	Partially validated because the sample size was 30 participants.

Table 3.10.: Confirmation of validation criteria for a two sample t-test

The following steps were undertaken to test our hypotheses (Mishra et al., 2019). The specific hypotheses will be categorized in sec. **3.5**. and tested in chap. **5.**

A. Hypothesis building

H_0: $\mu_1 = \mu_1$

H_1: $\mu_1 > \mu_2$

Where H_0 was the null hypothesis to be tested; H_1 was the alternative hypothesis; μ_1 was the average driving performance indicator during the distraction scenario; μ_2 was the average performance indicator used for the baseline intervention scenario.

B. Computation of test statistics

The t-value was calculated as follows:

$$t = \frac{m_A - m_B}{\sqrt{\frac{S^2}{n_A} + \frac{S^2}{n_B}}}$$

Where, A and B were the distraction and intervention populations to be compared; m_A and m_B represented the means of populations A and B, respectively; n_A and n_B were the population sizes of A and B. For the simulator trials, this was 30 participants who partook in both intervention and distraction drives; t was the t-test statistic value; S^2 was an estimator of the common variance of the two samples.

The S^2 value was calculated as follows:

$$S^2 = \frac{\sum (x - m_A)^2 + \sum (x - m_B)^2}{n_A + n_B - 2}$$

C. Tabulated value

A significance level $\alpha = 0.05$ was used as the threshold (Bendak et al. 2010).

$d_f = n_A + n_B - 2$

Where d_f is the degree of freedom.

The corresponding tabulated value of the *t*- test was considered using the t-test statistical table.

D. Comparison of t-value with tabulated value to validate or reject the null hypothesis

To check whether distraction has a significant impact on the driving performance variables.

3.4.3.1. T-test Between Intervention and Distraction Scenarios for Driving Performance Variables (driving simulator and ETA data)

Following the guidelines laid down in section **3.4.3.**, selected driving performance variables from table 3.9. for both intervention and distraction scenarios were used for a two sample t-test. This was done for each event type described in table 3.3. For the eye tracking variables, 4 AOIs were common between the intervention and distraction drives. They were namely dashboard, i-DREAMS display, pedestrian and road ahead. The variables used for each AOI were Total Fixation Duration and the Fixation Count. They have been extracted from table 2.5. The aim was to evaluate if distraction had a significant effect on any of the metrics described above.

3.4.3.2. T-test to Compare Between VRU and Tailgating Events Using Mobile Phone Screen AOI in Distraction

The next step was to focus on only the distraction scenario since the mobile phone was used here. The mobile phone screen AOI couldn't be taken into consideration in the calculation in the previous section for this reason. The aforementioned AOI has mainly 2 eye tracking variables: fixation count and total fixation duration.

The aim was to conduct t-tests between VRU and tailgating events for the aforementioned eye-tracking metrics. The significant relationships were then plotted. There were six comparisons in total, which were as follows:

A.Tailgating:

- CE1–Tailgating-Rural vs CE2-Tailgating-Highway
- CE2-Tailgating-Highway vs CE3-Tailgating-Urban
- CE3-Tailgating-Urban vs CE1–Tailgating-Rural

B.VRU collisions:

- CE1-Pedestrian-Rural vs CE2-Pedestrian-Urban
- CE2-Pedestrian-Urban vs CE3-Pedestrian-Urban
- CE3-Pedestrian-Urban vs CE1-Pedestrian-Rural

This was done in order to identify possible patterns in gaze behaviour that differentiated how drivers reacted to possible tailgating and pedestrian crashes.

3.5. Tested Hypotheses

The following hypotheses were taken into account based on the synthesis of existing literature before data could be analyzed. The hypotheses are listed as distraction-related, traffic environment-related, safety critical event-related, driver gaze behaviour-related and context-aware ADAS-related. The verification or rejection of each of the following hypothesis is discussed in chapter **5**.

Distraction-related hypotheses:

Hypothesis 1: Impact of distraction on longitudinal control parameters: Does in-vehicle distraction via texting have a significant negative impact on longitudinal control parameters such as the average longitudinal velocity and time headway when compared to the baseline scenario?

Hypothesis 2: Impact of distraction on lateral control parameters: Does in-vehicle distraction via texting have a significant negative impact on lateral control parameters such as the lateral position and steering wheel angle when compared to the baseline scenario?

Hypothesis 3: Impact of distraction on reaction time measures: Does in-vehicle distraction via texting have a significant negative impact on reaction time measures such as the Time to Collision (TTC) when compared to the baseline scenario?

Hypothesis 4: Impact of distraction on associated longitudinal control parameters: Does in-vehicle distraction via texting have a significant negative impact on the longitudinal acceleration and deceleration when compared to the baseline scenario?

Hypothesis 5: Impact of distraction on associated lateral control parameters: Does in-vehicle distraction via texting have a significant negative impact on lateral velocity and lateral acceleration when compared to the baseline scenario?

Traffic environment-related hypotheses:

Hypothesis 1: Do urban road segments and its associated speed limit have a negative impact on the long. control performance during distracted driving?

Hypothesis 2: Does an urban road segment and its associated speed limits have a negative impact on the lat. control performance during distracted driving?

Hypothesis 3: Does an urban road segment and its associated speed limits have a negative impact on the reaction time during distracted driving?

Hypothesis 4: Does a rural road segment and its associated speed limits have a negative impact on the long. control performance during distracted driving?

Hypothesis 5: Does a rural road segment and its associated speed limits have a negative impact on the lat. control performance during distracted driving?

Hypothesis 6: Does a rural road segment and its associated speed limits have a negative impact on the reaction time during distracted driving?

Hypothesis 7: Do highway segments and its lack of speed limits in Germany have a negative impact on the long. control performance during distracted driving?

Hypothesis 8: Do highway segments and its lack of speed limits in Germany have a negative impact on the lat. control performance during distracted driving?

Hypothesis 9: Do highway segments and its lack of speed limits in Germany have a negative impact on the reaction time during distracted driving?

Hypothesis 10: Does driving performance degrade significantly during distracted driving during a non-event (NE) on the highway?

Hypothesis 11: Does driving performance degrade significantly during distracted driving during a non-event (NE) in the urban area?

Safety critical event-related hypotheses:

Hypothesis 1: Do possible VRU collision scenarios in rural and urban areas have a negative impact on long. control performance during distracted driving?

Hypothesis 2: Do possible VRU collision scenarios in rural and urban areas have a negative impact on lat. control performance during distracted driving?

Hypothesis 3: Do possible VRU collision scenarios in rural and urban areas have a negative impact on the reaction time performance during distracted driving?

Hypothesis 4: Do possible tailgating scenarios in rural, highway and urban areas have a negative impact on long. control performance during distracted driving?

Hypothesis 5: Do possible tailgating scenarios in rural, highway and urban areas have a negative impact on lat. control performance during distracted driving?

Hypothesis 6: Do possible tailgating scenarios in rural, highway and urban areas have a negative impact on the reaction time during distracted driving?

Driver gaze behaviour-related hypotheses:

Hypothesis 1: Is fixation on the i-DREAMS display increased when in-vehicle distraction is present during safety critical events involving VRU collisions, as compared to the baseline intervention scenario?

Hypothesis 2: Is fixation on the i-DREAMS display increased when in-vehicle distraction is present during safety critical events involving tailgating, as compared to the baseline intervention scenario?

Hypothesis 3: Does traffic environment (roadway segment) have a significant impact on driver glance behaviour in terms of fixation on the mobile phone screen during safety critical events involving VRU collisions in urban and rural roadway segments?

Hypothesis 4: Does traffic environment (roadway segment) have a significant impact on driver glance behaviour in terms of fixation on the mobile phone screen during safety critical events involving tailgating in urban, highway and rural roadway segments?

Hypothesis 5: Is eye tracking an effective method to study driver distraction?

Context-aware ADAS-related hypotheses:

Hypothesis 1: Is the i-DREAMS system effective in mitigating distraction & improving driving performance during safety CE involving VRU collisions?

Hypothesis 2: Is the i-DREAMS system effective in mitigating distraction & improving driving performance during safety CE involving tailgating scenarios?

*

Chapter 4. Overview of Results

This chapter presents a summary of the results of the data analysis. This includes analysis of critical driving performance variables obtained from the simulator and eye tracker based on the literature review conducted in chapter **2**. An overview of the results based on exploratory, inferential and visual methods is given.

4.1. Explanatory Statistical Analysis of Driving Performance Variables

As discussed in section **3.4.2.**, box plots were used to show the distribution of skewness in the data and for a preliminary exploratory analysis. The plots are presented along with specific driving performance variables and their variations in both the intervention & distraction driving phases for 6 safety critical events & 2 non-events.

4.1.1. Variables obtained from the driving simulator:

I. **Longitudinal control parameters**: Longitudinal Velocity (mean), longitudinal velocity (maximum), headway (mean), headway (minimum).
II. **Lateral control parameters**: Lateral position (mean) and steering wheel angle (mean).
III. **Reaction time parameters**: TTC (mean) and TTC (minimum).
IV. Other parameters, including additional longitudinal and lateral control parameters: lateral velocity and acceleration, longitudinal acceleration.

Longitudinal Control Parameters:

Longitudinal Velocity (mean, m/s): In general, both distraction and intervention phases had a similar distribution (figure 4.1.). During CE2-Tailgating-Highway and NE1-Highway scenarios, however, drivers showed a higher variability in the mean values of *longitudinal velocities* when compared with the remaining safety critical events for both distracted driving and the baseline intervention phase. Interestingly, during the former safety critical event, higher variations were observed during the baseline scenario, when drivers has no supplementary task load except the driving task. Please note that the term mean value of a certain *parameter* (e.g.: mean value of *average longitudinal velocity* has been gathered from *t*-test results).

Longitudinal Velocity (maximum, m/s): Distracted drivers showed a wider variability range for the average value of *maximum longitudinal velocity* (speed) as compared to the baseline intervention scenario (figure 4.2.). As in the case with average speeds, they exhibited the highest variations in attaining maximum longitudinal velocity in CE2-Tailgating-Highway and NE1-Highway scenarios for both distracted driving and baseline situations. The solitary exception was CE2-Tail-Highway where non-distracted drivers showed higher variations in the maximum speed.

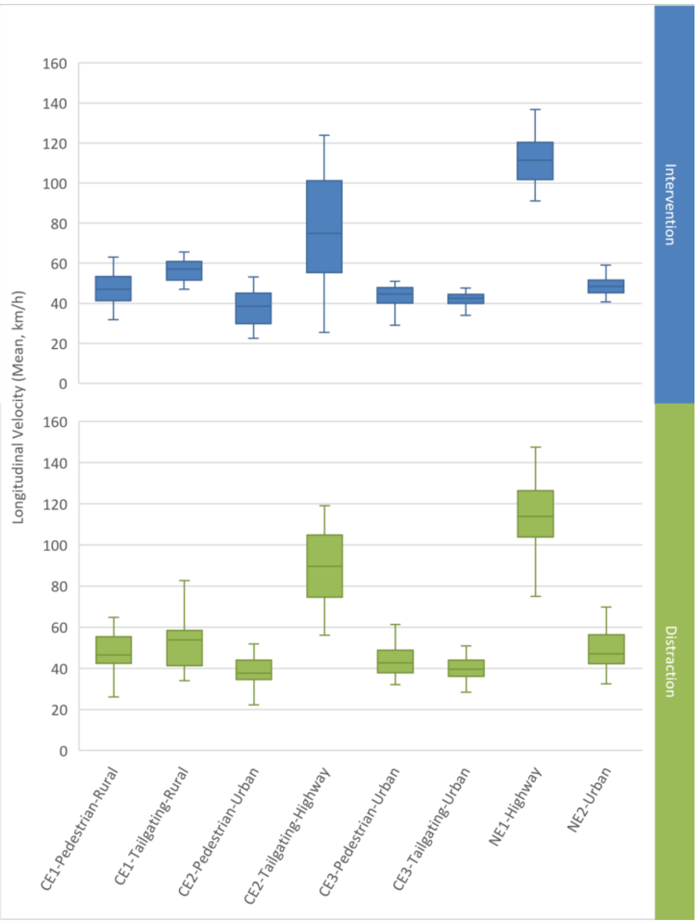


Figure 4.1.: Variation in mean values of mean longitudinal velocity across events (baseline vs. distracted driving) (source: own)

Headway (mean, s): During tailgating scenarios and non-events, the mean value of *average headway* showed negligible variation (figure 4.3.). In general, the variations occurred during VRU collision scenarios, especially during CE1-Ped-Rural and CE2-Ped-urban situations. The range of values observed was more varied in the distraction scenario as compared to the baseline.

Headway (minimum, s): The mean value of *minimum headway* showed much more interesting variations, with higher ranges of variability observed for both intervention and distraction driving scenarios (figure 4.4.). However, the variation during tailgating situations were almost negligible. The minimum headway distribution was more spread out in VRU collision scenarios on urban roadways.

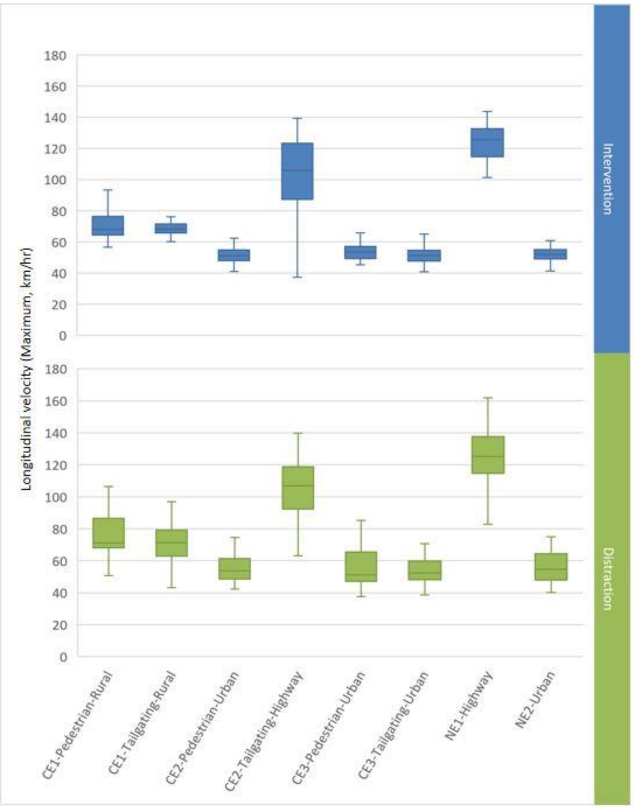


Figure 4.2.: Variation in mean values of maximum longitudinal velocity across events (baseline vs. distracted driving) (source: own)

Reaction Time Parameters

Time to Collision (TTC_{mean}, s): Drivers showed higher variations in mean values of *average TTC* when driving distracted (figure 4.5.). VRU collision scenarios tended to increase the mean TTC as well as the distribution of values. During NE-2-Urban, values below the median TTC went down and varied greatly.

TTC (minimum, s): Divergent behaviour was observed between distracted driving and the intervention scenario (figure 4.6.). When drivers were driving in urban environments (for both VRU collisions and tailgating), under the effect of distraction, they showed negligible variations in the mean value of *minimum TTC* as compared to the intervention scenario, which exhibited greater divergences. This was, however, reversed in the rural area where drivers showed a higher variation in the average value of minimum TTC during possible pedestrian collision scenarios.

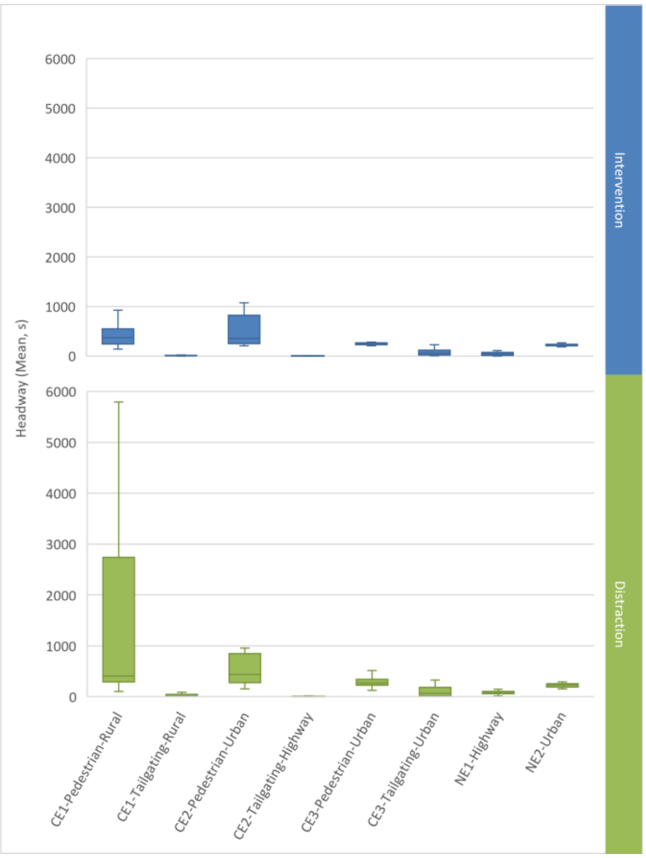


Figure 4.3.: Variation in mean values of mean headway across events (baseline vs. distracted driving) (source: own)

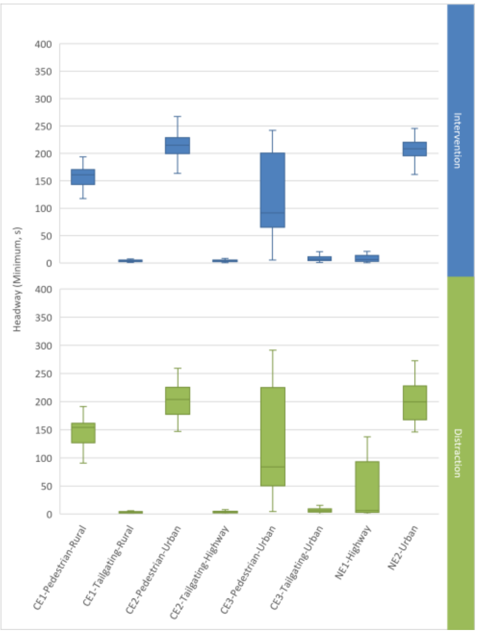


Figure 4.4.: Variation in mean values of minimum headway across events (baseline vs. distracted driving) (source: own)

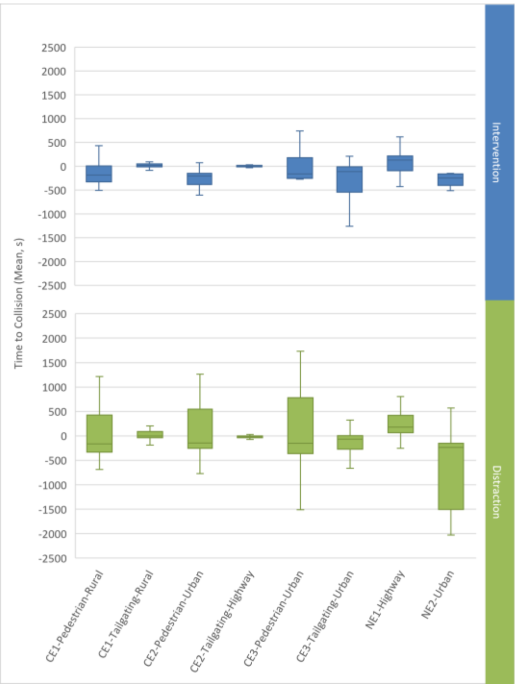


Figure 4.5.: Variation in mean values of mean TTC across events (baseline vs. distracted driving) (source: own)

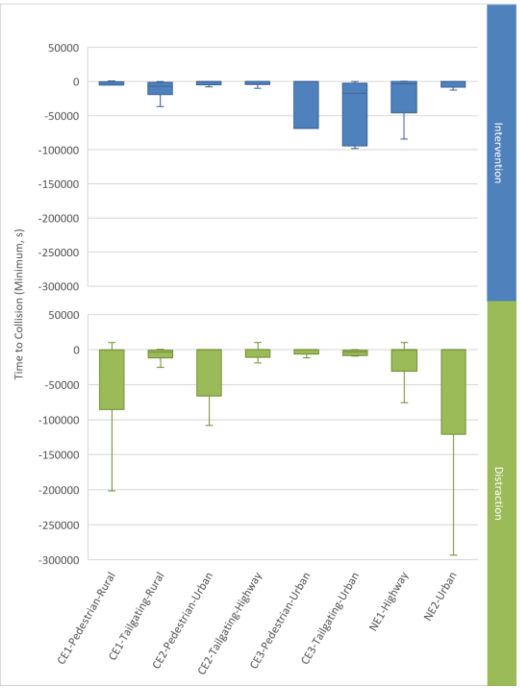


Figure 4.6.: Variation in mean values of minimum TTC across events (baseline vs. distracted driving) (source: own)

Lateral Control Parameters

Steering Wheel Angle (mean, degrees): Drivers showed very similar behaviours across driving environments as well as conditions (with and without distraction). There was minimum variation in the mean of the *average steering wheel angle* exhibited in every roadway segment except the urban area, where drivers showed highly distributed values during both tailgating and VRU collision cases.

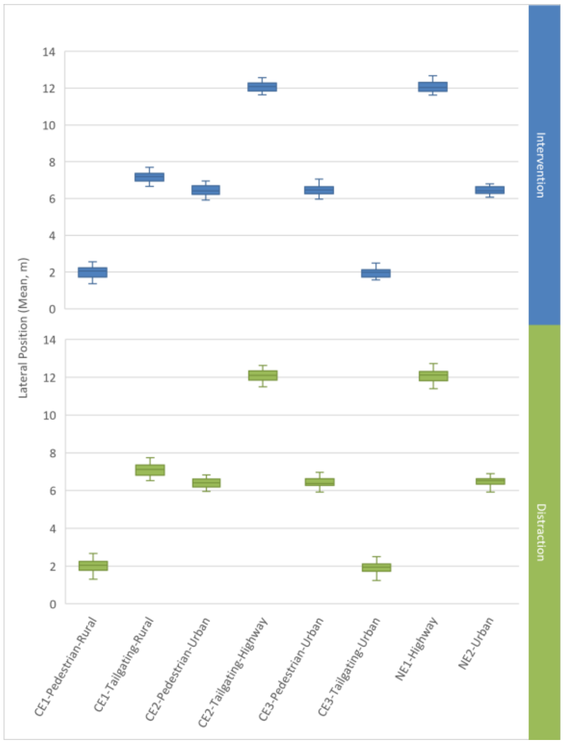


Figure 4.7.: Variation in mean values of mean lateral position across events (baseline vs. distracted driving) (source: own)

Lateral Position (mean, m): It was observed that during both intervention and distraction scenarios, drivers showed similar behaviour with regards to their lateral position. Very little variation was observed and there was negligible statistical distribution (figure 4.7.).

Longitudinal Acceleration (maximum, m/s²): Drivers exhibited similar behaviour irrespective of whether distraction was present or not. The mean of this metric showed relatively high variations in all safety critical scenarios except CE3-Tailgating-Urban (figure 4.8.).

Longitudinal Acceleration (mean, m/s²): As in the case of maximum longitudinal acceleration, the mean values of *average longitudinal acceleration* showed higher distributions in all roadway segments except CE3-Tailgating-Urban. Interestingly, drivers showed a higher deviation from mean acceleration values in the intervention scenario during possible pedestrian collisions in the rural area (figure 4.9.).

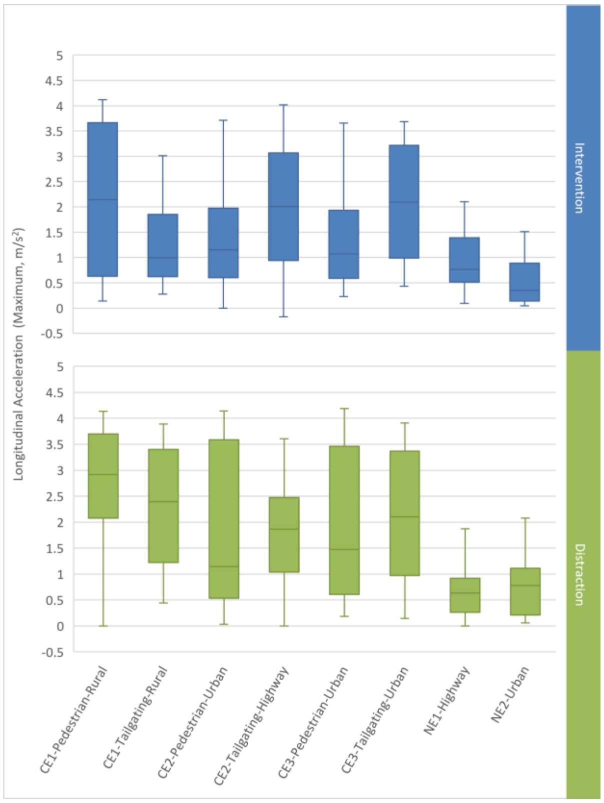


Figure 4.8.: Variation in mean values of maximum longitudinal acceleration across events (baseline vs. distracted driving) (source: own)

Lateral Acceleration (Mean, m/s^2): It was observed that drivers showed negligible deviations from mean behaviour in all traffic environment segments except the highway during both distraction and baseline scenarios. Mean values of *average lateral acceleration* were highly dispersed both in cases on non-events and tailgating for distracted driving (figure 4.10.).

Lateral Acceleration (Maximum, m/s^2): In general, drivers tended to show a higher divergence in the mean values of *maximum lateral acceleration* during distracted driving as compared to the non-test scenario. Values exhibited higher ranges of variation on the highway for both distraction and intervention drives. When the average driver was texting in the rural area and driving simultaneously, she tended to show higher variations in the maximum value of lateral acceleration during both pedestrian collision and car-following scenarios (figure 4.11.).

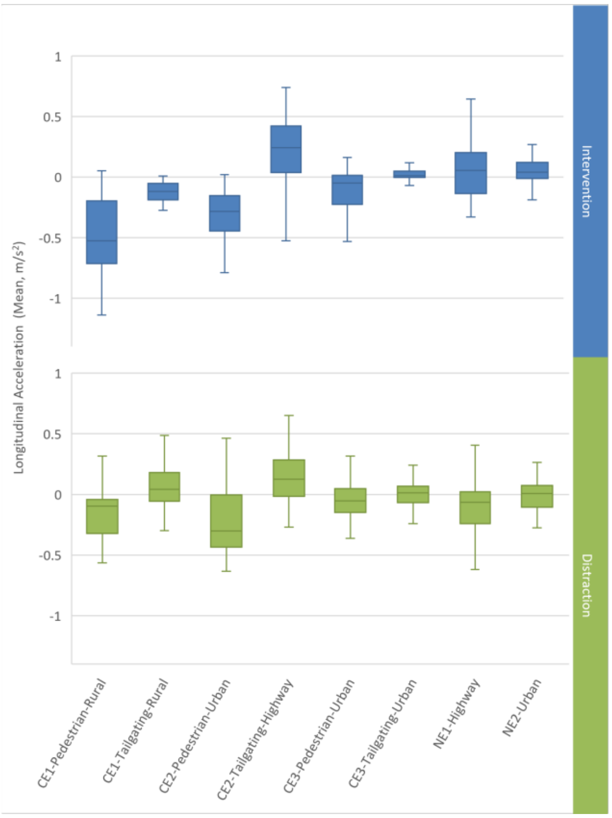


Figure 4.9.: Variation in mean values of mean longitudinal acceleration across events (baseline vs. distracted driving) (source: own)

Lateral Velocity (mean, m/s): Drivers showed similar behaviour in terms of change in lateral velocity during the test and baseline scenarios. High variations were observed across all events and roadways sections. It is interesting to note that during the intervention scenario, drivers showed a higher variation in the mean values of average lateral velocity during possible pedestrian collisions in the rural context as well as non-events on urban roadways as compared to distracted driving (figure 4.12.).

Lateral Velocity (Maximum, m/s): Distracted drivers showed a wider range of variation in this metric. This was especially true in the context of highway environments where for both tailgating and non-events (figure 4.13.).

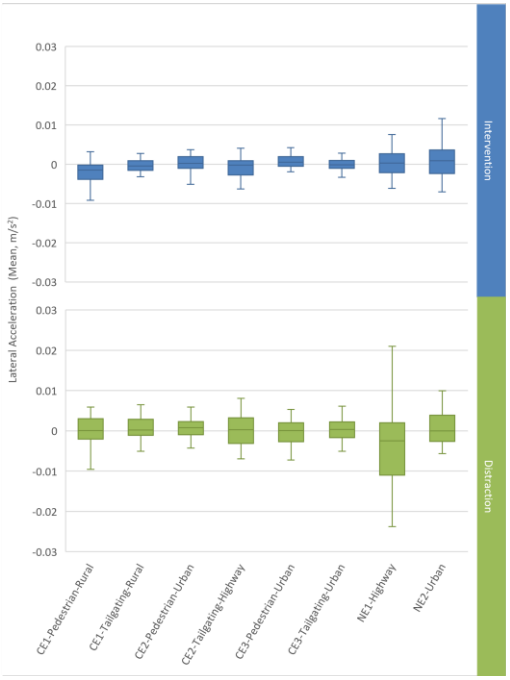


Figure 4.10.: Variation in mean values of mean lateral acceleration across events (baseline vs. distracted driving) (source: own)

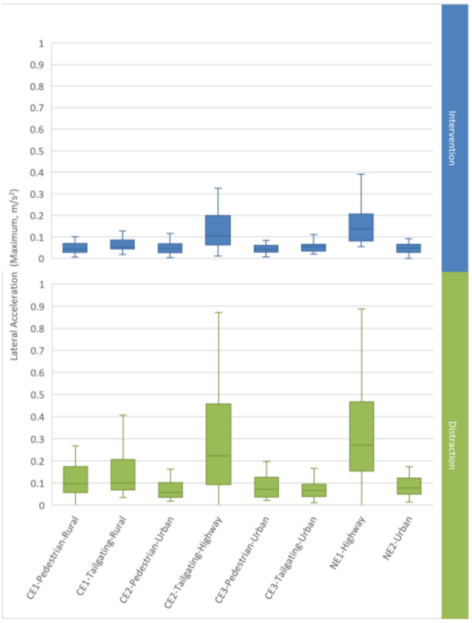


Figure 4.11.: Variation in mean values of maximum lateral acceleration across events (baseline vs. distracted driving) (source: own)

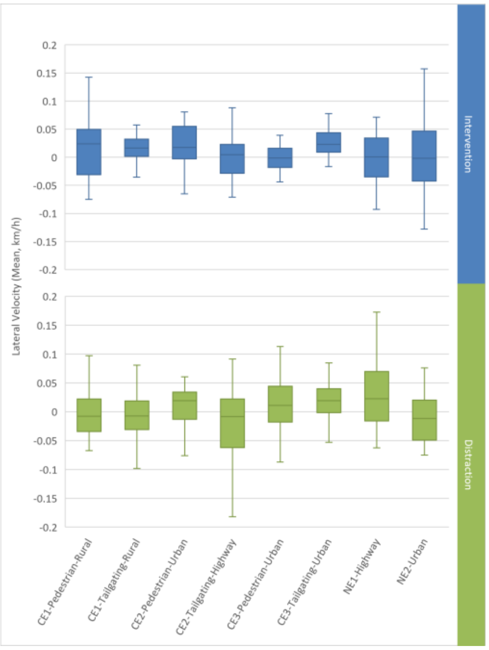


Figure 4.12.: Variation in mean values of mean lateral velocity across events (baseline vs. distracted driving) (source: own)

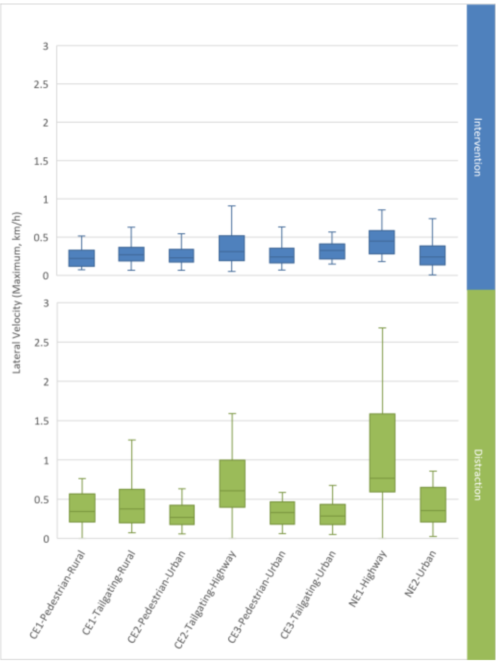


Figure 4.13.: Variation in mean values of max. lateral velocity across events (baseline vs. distracted driving) (source: own)

4.1.2. Variables obtained from the driving simulator:

Please refer to section **4.3.**

4.2. Inferential Statistical Analysis of Driving Performance Variables

As discussed in section **3.4.2.**, *t*-tests were conducted to show the impact of distraction on the driving performance as compared to the baseline intervention scenario. The plots are presented while each safety critical event is analyzed based on specific driving performance variables and their variations in both the intervention and distraction driving phases. This gives a measure of the impact of distraction on specific driving performance variables as compared to the intervention scenario. Variables that met the significance criterion in section **3.4.2.** and exhibited significant deviations in mean behaviour between distraction and intervention phases are presented in the following subsection.

4.2.1. Driving Performance Variables Obtained from the Simulator

Risk factor type: Vulnerable User Collision

CE1-Ped-Rural

It was observed that the lateral control metrics varied significantly. Drivers leaned towards higher maximum values of lateral velocity and lateral acceleration. The latter nearly doubled during the distraction scenario as compared to the baseline. On average, drivers tended to have higher longitudinal velocities and headways. During distracted driving, drivers nearly doubled the time headway that was available to them. This confirms the findings of Greenberg et al. (2003) and Östlund et al. (2004), who stated that drivers tend to implement increased headways when interacting with secondary tasks. The secondary task in this case was the interaction with the cell phone. Thus, it can be concluded that both longitudinal and lateral control parameters were affected significantly during this event (figure 4.14.).

CE2-Ped-Urban

During the aforementioned safety critical event involving pedestrians in an urban traffic environment, it was assessed that reaction time, longitudinal control as well as lateral control parameters were affected. Lateral control measures such as the steering wheel angle and peak values of lateral acceleration increased by almost 100%. Longitudinally, the driver saw a degradation in the driving performance. The maximum values of longitudinal acceleration increased by over 50% and the time headway was reduced during distracted driving. Thus, the driver was less in control of the vehicle speed while distracted. Surprisingly, the Time to Collision increased by 125% in the distraction scenario, implying that drivers were cognitively more aware of being distracted. This refutes the findings of Wright (2005), who stated that distracted drivers are unaware of their situation and visual experiences while involved in a secondary driving task. This is a metric that separates normal driving behaviour from aggressive behaviour (van der Horst et al., 1994). An increase in the TTC suggests that drivers tended to be less aggressive longitudinally (figure 4.15.).

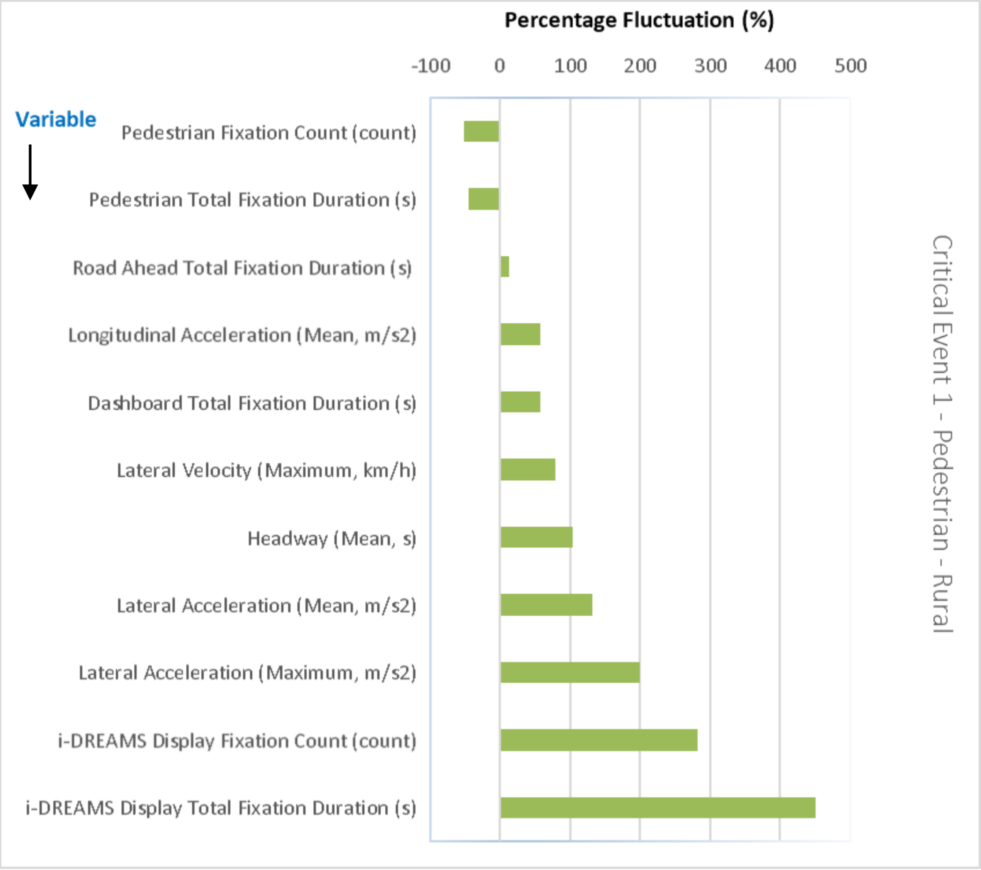


Figure 4.14.: Percentage fluctuations in driving performance variables during distracted driving as compared to the baseline during CE1-Ped-Rural (source: own)

CE3-Ped-Urban

It was observed that there were no major differences in the driving performance between the baseline intervention scenario and the distracted driving phase. This is surprising given the fact that this scenario has the highest distraction potential of all VRU collision possibilities, since the pedestrian is jaywalking and crossing the intersection illegally when the signal is still green. However, contradictory results were seen in the case of lateral control. Drivers reduced their mean lateral accelerations by almost 200% in the distracted driving scenario, but increased their maximum lateral accelerations by almost 100% (figure 4.16.).

Figure 4.15.: Percentage fluctuations in driving performance variables during distracted driving as compared to the baseline during CE2-Ped-Urban (source: own)

CE1-Tail-Rural

It was observed that driving performance degraded with respect to lateral control. Both maximum values of lateral acceleration and velocity increased significantly. The mean values of longitudinal velocity and acceleration almost doubled during the distraction scenario as compared to the intervention scenario. Thus, the driver was less in control both longitudinally and laterally during tailgating scenarios in a rural context. This corroborates the findings of Bunker et al. (2005) given in table 2.3. The authors stated that as headways became smaller in congested networks due to increasing proximity to other vehicles, the Level of Service worsened and drivers appeared to compensate by increasing their lateral position to other drivers. According to Zatmeh-Kanj et al. (2021), it was found that during tailgating scenarios under distraction, average speeds were lower, on the other hand Coefficient of Variations of speeds were much higher. This has been found to be true in this case. The maximum value of longitudinal acceleration also rose significantly. The above signifies that the driver had compromised longitudinal and lateral control during tailgating scenarios on rural roadways with relatively lower speed limits (figure 4.17.).

CE2-Tail-Highway

When drivers were distracted via text messages during a tailgating scenario on a highway environment with no speed limits, it was observed that the loss of lateral control was significant. The maximum values of lateral acceleration and lateral velocity rose by almost 100%. Thus, drivers were more prone to sudden divergences from their lane. This is in line with the findings of Bunker et al. (2005). According to Przybyla et al. (2014), distracted vehicles that were in a car-following scenario maintained their previous mean speeds rather than reacting to leading vehicles. This has been found to be relevant in this case since there was negligible change in longitudinal control parameters between the baseline intervention scenario and the distraction test scenario (figure 4.18.). Zatmeh-Kanj et al. (2021) mentioned that during tailgating scenarios, it was found that drivers accelerate at a lower rate when their speed was higher. However, the sensitivity of the acceleration to the driver's speed was lower in the scenario where she was distracted by text messages. This has been proven to be true in this case.

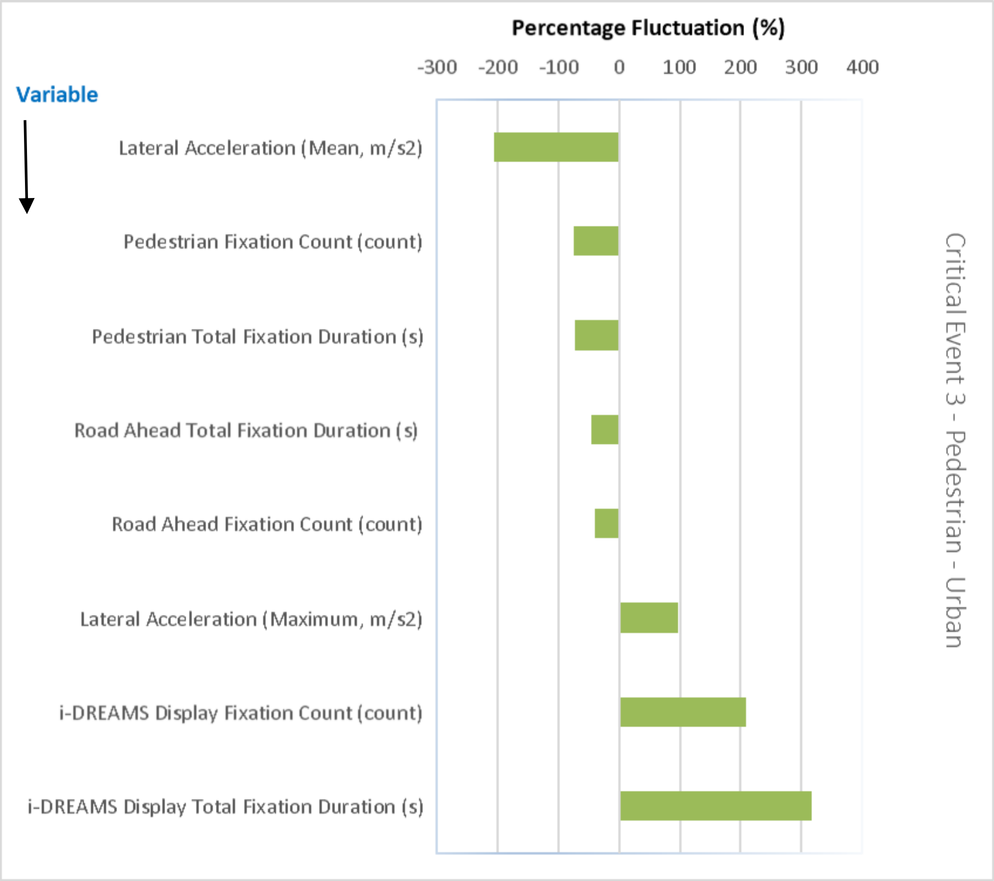


Figure 4.16.: Percentage fluctuations in driving performance variables during distracted driving as compared to the baseline during CE3-Ped-Urban (source: own)

CE3-Tail-Urban

During tailgating scenarios in the urban context, where the speed limit is the most restrictive (50 km/hr in this case), it was noticed that distraction had a compensatory effect on the longitudinal performance (figure 4.19.). The Time to Collision (TTC) went up by almost 85%. According to Horst et al. (1994), the TTC is a measure of aggressive driving. Increased TTC values imply that drivers were more aware of their driving conditions owing to the lowered speed limits and the traffic environment (this particular segment was one-way and has parked vehicles on both sides, thus reducing the space for lateral maneuvers). The leading vehicle forces the driver to adjust its speed accordingly in this scenario (Ezzati Amini et al., 2021). In addition to the TTC, the average longitudinal velocity also went down. Thus longitudinal performance measures were improved during distracted driving during car-following scenarios in an urban context. However, maximum value of lateral acceleration increased by about 60%. This happened despite the fact that drivers had lesser lateral deviation opportunities owing to the stretch being one way and relatively congested owing to parked vehicles.

Figure 4.17.: Percentage fluctuations in driving performance variables during distracted driving as compared to the baseline during CE1-Tail-Rural (source: own)

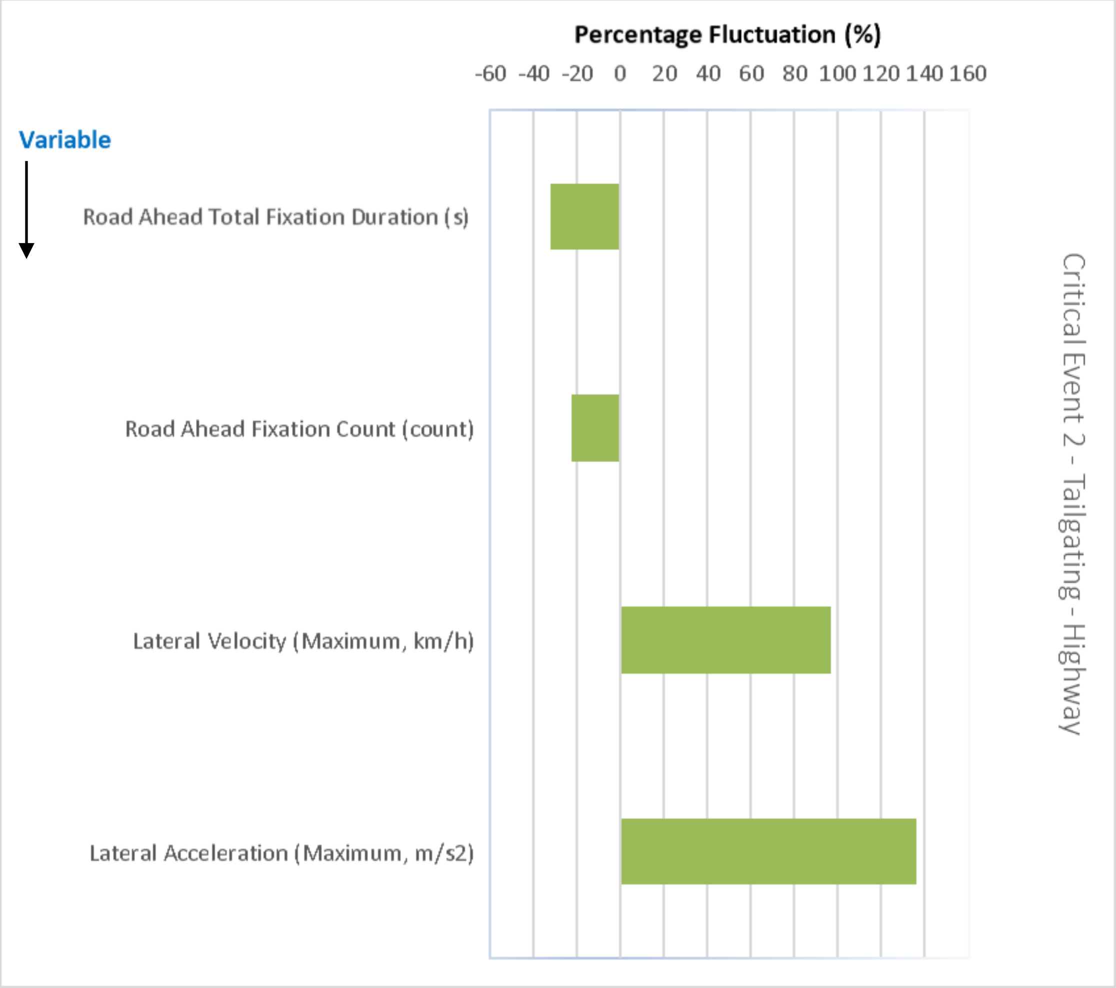


Figure 4.18.: Percentage fluctuations in driving performance variables during distracted driving as compared to the baseline during CE2-Tail-Highway (source: own)

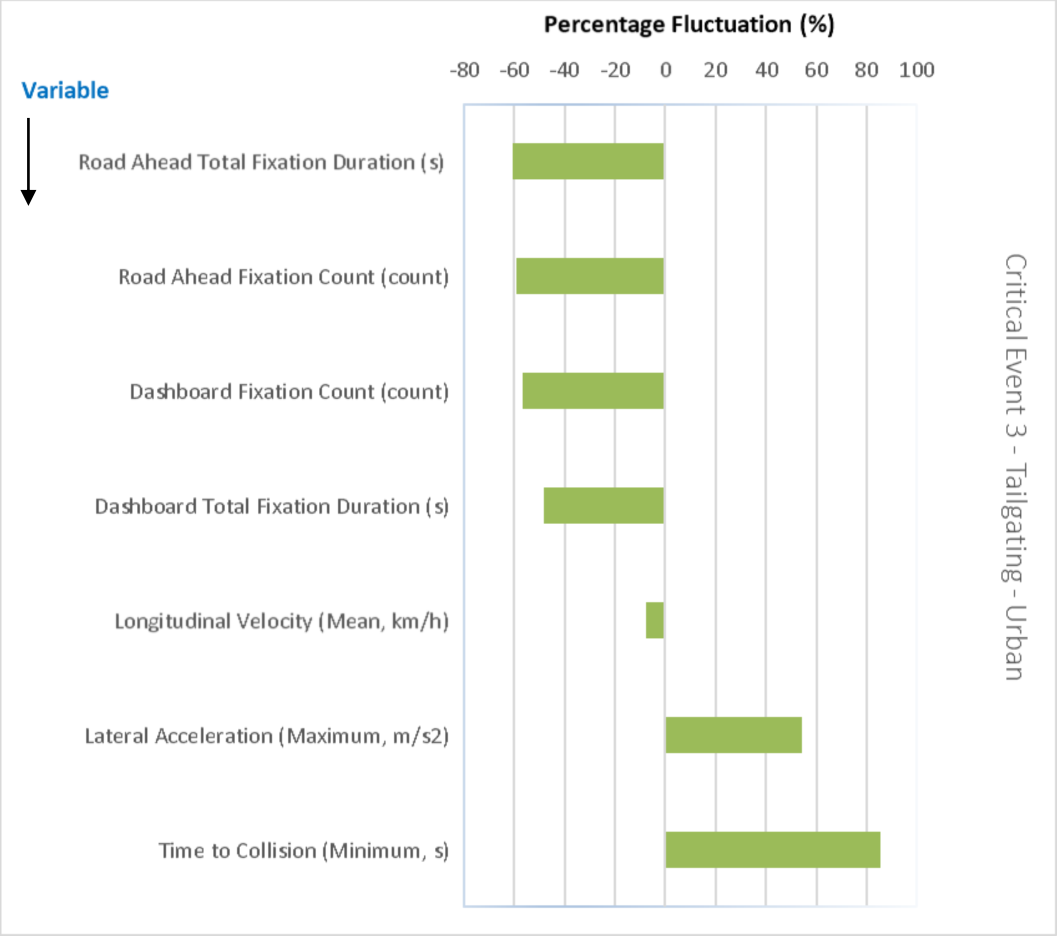


Figure 4.19.: Percentage fluctuations in driving performance variables during distracted driving as compared to the baseline during CE3-Tail-Urban (source: own)

NE1-Highway

When drivers were driving in the presence of distraction but the absence of a safety critical event on highway segments with no speed limits, it was observed that the average longitudinal acceleration decreased by over 200%. This was probably owing to the fact that drivers were busy reading the text messages and the cognitive distraction had a compensatory effect in reducing the longitudinal acceleration considerably. One interesting aspect observed during this scenario was that mean lateral velocity increased significantly. Thus the driver had poor lateral control on lane deviation operations because he was busy reading the text message. The average lateral acceleration showed a substantial decrease. This was probably owing to the fact that the driver wasn't aware of the situation because of being distracted and couldn't implement lateral acceleration maneuvers voluntarily. (figure 4.20.).

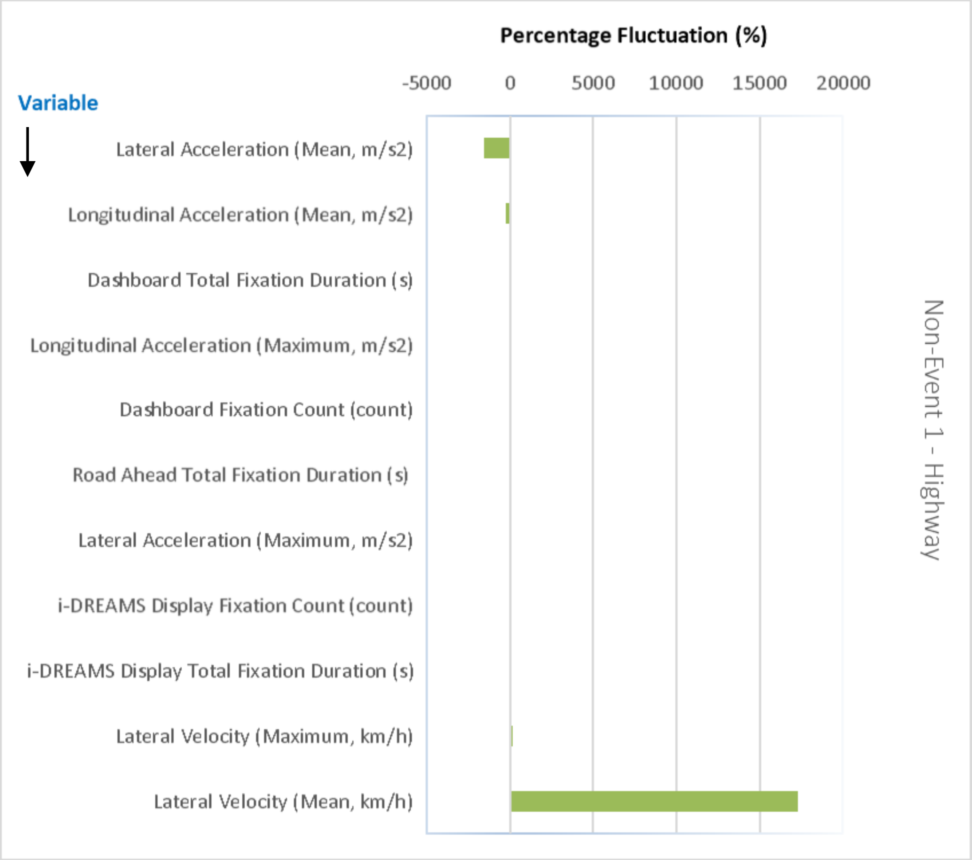


Figure 4.20.: Percentage fluctuations in driving performance variables during distracted driving as compared to the baseline during NE-Highway (source: own)

NE2-Urban

When distracted driving took place in an urban traffic environment in the absence of safety critical events, it was assessed that lateral control deteriorated significantly. The maximum values of lateral acceleration increased by over 50%. The maximum lateral velocity showed very similar characteristics (figure 4.21.).

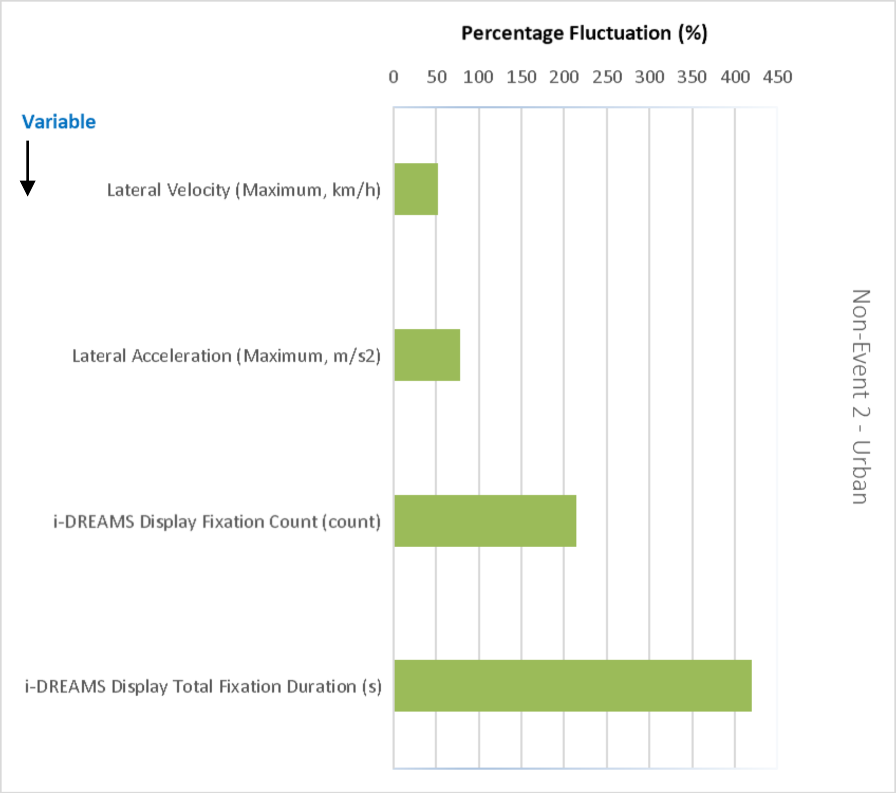


Figure 4.21.: Percentage fluctuations in driving performance variables during distracted driving as compared to the baseline during NE-Highway (source: own)

Tables 4.22., 4.23. and 4.24. summarizes the events during which distraction had a significant impact on driving performance variables obtained from the driving simulator. These take into consideration only events which meet the significance criterion in the two sample *t*-test as described in section **3.4.3.** Variables and events that meet the significance criterion in section **3.4.2.** are presented here. For plots of all selected variables across all 8 events, please refer to appendix **A**.

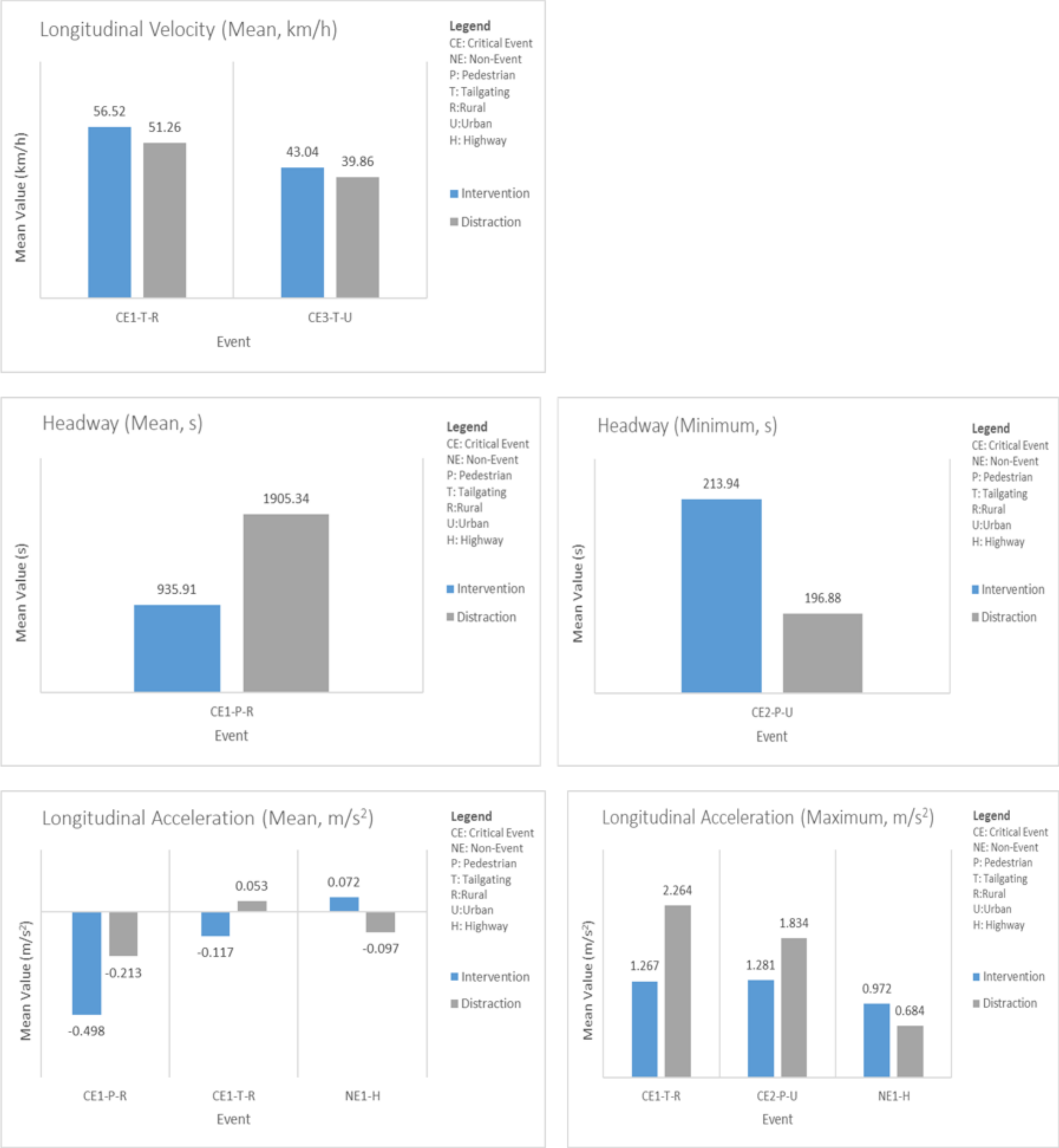


Figure 4.22.: Summary of events (CE+NE) in which distraction had a significant effect on the longitudinal control parameters (source: own)

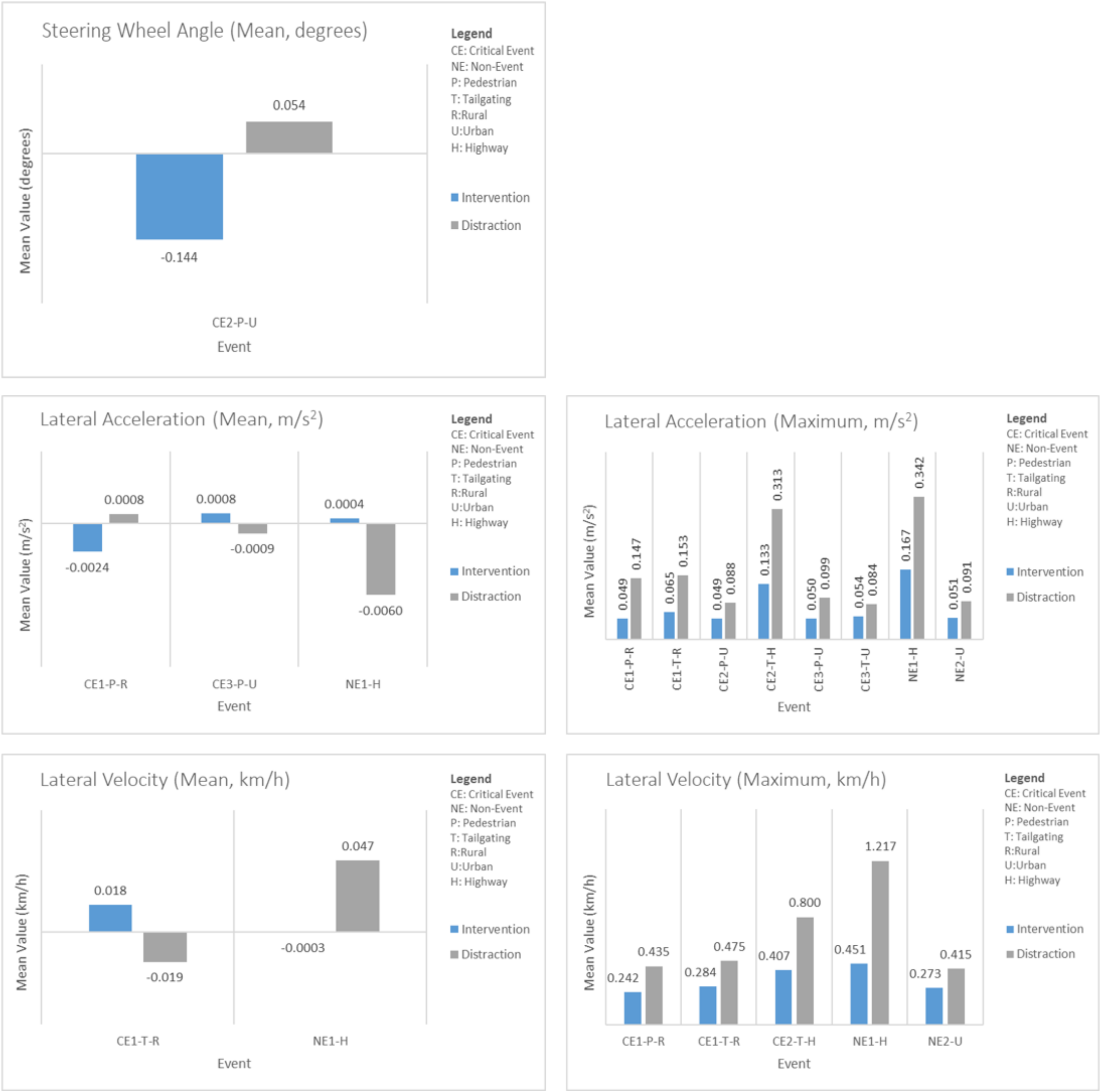


Figure 4.23.: Summary of events (CE+NE) in which distraction had a significant effect on the lateral control parameters (source: own)

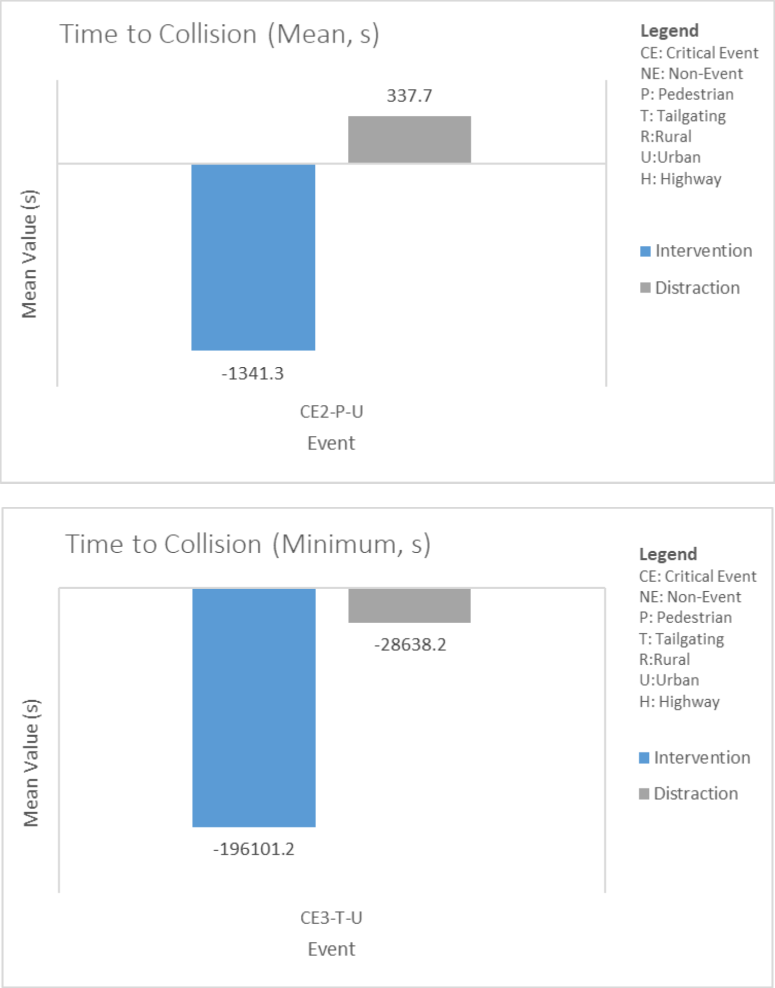


Figure 4.24 (top and bottom).: Summary of events (CE+NE) in which distraction had a significant effect on the reaction time parameter TTC (source: own)

4.2.1. Driving Performance Variables Obtained from the Eye Tracker

Please refer to section **4.3.**

4.3. Analysis of Eye Tracking Metrics

This section combines descriptive and inferential statistical methods as well as the qualitative Eye Tracking Analysis using heat maps generated for the six safety critical events and two non-events based on driver gaze data.

Initially, the results of the descriptive statistical analysis for eye tracking metrics based on count and fixations is presented. This was done with the help of box plots similar to what has been described in section **4.1.** Next, information about how distraction impacts driver gaze behaviour for events that meet the significance criterion laid down in subsection **3.4.3.** is depicted. Additionally, heat maps are put forward for both intervention and distraction scenarios in order to provide a qualitative assessment of the impact of distraction on driving performance based on gaze behaviour of the driver. Finally, as a supplement, driver gaze behaviour while using the mobile phone during distracted driving is presented.

4.3.1. Descriptive Analysis of Visual Tracking Metrics

Eye Tracking Metrics Based on Gaze Counts and Durations (Fixation Count and Total Fixation Duration)

Figures 4.25.-4.32. depict box plots based on the variation of fixation counts and total fixation durations for specific Areas of Interest (AOI) across all events (CE+NE) and scenarios (distraction vs. intervention). The AOIs include the road ahead, dashboard, i-DREAMS display and pedestrian (only during possible VRU collision events). Finally, the impact of distraction on the gaze behaviour and attention allocation across all AOIs are summarized in tables 4.33. and 4.34., where events are selected based on the corresponding value of eye tracking metrics meeting the significance criterion laid down in subsection **3.4.3.**

Fixation Count and Total Fixation Duration for the AOI dashboard: Figure 4.25. depicts the dispersion in the data indicating the mean number of fixations occurring on the dashboard across participants. The dashboard houses the speedometer and tachometer, thus it becomes essential for drivers to look at it on segments where on-road speed limits are absent. It can be observed that the number of fixations varies significantly during both intervention and distraction scenarios. This can be explained by the participant sample space used for the simulation runs. According to Lavallière et al. (2017), age and gender were found to have a significant impact on visual search behaviour during driving. The sample space for this experiment consisted of 30 participants of four age groups and both genders. In this case, the fixation behaviour of each particular group was assumed to be different when interacting with in-vehicle devices such as those present on the dashboard. Additionally, larger dispersion in the dataset was observed during the intervention drive as compared to the test scenario. This could be owing to the presence of the i-DREAMS real-time intervention-based system that shows the speed limit of a particular section as well as warns the driver in cases of safety critical events. However, this is also true for the intervention scenario where the i-DREAMS system has the exact function. Therefore, this explanation isn't fully plausible. One realistic elucidation could be that a part of the driver's attention is allocated to the mobile phone screen during distracted driving.

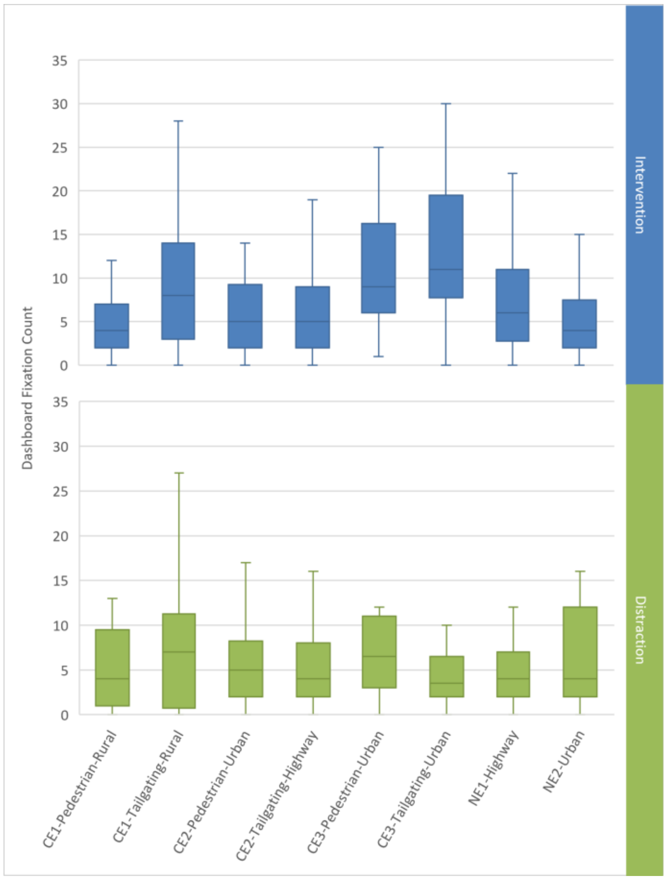


Figure 4.25.: Variation in mean values of fixation count (dashboard AOI) across events (baseline vs. distracted driving) (source: own)

Drivers tend to show higher variation of mean total fixations during the baseline intervention scenario across all events. However, the widest standard deviations were observed during tailgating scenarios in the rural and urban contexts.

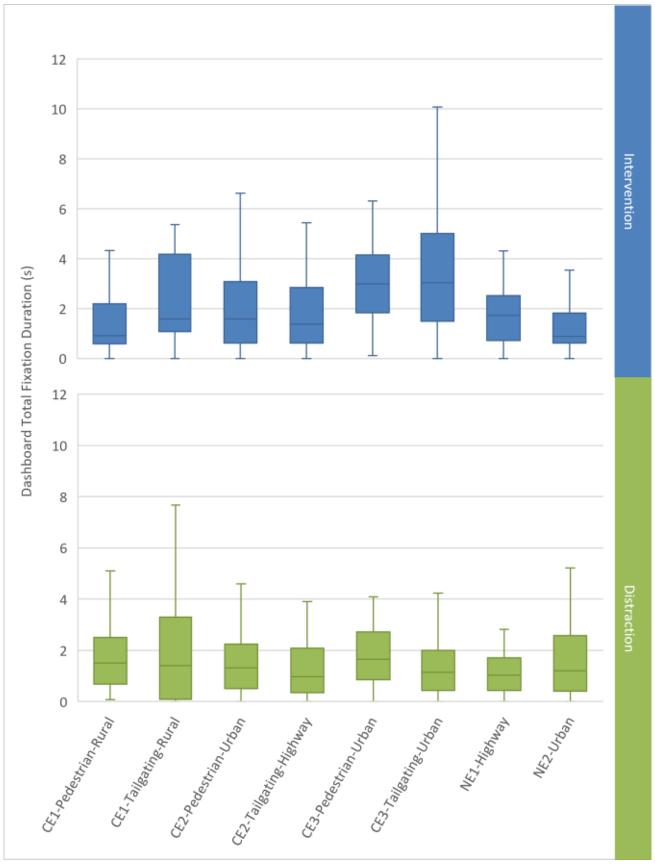


Figure 4.26.: Variation in mean values of total fixation duration (dashboard AOI) across events (baseline vs. distracted driving) (source: own)

Fixation Count and Total Fixation Duration for the AOI i-DREAMS display: It was observed that distracted driving led to wider variations in the fixation count as compare to the intervention scenario. However, on close examination it was seen that during tailgating scenarios during the baseline drive, drivers tended to fixate more number of times on the i-DREAMS display, irrespective of the traffic environment.

The distracted drive also showed variations, but not as high as in the baseline scenario. This was owing to the fact that in the former scenario, the driver's attention was allocated between the mobile phone screen, the road ahead. In addition, probable real-time headway warnings during close proximities with leading vehicles was the time when the driver focused on the i-DREAMS display AOI. For events involving pedestrians, drivers showed higher variations in fixation count during distracted driving. The situation was similar during non-event scenarios during the distraction test phase.

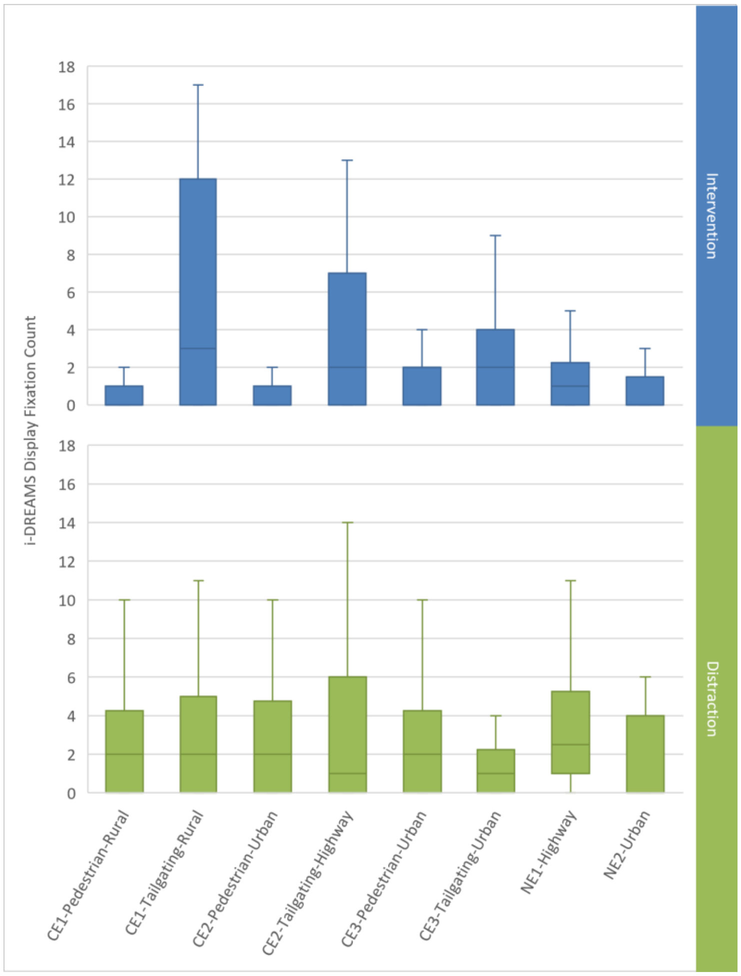


Figure 4.27.: Variation in mean values of fixation count (i-DREAMS display AOI) across events (baseline vs. distracted driving) (source: own)

During the intervention scenario, drivers showed extremely high variations in the mean value of the total time they fixated on the i-DREAMS display during tailgating scenarios on urban, rural and highway segment. However, during distracted driving higher dispersion in the total fixation duration was observed across all events, thus factoring in the demographic factor and its impact on visual search behaviour during driving (Lavallière et al., 2017).

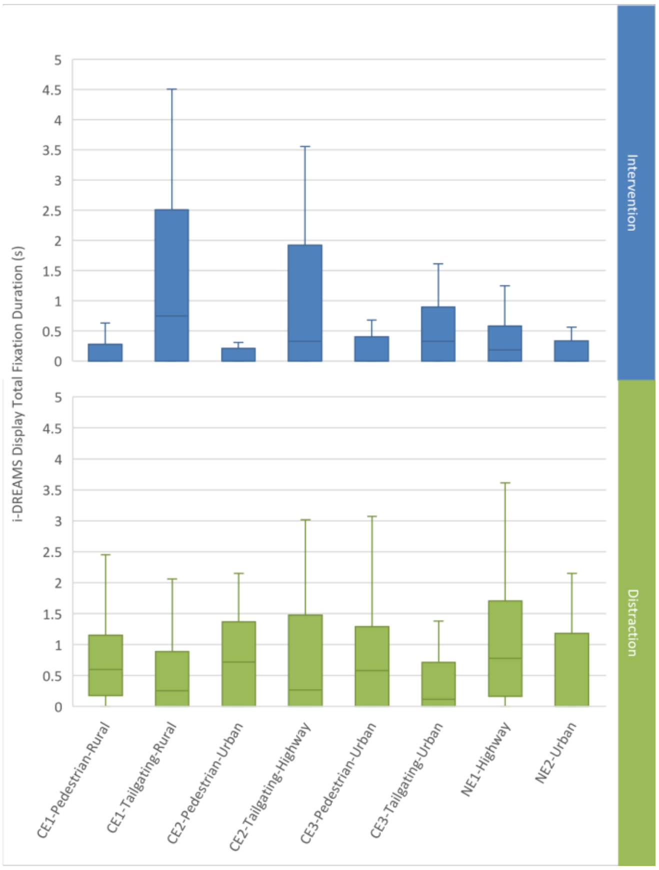


Figure 4.28.: Variation in mean values of total fixation duration (i-DREAMS display AOI) across events (baseline vs. distracted driving) (source: own)

Fixation Count for the AOI pedestrian: No variations were observed during non-events and car-following scenarios. This is because the pedestrian AOI is only visible during possible VRU collision situations. In both scenarios, higher variations in fixation count were observed in the urban context as compared to the rural segment. This is due to urban areas having the most restricted speed limits (50 km/hr) and the highest levels of lateral congestion (parked vehicles, etc.). In addition to this, the pedestrian AOI coincides with the road ahead AOI. Owing to the above factors, drivers are more inclined to look at the road ahead in urban areas for possible obstacles. It is interesting to note that very high variability was observed during distracted driving in the CE2-Pedestrian-Urban scenario even though the average driver's attention was partially allocated to the mobile phone display.

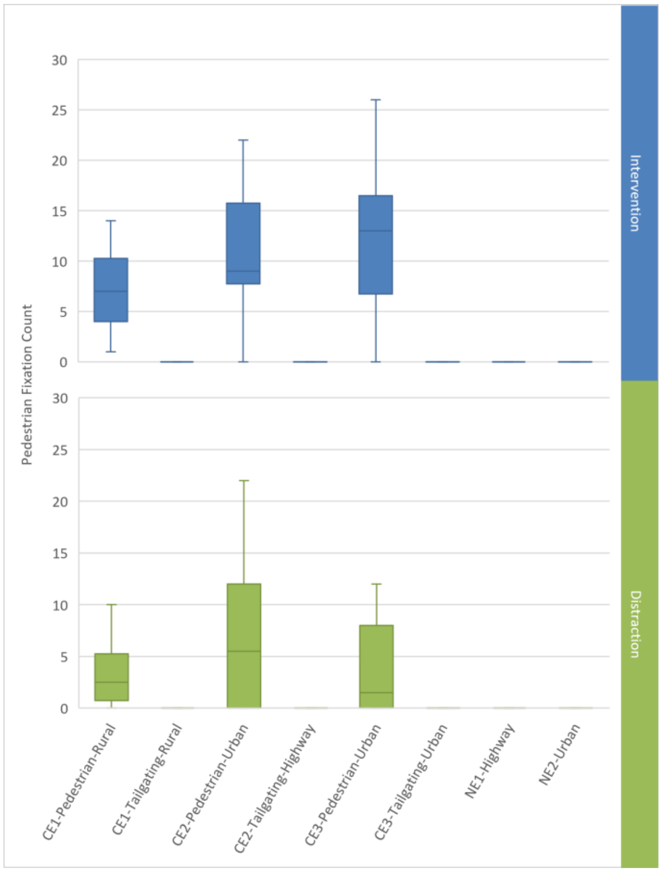


Figure 4.29.: Variation in mean values of fixation count (pedestrian AOI) across events (baseline vs. distracted driving) (source: own)

As for the total fixation duration, similar behaviour was observed.

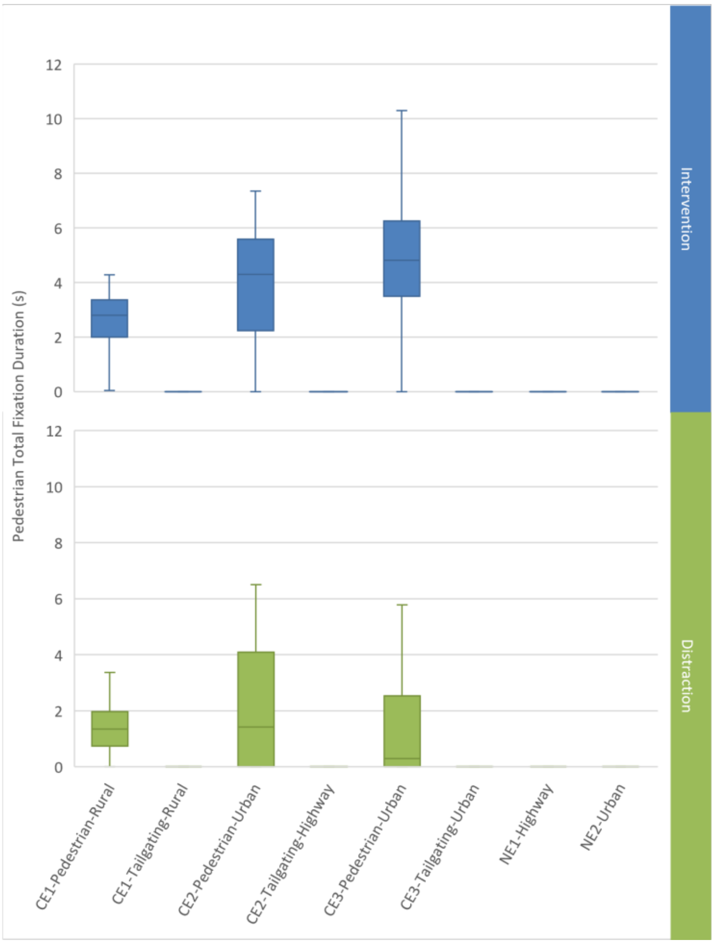


Figure 4.30.: Variation in mean values of total fixation duration (pedestrian AOI) across events (baseline vs. distracted driving) (source: own)

Fixation Count and Total Fixation Duration for the AOI road ahead: The mean value of the fixation count showed a dispersed behaviour during both the baseline and test phases. This is primarily because the bulk of the driver's attention is allocated to the road ahead during the driving task. In addition to this, several AOIs, like the pedestrian AOI coincide with the road ahead. Thus, this Area of Interest has the highest values of fixation, irrespective of the roadway environment or scenario. This is also confirmed by heat maps given in section **4.3.2**.

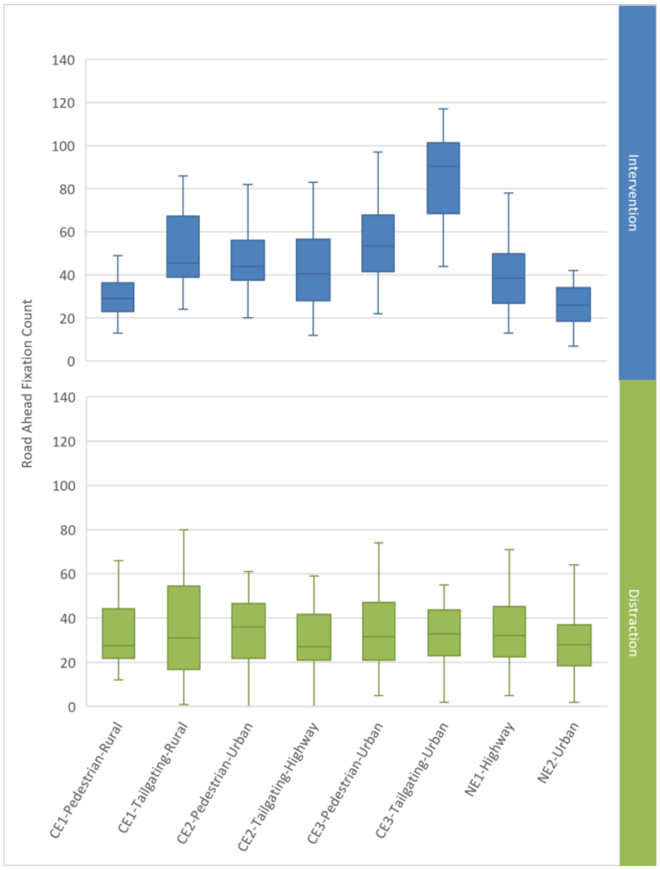


Figure 4.31.: Variation in mean values of fixation count (road ahead AOI) across events (baseline vs. distracted driving) (source: own)

During distracted driving, the range of variations for Total Fixation Duration for the road ahead AOI was restricted to a uniform range. However, this varied greatly for the baseline scenario. On an average, drivers tended to show more divergence in the total amount of time they focused on the road ahead during possible VRU collision scenarios during distracted driving. An explanation could be because the pedestrian AOI coincides with the road ahead AOI during VRU scenarios and thus a part of the former's attention is allocated to the road ahead.

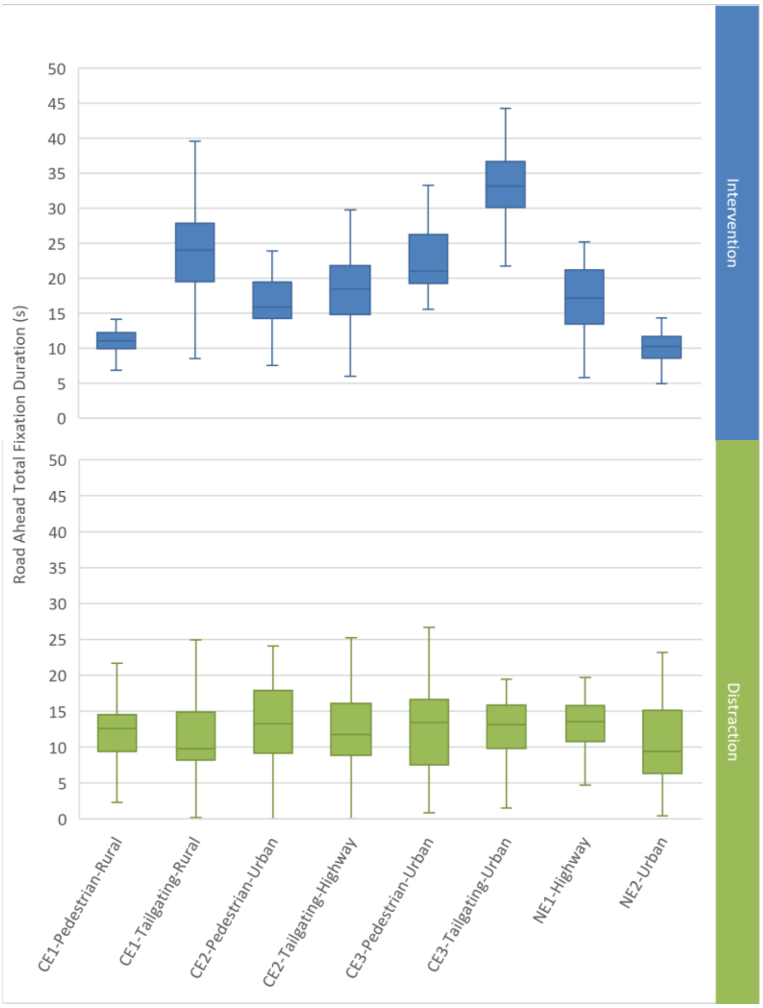


Figure 4.32.: Variation in mean values of total fixation duration (road ahead AOI) across events (baseline vs. distracted driving) (source: own)

Tables 4.33. and 4.34. summarizes the events during which distraction had a significant impact on the driving performance variables obtained from the eye tracker. These take into consideration only events which meet the significance criterion in the two sample *t*-test as described in section **3.4.3.**

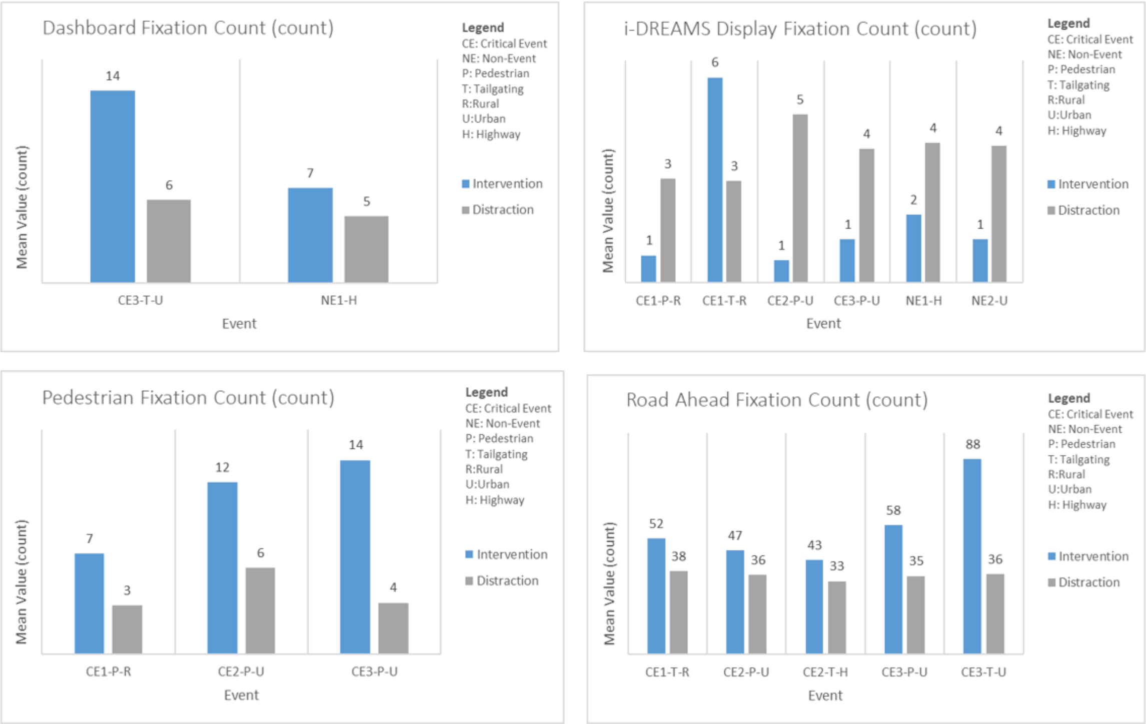


Figure 4.33.: Summary of events (CE+NE) in which distraction had a significant effect on the fixation count (source: own)

4.4. Assessment of the Impact of Distraction on Driving Performance

This section presents the heat maps and links the gaze behaviour with driving performance variables during the 8 events analyzed throughout this thesis in tables 4.1., 4.2. and 4.3.

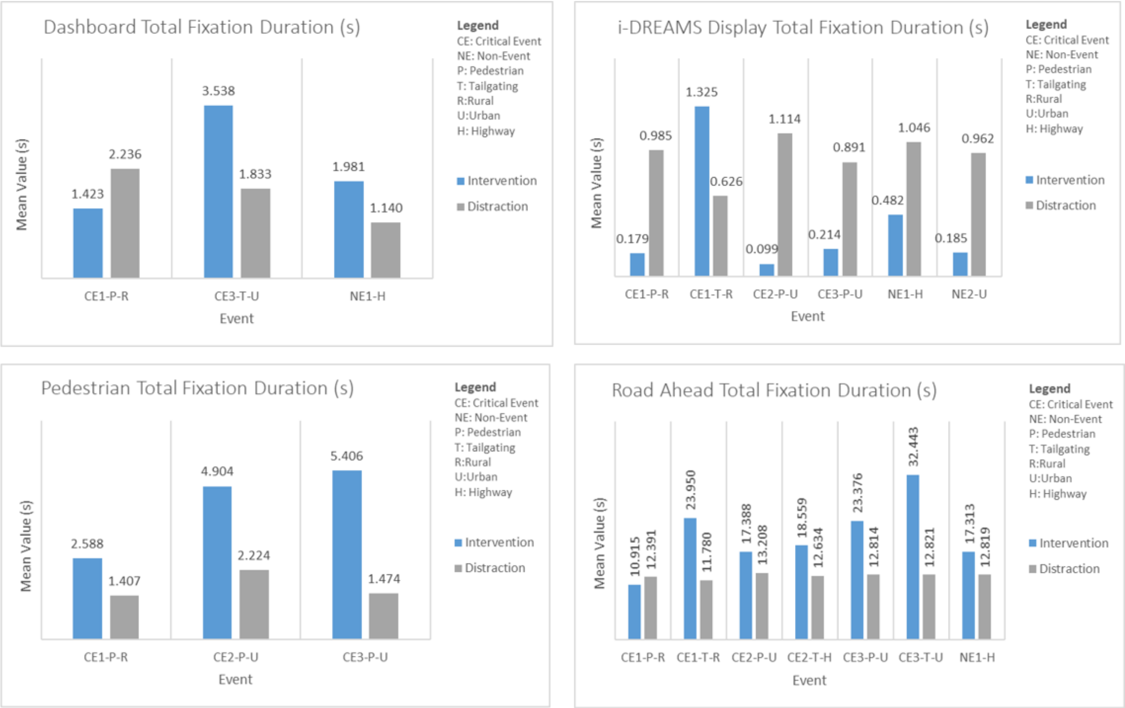


Figure 4.34.: Summary of events (CE+NE) in which distraction had a significant effect on the total fixation duration (source: own)

Critical Event 1-Pedestrian-Rural (CE1-P-R): From table 4.14., it was observed that distracted driving had a significant effect on the gaze allocation on the i-DREAMS AOI in terms of both number and total duration of fixations. The mean value of the former increased approximately 280% as compared to the intervention scenario. The average of the Total Fixation Duration had an even more significant increase: over 400%. Thus, distracted drivers gazed significantly more number of times and for longer at the i-DREAMS display during possible VRU collisions in the rural context. This happened in spite of a part of the driver's gaze being allocated to the mobile phone screen during the distraction scenario. The same is confirmed by the heat maps given in figure 4.35., with a high concentration of gaze allocation focused on the i-DREAMS display.

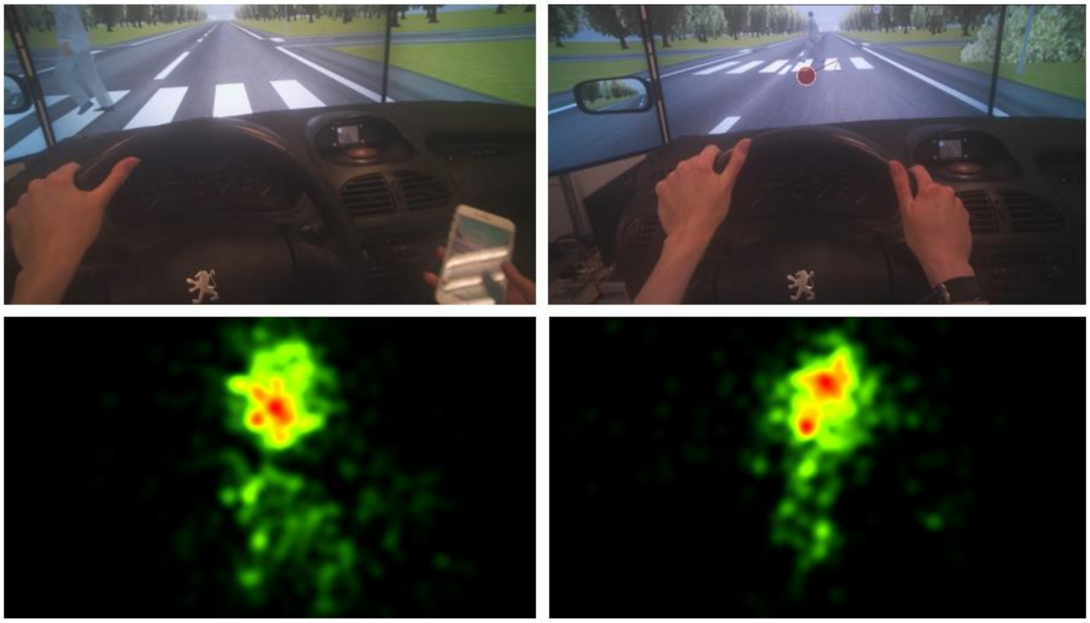


Figure 4.35.: Comparison between heat maps for CE1-P-R between distraction and intervention phases (Anticlockwise: Left Top (LT) - CE1-P-R during distraction phase, Left Bottom (LB): heat map for CE1-P-R in distraction phase, Right Top (RT): CE1-P-R during intervention phase, Right Bottom (RB): heat map for CE1-P-R in intervention phase) (source: own)

Critical Event 2-Pedestrian-Urban (CE2-P-U): Figure 4.15. depicts the change in driving performance variables from both the simulator and eye tracker under the effect of in-vehicle distraction. It was observed that drivers had an increased mean value of fixation count by approximately 600% during the distraction test scenario as compared to the baseline intervention scenario on the i-DREAMS display. Additionally, the average total duration of fixations increased by over 10 times, which is a critical finding. It was also found that drivers tend to allocate less attention in terms of the number of fixation and the total duration of fixations on the road ahead during distracted driving in the aforementioned safety critical event. The observations are validated by the heat maps given in figure 4.36. There is a significant increase of gaze density in the distraction scenario.

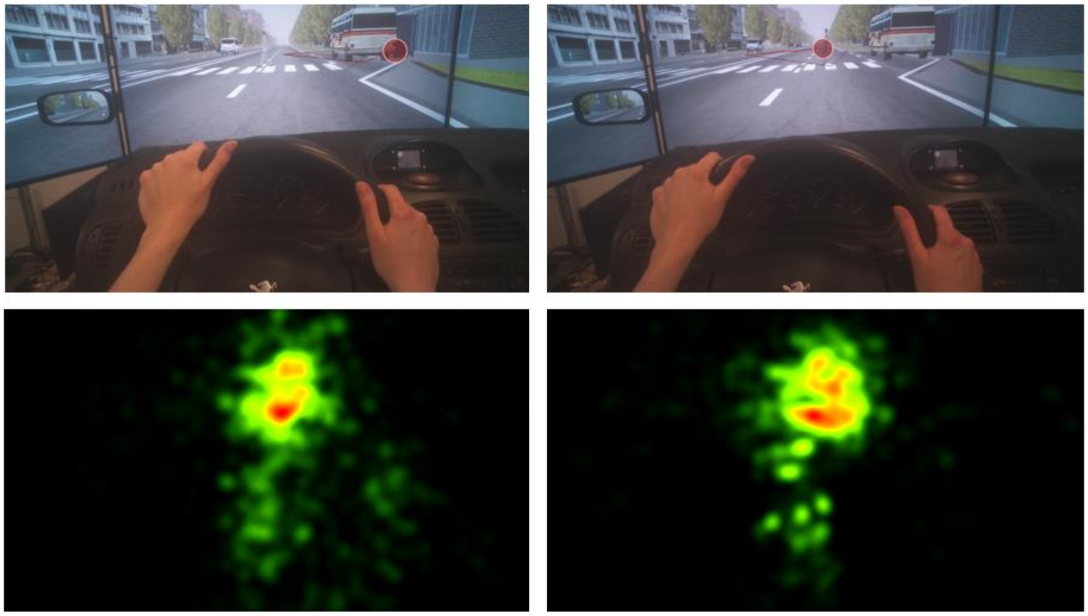


Figure 4.36.: Comparison between heat maps for CE2-P-U between distraction and intervention phases (Anticlockwise: LT – CE2-P-U during distraction phase, LB: heat map for CE2-P-U in distraction phase, RT: CE2-P-U during intervention phase, RB: heat map for CE2-P-U in intervention phase) (source: own)

Critical Event 3-Pedestrian-Urban (CE3-P-U): From figure 4.16. it was assessed that during distracted driving the mean fixation count and mean total fixation duration went up by over 200% and 300% respectively for the i-DREAMS display AOI. At the same time, there was a substantial decrease in the mean fixation count and mean total fixation durations for the pedestrian AOI and the road ahead AOI. This was critical given the fact that this event dealt with a possible VRU collision in the urban context. The heat maps given in figure 4.37. supplements the aforementioned observations.

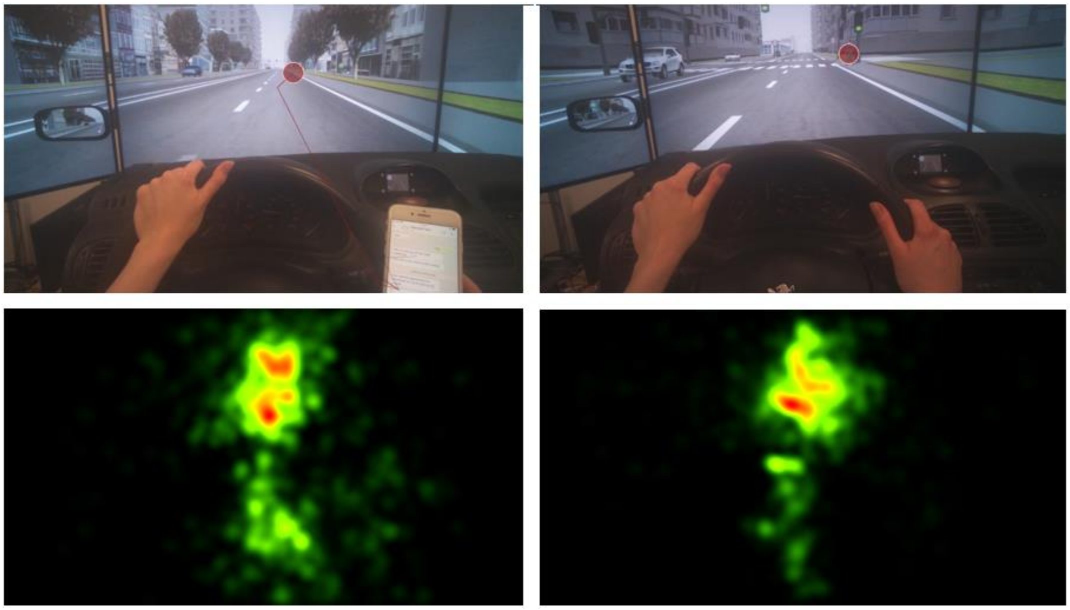


Figure 4.37.: Comparison between heat maps for CE3-P-U between distraction and intervention phases (Anticlockwise: LT – CE3-P-U during distraction phase, LB: heat map for CE3-P-U in distraction phase, RT: CE3-P-U during intervention phase, RB: heat map for CE3-P-U in intervention phase) (source: own)

Critical Event 1-Tailgating-Rural (CE1-T-R): During distracted driving on a rural roadway segment during a tailgating event, drivers showed a reduced average values of the total fixation duration and fixation count by about 50% (figure 4.17.). The same metrics went down substantially for the road ahead AOI, suggesting that the residual attention allocation was diverted to the mobile phone screen AOI during this event. Figure 4.38. corroborates these observations qualitatively.

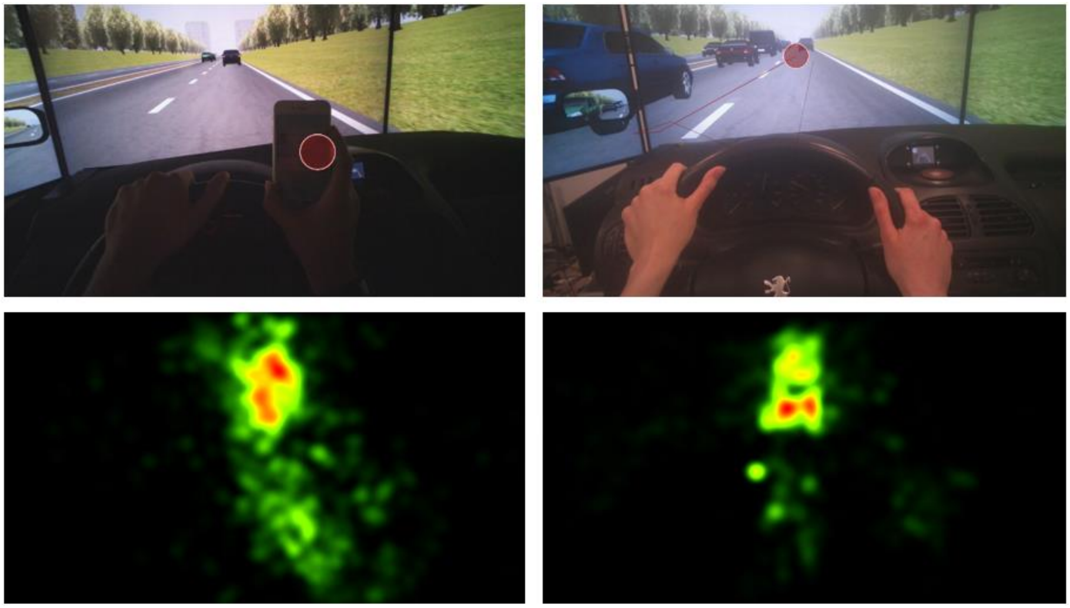


Figure 4.38.: Comparison between heat maps for CE1-T-R between distraction and intervention phases (Anticlockwise: LT – CE1-T-R during distraction phase, LB: heat map for CE1-T-R in distraction phase, RT: CE1-T-R during intervention phase, RB: heat map for CE1-T-R in intervention phase) (source: own)

Critical Event 2-Tailgating-Highway (CE2-T-H): For the most part, there was negligible difference in gaze behaviour between the baseline and distracted driving scenarios (figure 4.18.). However, during the latter, it was noted that the mean of the fixation count for the road ahead went down by approximately 20%. The mean total fixation duration for the same AOI declined by over 30%. As with the previous critical event, one explanation for this could be the diversion of gaze to the mobile phone screen AOI during distracted driving. The variations in gaze behaviour can be observed from the heat maps given in figure 4.39.

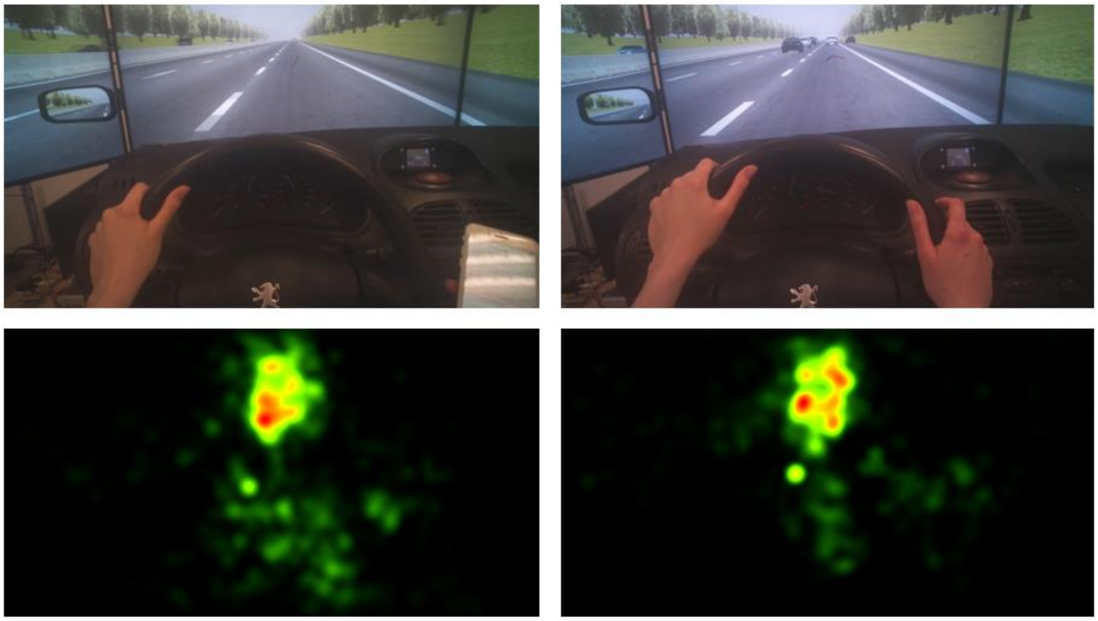


Figure 4.39.: Comparison between heat maps for CE2-T-H between distraction and intervention phases (Anticlockwise: CE2-T-H during distraction phase, LB: heat map for CE2-T-H in distraction phase, RT: CE2-T-H during intervention phase, RB: heat map for CE2-T-H in intervention phase) (source: own)

Critical Event 3-Tailgating-Urban (CE3-T-U): Distracted driving had no impact on the gaze allocation on the i-DREAMS display AOI. However, from figure 4.19. it was noted that there were substantial reductions in the mean of the Total Fixation Duration and Fixation Count for both dashboard and road ahead AOIs during the test phase. Each metric declined by approximately 50% for the aforementioned AOIs. This can be observed in figure 4.40.

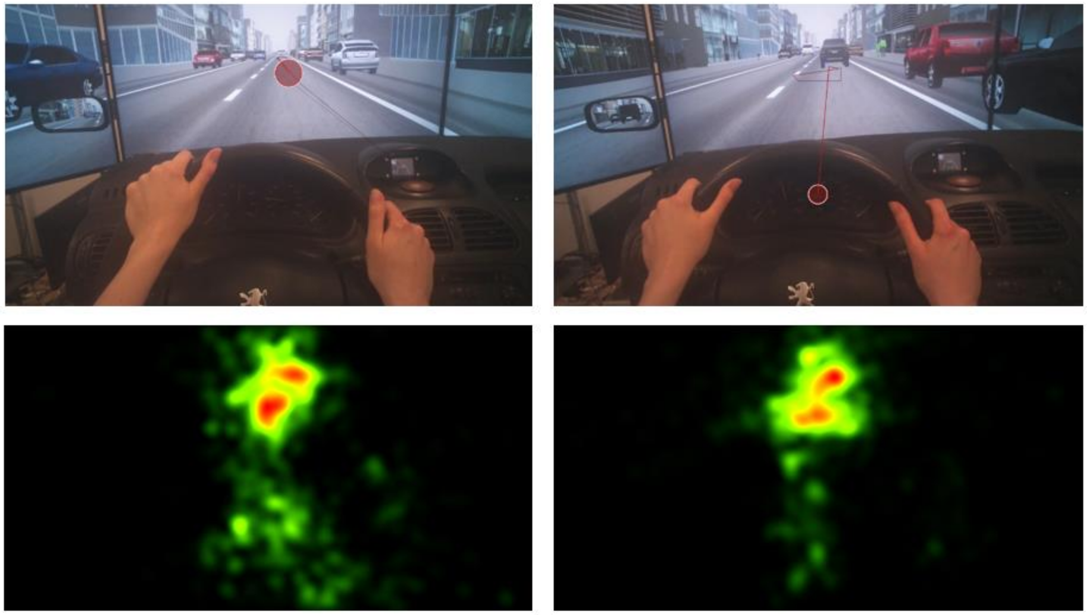


Figure 4.40.: Comparison between heat maps for CE3-T-U between distraction and intervention phases (Anticlockwise: CE3-T-U during distraction phase, LB: heat map for CE3-T-U in distraction phase, CE3-T-U during intervention phase, RB: heat map for CE3-T-U in intervention phase) (source: own)

Non-Event 1-Highway (NE1-H): No significant changes were observed between baseline and distracted driving scenarios for the gaze behaviour occurring on the i-DREAMS display, road ahead and dashboard AOIs (pedestrian AOI not factored in since this is a non-event) based on figure 4.20. A plausible explanation for this could be that the only difference between the NE1-H in intervention phase and the test phase is that a substantial part of the driver's attention is allocated to the mobile phone display during distracted driving in the Non-Event scenario. This can be seen from figure 4.41.

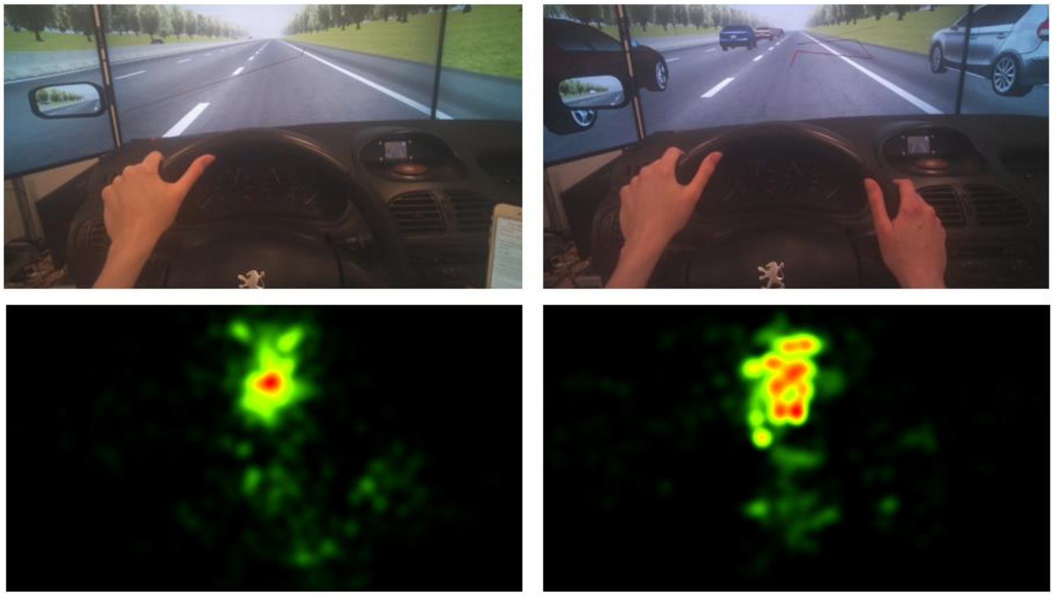


Figure 4.41.: Comparison between heat maps for NE1-H between distraction and intervention phases (Anticlockwise: LT: NE1-H during distraction phase, LB: heat map for NE1-H in distraction phase, RT: NE1-H during intervention phase, RB: heat map for NE1-H in intervention phase) (source: own)

Non-Event 2-Urban (NE2-U): From figure 4.21. it was observed that distracted drivers tended to fixate more and longer on the i-DREAMS display as compared to the baseline scenario. The mean fixation count went up by 200% and the mean total fixation duration increased by over 400% for this AOI due to the impact of distraction. This has been portrayed in the heat maps given in figure 4.42.

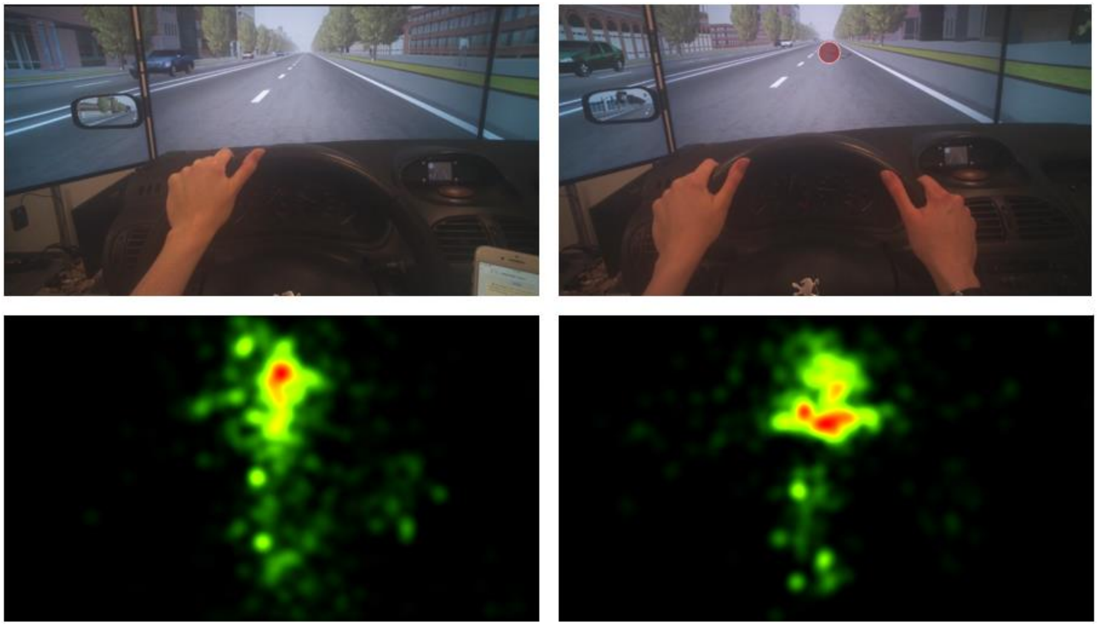


Figure 4.42.: Comparison between heat maps for NE2-U between distraction and intervention phases (Anticlockwise: NE2-U during distraction phase, LB: heat map for NE2-U in distraction phase, NE2-U during intervention phase, RB: heat map for NE2-U in intervention phase) (source: own)

The impact of distraction on the primary drivin task based on driving performance variables obtained from the simulator and the eye tracker have been summarized in tables 4.1., 4.2. and 4.3.

		Fluctuation in variable mean between intervention and distraction (%)		
Variable category	**Variable**	**CE1-P-R**	**CE2-P-U**	**CE3-P-U**
Longitudinal control	Longitudinal Velocity (Mean, km/h)	-	-	-
	Longitudinal Velocity (Maximum, km/h)	-	-	-
	Headway (Mean, s)	103.58	-	-
	Headway (Minimum, s)	-	-7.97	-
Lateral control	Lateral Position (Mean, m)	-	-	-
	Steering Wheel Angle (Mean, degrees)	-	137.42	-
Reaction time	Time to Collision (Mean, s)	-	125.18	-
	Time to Collision (Minimum, s)	-	-	-
Others (supplementary longitudinal and lateral control parameters)	Longitudinal Acceleration (Mean, m/s2)	57.11	-	-
	Longitudinal Acceleration (Maximum, m/s2)	-	43.21	-
	Lateral Acceleration (Mean, m/s2)	132.55	-	-206.14
	Lateral Acceleration (Maximum, m/s2)	199.24	79.31	97.42
	Lateral Velocity (Mean, km/h)	-	-	-
	Lateral Velocity (Maximum, km/h)	79.64	-	-
Eye tracking variables based on gaze count	Dashboard Fixation Count	-	-	-
	i-DREAMS Display Fixation Count	281.82	655.56	208.57
	Pedestrian Fixation Count	-51.87	-49.86	-73.67
	Road Ahead Fixation Count	-	-23.51	-39.33
Eye tracking variables based on gaze duration	Dashboard Total Fixation Duration (s)	57.15	-	-
	i-DREAMS Display Total Fixation Duration (s)	450.38	1025.13	316.35
	Pedestrian Total Fixation Duration (s)	-45.63	-54.65	-72.73
	Road Ahead Total Fixation Duration (s)	13.52	-24.04	-45.18

Table 4.1.: Summary of the impact of distraction on driving performance variables across all 3 VRU collision scenarios (source: own)

		Fluctuation in variable mean between intervention and distraction (%)		
Variable category	**Variable**	**CE1-T-R**	**CE2-T-H**	**CE3-T-U**
Longitudinal control	Longitudinal Velocity (Mean, km/h)	-9.29	-	-7.38
	Longitudinal Velocity (Maximum, km/h)	-	-	-
	Headway (Mean, s)	-	-	-
	Headway (Minimum, s)	-	-	-
Lateral control	Lateral Position (Mean, m)	-	-	-
	Steering Wheel Angle (Mean, degrees)	-	-	-
Reaction time	Time to Collision (Mean, s)	-	-	-
	Time to Collision (Minimum, s)	-	-	85.39
Others (supplementary longitudinal and lateral control parameters)	Longitudinal Acceleration (Mean, m/s2)	145.64	-	-
	Longitudinal Acceleration (Maximum, m/s2)	78.62	-	-
	Lateral Acceleration (Mean, m/s2)	-	-	-
	Lateral Acceleration (Maximum, m/s2)	136.90	136.20	54.38
	Lateral Velocity (Mean, km/h)	-207.86	-	-
	Lateral Velocity (Maximum, km/h)	66.98	96.69	-
Eye tracking variables based on gaze count	Dashboard Fixation Count		-	-56.90
	i-DREAMS Display Fixation Count	-50.60	-	-
	Pedestrian Fixation Count	-	-	-
	Road Ahead Fixation Count	-28.22	-22.37	-58.95
Eye tracking variables based on gaze duration	Dashboard Total Fixation Duration (s)	-	-	-48.17
	i-DREAMS Display Total Fixation Duration (s)	-52.75	-	-
	Pedestrian Total Fixation Duration (s)	-	-	-
	Road Ahead Total Fixation Duration (s)	-50.81	-31.92	-60.48

Table 4.2.: Summary of the impact of distraction on driving performance variables across all 3 tailgating scenarios (source: own)

		Fluctuation in variable mean between intervention and distraction (%)	
Variable category	**Variable**	**NE1-H**	**NE2-U**
Longitudinal control	Longitudinal Velocity (Mean, km/h)	-	-
	Longitudinal Velocity (Maximum, km/h)	-	-
	Headway (Mean, s)	-	-
	Headway (Minimum, s)	-	-
Lateral control	Lateral Position (Mean, m)	-	-
	Steering Wheel Angle (Mean, degrees)	-	-
Reaction time	Time to Collision (Mean, s)	-	-
	Time to Collision (Minimum, s)	-	-
Others (supplementary longitudinal and lateral control parameters)	Longitudinal Acceleration (Mean, m/s2)	-234.89	-
	Longitudinal Acceleration (Maximum, m/s2)	-29.66	-
	Lateral Acceleration (Mean, m/s2)	-1538.6	-
	Lateral Acceleration (Maximum, m/s2)	104.31	78.47
	Lateral Velocity (Mean, km/h)	17281.9	-
	Lateral Velocity (Maximum, km/h)	169.79	51.78
Eye tracking variables based on gaze count	Dashboard Fixation Count	-29.55	-
	i-DREAMS Display Fixation Count	105.45	214.70
	Pedestrian Fixation Count	-	-
	Road Ahead Fixation Count	-	-
Eye tracking variables based on gaze duration	Dashboard Total Fixation Duration (s)	-42.45	-
	i-DREAMS Display Total Fixation Duration (s)	117.05	419.50
	Pedestrian Total Fixation Duration (s)	-	-
	Road Ahead Total Fixation Duration (s)	25.95	-

Table 4.3.: Summary of the impact of distraction on driving performance variables across 2 non-events (source: own)

It should be noted however that the above analysis excluded the mobile phone display. This was because in order to conduct a t-test, both populations (intervention and distraction datasets for a particular variable) must be similar. There was no mobile phone usage during the baseline intervention scenario. As a result, there was no way to know how drivers changed their attention allocation between the two drives. However, figure 4.43. summarizes how the fixation metrics for the above AOI changed across the eight events.

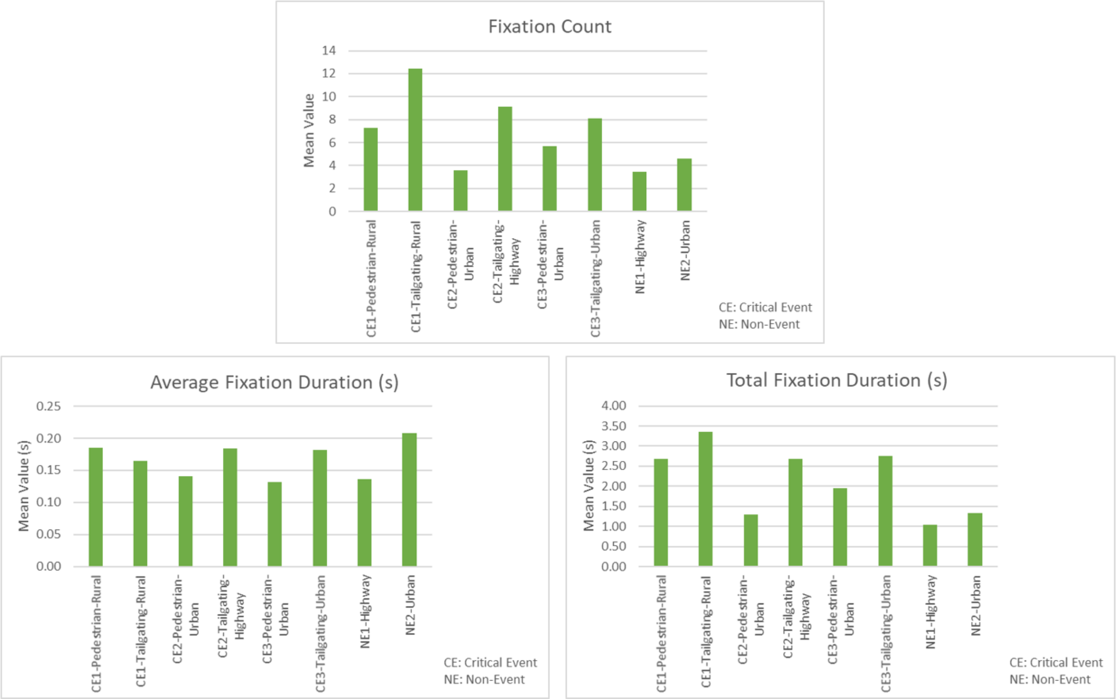


Figure 4.43: Change in fixation metrics for the mobile screen AOI across events in the distracted driving phase (source: own)

A t-test was conducted in between: 1) each of the three VRU collision events and, 2) each of three tailgating scenarios to assess the impact of the traffic environment (highway, rural or urban) on the gaze behaviour of the driver when focussing on the mobile phone screen. The results have been presented in appendix **B**. It was found that there was no significant difference between the fixation count, total fixation duration and average fixation duration for either car-following scenarios or possible pedestrian collisions across rural, urban and highway road segments. The only exception were the relationships between the events CE1-Ped-Rural and CE2-Ped-Urban. For these the mean fixation count went down by approximately 40% in the urban environment. Similar behaviour was noticed for the mean TFD. Drivers in the urban context tended to fixate about 50% less on the mobile phone display than on the rural roadway segment. This has been depicted in figure 4.44.

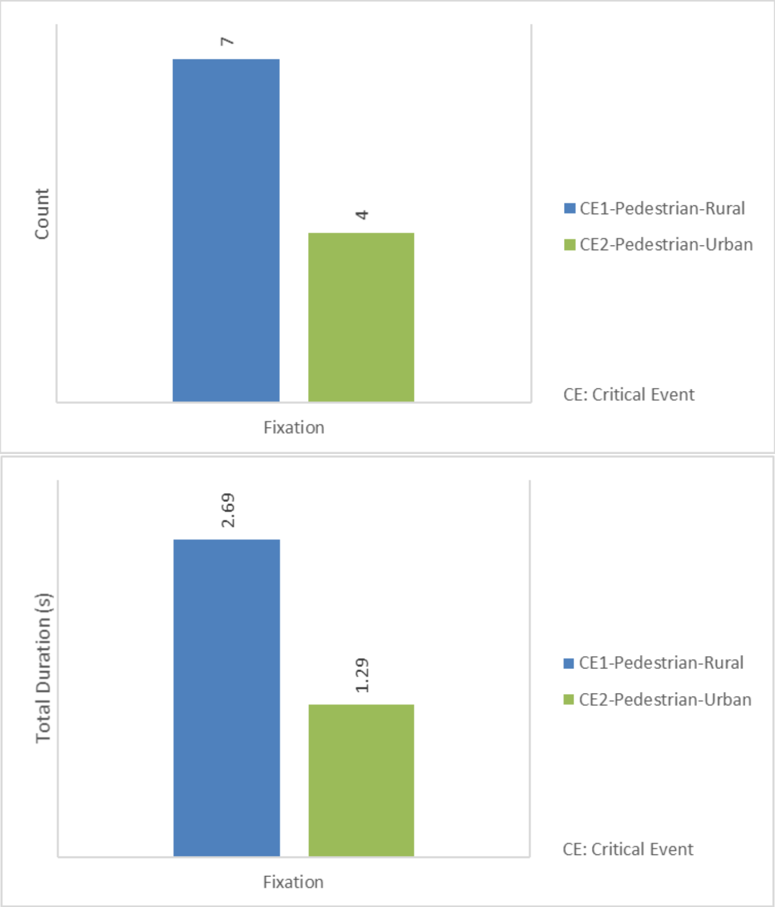


Figure 4.44 (top and bottom): Change in fixation metrics for the mobile screen AOI across CE1-Ped-Rural and CE2-Ped-Urban (source: own)

The data analysis in this chapter forms the basis for understanding the built hypotheses and will be synthesized in the next chapter to answer the research questions and objectives.

*

Chapter 5. Discussion

This chapter synthesizes the most important findings of the data analysis and utilizes them to answer the research questions and objectives. Additionally, the hypotheses laid down in chapter **3** are tested. Finally, the implication of the results observed on road safety policy-making and future research directions are discussed.

6.1. Main Findings of the Study

6.1.1. The Impact of Distraction on Driving Performance

Distraction had a significant impact on the driving performance in terms of longitudinal, lateral and reaction time control measures. This occurred irrespective of safety critical events and traffic environments. This impact has been presented in figures 4.14.-4.24.

Distracted drivers showed a reduction in longitudinal control on urban, rural and highway segments. Higher variations in the maximum longitudinal velocity was observed. This was especially true for safety critical events on the highway. In addition to maximum longitudinal velocity, drivers also showed higher divergences in the mean time headway. According to Rhodes et al. (2011), demographic factors have an impact on risk perception during driving. The sample space used for the i-DREAMS simulator run had categorized participants according to age and gender. The disparity in risk perception in terms of higher variations in maximum longitudinal velocity and mean time headway can be explained owing to the differences in the way individual groups perceived the risk (safety critical events) and distraction (texting).

Mean speeds were lower on both rural and urban stretches during car-following when a driver was reading or replying to text messages. Average accelerations were higher during both tailgating and possible pedestrian collision events on rural and urban roads while being distracted.

Distracted drivers during non-events on the highway segment showed significant reductions in time headway available. There were substantial reductions in average acceleration and maximum acceleration values. This is critical because during non-events, drivers did not encounter potentially dangerous situations involving the risk of a collision. The only difference between the baseline scenario and the test scenario during a non-event was the usage of the mobile phone. Thus, drivers showed loss of longitudinal control while being distracted, even though no potentially dangerous conditions were encountered.

Distraction via texting affected lateral control performance most significantly out of the three performance measures mentioned previously. Findings suggested that drivers on urban, rural and highway traffic environments showed a marked increase in maximum lateral acceleration irrespective of the safety critical event encountered. In most cases that were observed, the maximum value of lateral acceleration more than doubled (figure 4.23.). The maximum lateral velocity during distracted driving showed a proportional increase. Drivers also showed aggressive lateral behaviour in terms of the steering wheel angle, which appreciated substantially. In some cases, involving VRU collisions, steering wheel angle and peak values of lateral acceleration increased by almost 100%. Thus, distraction had a major role in reducing driving performance during distracted driving as compared to non-distracted driving.

In contrast to longitudinal and lateral control performance, reaction time measures improved as a result of distraction. Both mean and minimum values of Time to Collision improved. According to van der Horst et al. (1994), this is a metric that separates normal driving behaviour from aggressive behaviour. An increase in the TTC suggests that drivers tended to be less aggressive while being distracted as compared to the baseline condition.

Thus, it can be concluded that distraction due to texting had a significant impact on driving performance. Distraction deteriorated longitudinal performance in terms of mean speed, acceleration and mean time headways. There were also higher variations in the metrics from central behaviour, thus suggesting distraction has more repercussions on some demographic groups than others. In addition to longitudinal control, lateral performance had a marked decline. However, reaction time increased as a result of distraction when compared to the baseline condition and this had a compensatory effect as a result on distracted driving. However, large variations in the mean Time to Collision value were observed amongst participants, irrespective of the scenario (distracted or non-distracted).

6.1.2. Gaze Behaviour of Drivers During Distracted Driving

There is strong evidence from figures 4.33.-4.34. and heatmaps 4.35.-4.42. that drivers allocate their attention on the i-DREAMS system for more number of times and longer during distracted driving involving pedestrian collisions and non-events in the urban context. It was assessed that the average total duration of fixations on the i-DREAMS display sometimes increased by up to 10 times as compared to the baseline scenario.

This finding is critical because during distracted-driving, a large part of the driver's attention is allocated to the mobile phone screen in the process of texting. An increase in the duration of and number of fixations on the i-DREAMS interface suggests that this happened in spite of a substantial part of the driver's gaze being allocated to the mobile phone screen during the distraction scenario. However, the evidence isn't as strong for car-following situations.

Another significant trend that was observed during distracted driving was that in almost all of the cases, there was a substantial decline in the mean fixation count and mean total fixation durations for the pedestrian AOI and the road ahead AOI. This was critical given the fact in cases of events dealing with a possible VRU collision in the urban context. This can be explained by the fact that drivers fixate their gaze predominantly on the mobile phone screen during safety critical events that occurred when they received text messages. Thus, a part of the driver's attention was allocated to the cell phone. This, however, brings to the forefront two very significant findings. Drivers' gaze behaviour in terms of decline in the fixation on the road ahead and on critical objects (such as pedestrians during VRU events) suggests that they are distracted by text messages even during safety critical scenarios involving possible VRU collisions. Secondly, it was also implied that drivers showed a noteworthy increase in fixation on the i-DREAMS system during distracted driving as compared to the baseline scenario.

6.2. Tested Hypotheses

In this section, the hypotheses laid down in section **3.5.** are tested for validity.

Distraction-related hypotheses:

Hypothesis 1: Yes, results summarized from figure 4.22. agrees strongly with this. This has been described in detail in subsection **6.1.1.**

Hypothesis 2: Yes, there is strong evidence based on results observed from figure 4.23. that distraction has the most negative impact on lateral control parameters. This has been described in detail in subsection **6.1.1.**

Hypothesis 3: No, this hypothesis is rejected based on figure 4.24. The mean and minimum TTC, which is a measure of the reaction time performance of a driver, increase during distracted driving and this has a compensatory effect on distraction according to van der Horst et al. (1994).

Hypothesis 4: Associated longitudinal control parameters include longitudinal acceleration and deceleration. From figure 4.22., it can be seen that the mean and maximum values of longitudinal acceleration increase during both tailgating and pedestrian collision scenarios in urban and rural contexts. Thus, this hypothesis is validated.

Hypothesis 5: Associated lateral control parameters include lateral velocity and lateral acceleration. From figure 4.23., there is overwhelming evidence that the maximum values of lateral velocity and lateral accelerations increase significantly during distracted driving. Thus, the lateral control is compromised. Thus, the hypothesis is validated.

Traffic environment-related hypotheses:

Hypothesis 1: From figure 4.15. it was seen that longitudinal control was affected during VRU scenarios in the urban context. However, figure 4.19. depicts that distraction had a compensatory effect on the longitudinal performance. The Time to Collision (TTC) went up by almost 85%. Hence, this hypothesis is neither validated nor rejected.

Hypothesis 2: From figures 4.15., 4.16. and 4.18. it was observed that lateral control parameters such the steering wheel angle and lateral acceleration degraded significantly. Thus, this hypothesis is validated.

Hypothesis 3: From figure 4.15., it is observed that the TTC improves as a result of distraction on the urban segment. However, figures 4.16. and 4.18. offer no additional information on this. Hence, this hypothesis can neither be validated or rejected.

Hypothesis 4: From figure 4.14., it was seen that the value of longitudinal acceleration increased substantially. This was confirmed in figure 4.17. as well. Hence, this hypothesis is accepted.

Hypothesis 5: From figures 4.14. and 4.17. we observe that the mean and maximum values of lateral accelerations well as the maximum lateral velocity appreciate during distracted driving on rural segments. Thus, this hypothesis is validated.

Hypothesis 6: From tables 4.14. and 4.17. no information was found about the reaction time performance. Hence, this hypothesis can be neither validated or rejected.

Hypothesis 7: From figures 4.18. and 4.20. no information was found about the longitudinal control performance. Hence, this hypothesis can be neither validated or rejected.

Hypothesis 8: From figures 4.18. and 4.20. it was assessed that the mean and maximum values of lateral acceleration as well as maximum value of lateral velocity increased significantly. Hence, this hypothesis is validated.

Hypothesis 9: From figures 4.18. and 4.20. no information was found about the reaction time performance. Hence, this hypothesis can be neither validated or rejected.

Hypothesis 10: Yes, from figure 4.20. it is noted that the maximum value of lateral acceleration increases significantly during distracted drives in the presence of non-events on the highway. Thus, lateral control is degraded and this has an effect on the overall driving performance. Thus, this hypothesis is validated.

Hypothesis 11: From figure 4.21. it is observed that maximum values of both lateral acceleration and velocity increase during distracted driving. Thus, lateral control is degraded and this has an effect on the overall driving performance. Thus, this hypothesis is validated.

Safety critical event-related hypotheses:

Hypothesis 1: In figure 4.15. it can be seen that the maximum value of longitudinal acceleration increases during distracted driving in an urban context while encountering a probable VRU collision. However, this isn't the case with the rural segment. Hence, this hypothesis is only partially true and cannot be validated or rejected.

Hypothesis 2: Evidence based on figures 4.14.-4.16. prove this hypothesis to be true.

Hypothesis 3: From figure 4.15. we know that the TTC increases during distracted driving in the urban context, thus providing a compensatory effect. However, this isn't the case on rural stretches. Hence, this hypothesis is only partially true and cannot be validated or rejected.

Hypothesis 4: In figure 4.17. it can be observed that mean and maximum values of longitudinal acceleration increased substantially during tailgating scenarios in the distraction phase, irrespective of the roadway segment. An increase in longitudinal control parameters like acceleration implies a deterioration in control. Thus, this hypothesis is validated.

Hypothesis 5: From figures 4.17.-4.19. we can observe that lateral performance in terms of lateral acceleration and lateral velocity degrade significantly during tailgating, irrespective of the roadway. Thus, this hypothesis is validated.

Hypothesis 6: From table 4.19., we can observe that the TTC increases by about 80% during tailgating at relatively low speeds (urban segment). However, the variations in the TTC for rural and highway segments, which have higher speeds, is not significant (appendix A). Thus, this hypothesis is rejected.

Driver gaze behaviour-related hypotheses:

Hypothesis 1: From section 6.1.1. we know this to be true.

Hypothesis 2: From section 6.1.2. we know this to be not true.

Hypothesis 3: From figure 4.44., we know that the total fixation duration and fixation count went down between CE2-Ped-Urban and CE1-Ped-Rural. However, the other relationships between VRU collision events in different roadways are not as significant (appendix **B**). This, this hypothesis is rejected.

Hypothesis 4: From appendix **B**, we know that this is not true.

Hypothesis 5: From heat maps obtained from figures 4.35.-4.42., we get a detailed overview about a driver's gaze behaviour and attention allocation during distraction driving involving a wide variety of safety critical events. This overview is qualitative. In addition, eye tracking metrics can be used in inferential analyses to understand driver gaze behaviour during critical events. Thus, this hypothesis is validated.

Context-aware ADAS-related hypotheses:

Hypothesis 1: From subsection **6.1.2.** we know that distracted drivers fixate substantially more on the i-DREAMS display as compared to the baseline scenario involving VRU collisions. However, from figures 4.14.-4.16. we can gather the information that longitudinal control parameters like headway and TTC improve, while lateral control parameters like the steering wheel angle and lateral acceleration degrades in the urban context involving VRU collisions while under the influence of distraction. Hence, this hypothesis can neither be validated nor rejected.

Hypothesis 2: From subsection **6.1.2.**, we know that there was minimal change in the gaze behaviour of drivers on the i-DREAMS interface between distraction and non-distraction simulation runs during tailgating scenarios. Hence, the i-DREAMS system doesn’t play a major role in safety critical events involving tailgating. Thus, this hypothesis is rejected.

Category	**Hypothesis**	**Validated**	**Rejected**	**Neither Validated nor Rejected**
Distraction-related hypotheses	Hypothesis 1	+		
	Hypothesis 2	+		
	Hypothesis 3		+	
	Hypothesis 4	+		
	Hypothesis 5	+		
Traffic environment-related hypotheses	Hypothesis 1			+
	Hypothesis 2	+		
	Hypothesis 3			+
	Hypothesis 4	+		
	Hypothesis 5	+		
	Hypothesis 6			+
	Hypothesis 7			+
	Hypothesis 8	+		
	Hypothesis 9			+
	Hypothesis 10	+		
	Hypothesis 11	+		
Safety critical event-related hypotheses	Hypothesis 1			+
	Hypothesis 2	+		
	Hypothesis 3			+
	Hypothesis 4	+		
	Hypothesis 5	+		
	Hypothesis 6			+
Driver gaze behaviour-related hypotheses	Hypothesis 1	+		
	Hypothesis 2		+	
	Hypothesis 3		+	
	Hypothesis 4		+	
	Hypothesis 5	+		
Context-aware ADAS-related hypotheses	Hypothesis 1			+
	Hypothesis 2		+	

Fig 5.1.: Summary of tested hypotheses (source: own)

6.3. Policy Implications

The i-DREAMS project seeks to "establish a framework to define, develop, test and validate a context-aware safety envelope for driving in a 'Safety Tolerance Zone' (STZ)" (Pilkington-Cheney et al., 2020). The first stage of this study involved the simulator trials in order to test driver background factors, physiological factors and driving environment factors and how they influenced the driving performance. Additionally, a secondary objective was to test the effectivity of the real-time, intervention based i-DREAMS system and its effectivity in warning drivers during safety critical events. Finally, the project also set out to gather user feedback and an assessment of technological acceptance about the i-DREAMS technology (Pilkington-Cheney et al., 2020).

In order to have representativeness in the sample space of participants for studying their background factors, it is advisable to hold trans-national studies involving drivers from diverse backgrounds in terms of gender, age and nationality. Secondly, simulator studies can also be supplemented with naturalistic studies to get a better picture of how drivers interact with in-vehicle technologies. However, this is dependent on the reliability of the equipment used (most context-aware devices used for such studies are prototypes), cost concerns and data protection regulations with regards to the driver's information.

From section **6.1.2.** it was assessed that during safety critical events involving possible pedestrian collisions, drivers allocate a significant part of their attention to the i-DREAMS display as compared to the baseline condition. Simultaneously, they show a decline in the fixation on the road ahead and on critical objects (such as pedestrians during VRU events). In addition to this, it was also observed that drivers are distracted by text messages and focus on secondary tasks while driving even during safety critical scenarios involving possible VRU collisions. Thus, it can be concluded that in-vehicle devices such as mobile phones are a major source of distraction during safety critical events like VRU collisions. Regulations penalizing the usage of mobile phones while driving should be considered, especially for zones with a higher density of pedestrian crossings and lateral congestion.

From figures 4.14.-4.16., we know that longitudinal control parameters like headway and TTC improve, while lateral control parameters like the steering wheel angle and lateral acceleration degrades in the urban context involving VRU collisions while under the influence of distraction. Hence, we cannot be certain if the i-DREAMS system has a beneficial effect on the driving task or not. Brodeur et al. (2020) found that vocal assistants were found to have less impact on the driving task as compared to systems where information has to be input manually. This study was based on driver gaze distribution focus. Context-aware ADAS systems leaning towards voice functionality that minimizes visual interaction with the driver becomes important in this context and laws that incentivize OEMs to act as a push factor to shift from systems that interact with the driver's visual attention to one that is context-aware and focuses more on voice commands and auditory interventions.

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Chapter 6. Conclusion

The final chapter presents the conclusion of this research, its limitations, recommendations and proposal for future research in this direction.

6.1. Conclusion

Texting during driving has a detrimental impact on the longitudinal, lateral and reaction time performance measures. As the market for in-vehicle technologies such as mobile phones integrated with In-Vehicle Information Systems increase, more and more drivers would be under the impact of physical, aural, cognitive and visual distraction. There have been driving simulator studies that have investigated visual distraction. However, none of them did so in a context-aware system in the presence of real-time interventions during safety critical events such as tailgating or possible Vulnerable User Collisions using eye tracking. This presented an opportunity to expose drivers to potentially critical events in a controlled environment and assessing its impact on attention allocation and consequently its effect on driving performance.

In this research, the impact of texting on driving performance and attention allocation is investigated using a high-fidelity driving simulator with a context-aware ADAS, developed as part of the i-DREAMS project. Simulation runs were held for thirty participants who drove three scenarios wearing an eye tracker involving no interventions, fixed timing interventions and variable timing interventions in the presence of distraction. Distractions were triggered via text messages during safety critical events involving pedestrian collisions and tailgating situations in urban, rural and highway segments. Gaze data as well as driving performance data were collected and analyzed using descriptive and inferential statistical methods, in addition to visualization techniques. The results corroborated the findings in the literature review and validated most of the built hypotheses involving deterioration in longitudinal, lateral and reaction time measures during distracted driving, as well as visual tracking being an effective method to analyze distraction. The findings related to in-vehicle distraction can be used to supplement naturalistic studies investigating external visual distraction sources. Recommendations for future research in this area incorporating the impact of demographics and traffic environments were laid down.

In addition to the above, the main research questions formulated in chapter **1.** Can be summarized as:

1. **What impact does in-vehicle distraction in the form of texting have on the primary driving task?**
   Texting has a significant effect on the longitudinal control, lateral control and reaction time parameters across diverse traffic environments and safety critical events. It has been found to have an extremely negative impact on the lateral control as well as certain longitudinal control measures. However, it was also observed that distraction had a compensating effect on the reaction time. The latter showed an increase as compared to the baseline scenario with no-distraction.

2. **Do driving performance parameters degrade significantly when the driver encounters safety critical events in the presence of in-vehicle distraction in a simulated driving environment (when compared to the baseline scenario with no distraction)?**
   This is dependent on the driving performance parameter in question. Lateral control measures such as lateral acceleration, lateral velocities, the steering wheel angle showed significant increases during distracted driving, thus implying a degradation in driving performance. However, this wasn't true for reaction time parameters like the Time to Collision, which improved driving performance under distraction load. The deterioration of driving performance parameters is also dependent on the safety critical event in question. Similar parameters have shown contrasting behaviour across related safety critical events in different traffic environments.

3. **If yes, which driving performance variables are affected the most during safety critical events?**
   The longitudinal, lateral and reaction time driving performance variables. These include the statistically relevant parameters of longitudinal acceleration, longitudinal velocity, time headway, Time to Collision, lateral position, steering wheel angle, lateral velocity and lateral acceleration for variables obtained from the simulator and the Fixation Count and Total Fixation Duration for variables extracted from the eye tracker.

4. **Can Eye Tracking Analysis (ETA) be used to analyze driving performance satisfactorily and reliably?**
   Heat maps in addition to eye tracking metrics obtained from the visual tracking analysis was critical in getting a detailed overview about a driver's gaze behaviour and attention allocation during distraction driving involving a wide variety of safety critical events. This overview was qualitative. Metrics such as the fixation count as well as the total fixation duration were used in inferential analyses to understand how driving control changes with gaze. Thus, ETA in combination with statistical methods focusing on parameters obtained from the driving simulator can be used effectively to analyze driving performance as well as the impact of visual and cognitive distraction in influencing it.

5. **Is there an association between the gaze behaviour of drivers during safety critical events like tailgating and possible Vulnerable Road User (VRU) collisions and the deterioration of driving performance?**
   From tables 4.1. and 4.2. one could comment that lateral performance measures show signs of decline when fixation on in-vehicle interfaces increase during tailgating and VRU collision scenarios. Similar results were observed for longitudinal control measures like longitudinal acceleration. However, in the case of other longitudinal control parameters like the time headway, an increase in performance was shown. Thus, it is clear that there is an association between gaze behaviour and driving performance during safety critical events. However, further investigation is required to confirm if this indeed has a deteriorative effect.

6. **Does a context aware system like the i-DREAMS intervention system help in mitigating distraction during safety critical events?**
   From subsection 6.1.2. it was noted that distracted drivers fixate substantially more on the i-DREAMS display as compared to the baseline scenario involving VRU collisions. However, from figures 4.14.-4.16. we can conclude that longitudinal control factors like headway and TTC improve, while lateral control variables like the steering wheel angle and lateral acceleration degrades in the urban context involving VRU collisions while under the influence of distraction. Thus, results are ambiguous in this context and further investigation is required to confirm if the i-DREAMS system has indeed a mitigating effect on distraction during safety critical events.

6.2. Limitations of the Study

The research conducted has some limitations which should be considered for future studies.

- Limited information was found in the synthesis of literature in section 2.6. regarding the effect of possible VRU collisions on driving performance. Only two were selected as a result: reaction time (TTC) and steering wheel angle. Consequently, the study was limited in its ability to select driving performance variables that were most sensitive to distraction for this safety critical event.
- The experimental design took into consideration randomization by changing the order of traffic environment with the help of scenarios (A, B or C) and the configuration (monitoring, intervention or distraction). However, owing to the limited number of events (6 critical events) and the repetition of similar events at the same traffic location in the traffic environment across three drives by the same driver due to the within-participant design of the experiment (Pilkington-Cheney et al., 2020), learning behaviour is induced.
- Due to an induced learning effect, some of the participants knew when to react to specific events and the impact of distraction was compensated as a result. This introduced some bias in the dataset owing to the predictability of the scenarios.
- Thirty participants were recruited for the i-DREAMS simulator trials. The sample size was statistically limited as a result.
- The sample space met Munich's driver demographics for all groups except the 65+ group across both genders. Thus, the sample was limited in its representativeness.
- Some drivers didn't use the mobile phone to read or reply to text messages during the distraction scenario. Thus, they were not distracted during critical events. This might cause a skewing of the dataset.
- The impact of distraction on driving performance was done in a driving simulator under a controlled environment. The results may diverge from actual on-road naturalistic studies.
- Contradictory behaviour between driving performance variables of the same group in certain scenarios.

- This study does not consider the impact of demographics on the driving performance. According to Rhodes et al. (2011), age and gender determined risk perception during potentially critical events. From the results of the descriptive analysis, it was observed that for driving performance variables, a high degree of dispersion from the central value was present. This can be justified by Rhodes et al.'s findings since the i-DREAMS trials took into consideration both genders and four age brackets. Thus, participants from different groups assessed distraction and risk during safety critical events differently. This was reflected in the driving performance.

6.3. Recommendations and Future Work

The results of this study indicate that there are many challenges associated with simulator studies, including recruitment and design of the experiment. As mentioned in section 6.2., due to a within-participant design of the i-DREAMS simulator trials, learning behaviour and predictability was introduced. This was due to the limited number of safety critical events occurring in a single drive. A within-participant design involves a single driver driving the monitoring, intervention and distraction scenarios, in addition to practice runs. The learning effect can be off-set to some extent by introducing a between-subjects design (at least partially), thus eliminating one of the scenarios for some participants. This would reduce some bias in the dataset.

The findings of this study suggested that there are wide variations in the driving performance from the mean value. This is because different demographic groups have different perceptions of risk as well as distraction. Hence, there could be two possibilities. Firstly, the sample size of the experiment and thus, its statistical power could be increased. It would also be reasonable to investigate the impact of distraction during safety critical events on different demographic groups. Furthermore, the impact of in-vehicle distraction and the corresponding driving behaviour in different traffic environments can be studied in more detail using visual tracking.

Driving simulators offer controlled environments and may facilitate results that might vary from on-road driving. Hence, it would be beneficial to supplement simulator trials with naturalistic driving experiments, as is being done in stage 2 of the i-DREAMS project.

This research can be supplemented by inferential statistical methods such as regression analysis between driving performance variables to explain relationships between them. It could be used to identify sets of descriptive variables that covary with certain driving performance measures of the data that was obtained from the driving simulator.

Eye tracking is effective in measuring the allocation of visual attention. However, there are other aspects of factors that cannot be captured in gaze behavior. For example, the emotional state of a driver that could be a predictor to his driving performance under cognitive distraction. This can be done by adding supplementary biometric methods such as GSR (Galvanic Skin Response) to visual tracking.

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Appendix A: Driving Performance Variables

The plots for all driving performance variables selected as a result of reviewing relevant literature in sections 2.5.-2.7. across all events in the baseline intervention scenario and the distraction test scenario have been presented here. These result from the two sample t-test conducted in section 4.2. The cases where the significance criterion laid down in section 3.4.3 is met have been presented in figures 4.22., 4.23., 4.24., 4.33. and 4.34.

A] Variables obtained from the driving simulator:

A.1] Longitudinal control parameters: Longitudinal Velocity (mean), headway (mean), headway (minimum).

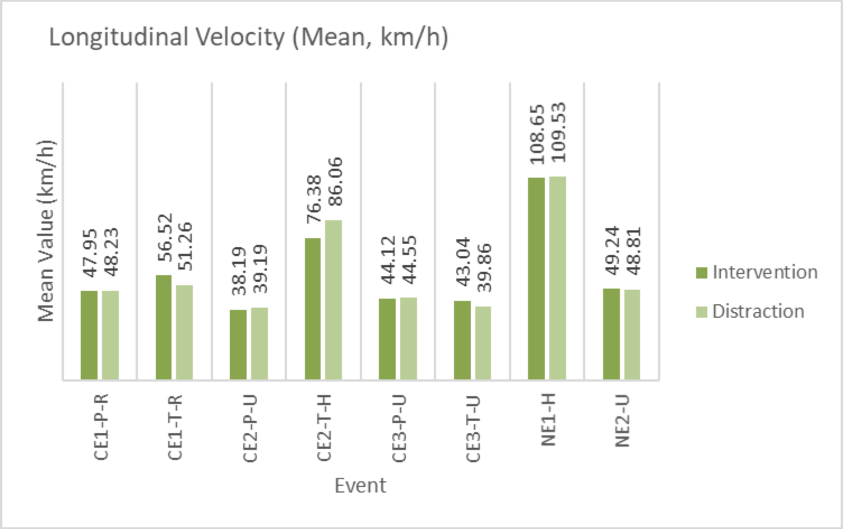

Figure: The impact of distraction on mean longitudinal velocity across events during intervention and distraction drive scenarios

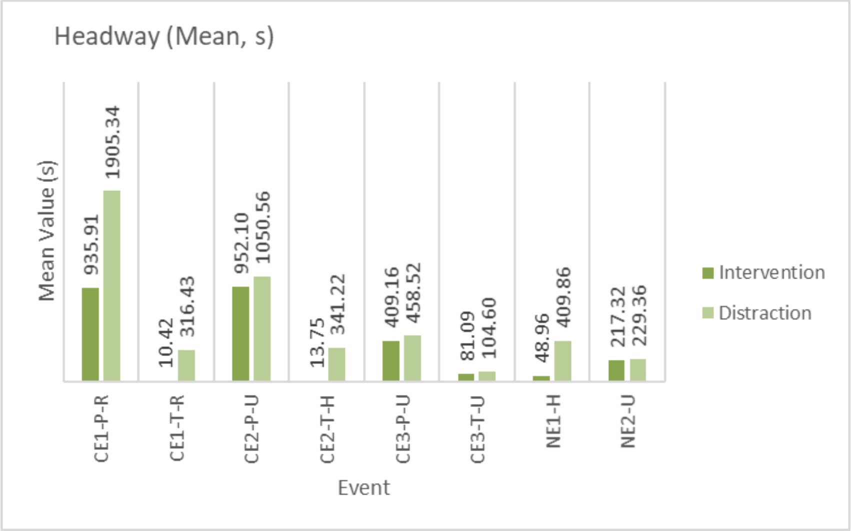

Figure: The impact of distraction on mean headway across events during intervention and distraction drive scenarios

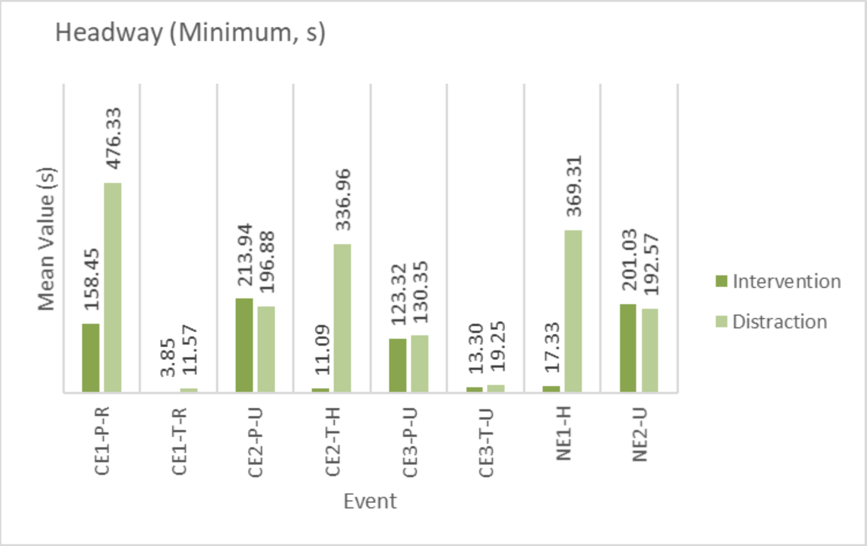

Figure: The impact of distraction on minimum headway across events during intervention and distraction drive scenarios

A.2] Lateral control parameters: Lateral position (mean)

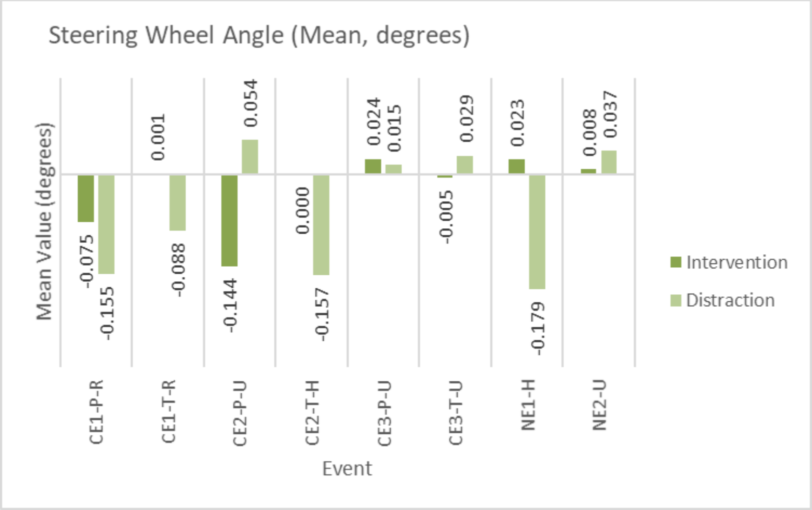

Figure: The impact of distraction on mean lateral position across events during intervention and distraction drive scenarios

A.3] Reaction time parameters: TTC (mean) and TTC (minimum)

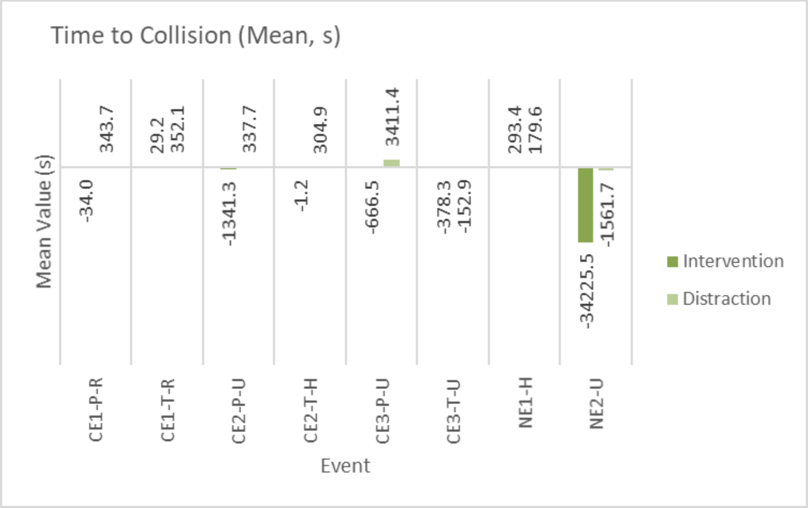

Figure: The impact of distraction on mean TTC across events during intervention and distraction drive scenarios

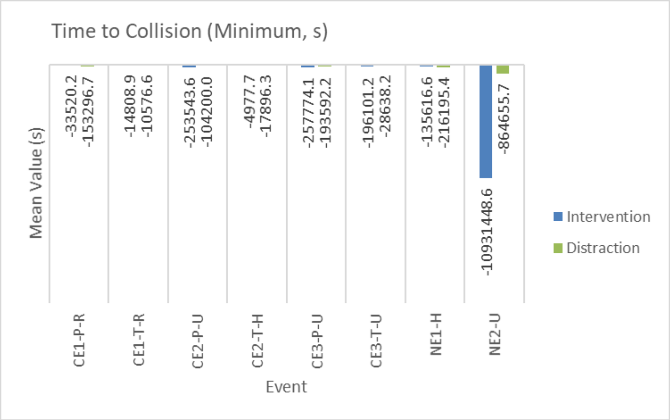

Figure: The impact of distraction on minimum TTC across events during intervention and distraction drive scenarios

A.4] Other parameters, including supplementary longitudinal and lateral control parameters: longitudinal acceleration (mean and maximum, m/s^2), lateral acceleration (mean and maximum, m/s$^{2)}$ and lateral velocity (mean and maximum, m/s)

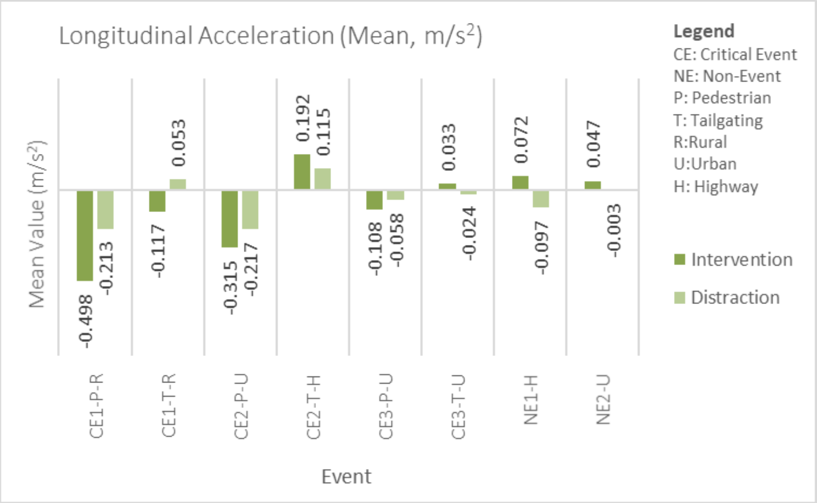

Figure: The impact of distraction on mean longitudinal acceleration across events during intervention and distraction drive scenarios

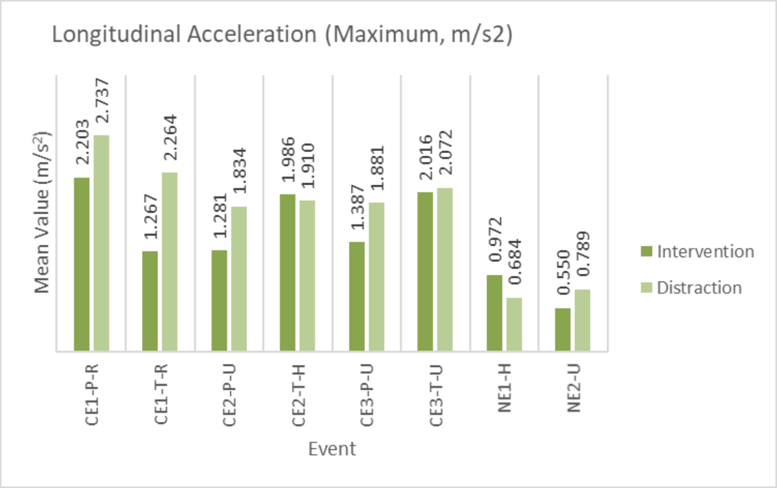

Figure: The impact of distraction on maximum longitudinal acceleration across events during intervention and distraction drive scenarios

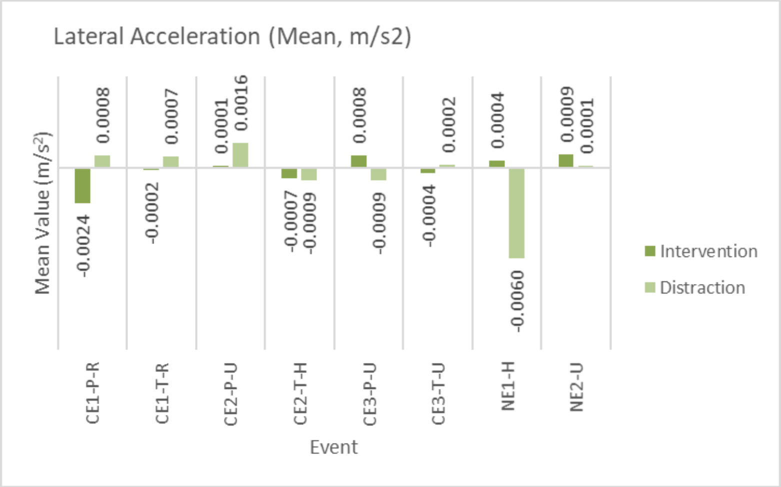

Figure: The impact of distraction on mean lateral acceleration across events during intervention and distraction drive scenarios

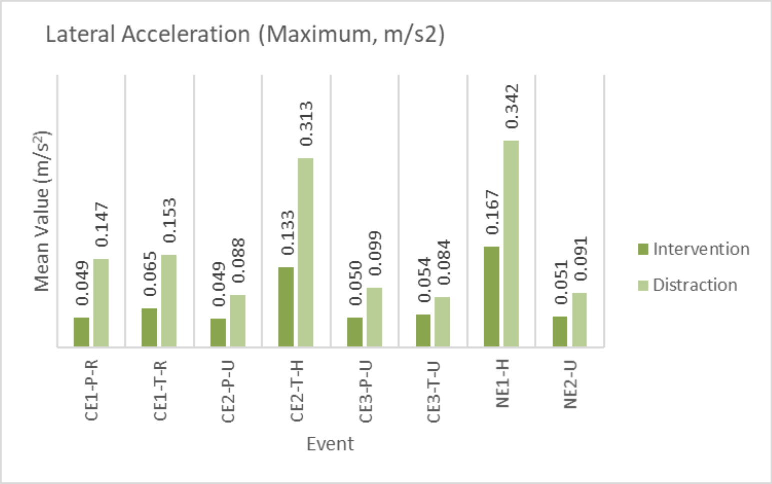

Figure: The impact of distraction on maximum lateral acceleration across events during intervention and distraction drive scenarios

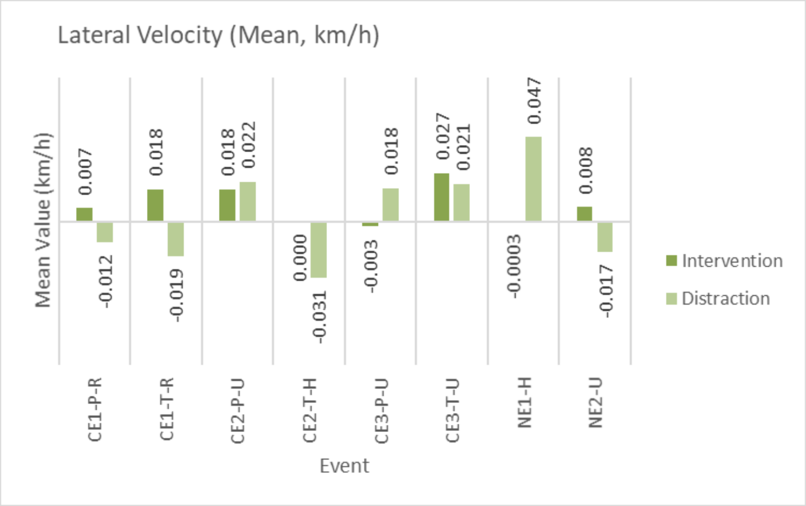

Figure: The impact of distraction on mean lateral velocity across events during intervention and distraction drive scenarios

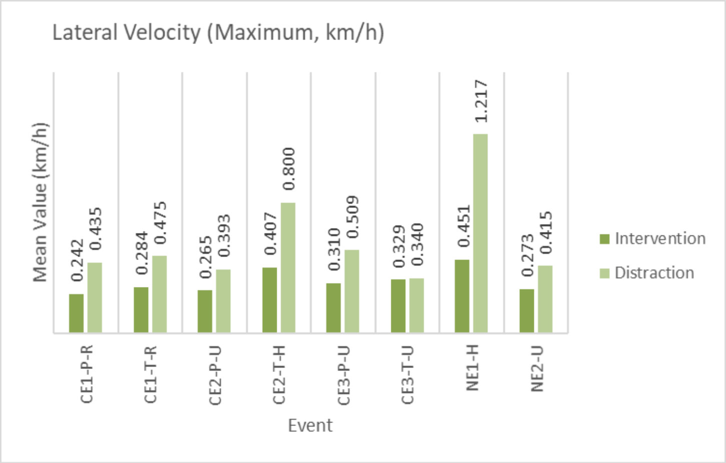

Figure: The impact of distraction on maximum lateral velocity across events during intervention and distraction drive scenarios

B] Variables obtained from the eye tracker:

B.1] Variables based on gaze counts: fixation count

Figure: The impact of distraction on fixation count across events during intervention and distraction drive scenarios for different Areas of Interest

B.2] Variables based on gaze durations: total fixation duration

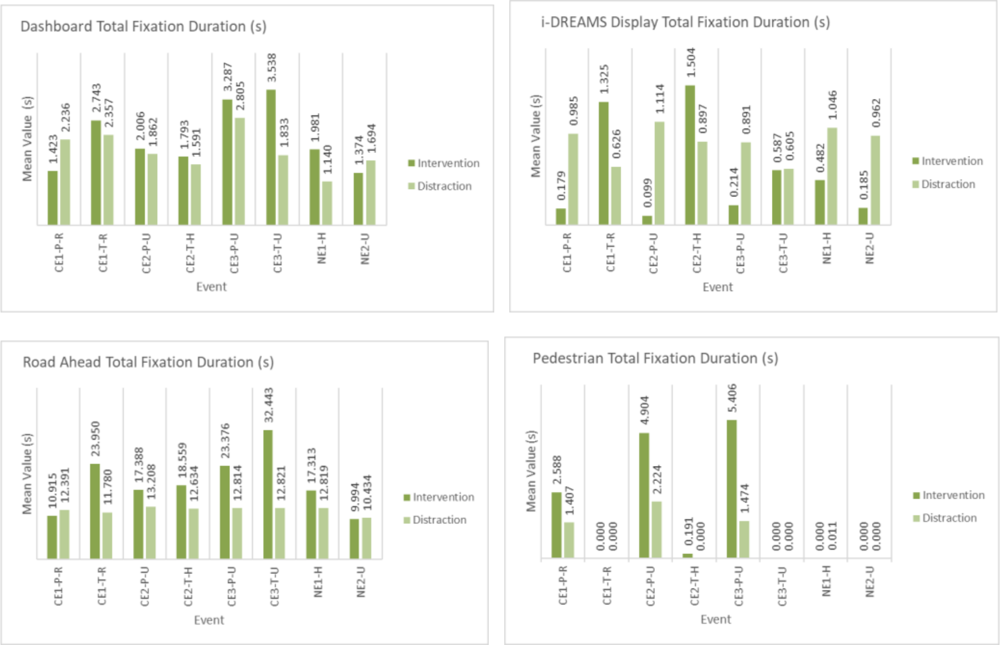

Figure: The impact of distraction on total fixation duration across events during intervention and distraction drive scenarios for different Areas of Interest

Appendix B: Eye Tracking Metrics for Mobile Phone Screen AOI

A] Safety critical events involving VRU collisions during distracted driving between urban, rural and highway traffic environments

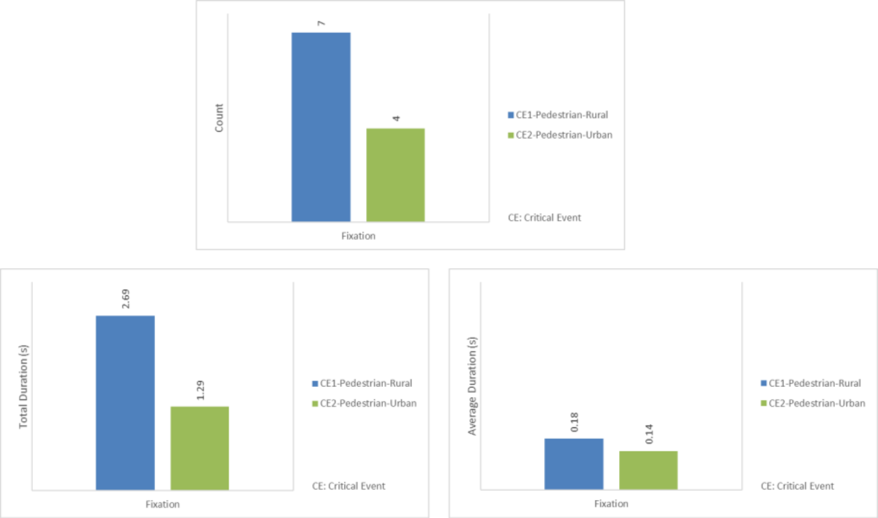

Figure: Change in values of eye tracking metrics for CE1-P-R and CE2-P-U for the mobile phone screen AOI

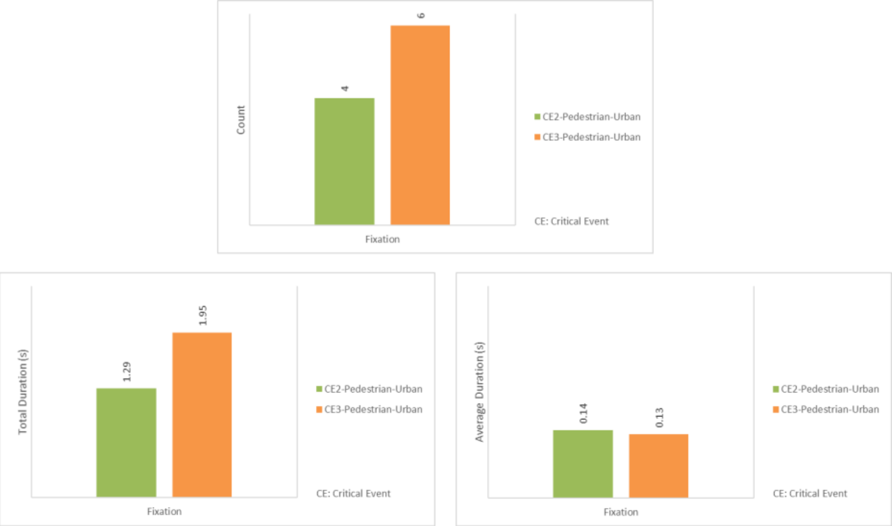

Figure: Change in values of eye tracking metrics for CE2-P-U and CE3-P-U for the mobile phone screen AOI

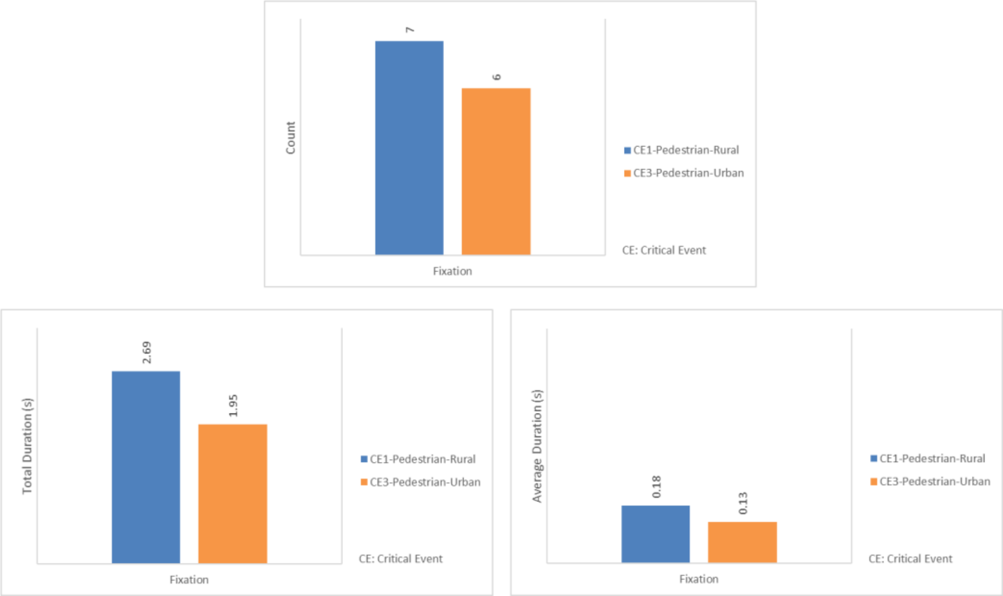

Figure: Change in values of eye tracking metrics for CE1-P-R and CE3-P-U for the mobile phone screen AOI

B] Safety critical events involving tailgating scenarios during distracted driving between urban, rural and highway environments

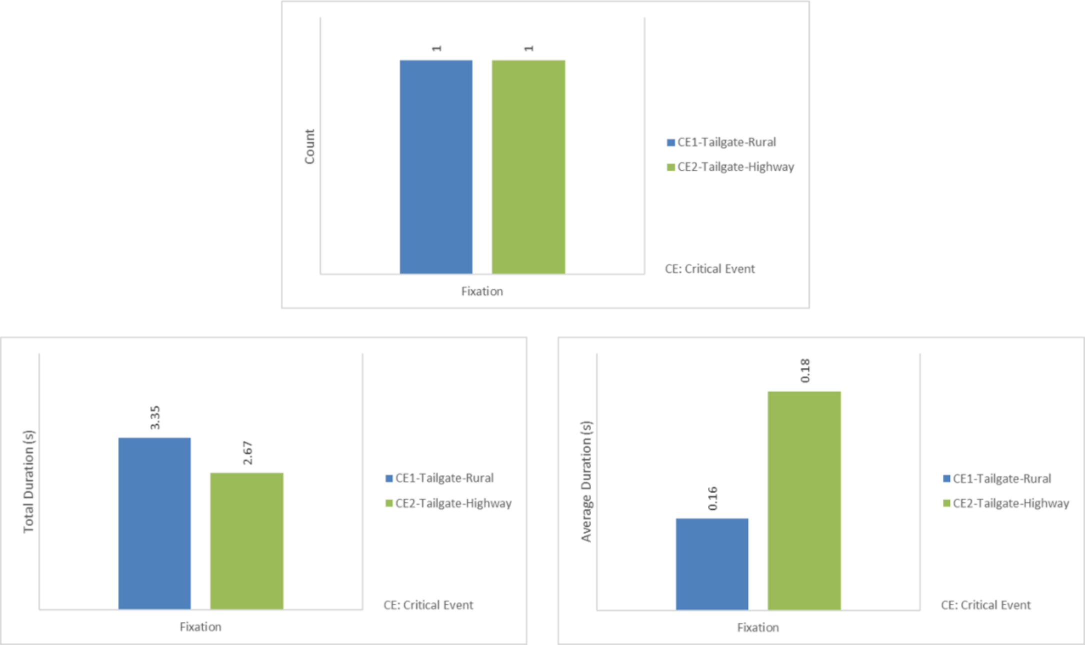

Figure: Change in values of eye tracking metrics for CE1-T-R and CE2-T-H for the mobile phone screen AOI

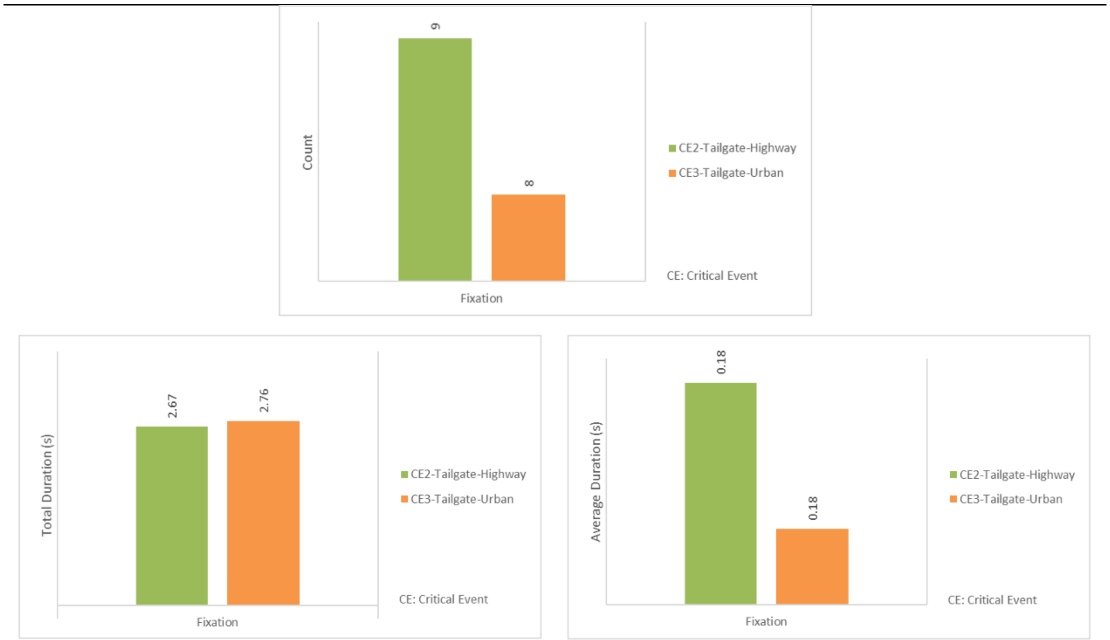

Figure: Change in values of eye tracking metrics for CE2-T-H and CE3-T-U for the mobile phone screen AOI

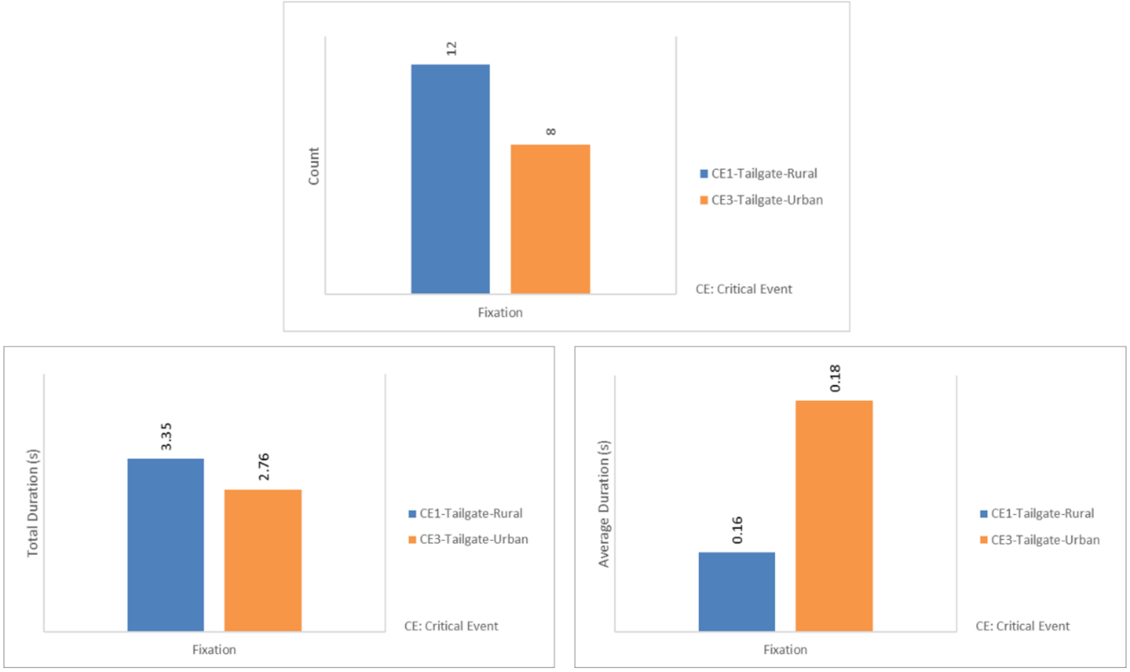

Figure: Change in values of eye tracking metrics for CE3-T-U and CE1-T-R for the mobile phone screen AOI

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