Delivery Report for

MeBeSafe

Measures for behaving safely in traffic

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Deliverable	D3.2
WP	WP3 Infrastructure measures
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Abstract

Excessive speeding and an unsafe trajectory are seen as some of the key factors contributing to fatal crashes. Since MeBeSafe aims to prevent traffic accidents, both factors are addressed within MeBeSafe project. The aim is to design nudging measures that gently nudge drivers to a safer driving behaviour in terms of a safe, reduced driving speed and an appropriate trajectory.

This report provides detailed insights on state of the art for technology, the process from researching relevant literature, over the results of focus groups on useful measures, to the testing of the most promising nudging measures in driving simulator experiments and the evaluation of these nudging measures, as well as implications for further research.

The chosen approach for the nudging measures targeting driving speed are based on the concept of optic flow and function by the illusion of driving faster than the actual driving speed. This is achieved by lights, moving towards the driver and thus altering the optic flow. Promising results were revealed in both quantitative and qualitative results of the simulator studies: Participant's driving behaviour was influenced by the lights by showing earlier braking in the condition with the lights moving against the driver. A second simulator study revealed that the light interventions have an effect on drivers' attention on the road and don't influence driver's workload negatively. The simulator study on the trajectory nudge is not conducted yet, however the report provides insights into the details of the planned simulator study. The Monte Carlo Simulation gives first estimations for different scenarios based on the available data base, and results revealed that especially those drivers who are driving riskily should be nudged.

The research conducted within WP3 provides important information for the field test in Eindhoven (WP5) that will evaluate the efficiency of the nudging measure in a real life situation.

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table of document history

Table of Contents

List of Figures

List of Tables

Acronyms

ADAS	Advanced driver assistance systems
ANOVA	Analysis of variance
BMW	Bayrische Motoren Werke
EU	European Union
ESC	Electronic Stability Control
FCD	Floating Car Data
FPD	Floating Phone Data
GIDAS	German In-Depth Accident Study
GPS	Global positioning system
GSM	Mobile Phone Data
H	Hypothesis
HGV	Heavy goods vehicles
ika	Institute for Automotive Engineering, RWTH Aachen University
ISA	Intelligent Speed Adaption
ISAC	Institute of Highway Engineering, RWTH Aachen University
LED	Light-emitting diodes
MATLAB	Matrix Laboratory
NASA-TLX	Nasa Task Load Index
OECD	Organisation for Economic Co-operation and Development
p	position
RAA	Royal Automobile Association of South Australia
SCR	Skin Conductance Response
SuRT	Surrogate reference task
VTD	Virtual Test Drive
WP	Work Package

1 Executive Summary

Even though road safety improved over time, road accidents still cost many thousands of lives and cause numerous casualties (European Commission, 2017). MeBeSafe addresses this issue by aiming to reduce the number of accidents and fatalities on European roads by using nudging measures. As technological progress minimizes the likelihood of technical failure leading to a crash to a minimum, the human factor can be seen as one of the key factors, contributing to accidents the most (Ruman, 1990). Existing measures targeting safe driving behaviour often require deliberate processing whereas driving itself can be generally seen as a habitual, automatic task (Ranney, 1994). Since there is a lack of measures targeting drivers who are unaware of their potential misbehaviour, WP3 (Driver Nudge) of MeBeSafe aims to target exactly this group of drivers by using nudges that gently lead people to a desired and safe behaviour without requiring deliberate processing (Thaler & Sunstein, 2008).

This report provides detailed information on WP3 of the MeBeSafe project, including the state of the art of technology and existing interventions of nudging drivers, as well as alternate infrastructure interventions (chapter 5). After the careful deduction and development of nudging interventions (chapter 6), including descriptions of the theoretical background and the results of expert workshops on the design of the measures, the nudging measures are individually tested in the simulator to verify the effectiveness of each nudging system in a controlled manner (see chapter 7 - 9). In the first simulator study (chapter 7) various light scenarios were compared. The design of the nudging measures on speed reduction is based on the logic of the optic flow (Gibson, 1950) by altering the optic flow in order to create the impression of driving faster than the actual personal speed. Therefore lights are implemented on a simulated replication of a highway exit in Eindhoven, where the following field test (WP5) takes place. Results reveal that the driving behaviour changed throughout the exit, indicating that the nudging measure leads to a changed and presumably safer driving behaviour. This promising result supports the approach of altering the optic flow in order to improve safe driving behaviour. Qualitative results on the impression of the participants are in line with the quantitative results of the driving parameters: Participants reported that the nudging measure affects their speed perception and lead to a safer driving behaviour. However, the results of the quantitative results were relatively small which may be due to the artificial situation in the driving simulator leading to simulator effects. Therefore the results of the field test, which is part of WP5, are going to reveal deeper insights in the effectiveness of the measures in a real life situation.

Since the tested nudging measure is supposed to function without deliberate processing, the second simulator study (chapter 8) examines the effects of the nudging measure on attention and the workload. Results show that the movement component in the moving light condition did not appear to add to the driver's workload, indicating that the lights moving towards the driver are processed automatically and can therefore be seen as a system 1 nudge, resulting in quick and subconscious behavioural changes that do not add to the driver's cognitive load (Kahneman, 2011). Since results give a first indication that the workload in the motorway exit is already relatively high, the initial approach to use a nudging intervention either targeting an appropriate driving speed or a safe trajectory is pursued as intended. Targeting both trajectory and the driving speed at once could be confusing for drivers. Therefore, an additional study on the trajectory nudge is planned and described in chapter 9. An overview of the theoretical background, the design of the nudging measure and the planned procedure is given.

Finally, chapter 10 presents the results of the computer simulations investigating the potential safety impact of an infrastructure nudge by following the Monte Carlo approach. The results of the Monte Carlo Simulation revealed that especially those drivers who are driving riskily should be nudged. This implies that even if only a small percentage of drivers is nudged, a safety benefit can be achieved.

2 Contribution by each Partner

BMW has contributed to the completion of work in WP3 by taking part in discussions on developing the infrastructure nudging measures for drivers, conducting the Monte Carlo Simulation, reviewing this deliverable D3.2, and writing the corresponding chapter 9. Furthermore, BMW participated in the majority of biweekly conference calls and driver nudge meetings.

Heijmans has been involved in WP3 by taking part in discussions on developing the infrastructure nudging measures for drivers, provided expertise in designing road interventions, organized the field test location, and ensured the link to Task 3.3 Instrumentation and WP5. Furthermore, Heijmans participated in the majority of biweekly conference calls and driver nudge meetings.

ika of **RWTH Aachen University** is leading WP3, especially T3.1 Driver Nudge, and was responsible for writing D3.2 and compiling the input by partners. ika led the design, testing and further development of infrastructure nudging measures, including application of the integrated framework, conducted the driving simulator studies, and has the overview over testing of measures and analysis of data from the test phase in simulators. Furthermore, ika hosted the biweekly conference calls and organized and participated in driver nudge meetings.

ISAC of **RWTH Aachen University** has been in the lead for Task 3.3 Instrumentation and was involved in discussions on developing the infrastructure nudging measures for drivers. ISAC has been involved in defining safe speeds and trajectory, provided expertise on road design, and ensured the link to Task 3.3 Instrumentation and WP5. Furthermore, ISAC participated in the majority of biweekly conference calls and driver nudge meetings.

3 Introduction

Although a number of measures to reduce road accidents have already been established on European roads, 24.400 fatal accidents occurred on European roads only in 2015 (European Commission, 2017). So far, those measures focussed on the driver's deliberate self, for instance by positioning awareness campaigns or imposing fines. Also, supportive advanced driver assistance systems (ADAS), rumble strips, radars or intelligent traffic signs were established in road traffic in order to decrease the high number of accidents. Problematic about those interventions can be that they might not appeal to experienced drivers since navigating through frequently used roads is part of the daily routine of many car drivers and therefore becomes a habitual task „which does not require much elaborate decision-making" (Köhler, Op den Camp, van Mierlo, Ladwig, & Schwalm, 2019). Therefore, it is necessary to implement measures that address automatic and habitual behaviour in road traffic.

When acting in a new environment for the first time, people usually think about their actions as well as their desired outcome. According to the theory of planned behaviour (Ajzen, 1991), this process is determined by our intentions which are indirectly constructed based on our attitude, our subjective norms and our perceived behavioural control. After performing actions within the same context for several times, a behaviour becomes more automatic (Aarts, Verplanken, & Knippenberg, 1997; Ouellette & Wood, 1998; Verplanken & Aarts, 1999) and thus habitual, guided by environmental cues (Verplanken & Wood, 2006).

Navigating frequently used roads is part of most people's daily driving routine and adopting a driving behaviour to different conditions is therefore a well-trained process for experienced drivers, especially when undertaking tactical or operational tasks (Ranney, 1994). Choices of manoeuvring, obstacle avoidance, speed selection, and lane choice are tactical level concerns the driver has to approach. The operational level concerns vehicle control tasks, such as keeping a desired speed or lane. The difference between novice and experienced drivers is that for the latter, these tasks are performed mostly automatic and based on skills or stored rules. Thus, those tasks ask for low cognitive processing (Ranney, 1994).

Behaviour is more likely to be performed without deliberate thought or explicit decision-making when it is habitual or automatic. This can reduce driver's mental workload when performing driving tasks (Köhler et al., 2019). As a result, drivers might fail to detect changes in the road environment they are usually familiar with, since habitual driving is usually executed with lower awareness (Verplanken & Wood, 2006, Martens & Fox, 2007). Therefore, driving without deliberate thought might lead to being too late to adjust driving behaviour when needed. This can then lead to driving errors and decreasing safety margins, and ultimately to possibly hazardous traffic situations.

Within the MeBeSafe project, WP3 has determined a number of objectives for the infra driver nudge. The focus was to develop and implement the sensing system, the decision-control logic and the interaction with the driver by using an infrastructure based system that leads the driver to reduce speed (objective 6), especially when driving on certain hazardous road sections. In addition, drivers of motorized vehicles were to be guided along a preferred trajectory by making use of the implemented systems (objective 7). Measures were selected and designed and, in a next step, tested on their performance in a virtual environment and then compared to conventional traffic situations without a nudging intervention.

Within WP3, the selection and design as well as the virtual and real life testing was conducted. The main aim was to define the most effective nudging measures, which will be used in the field evaluation phase in WP5.

4 Description of Tasks

The objective of task 3.1 (infra driver nudge) was to develop adaptive and active infrastructure measures directed towards drivers. In this context, the nudging measures that were based on the integrated framework from WP1 were designed. The experimental design was developed in a next step, meaning that test scenarios and parameters were developed, the sample size was defined and the analysis methodology for the driving simulators and test pilots were defined. Subsequently, the driving simulator test phase was conducted with real subjects under virtual conditions to test selected intervention designs for effectiveness and to consider driver distraction. The most effective measures tested in the simulator were evaluated in the virtual modelling in order to improve the design further. The overall aim of WP3 was to select the most effective infrastructure driver nudging measures, both for speeding and for trajectory and to recommend these for the subsequent real life testing phase (WP5).

ika led the task, based their studies on the integrated framework developed in WP1, and worked closely with its network of experts and access to driver psychology models for the design of nudging interventions. Furthermore, ika had the overview of testing measures and the analysis of data from the test phase and simulators. Heijmans, having long track record of designing and implementing innovative infrastructure measures, provided expertise in designing road interventions concerning feasibility, possibilities and limitations. They also provided expertise and information concerning prior fields tests and the selection of the test location for nudging measures in cooperation with ISAC and ika. ISAC added their expertise in the design of measures, mainly focusing on speeding and driver trajectories. The first design developed in cooperation between ISAC, ika, BMW, and Heijmans was used as an input to the upcoming tasks (e.g. Driving-Simulator studies and Monte Carlo Simulations). Subsequent to T3.1, ISAC contributed to the construction of the nudging items by ensuring the thorough implementation of the results of preceding tasks. The simulation results were precisely implemented. BMW supported the road design interventions concerning effectiveness, possibilities and limitations of nudging measures based on simulation and was responsible for the virtual modelling. Additionally, BMW made sure that the experiment data was considered in the implementation of simulation models.

4.1 Scope and Structure of Deliverable

This chapters gives an overview over the content and approach of deliverable 3.2. First, the overall scope is stated, followed by a description of the structure of the overall document. Subsequently, the contextual approach is targeted.

4.1.1 Scope

This report summarises the infrastructure measures to be tested in WP5. It serves as a basis for journal publications containing a scientific evaluation of adaptive and active infrastructure measures directed towards drivers and tested in the virtual environment. As specified in the Grant Agreement, the specification of infrastructure measures directed towards cyclists is not targeted in this report, but in D3.1 (lead beneficiary: Chalmers/SAFER).

4.1.2 Structure

Deliverable D3.2 starts with an overall introduction into the topic addressed within this report and shows the relevance of the development of nudging measures in order to improve road safety. Also the contribution by each partner and the objectives of task 3.1 are presented. In the following, the involved tasks are described, followed by the approach to prompt drivers to reduce their speed and to guide them along a preferred trajectory. In this context, the use of light as an intervention and the location selection is discussed. Chapter 5 is concerned with outlining the state of the art regarding existing interventions regarding infrastructure and nudging in literature and in the traffic environment, as well as the discussion of different light systems. The chapter concludes with an overview over detection and refers to design guidelines to be considered for the derivation of nudging interventions. In chapter 6, the derivation of infrastructure nudging measures to meet our objectives is described before giving detailed reports about the simulator studies (chapters 7, 8, and 9). The Monte Carlo Simulation and virtual modelling approach are outlined in chapter 10, focusing on the simulation approach, the simulation scenarios and input data, the analysis of the study and its limitations. A general discussion is part of chapter 11. Finally, a conclusion summarises the report (chapter 12).

4.2 Approach

This subchapter describes the approach taken within WP3 Driver Nudge. First, details on the relevance for prompting drivers to reduce their speed and for guiding them along a preferred trajectory are given and the approach is stated. The chapter is completed by giving details on using light as an intervention and the location selection process in preparation for the field test in WP5.

4.2.1 Prompt Drivers to Reduce Their Speed

Over 60 % of all accidents occur on inter-urban roads, as the Annual Accident Report of 2017 by the European Commission (2017) reveals. This number includes a large amount of single-vehicle accidents caused by drivers losing control of the vehicle. Speeding is, according to the OECD (2006), the main issue in road safety, as both excessive and inappropriate speed is often used. Karlsson et al. (2017) reinforce this by stating that drivers unintentionally adapt to an unsafe speed due to unfavourable temporary or given circumstances at a certain location, such as unpredictable road layouts, traffic congestions, the effects of low situational awareness (Jones & Endsley, 2004) and further. According to Aarts and Van Schagen (2006), speed and accident severity correlate positively. The higher the speed, the less time there is for the driver to react to unforeseen events. The following reaction is likely either too late or an overcorrection.

In order to support as much drivers as possible towards safe driving behaviour on a certain location, appropriate cues are needed. By addressing speeding drivers through a nudging system in the infrastructure, not just the behaviour of those traffic participants who are driving cars with the newest technological advances can be influenced, but measures are at the disposal of every single driver passing a risky road section (see Köhler et al., 2019).

A safe speed for the majority of drivers is predetermined by the speed limit on the roadside. The margin of safety takes into account the difference between actual and required friction on the road including tangential and radial friction (Pratt, Geedipally, & Pike, 2015). Speed limits on Inter-urban two-lane roads (single carriageways) in the EU vary between 80km/h and 100km/h in most countries. Within the infra driver nudge, nudging drivers towards adopting a safe speed is oriented towards these predetermined speed limits and focuses on deriving and validating interventions for nudging drivers who are usually unintentionally speeding or who are unaware that a dangerous location for which they are driving too fast is coming up, towards adopting a safer speed before such a dangerous situation can become imminent.

We have developed and demonstrated an infrastructure-based measure that increases a road user's proclivity to adopt a safer speed for a particular road segment. As will be explained throughout this deliverable, we have tested these measures by means of a motorway exit with speed limits between 100 km/h and 50 km/h. However, we are confident that the transition to other situations is feasible. Compared to vehicles, individual elements of roadside infrastructure lack the sensors to continuously observe individual user behaviour. However, elements of infrastructure tend to be connected in a network, and we used the input from a network of roadside sensors feeding into a decision control logic system developed to principled triggering conditions that will decide whether to deploy nudging interventions. We explored the potential of using adaptive, emissive road markings/displays in combination with roadside sensors and we have prototyped an infrastructure-based ADAS. The nudging system was tested in simulations for a specified traffic situation and will be tested in the field at this certain location. However, this is a means to develop a suitable nudging intervention that can later be adapted to more situations that are facing similar problems, with a much smaller testing and calibration effort.

4.2.2 Guide Drivers Along a Preferred Trajectory

In order to describe the best approach to guide drivers along a preferred trajectory, relevant information regarding trajectory is elucidated first. The trajectory of a vehicle is best described with the help of a local system of coordinates. This simplifies the analysis of the vehicle movements relative to the street. The x-coordinates describe the position with respect to the street axis. The y-coordinates describe the position crossways to the street axis. In the following, the coordinate origin of the y-axis is always located at the right edge of the road. Hence, the y-coordinates are always positive. *B* labels the width of a lane and the middle of the vehicle serves as our point of reference. In order to examine the driving dynamics, the routing of the road including curve radii, as well as the cross slope and longitudinal gradients have to be known.

Once a vehicle enters a curve, radial forces occur. Friction forces between the tyres and the street compensate these. The radial friction demand is described with the following equation with:

$$f_{R,Dem.} = \frac{v^2}{g * r} - s_x$$

v: velocity, g: gravity, r: curve radius, s_x: cross slope (Pratt et al., 2015)

During the braking and accelerating phases, friction forces are transferred in tangential direction. The friction coefficient is divided into tangential and radial friction, as shown in the circle of forces (see figure 4.1). Hence, it is safer to decelerate before the curve and drive with constant speed during the curve. In order to enable a sudden deceleration during the curve, parts of the obtainable radial friction should stay unused.

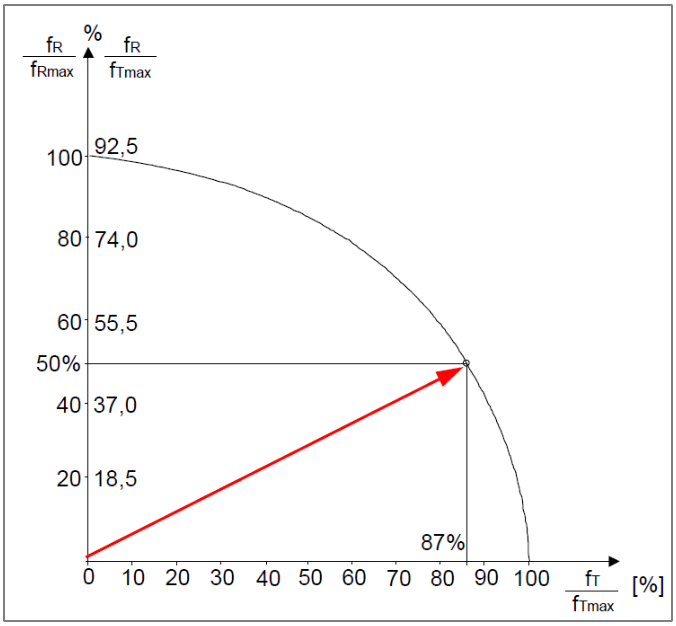


Figure 4.1: Circle of forces

The margin of safety describes the difference between the actual and the required friction coefficient including both tangential and radial friction (Pratt et al., 2015). This is necessary as the human driver is not able to assess the friction coefficient, the curve radius and the cross slope accurately. The driver can increase the margin of safety by decreasing their velocity or increasing the driven radius.

With the help of straight lines, circular arcs, and transition curve elements, roads are routed with a continuous curvature and hence a continuous lateral acceleration. It is advisable to always stay in the centre of the road (y = B/2), where W is the width of the road. According to Spacek (1999) when observing driver behaviour, there are two striking types of deviations from the ideal trajectory (see figure 4.2). The first one mostly occurs when 'sporty' drivers cut a corner. They increase the curve radius (y < W/2 in a right-hand bend, y > W/2 before and after the bend, conversely in a left-hand bend) in order to attain higher velocities by even lateral acceleration. The second deviation occurs mostly for distracted or unexperienced drivers. They assess the curve radius incorrectly or perceive the curve too late. This forces them to corrective manoeuvres (y > W/2 in a right-hand bend, conversely in a left-hand bend) with the result that for a fraction of time the driven curve radius is smaller than the curve radius of the street resulting in a great lateral acceleration.

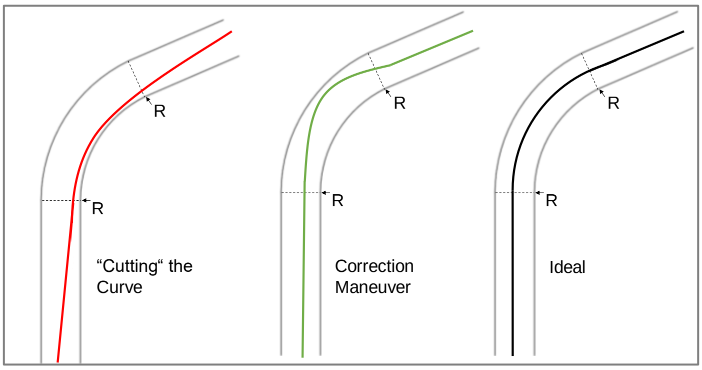


Figure 4.2: Types of trajectories in a curve (adapted from Spacek, 1999)

Velocity is the biggest influence on the required friction. In the equation for the required friction, in contrary to the curve radius, the velocity is squared. This outlines the overestimation of the benefit of 'cutting a curve'. In addition, corrective manoeuvres are less dangerous with smaller velocities. Hence, nudging measures aiming at reducing speeds consequently have a positive impact on the safety of a trajectory.

In longer curves the classification into the different types of trajectories (see figure 4.2) is not that simple, as multiple deviations from the ideal trajectory appear throughout the curve. Additionally, a large deviation from the middle of the road can become unsafe at speeds that would be regarded safe if driven on the ideal trajectory. Hence, nudging measures solely aiming at reducing velocities are not effective for every unsafe trajectory.

Within the infra driver nudge, we took a hierarchical approach and targeted driving at an inappropriate speed first. Based on the explanations in this chapter, we conclude that many risky situations that are caused by driving at an unsafe trajectory can already be solved by reducing the driver's speed. However, we researched for ways to additionally direct drivers towards adopting a different trajectory. This hierarchical approach is shown in table 4.1.

Case	Questions for decision making		What needs to be nudged?
	Driving higher than target speed?	Driving unsafe trajectory?	
1	yes	yes	Prioritize speed
2	yes	no	Only speed
3	no	yes	Only trajectory
4	no	no	No nudging needed

Table 4.1: Hierarchical approach for decision making regarding nudging drivers either towards adopting a safer speed, a safer trajectory or whether no nudging is needed

In this hierarchical approach, case 1 prioritises speed. One could assume that both speed and trajectory should be nudged here. However, we assume that nudging drivers towards two target behaviours at once results in workload that is too high, as humans can process only a certain amount of information due to the bottleneck of information processing (Broadbent, 1985), among other aspects. These are explained in more detail in chapter 8.1. A nudging measure should be easy to comprehend and work in the situation itself (see Karlsson et al., 2017). Based on this, we target nudging drivers towards a safe speed as a priority, before taking distinct measures to nudge drivers towards adopting a safe trajectory into account.

4.2.3 Using Light as an Intervention

Light has been chosen to for this intervention for multiple reasons. First, it provides a visual feedback which is beneficial, as almost 90 % of our information input for driving performance is visual (Hills, 1980). In addition lights lights have the potential to be turned on and off which makes goal-directed nudging of specific drivers possible, turning it into an intelligent intervention and averting a habitation effect.

Traditional lighting in the road environment is installed to increase visibility of the road environment and thereby traffic safety during the dark or to serve as a communication tool.

Day-to-night accidents ratios show that more accidents occur during the night despite the fact that less people drive at night, and that this ratio declines by the intervention of artificial light shows improvement of traffic safety (Bullough, Donnell, & Rea, 2013; Wanvik, 2009). This can be explained by the fact that 90 % of the information that is perceived by road users is visual (Hills, 1980). Darkness reduces the amount of information that can be perceived and the distance from which objects can be detected. Therefore it is generally acknowledged that road lighting increases traffic safety (Bullough et al., 2013; Elvik, 1995).

As for communication, one of the most familiar construct is the colour pattern of a traffic light with the meaning of the red –stop–, yellow –cautions/change– and green –go– light. Since 1928, these colours and their meaning have remained the same ever since the associations with a traffic light have become robust rules (Lidwell, Holden & Butler, 2010) which induce automatic behaviour in traffic (red – stop; Ranney, 1994). Besides light in the infrastructure, light cues are also used for communication between road users. Think about the blinking light to indicate a lane change or turn, or the breaking lights on the back of the car. Also the blue flashing lights of emergency services are a familiar construct and flashing amber coloured light are generally present at road works or special transport.

The introduction of **LED light** has broadened and extended the opportunities for light applications and thus amplified the opportunities for the use of lighting in traffic situations. LED lights come in different intensities, colour temperatures and different colour hues which broadens the light design possibilities. Additionally, LED has low energy consumption, an increased life expectancy compared to other type of light sources, and they are recyclable. Properties that have caused a massive increase in the amount of light used (Fouquet & Pearson, 2011), but also transformed the lighting industry from a hardware into a full solution and service industry (den Ouden,Valkenburg, & Aarts, 2014).

The new possibilities of different intensities, colour temperature, colour hue and dynamic lighting should however be carefully implemented. For example, it is very important to consider the Helmholtz-Kohlrausch effect (Nayatani, 1997), if increased visibility is a desired goal. This effect describes the perceived increase of brightness by an increase of saturation. In case of light this means that coloured light is perceived brighter compared to white light with the same luminance level (Wood, 2012). And this results in overestimation of the range of visibility by road users under coloured light conditions, especially for the colour blue. So while coloured light can be used for communication or priming effects, it is not the best choice to increase visibility during dark hours. This needs to be taken into account when developing our nudging interventions.

4.2.4 Location Selection

4.2.4.1 Short list

From the start of the project (May 2, 2017) Heijmans and RWTH Aachen started the search for a suitable location that could be used for the field test in WP5. The geometry of the road and the context at this location also served as input for the simulator and simulation study. Heijmans proposed a location in Eindhoven, The Netherlands, due to the following reasons:

The location must be in the Netherlands for Heijmans to be able to manage the project and install the system. This is helpful because of an agreement with the road owner, the needed knowledge of local (building) regulations, and the availability of employees to do the installation which can be provided by Heijmans in the Netherlands. Heijmans and Signify (formerly Philips Lighting) are working together in the project 'Jouw licht op 040' (www.jouwlichtop040.nl). In this project Heijmans and Signify maintain public lighting in several areas in the city and upgrade public lighting with new light innovations. Due to the nature of this project, it was expected the city of Eindhoven would be cooperative for this research. Furthermore, Eindhoven is within reasonable distance from Aachen for ISAC and ika to visit the location for research.

For the short list of possible locations, several requirements were used: The location should preferably be a traffic situation that can be improved in terms of safety, i.e. an unclear situation, with accidents or near accidents in the past. Speed and trajectory were to be part of the cause of unsafe situations at the location. The location should preferably have a curve for being able to nudge drivers into following a preferred trajectory. Further, it should preferably have a single lane to reduce confounding variables in the analysis and should provide the possibility to install infrastructure measures and to monitor traffic.

This resulted in the four possible locations within the city of Eindhoven which were discussed in a meeting (August 30, 2017). During this meeting, several experts were involved. From the city of Eindhoven a consultant on traffic, the asset manager for roads, the project manager for light and innovation, and the police participated. From Heijmans, a nudge expert and the project manager for the MeBeSafe project were present, along with the innovation manager for Jouw Licht op 040. Figure 4.3 illustrates the options.

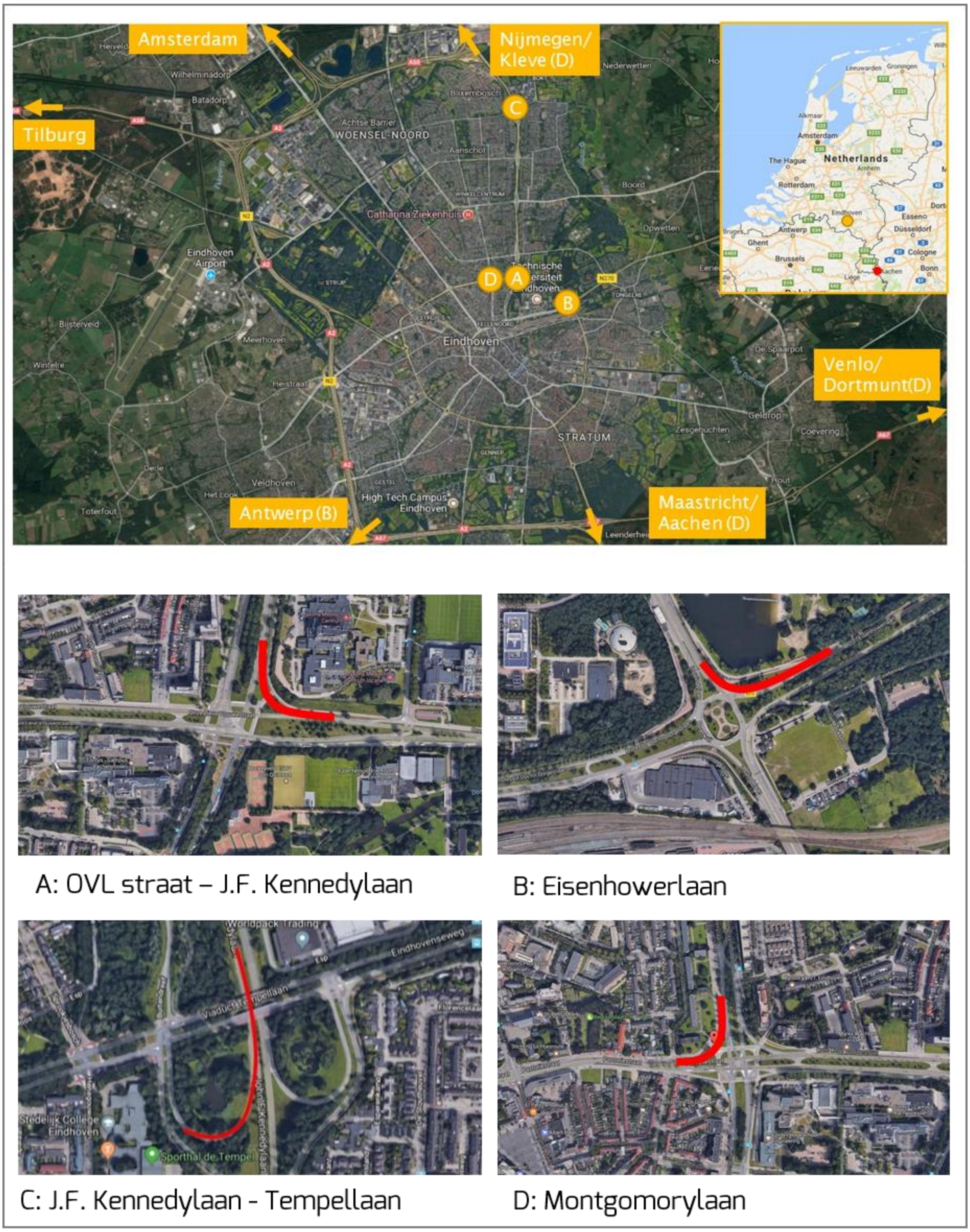


Figure 4.3: Short list of possible testing locations in Eindhoven

In order to find the best suitable test location, the four curves were evaluated on the following aspects: the possibility to improve traffic safety, traffic complexity, the circumstances for installation and maintenance and the accessibility and potential impact (table 4.2).

	A	B	C	D
Possibility to improve traffic safety with a nudge	*Poor*	*Good*	*Good*	*Poor*
Traffic complexity	*High*	*Low*	*Low*	*High*
Circumstances for installation and maintenance	*Poor*	*Ok*	*Good*	*Poor*
Accessibility an potential impact	*Ok*	*Good*	*Good*	*Good*

Table 4.2: Evaluation of four possible test locations in Eindhoven

4.2.4.2 Test location: Exit J.F. Kennedylaan – Tempellaan, Eindhoven

Based on the evaluation of the four locations the exit J.F. Kennedylaan – Tempellaan (location C) was selected by the research team as the best location for validation of the infrastructure driver nudge. This exit J.F. Kennedylaan – Tempellaan has a history of single car accidents. For a safe passing of the curve, a change of speed is required, from 100 km/h continuously slowing down to 50 km/h. The curve is tight and tightening further in progress, causing drivers to use unsafe trajectories. Additionally, there are poor visual conditions at the end of the curve, where a signal controlled intersection is located. The intervention therefore aims to help improving traffic safety.

The set-up requires a low traffic complexity in order to reduce confounding factors. As the exit has only one lane, a more robust validation of the results found in the simulation test is possible. To ensure this further, a single vehicle approach is used, with a minimum gap between two vehicles in order for one of them to be nudged.

The circumstances for the installation and maintenance of the lights should be set in a way that allows a safe work environment. For the installation to work, the asphalt has to be in reasonable condition and there must be space for cables and a relatively easy connection for power supply. The less disruption of the traffic situation in the city is caused during installation, measurements or maintenance, the better. The selected location fulfils all these criteria.

The location marks the entrance of the city of Eindhoven, it is visible for all vehicles entering the city via the J.F.Kennedylaan (A2 – North, A50). The potential impact is therefore high, as a large number of vehicles per day or week are to be expected. The recruitment for the driver feedback also gets easier, as the exit is the main entry for the surrounding suburbs. Furthermore, the curve resembles other highway/motorway exits, thus there is the potential for repeated installation of the driver nudge system which enhances the potential impact.

4.2.4.3 Agreement with City of Eindhoven

After the final selection it was necessary to have a formal approval from the city to implement the instrumentation in the road and to be able to conduct the research at the location. On February 6, 2018 the College van Burgemeester en Wethouders (Mayor and City Council Members) approved the location as a living lab for MeBeSafe under the condition that a maintenance agreement with Heijmans was to be set up. This agreement was to include responsibilities of applying and removing the marking, the minimum maintenance status of the road marking and the response and repair time in event of defects. The data to be collected was to be made available as open data, in line with the Eindhoven Smart Society Data Charter. Lastly, the evaluation of the field test has to be included in the evaluation of the innovations in the context of "Jouw Licht op 040".

The maintenance agreement was signed on January 23, 2019. The main points of this agreement include several aspects about the maintenance of the road and the handling of the data. Firstly, it determines the inspection of the current condition of the location by Eindhoven and Heijmans, as the road is to be restored to this state after the test. Hejimans is responsible for installation, maintenance and removal of the system which has to take place until December 2020. This is in line with the Grant Agreement of MeBeSafe. In the case of a direct dangerous situation, the city Eindhoven is able to stop the test. The collected data has to be made available as open data after the publication of the results by RWTH Aachen University and their explicit permission.

4.2.4.4 Location Circumstances & Baseline Measurement

In order to attain first insights regarding the driver behaviour at the chosen test location, ISAC installed four radar detectors along the exit in Eindhoven in January 2018. Three of these detect vehicles on the exit lane (see figure 4.4) while the fourth (not in figure) measured traffic passing on the continuous main lanes. With the help of these detectors, velocities and lengths of the passing vehicles were recorded. Additionally, two cameras were installed in the curve. The cameras did not automatically detect vehicle positions, but allowed for a closer examination of driver behaviour that is unusual according to the radar data.

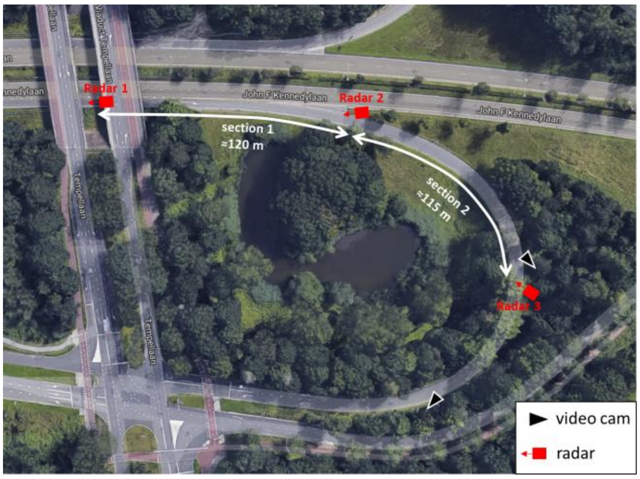


Figure 4.4: Set-up of the baseline measurement

The data was collected for three days. The average daily traffic volume adds up to 30,000 vehicles/day on the main lanes and 4,700 vehicles/day on the exit lane. Heavy goods vehicles (HGV) account for about 2 % of the traffic under the assumption that every vehicle longer than 10m is regarded as a HGV. This ratio is characteristic for a road with predominantly urban traffic.

Afterwards, the distribution of velocities on the exit lane was determined (see figure 4.5 and table 4.3). As expected, the average velocities slightly surpass the according speed limit of 70km/h before the beginning of the curve and 50 km/h in the curve. Before the beginning of the curve, velocities scatter further than the velocities in the curve which suggests a large number of relatively fast vehicles that decelerate abruptly before the curve. The minor differences between radar 2 and 3 outline that most vehicles decelerate before the beginning of the curve and maintain speed during the curve. However, the amount of outliers (vehicles faster than $\mu + 2\sigma$) is higher on radar 2 than on radar 3. This indicates that some drivers estimate the curve radius too high. These drivers approach the curve too fast and thus have to decelerate in the curve. For these drivers, Nudging measures seem most reasonable.

	Radar 1	Radar 2	Radar 3
Mean speed (μ)	82 km/h	57 km/h	56 km/h
Standard deviation (σ)	12 km/h	7 km/h	7 km/h
Percentage of vehicles faster than $\mu + 2\sigma$	2.6 %	3.0 %	1.5 %

Table 4.3: Results of the baseline measurement

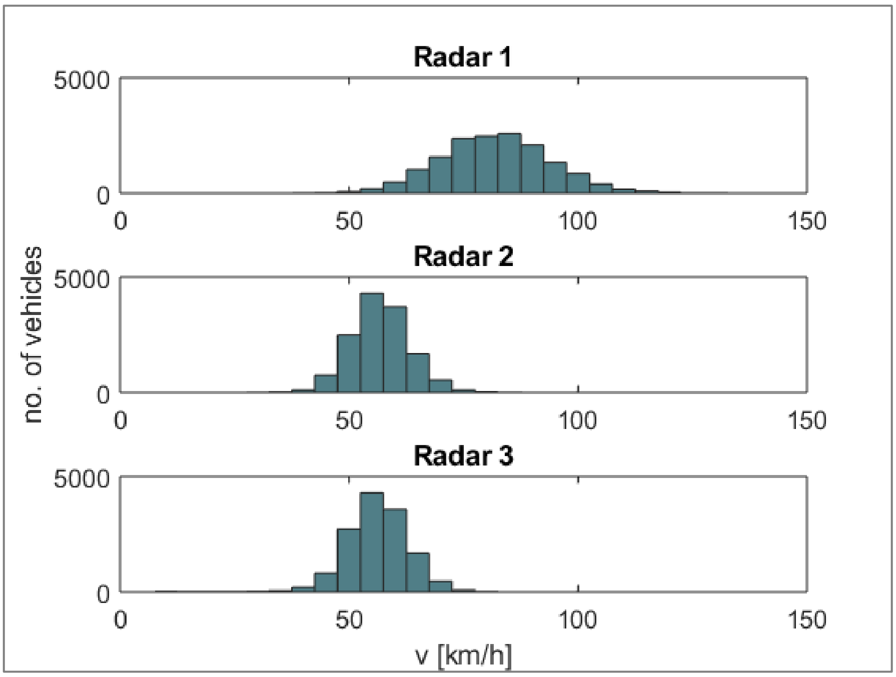


Figure 4.5: Speed distribution at the three cross sections

Figure 4.6 shows the velocities of the vehicles over time. It becomes apparent that the velocities at night other than expected are not significantly higher than they are in the daytime. Additionally, the outliers are predominantly during the day. Regarding the data of radar 2 and 3, one can see the forming of a congestion at the junction at one evening during rush hour (January 9th, 18:00).

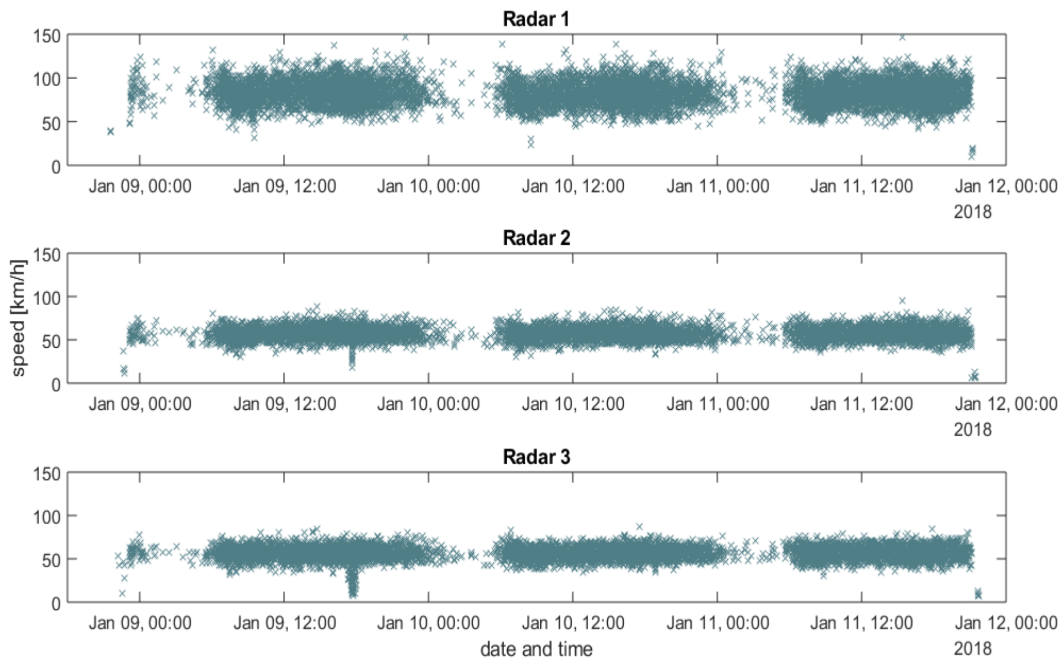


Figure 4.6: Distribution of speeds during day and night-time

The radar detectors only capture velocities in a given cross section. Hence, the velocity progressions between the detectors cannot be determined. Further, the accelerations of the vehicles are unknown. Thus, it is problematic to track a vehicle throughout the whole curve. Consequently, it is hard to determine whether those vehicles that are particularly fast at the first cross section are the same as those that are fastest at the second cross section. Only if the time gap between two vehicles is high enough, the measurements of the separate detectors can be assigned to one vehicle. In this way the velocity of approximately 75 % of vehicles along the curve can be estimated by fitting a continuous Bezier-curve between the detected velocities (see *Figure 4.7*). The methodology is described in further detail in Fazekas and Oeser (2019). However, this estimated velocity progression is rather inaccurate, as the velocity is detected with a resolution of only 1 km/h and the point of time of the vehicle passing the detector with a resolution of only 1 second.

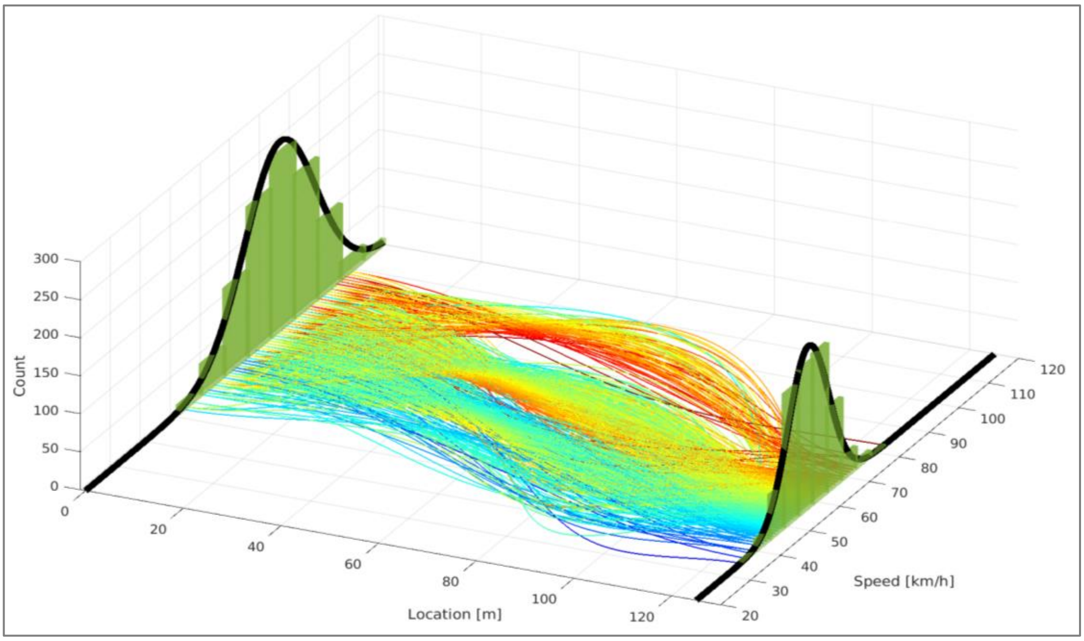


Figure 4.7: Reconstruction of trajectories between two cross sections

The results of the baseline measurement in Eindhoven outline the overall qualification of the location for a field test. In average, the velocities are higher than the speed restrictions and the amount of vehicles driving too fast is both before and in the beginning of the curve rather high.

5 State of the Art

This subchapter describes the state of the art regarding the application of infrastructure nudging, light technology, camera detection and design guidelines at the start of the research and development project.

5.1 Infrastructure Nudges for Drivers

As described in the integrated framework (Karlsson et al., 2017) and in Koehler et al. (2019), nudging in the original approach functions on a subliminal level, relating to the subconscious stimulation of humans and making them elect the desired choice without prohibiting any alternatives. According to Thaler & Sunstein (2008), people's behaviour can be influenced and determined by activating subconscious processes of human decision-making by modifying the cues that influence behaviour. An example for this is the arrangement of food in supermarkets. Hanks et al. (2012) organised the line in such a way that healthy foods, for example vegetables and salads, were laid out at the start of line and less healthy food was found at the end. The sales of the healthier food increased by 18 % and the consumption of less healthy food decreased by nearly 28 % when measured in grams.

Karlsson et al. (2017) referred to a broader understanding of nudging. According to them, nudging is not only a mere subconscious process, but can also consciously influence the choice of an action. A distinction can be made between system 1- and system 2-nudges, also described as mindless and mindful nudges (Sunstein, 2016; Hansen & Jespersen, 2013; House et al., 2013). Thaler & Sunstein's (2008) original definition relates to system 1-nudges and mainly refers to biases influencing automatic, subconscious processes. Systematic biases and decisions determine people´s choices so that a completely rational decision is impossible (Thaler & Sunstein, 2008; Kahnemann, 2011). System 1 and system 2 are independent from each other in regard of controlling behaviour and work in parallel. System 1 is defined as actions with little requirements for mental efforts, meaning actions that are automatic and intuitive, as well as quick and impulsive. System 2 requires mental capacity, as it concerns attention and control (Kahnemann, 2011). Usually, behavioural intervention strategies aim at the reflective decision-making processes of system 2. However, driving behaviour is often a collection of habitual processes (Ranney, 1994) and targeting system 2-processes alone seems to leave out those drivers who are unaware of unsafe traffic behaviour. Both approaches are relevant for nudging drivers towards safer traffic behaviour, according to Karlsson et al. (2017).

Most of already existing interventions tap into constructs on a conscious level, asking for a deliberate thought to change our behaviour. As unintended violations are usually made on a sub-conscious level, we also need interventions that tab into these cognitive abilities within MeBeSafe. This is in line with the theory of habitual behaviour by Verplanken and Wood (2006): As habits are dependent on environmental cues, introduction of interventions in the direct physical context intends to change the environmental cues and is likely to change habitual behaviour. A way to do this is by stimulating people to make a desired choice, yet preserving their freedom of action, is "nudging", a concept from behavioural economics. In MeBeSafe, the concept is adapted to the traffic context by reaching solutions to nudge traffic participants towards a safer traffic behaviour, implemented in the infrastructure within WP3.

In certain situations, drivers may not be aware of the fact that they drive at an inappropriate speed or are following an inappropriate trajectory (Karlsson et al., 2017). And when they do, it might be too late and an accident is the ultimate feedback that something went wrong. This behaviour can be the cause for dangerous situations or even accidents. Preventing these situations can increase safety margins, leading to increased accident avoidance and mitigation.

Speeding is a widely spread problematic behaviour among drivers (OECD, 2006). Slowing drivers down to a reasonable speed in a safe way is addressed with infrastructure interventions that are only activated if a vehicle does exceed the safe speed for a certain location. In order to support as much drivers as possible towards safer driving behaviour on a certain location, appropriate cues are needed. By addressing speeding drivers through a nudging system in the infrastructure, not just the behaviour of those traffic participants who are driving cars with the newest technological advances can be influenced, but measures are at the disposal of every single driver passing a risky road section.

5.1.1 Nudges and Alternate Infrastructure Interventions in Literature

As found in the integrated framework (Karlsson et al., 2017), it can be summarised that there are not many nudging interventions aiming to influence traffic safety that have been systematically tested on a large scale (Avineri, 2014). Nevertheless, the state of the art of nudges related to either influencing driving behaviour through the infrastructure, or speed and trajectory via different means are to be stated in the following.

Even though this is an in-vehicle system, the following publication researched a speed reduction system: Lai and Carsten (2012) investigated the effects of an in-vehicle Intelligent Speed Adaptation (ISA) system that was enabled by default und could be overridden by the driver through pressing a button. They found that if the system was switched on by default, it led to a reduction of excessive speeding and speed variation. However their research also shows that in situations where the system's use is, perhaps, the most useable, the driver tend to switch off the system. This is again in favour of infrastructure nudging systems which cannot be switched off by the driver, but rather ignored if the driver actively chooses to. Nevertheless, the presence of such a system can still serve as a reminder. This approach is discussed further in objective O3 of MeBeSafe, targeted in WP2/4.

Priming nudges are a very common practice in road design, although they are often not described as such. Examples are gateways, sightlines, or coloured or textured road surfaces to affect perceived speed and safety (Avineri and Goodwin, 2010). Thaler and Sunstein (2008) describe the Chicago street experiment, where the priming through optical speed bars (i. e. transverse lines on the driving lane that are painted closer to one another the closer the driver is progressing to the dangerous spot) was examined. The idea was that those lines create an optical illusion and should therefore influence the perceived speed of the driver. The result was a decrease of 36 % of crashes in a six month period compared to the same period the year before. Figure 5.1 shows the optical speed bars applied in the experiment. This approach is targeted in the infra cyclist nudge as described in D3.1. Within the infra driver nudge, a dynamic approach is taken by nudging only those drivers that show an inappropriate behaviour and only activating the system if needed. This example resembles a static nudging intervention.

Figure 5.1: Optical speed bars of Chicago Street Experiment (Thaler & Sunstein, 2008)

Mierlo (2017) conducted a study to test if driving behaviour was influenced by light via light emitting road markings. A five condition between-subject experiment was conducted with speed as the dependent variable with a baseline test and four different light plans. The light plans were constructed based on a literature study about road lighting, speed perception and familiarity in the road environment (Mierlo, 2017). Test conditions were defined as white static light (1), white dynamic light (2), amber coloured static light (3), and amber coloured dynamic light (4). The light conditions were compared to a baseline. Both quantitative (traffic data) and qualitative (online survey) measurements were conducted.

A difference was found in driving speed due to the activation of lights in the road marking and due to the differences in the light plans. Within test condition 1 (white static light), speed increased; an effect that can be attributed to a higher visibility on the course of the road. If the visibility of the course of the road increases, it can facilitate faster driving speed because it is easier to anticipate on the road which in this case was almost straight.

Mierlo (2017) recommended that in order to utilize the full potential of smart lighting technology in road marking, it is considered necessary to create well designed light plans which are accustomed to the road environment and the traffic situation in which they are placed. When light plans are constructed, the light settings, colour hue, colour temperature, and intensity are found to be very important and should be specified in detail. Light intensity should not be too high as it can cause glare and causes a discomfort which leads to a negative attitude towards the technology. The interventions developed within MeBeSafe test the findings of this study in more detail.

In the following paragraphs, only the results of studies are described that examine the influence of traffic calming measures on an optional and situational change of the habitual traffic behaviour. Measures that force the driver to adapt its traffic behaviour like speed restriction signs or speed humps are not included. Nevertheless those can also have a significant impact on the driver's traffic behaviour (Turner et al., 2017). The Road Safety Research Report by the Britain Department for Transport states that people rather prefer systems that warn the driver when the driving speed is too high compared to systems that limit their vehicle speed (Musselwhite, Avineri, Fulcher & Susilo, 2010). Similar to that, Jamson, Lai, Jamson, Horrobin and Carsten (2008) showed that advisory speed limits in rural bends have a positive impact on speeding. These findings are also taken into account within the infra driver nudge.

There are different studies examining the impact of the roadside environment on speeding. Edquist, Rudin-Brown and Lenné (2009) describe that multiple objects next to the road can increase the peripheral visual view and therefore raise the perceived speed. This raised perceived speed leads to a decrease of the actual speed. The same relation between perceived and actual speed influenced by a more complex environment is also mentioned by Jamson et al. (2008). A more complex environment can be realised with the placing of trees with decreasing distances between them or planted on a 'lazy diagonal' getting narrower towards the hazardous situation resulting in a mean speed reduce of 1.5 % (King & Chapman, 2010, described in Avineri, 2014). Congruently, a survey of speeding attitudes and behaviours by the US National Highway Traffic Safety Administration (Schroeder, Kostyniuk, & Mack, 2013) showed that drivers are more receptive to countermeasures for speeding if the non-compliance is without penalty.

Other studies have researched the effect of transversal and longitudinal lane markings. A result of a simulator experiment by Jamson et al. (2008) was that hatching, especially peripheral or coloured was effective in lowering speed. Consistently, Gates, Qin and Noyce (2008) revealed that transverse-bar pavement marking with continuously decreasing spacing lead to a reduction of 1 to 4 mph of mean speed, similar to the Chicago street experiment described by Thaler and Sunstein (2008) as stated earlier in this chapter. Another study by Manser and Hancock (2007) using a static simulator showed that strips on a tunnel wall are an effective measure for influencing driving speed. The effectiveness of those measures using distinct patterns on the ground or on the wall can be explained with the concept of optic flow (Gibson, 1950). The principle of optic flow includes that human beings perceive their own speed relative to the speed of the environment, saying that the faster objects pass by, the faster is the perceived personal speed. By placing strips on a tunnel on a tunnel wall that gradually decrease in width, human speed perception is tricked because the strips are perceived to pass by gradually faster, inducing the feeling of acceleration (Manser & Hancock, 2007).

Regarding colour effects, Burney (1977) and Jarvis (1989) found that yellow, a warning colour, road marking patterns can have a speed reducing effect. The treatment was most effective for shoulder and middle lanes. The colour red functions as a warning signal as well, because of humans being conditioned to respond to red lights with caution (Donald, 1988; Edworthy & Adams, 1996). Davidse, van Dreil and Goldenbeld (2004) found that adding edge lines or centre lines to roads that previously were without any markings leads to a driver's speed raise and a shift of the lateral position towards the edge of the road. The raised speed in this finding is in line with the findings of Mierlo (2017) as described earlier in this chapter, who found higher speeds when drivers were able to see the road layout better in the dark, thus felt safer, and showed higher speeds.

Another effective measure was the installation of vehicle-activated signs (Jamson et al., 2008). Vehicle-activated signs only show an advisory message like ‚slow down' if the vehicle is speeding. Another result of Jamson et al.'s (2008) simulator experiment was that all of the described treatments were sustainable and effective over time. According to the Karlsson et al. (2017), this can be either a mindful nudge or a so-called hug (French, 2011). The effect of special signs was also researched by Arnold and Lantz (2007) who found that a flashing LED stop sign decreased speeding significantly by 1 to 3 mph. Red LED lights were installed at each corner of the stop sign. It has to be mentioned that lighting has only a speed reducing effect when the installation of lights is not expected like in the experiment described above. On the contrary, the mere installation of street lighting leads to an increased average speed and decreased concentration level (Jørgensen & Pedersen, 2002). Still, it is also linked to a decreased accident rate. This is in line with other findings described in this chapter. When developing infrastructure interventions within MeBeSafe, the findings described in this chapter need to be taken into account.

5.1.2 Existing Nudging Interventions in the Traffic Environment

A variety of nudging interventions already exists in today's traffic environment. Table 5.1 gives an overview over these measures.

Example	*Type of nudge as defined in the integrated framework (D1.1, Karlsson et al. (2017))*
Rumble strips – Haptic feedback for lane keeping	*Activates behavioural standards (system 1+2)*
Rough Pavement – Haptic feedback to avoid high speeds	*Other imposed nudge (system 1)*
Curves in road design – blocked view to maintain concentration and alertness	*Other imposed nudge (system 1)*
Road marking (centre and edge lines) – for guidance, lane keeping, speed perception	*Other imposed nudge (system 1)*
Shared space – determines a different social norm and forces interaction between road users.	*Other imposed nudge (system 1)*
Special signing – using associations with children to reduce speed.	*Mindless nudge (system 1 + 2)*
Speed feedback – a reminder of desired behaviour	*Mindful nudge (system 2)*
Dynamic speed sign for a green wave – improve traffic flow and to create homogenous speeds	*Mindful nudge (system 2)*
Countdown at traffic light – to reduce perceived waiting time to avoid red light negation	*Mindless nudge (system1)*
Variable route information/message signs – communication of travel times for traffic management	*Mindful nudge (system 2)*
Transverse roadmarking, trees & repeated vertical objects in the road side – to increase speed perception	*Other imposed nudge (system 1)*
Chevron road markings – to maintain a safe vehicle distance	*Mindless nudge (system 1)*

Table 5.1: Examples of existing nudges in the road environment linked to the classification of nudges in WP1

Within MeBeSafe, we adapt nudging in the infrastructure to a dynamic measure that will only be activated if drivers show the need for it. For details of the dynamic decision control logic, please see deliverable D3.3.

5.2 Light Systems

A number of light systems were taken into account for the infra driver nudge. Lights have the potential to be actively turned on and off if needed which meets the dynamic approach within the infra driver nudge of lights being able to be turned on demand, more specifically if the camera system as described in D3.3 detects a driver who should be nudged. This chapter outlines the options.

Overhead lighting is used to increase visibility of the course road, other users and objects on the road in the dark. Dynamic roadlighting is able to change colour temperature (warm – cold white light) and intensity (off – bright). Occasionally red or green light is used for overhead lightning (*Figure 5.2*) to reduce light pollution for flora and fauna, while maintaining the visibility as high as possible. As previously explained, the Helmholtz-Kohlrausch effect (Nayatani, 1997) describes the perceived increase of brightness by an increase of saturation, and this effect is smallest for red and green colour hues.

Figure 5.2: Example for overhead lightning

Roadstuds are single coloured - LED lights implemented in the road pavement (*Figure 5.3*). The light signal is therefore easily perceived, as it falls in the direct visual field of drivers. Roadstuds are used for guidance along the course of a road or to increase alertness. They are visible during day and night and therefore suitable for communication or signalling a message.

Figure 5.3: Example for roadstuds

SenSight is a light product developed by Heijmans. It is a dynamic system with lines of light embedded in the road marking (see figure 5.4). With SenSight, it is possible to change light colour and create simple dynamic patterns but is not clearly visible under bright daylight conditions. The system provides guidance to the driver by increasing visibility of the course of the road. The technology has been observed to be able to change a driver's perceived speed, based on the light colour and movement (see chapter 5.1.1, Mierlo, 2017).

Figure 5.4: Example for SenSight

The **light barrier** is a guard-rail / crash barrier that illuminates diffuse light (*Figure 5.5*). It is designed to guide traffic along the course of the road during the dark at night or low light levels during dusk, dawn, mist or heavy rain.

Figure 5.5: Example for light barrier

The intended light nudge should be visible during day and night-time and have the flexibility to accommodate different light scenarios. Therefore it was decided to develop a new light source based on existing technologies by combining a road stud, which is visible day and night, and SenSight, which can change colour and add the possibility to control each road stud individual. This type of road stud is used in the simulator and developed for the field test. More about this development is described in deliverable 3.3.

5.3 Detection

Traffic data detection changed in the last century in an essential way. The most common way for collection of traffic data was done manually in the past. New technologies enable a better detection of traffic data. Especially optical detection systems improved the analysis of traffic data.

Traffic data detection systems can be classified into manual and automated systems. Furthermore, a separation of traffic data systems can be done in online and offline detection. Offline detection restores historical data in storage devices. The analysis of data is done afterwards, however an online/real time traffic data detection systems allow to analyse traffic data at the same time/ real time. Traffic data detection systems are used statically or temporary (position). The choice of the detection system is based on the goals of the data detection, available resources, coverage feasibility and amount of data. In the following list you will find different traffic data detection systems, which allows to collect traffic data like volume, speed, vehicle classification, time headway etc.:

Traffic data detection with sensors:

- Inductive loops
- Magnetic sensors
- Photoelectric sensor
- Infrared sensors
- Ultrasonic sensors
- Radar devices
- Laser-Speed sensor
- Combinations of sensors
- Bluetooth sensor

Traffic data detection with optical system:

- Video camera
- Thermal camera

Traffic data detection with communication and navigation systems

- Global positioning system (GPS)
- Mobile Phone Data (GSM)
- Floating Car Data (FCD)
- Floating Phone Data (FPD)

In the MeBeSafe project and especially in WP3 Driver Nudge, optical systems are used for data acquisition (also, radar sensors are used to collect traffic volumes, speed and vehicle classification). Optical systems work with virtual zones (detections zones). If this zone is entered by a vehicle, it will be detected and can be tracked. The setup of the zones can be managed flexibly. The use of optical systems requires the guarantee of the privacy. The development of video systems allows getting high quality images. Usually, number plates, face profile, or other details can be perceived easily. Regarding data privacy, this is not preferable or demands action to protect these data (lower quality of images, data encryption). Thermal camera system fulfil the legal data privacy requirements and they provide all necessary data. One of the most important functionality is that the collecting of data under different lighting conditions is possible. The detection is described in detail in D3.3.

5.4 Design Guidelines

5.4.1 Integrated Framework

The integrated framework (D1.1) developed within MeBeSafe has formulated a number of design guidelines for deriving nudging measures. These were applied in WP3 based on the design considerations stated in chapter 7.1 of the integrated framework by Karlsson et al. (2017) for objective 6 and chapter 7.3 for objective 7.

5.4.2 Road Design Guidelines

As the field test for measures developed within WP3 Driver Nudge will take place in Eindhoven, the Netherlands, Dutch road design guidelines need to be taken into account. In the Netherlands, guidelines for road design and road layout are issued by CROW, the knowledge platform for infrastructure, traffic, transport and public space (www.crow.nl). These guidelines are established in so-called CROW working groups that consist of traffic and traffic safety experts from various local authorities, consultancy firms and knowledge institutes. The guidelines are often a compromise between accessibility, the environment and safety. Where possible, guidelines are supported by scientific knowledge, but for the time being not all aspects have sufficient scientific knowledge available. This means that practical experiences are also important when drawing up guidelines.

The guidelines for road design are not legally binding. However, there must be good reasons to deviate from the guidelines. A roadmanager is responsible for the quality of the roads. In the event of an accident on a road where the guidelines have not been properly applied, the road manager can be held liable. In a possible court case, the road administrator must be able to substantially explain why the directive has been deviated from. He must also demonstrate that the alternative solution chosen is at least as safe as the original solution in the directive.

One of the most important aspects of road design in our case is the relationship between design speed and curve radius. The larger the design speed of a road, the larger the curve radius has to be. Table 5.2 shows this relationship according to the German motorway design guideline (RAA, 2008). Given that the smallest curve radius in the motorway exit in Eindhoven is approximately 60 m, the design speed should less than the speed limit of 50 km/h. However, this guideline applies only to German motorways.

Design Speed of exit (km/h)	30	40	50	60	70	80
Minimum curve radius (m)	30	50	80	125	180	250

Table 5.2: Relationship between design speed and minimum curve radius (RAA, 2008)

6 Derivation of Infrastructure Nudging Measures

This chapter describes the approach and steps taken in the design of nudging interventions. First, the general design of interventions is stated, before the derived ideas for interventions are divided into interventions nudging drivers towards safer speed and interventions nudging drivers towards adopting a safe trajectory. The outcome of this chapter provides direct input into the subsequently described simulator studies.

6.1 Design of Interventions

In order to develop appropriate infrastructure-nudging measures suitable to guide drivers towards adopting a safe speed, nudging interventions aiming only at drivers driving at an inappropriate speed were developed. As the classification of trajectory is highly dependent on the chosen speed (see chapter 4.2.2), interventions first focus on inappropriate speed and subsequently on inappropriate trajectory, as described in chapter 4. This order was chosen, because we concluded that the risk to adopt an inappropriate trajectory was much lower when drivers are driving at a safe speed. The speed nudging system aims at detecting speeding vehicles in order to activate the intervention until the appropriate speed is reached. Lights have the potential to be turned on and off, which makes goal-directed nudging of specific drivers possible, turning it into an intelligent intervention. Interventions were derived in several steps.

In order to design road interventions within the scope of WP 3, an expert workshop was organized on November 7th, 2017 by ika in Aachen. The aim was to conceptualize and design driver directed infrastructure nudging measures to reduce speed in a certain hazardous situation and guide drivers along a preferred trajectory.

As described in chapter 4.2.4, a motorway exit in Eindhoven, the Netherlands, was chosen as location for testing the infrastructure nudging interventions of the infra driver nudge as described in this deliverable. One problem at this motorway exit is that some of the drivers are too fast when driving into the curve, especially with cars queueing up at the traffic lights, which can only be seen once you reach the end of the queue (see 4.2.4). Also, the curve becomes tighter and drivers might not realize that they are going at an inappropriate speed until is too late to react. Consequently, drivers will be in the hazardous situation of either going out of the curve or approaching the end of the queue at the traffic lights way too fast. The question of the workshop therefore was how drivers can be nudged towards (a) reducing their speed and (b) adopt a safer trajectory in this motorway exit situation. The *N* = 16 experts from the MeBeSafe consortium went into a free Collection of possible and impossible nudging measures according to the design criteria stated in D1.1. In a second step, the ideas were evaluated regarding their technical feasibility after the participants were informed about the state of the art as described in chapter 4 of this deliverable.

A variety of first concept ideas was the outcome of a first brainstorming. The subsequent table 6.1 displays these keywords, along with a classification with regards to the project goals and nudging. Some ideas, however, were either not applicable to the testing location or are not classified as nudges.

Targeted behaviour	Solution	Classification
Nudging drivers towards adopting a safe speed (objective 6)	Optical narrowing	System 1 nudge
	Distance between the lines	System 1 nudge
	Light moving in opposite direction	System 1 nudge
	Rough surface/potholes	System 2 nudge
	Holograms/projections	Not a solution but a technology
	Lines across the road at decreasing distance	System 1 nudge
	Warning signs	System 2 nudge
	Info about accidents and kills	System 2 nudge
	Actual speed information	System 2 nudge

	Billboards with association to danger	System 2 nudge
	Reduce visibility/spot lighting	System 1 nudge
	Paint colours on road markings or used coloured lights	System 1 nudge
	Road design (curvy roads)	Not applicable to traffic situation
	Create a closed environment (like in a tunnel)	Not applicable to traffic situation
	Rain or fog according to the speed	System 1 nudge/shove according to French (2011)
	Flash light depending on the speed as warning	System 2 nudge
	Rumble strip distance in accordance to flashing lights	System 1 nudge/shove according to French (2011)
	Speed dependent opening over the road	System 1 nudge
Nudging drivers towards adopting a safe trajectory	Poles along the road	Shove according to French (2011)
	Guardrail warning	System 2 nudge
	Guardrails with or without lights	System 1 nudge
	Combining smooth road surface with rough road surface	System 1 nudge/shove according to French (2011)
	Elevated road surface towards the outer periphery	System 1 nudge/can be shove according to French (2011) when not avoidable
	Colour segments on the pavement	System 1 nudge
	Follow-me line	System 1 nudge
	Coloured lights next to streets	System 1&2 nudge

	Small middle barriers	Shove according to French (2011)

Table 6.1: List of unordered keywords and classification into the frame of the MeBeSafe project

From these keywords, the participants of the workshop then created distinct interventions. Most interventions target only one objective, some target both objectives. They are described in the following:

Intervention 1 was a moving light in the visual field with a light spot that starts moving with the desired speed (50 km/h) in the direction of vehicle motion (1.1). If the car is being driven at 50 km/h, it stays with the light and hence has the road illuminated by it. Else, the car overtakes the light and navigates the curve in the dark. The required technology for this is vehicle speed detection. The measure has the advantage that the interest of the driver can be aroused because attention is actively directed towards the road. As drivers slow down, it is also assumed that drivers are taking the safest trajectory instead of the perfect trajectory. Possible variations of technology of this intervention were moving lights placed on the road along the centre line, moving lights placed on the road or at the very edge of the road along the outer and inner periphery, and moving lights projected onto the road from the guardrail. A variation of this could be moving lights moving towards the driver (1.2), creating an illusion of the drivers to be faster than they actually are. Another variation of this intervention was the so-called running-man-solution (1.3). This described a man that runs beside the vehicle on the guardrails and monitors at the desired speed (50 km/h). If vehicle speed is higher: the running man is left behind. The driver has to reduce his speed to see the running man again, making it a system 2 nudge. The running man could also be used when the vehicle speed is lower than the desired limit. The disadvantage of this solution was that this would be too distracting.

Intervention 2 displayed a corridor solution that involves a corridor painted on the road that indicates the safe trajectory for navigating the curve, including a corridor depicting a no-go zone marked in red (2.1). A variation for this was to have the no-go corridor laid with rumble strips to inhibit the driver from using an unsafe trajectory (2.2). However, this would be considered a shove instead of a nudge according to French (2011). Another variation of this would be to mark the go- and no-go zones with lights embedded in or under the asphalt (2.3). Furthermore, another variation would include for the narrowing to be speeding up from the beginning of the measure to the end, thus the driver additionally gets the visual impression of speeding up (2.4). A variation in technology was to use thin stripes in small distances to one another, because it was assumed that thin light stripes might be more feasible than large illuminated translucent surfaces under see-through asphalt.

Intervention 3 were speed bumps with the intention to bring down drivers' speed to the desired speed. Again, this was not a nudging solution but a shove according to the classification of French (2011).

Intervention 4 were the so-called dragon teeth. This involved gradually closing dragon teeth that were projected onto the road to reduce speed. This should give the impression of the road narrowing optically and could also be used for nudging drivers along a preferred trajectory, depending on the direction of the narrowing.

Intervention 5 featured interactive lights (static, without movement) at the side of the road that would indicate safe or unsafe speed using colours, with unsafe speed being indicated with red lights and safe speed indicated by green lights.

Intervention 6 showed light strips that get gradually closer and longer, placed along the outer periphery of the curve. This intended to make the drivers feel like they are going too fast and moving towards the edge of the road, hence reducing the speed of the vehicle. It was assumed that this intervention could help for speed reduction as well as trajectory control. Here, the light strips would be activated only when the speed is determined to be more than the safe limit, using a speed camera. The disadvantage was that the driver might attempt to navigate a tighter trajectory without reducing the speed and this intervention might then become counter-productive.

Intervention 7 featured a dynamic warning to inform drivers of the correct stopping distance in order to avoid crashing the queue at the traffic lights. This could be done via (7.1) a dynamic sign that indicates the meters until the end of the queue, (7.2) uses a gradual change in pattern or colour of lights placed along the road dependent on the distance until the queue.

After this collection, the infra driver nudge-team evaluated the different interventions and variations according to four criteria regarding the technology: (1) being at hand and usable, (2) being at hand and usable with minor adjustments, (3) being at hand and usable with major adjustments, and (4) nice to have but only applicable for future development. The previously described interventions were then sorted into the matrix as displayed in figure 6.1. Technically not feasible solutions included interventions that used projections or technologies like lights underneath a see-through asphalt, which are not fully developed for our intended purpose yet. Furthermore, the light solution was to be dynamic, therefore light as a means to turn on and off the nudge was set. Furthermore, solutions were to be directly attributable to nudging, not shoving (see French, 2011). Therefore, rumble strips and technologies providing a haptic feedback were taken out as well.

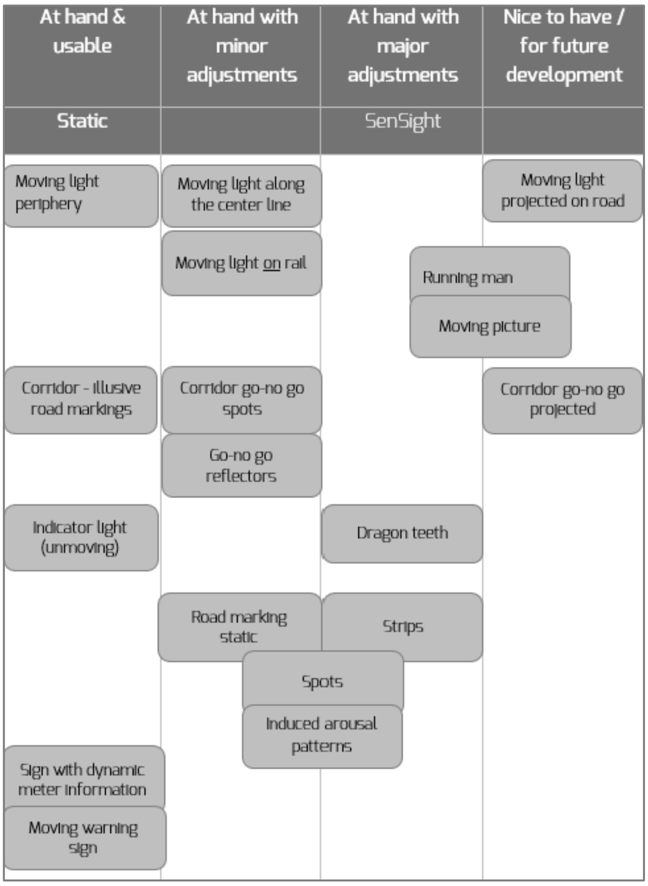


Figure 6.1: matrix for decision on feasibility of derived nudging interventions

Subsequently, the measures were attributed to the two different objectives of reducing speed and trajectory guidance, separately. These are described in the following.

6.2 Measures for Speed Reducing Nudges

The final decision for the nudging measures was made to use moving lights. This decision was based both on technological factors and safety considerations, such as being usable as a nudge, visibility night and day, technical development feasibility, justifiable level of distraction, and the possibility to test in a simulator study.

Once the decision for using the moving light concept was set, there was a need for a reduction of possible variations for testing in a first simulator study. Summing up all features and possibilities to use moving light along with comparisons of different movement components as a nudge, the complete test design, would have had over 9000 different possible combinations to be considered. These factors included features such as blinking, colour, and speed, among others, and are displayed in table 6.2. The subsequent testing specifications and hypotheses are described in chapter 7.

Factor	Variation	Specification	Prioritization	
Level (Horizontal Position)	Up	(e.g. on guardrail)	constant	On street level, because most technologies are applicable there
	Down	On street level		
Technology	**Strips**	SenSight technology	varied	Guardrail and SenSight are not visible during daytime. Decision made for spots
	Guardrail			
	Spots			
	Projec-tions & anima-tions			Technology doesn't exist yet. Possible testing only for further research/product development interest in later studies
Side (Vertical Position)	Right		constant	Starting with both sides as most relevant scenario. Differences to using just one side to be targeted in later study for trajectory guidance
	Left			
	Both			
	Centre	Targeting trajectory as well		Not feasible for implementation because effect cannot be attributed on visual impression alone (haptic feedback with current technological possibilities)
Colour	**White-off**	Lights turned on as a warning,	Varied	Variation to be tested only in qualitative study within
	Orange-off			

	Red-off	turned off/green when target behaviour is achieved		simulator study 1 (see chapter 7)
	Orange-green			
	Red-green			
Distance	Different distances between lights (if spacing is needed)		Constant	Specification as fine-tuning possible on qualitative level after identification of solution
Form	Different lengths of strips		Constant	If necessary to be tested later
Brightness	Different levels of intensity		Constant	Not possible in simulator study (not possible to display luminance). To be targeted in field test (WP5)
Movement of lights	**Stable**	Is there a difference if the lights are moving or not?		Distinct assessment to be part of additional study in either the simulator or in field test (WP5)
	Dynamic (direction & speed; blinking)			
Target Speed	**50 km/h**		**Constant**	as set by the speed limit
	80/100/130 km/h			Lower priority
Location/ road environment	**60m curve radius**	Eindhoven motorway exit	Constant	Rest: Later/additional study
	Bigger curve radius	Would people still drive slowly if the situation would allow for a higher speed?		
	Other road environments	e.g. straight road		

Individual detection	**Individual**	Individual detection of drivers overspeeding/with wrong trajectory	**Constant**	
	Non-individual (always on/off)			No
Context	Day/ Night		Not feasible	Not possible in simulator study (not possible to display luminance)
	Different weather conditions			Friction changes when weather conditions change. This is applicable for the field test

Table 6.2: Complete compilation of all factors that can possibly be varied for testing. Bold entries mark the factor specifications that were tested in the first simulator study described in chapter 7, including a prioritisation whether the choice was to be a constant factor or a variation, including an explanations for the prioritisation

For the first simulator study, the final decision resulted in a reduction to a baseline and two nudging conditions, namely lights moving towards the driver and static indicator lights. These conditions were tested in a quantitative study with a fully crossed experimental design. Here, participants were left unaware of the nudging interventions and their behavioural response was tested with a systematic variation of the movement component. Further factors of interest were tested in an additional qualitative study, asking for feedback from participants after they had been informed about the purpose of the measures. The details of this study are described in chapter 7.

6.3 Measures for Trajectory Guidance

As described in chapter 4.2, nudging drivers towards adopting a preferred trajectory has a lower priority than nudging drivers towards adopting a safe speed due to a safe trajectory being highly dependent on speed (see chapter 4.2.2). Therefore, the impact of speed-reducing nudging interventions on the driven trajectory will be measured without systematically varying a trajectory nudge, specifically. Based on the results of the simulator study as described in chapter 7, specific nudging interventions for directing drivers towards adopting a different trajectory are studied in a distinct simulator study (see chapter 9).

7 Simulator Study 1

Building on the derived nudging interventions described in chapter 6, the first simulator study was conducted. This aimed at evaluating interventions for speed reduction as described in chapter 6.2. The subsequent subchapters outline the hypotheses for testing based in the theoretical background given in chapter 3, chapter 4 and chapter 5, followed by the methodological approach of this simulator study. This is followed by the detailed results of the two parts of the study, quantitative and qualitative assessment, which are discussed and interpreted in subchapter 7.4. Along with this last step, the next steps within the infra driver nudge are outlined.

7.1 Hypotheses

Based on the theoretical background of the concept of nudging and human speed perception provided in chapter 3, chapter 4.2 and chapter 5.1, hypotheses were constructed. Within these hypotheses, the same pattern is expected for the data of velocity and brake pedal onset, since velocity as a dependent variable is a direct result of other behavioural variables such as the brake pedal onset the same pattern is expected for the data of the brake pedal onset.

As a human being is conditioned to respond to red lights with caution (Donald, 1988; Edworthy & Adams, 1996), it is expected that the velocity decreases earlier when the red lights appear on the road compared to no lights appearing on the road **(H1a)**. Besides that drivers are expected to react earlier with pressing the brake pedal when the red lights appear on the road compared to no lights appearing on the road (**H1b**).

Because drivers perceive a large proportion of their speed based on optical flow, it is likely that drivers perceive their own driving speed to be higher than it actually is with lights moving towards them at both sides of their lane (Gibson, 1950; Manser & Hancock, 2007). That is why the velocity of drivers is expected to decreases earlier when lights move towards the driver compared to no light movement on the road

(**H2a**). Moreover drivers are expected to press the brake pedal earlier when lights move towards the driver compared to no light movement on the road (**H2b**).

The stated hypotheses focus on velocity and brake pedal onset as main interest of this first simulator study to examine whether nudging drivers towards a desired speed (objective 6) can be achieved by the derived nudging interventions. Furthermore, we investigated in an explorative approach whether nudging drivers towards adopting a certain speed does also influence the driven trajectory (objective 7). In addition, another explorative analysis focuses on the glance behaviour of participants to examine whether the light stimuli and the 50 km/h-sign at the beginning of the curve are likely to be perceived by drivers. The results of the aspects stated in this paragraph are displayed in chapter 7.3.1

Subsequently, a qualitative study evaluated the influence of further variations of the variables, more specifically different colours, light movements, blinking light conditions, different technologies, and different locations in the curve where the lights were displayed. For details on this, please see table 7.1 in chapter 7.2.2. The results of the aspects described in this paragraph are displayed in chapter 7.3.2.

7.2 Methods

The following chapter states the methods used in this study including participants, apparatus, task and stimuli, procedure, design, and the analysis.

7.2.1 Participants

N = 54 participants recruited by a research panel in April 2018 took part in the simulator study, thereof 52 % being female. All participants were naïve to the purpose of the experiment, took part voluntarily and received a monetary compensation. Every participant had a valid driver's license, a normal or corrected-to-normal vision and no relevant colour weaknesses. The mean age of the sample was *M* = 31 (*SD* = 11.37). The mean number of kilometres a participant drove annually was *M* = 10856 (*SD* = 10694). When being asked to give a percentage distribution on how much time participants relatively spend on highways, country roads or in city traffic, participants reported to spend most of the time in city traffic (*M* = 44.23; *SD* = 18.89) followed by highways (*M* = 33.32; *SD* = 18.08). Participants rated their relative time spend on country roads to be the lowest (*M* = 24.49; *SD* = 15.75). A percentage of 11.1 % of the participants reported to have taken part in a driving simulator study before.

7.2.2 Apparatus, Task & Stimuli

The experiment was conducted in the static driving simulator at ika, including a mock-up car with automatic transmission, a curved screen for front vison (4.8 × 2 m, 220° × 50° visual range, 5 arcmin/OLP resolution, 1024 × 600 Hz refresh rate) and two screens for rear vision (Telefunken A50F446A, 127 cm, 600 Hz refresh rate). The simulation of the Eindhoven Testing Location was modelled via Virtual Test Drive 2.1 (VTD, by Vires) and operated on Ubuntu Linux 16.04. VIRES road network editor based on OpenDRIVE road networks was used for interactively creating and editing the various test scenarios. Figure 7.1 illustrates the setup.

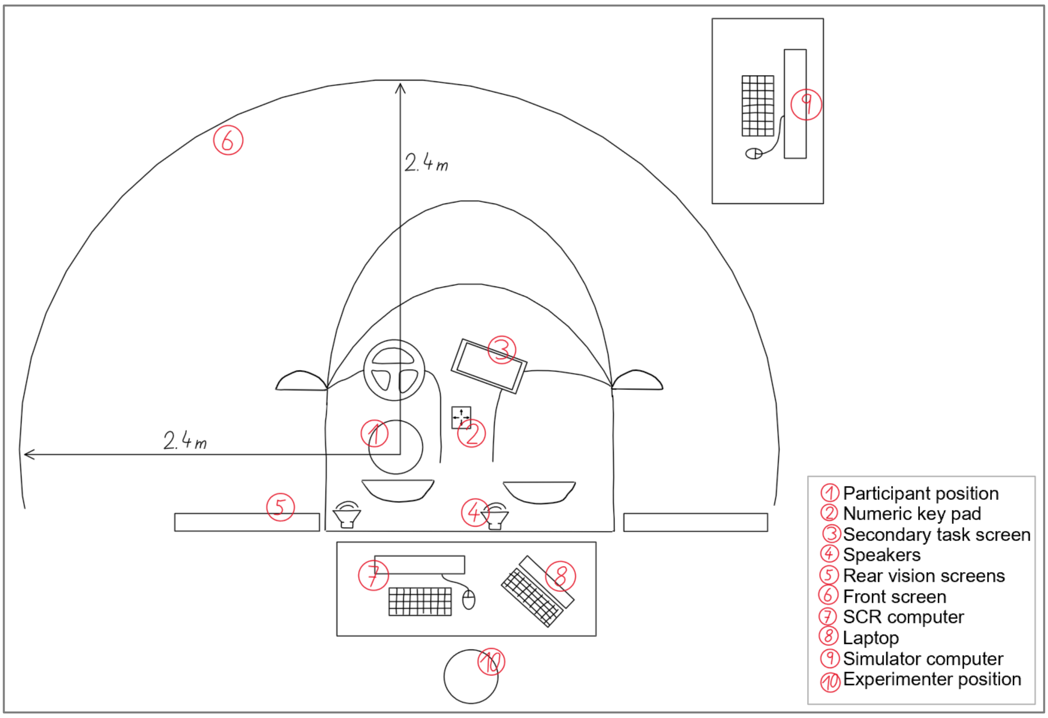


Figure 7.1: Sketch of experimental setup with the participant position, the numeric keypad and screen for the secondary task, and screens of the simulator setup

At both sides of the road was a row of simulated light sources similar to the spots described in chapter 5.2, with a distance of 4 m to the next light source. For the nudging effect to take place, every fifth light turned on when the driver entered the motorway exit (figure 7.2, part A, step 1). In the moving light condition, the activated lights had the same distance as in the static light condition, but moved one spot further towards the driving direction, creating the illusion of movement at 50 km/h towards the driver. Five examplary steps of the light movement are illustrated in figure 7.2 (part A, steps 1-5). Figure 7.2 part B illustrates what participants saw in the driving simulation. The relevant stretch of the road started at the trigger point, marking position p0. Driving over the trigger point activated the lights of the nudging measure. The relevant sections extends to p160, which is equal to a distance of 160 meters. P160 marks the position where the 50km/h sign is placed.

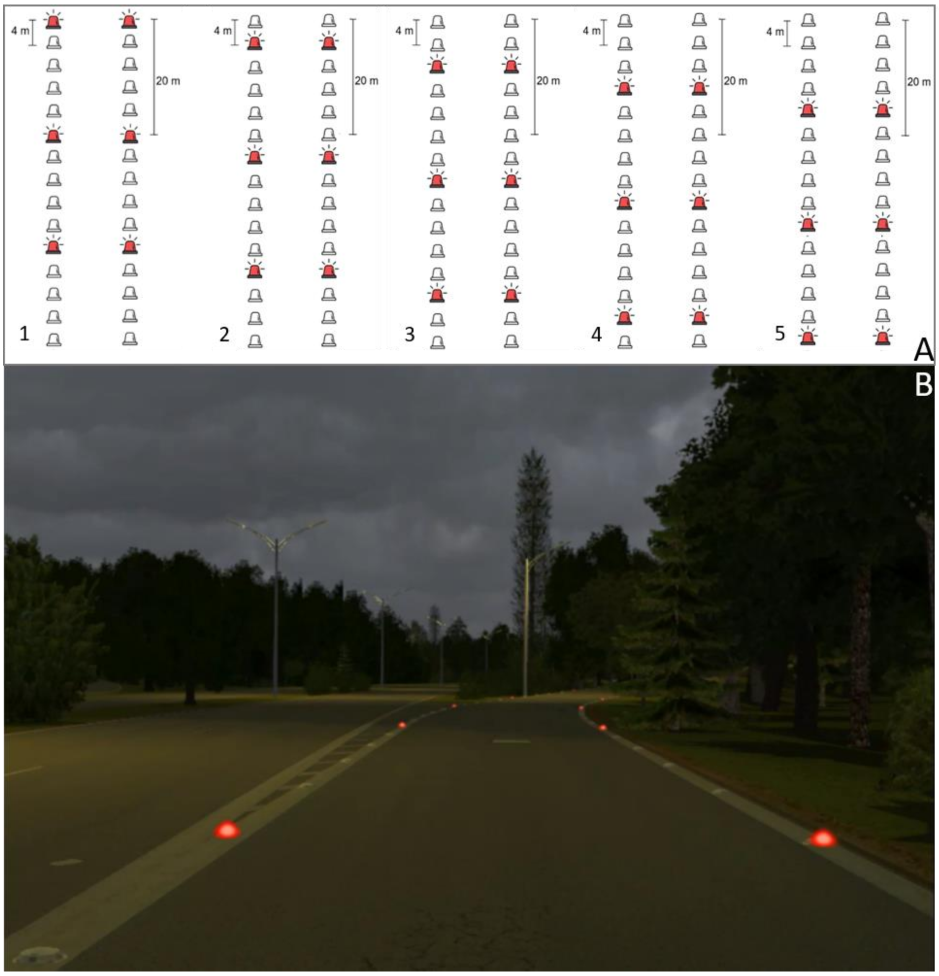


Figure 7.2: Part A: distance of illuminated lights during conditions with static or moving lights. Part B: Picture of simulated motorway exit with illuminated lights

The participants sat in a modified vehicle chassis. The interior of the car consisted of the original equipment of the car with some additional items: a tablet used for the secondary task (Dell Latitude 3340 with Windows10) and a numeric keypad (Logilink® ID0120) mounted on the centre console of the car, and a video camera was placed behind the front passenger's seat. The camera was installed to provide additional backup footage to be able to get a detailed reconstruction every drive in case of need. Participants wore a head-mounted Ergoneers Dikablis eye-tracker that provided information on gaze-direction of the participants.

The experiment was split into two parts. In the first part participants were told that the aim of the study was to examine multitasking in the context of driving (for details, please see chapter 7.2.3). This cover story was used to draw the attention on an irrelevant aspect to make sure the participant's reaction is as unbiased as possible. The task consisted in driving on a highway at a set speed while simultaneously performing a secondary task, which was the Surrogate Reference Task (SuRT; Mattes & Hallén, 2009) modelled via VisualTask (run on Dell Latitude 3340 with Windows10). The aim of the SuRT task is to detect and select a big circle. This target stimulus is surrounded by 50 white circles of a smaller size that function as distractor stimuli. In order to select the target, participants pressed a right or a left key to move the selection area to the desired section with the target stimulus. For this visual search task, 50 white circles (120 pixel circumference, 4 pixel line width) were randomly scattered across a black screen (Reflexion LED1014DV, 60 Hz refresh rate, 25.5 cm, 1024 × 600). Approximately 10 seconds before reaching the motorway exit, participants were told to stop performing the SuRT task in order to take the exit of the highway.

After the first part of the experiment, participants were informed about the actual subject of the study. The task in the second part of the experiment was to take the highway exit again and to draw attention to the lights and to rate them against the backdrop of their efficiency to reduce speed. The aim of the second part of the study was to gather more information on possible design aspects of infrastructural nudging measures. The factors tested in this second, qualitative part of the study are displayed in table 7.1 below. Factor 1 (colour) was tested twice, once with lights moving towards the driver and once with static lights. This was done to control for movement effects within the colour condition. Also, the decision on colours was crucial at this stage of the development process, which is why this was focused on in this level of detail. Lights were either white, orange, or red and turned off when the participant reached the target speed of 50 km/h, or were orange or red and turned green when participants reached the target speed of 50 km/h. Factor 2 (movement) was divided into the levels *with the driver*, *towards the driver*, and *no movement* (static lights). This was done to gather qualitative impressions of participants on the different movement conditions. For factor 3 (blinking), static lights and blinking lights were compared qualitatively. In factor 4 (technology), spots were compared with simulated stripes, which aimed at simulating the SenSight technology as described in chapter 5.2. However, as the simulator cannot display real light sources but rather gives the impression of a light source by using pictograms, this gives only limited insights as external validity is questionable. As factor 5 (location), we varied whether the lights were displayed in the straight part of the exit or later in the curve only. Each participant encountered one factor in this second qualitative part of the study (between-subjects design). This resulted in each factor being assessed by $N = 9$ participants. The sequence of factor levels within each factor was randomized.

No.	Factor	Variations	Notes
F1	Colour		
		White-off	
		Orange-off	
		Red-off	
		Orange-green	
		Red-green	
F2	Movement		
	Direction	With the driver	
		Towards the driver	
		No movement	

F3	Blinking (only for the indicator lights (no movement))		
		blinking	
		No blinking	
F4	Technology (only for the indicator lights (no movement))		
		Spot	
		Strip	Array of spots
F5	Location (single-lane road without oncoming traffic)		
		Curve	Curved part of the exit
		Straight	straight part of the exit

Table 7.1: Factors and variations tested in the second part of the first simulator study

7.2.3 Procedure

The experiment took place in April 2018 at ika in Aachen. As mentioned before, the experiment was split into two parts. In the first part, the participants were naïve to the subject of the experiment: a cover story was used to distract the attention from the lights as the actual subject of the study. The participants were told that the aim of the study was to examine the effect of a secondary task on driving performance. After that, participants were briefed about the pretended aim of the study they signed a secrecy agreement, a declaration of consent and a pre-questionnaire, including demographics and information regarding their mobility behaviour. After filling out all documents, participants started with a three minute introductory drive in the driving simulator to get to know the driving feel in the static simulator. Therefore the participants adjusted their seats and were informed that the recommended speed was 100km/h. This speed is higher than the allowed speed of 70 km/h of the reference real-traffic location in Eindhoven and was set to simulate a more risky driving situation. Moreover, participants were told to drive according to their normal driving behaviour. After the introductory drive the SuRT as a secondary task was presented, followed by a dry run of the SuRT. After that a second introductory drive started, this time with the SuRT as a secondary task. After finishing the second introductory drive, the eye-tracker was mounted, adjusted and calibrated to the participant's head. After that the actual experiment started.

Participants were again told to behave the way they would in a regular car. They were reminded that the recommended speed was 100km/h and that they are going to drive three experimental drives. As soon as they reached 100km/h the experimenter told the participants to start the secondary task. At a given point before entering the highway exit, participants were told to stop performing the SuRT. Each drive ended with the participants taking the exit with the nudging measure or the baseline with no lights. In experimental conditions with lights, the lights were always activated to ensure a controlled experiment. After each drive the experimenter asked the participants if there was something they observed or perceived during the previous trial. Answers were recorded on a voice recorder. After all three experimental drives, the participants were informed that the cover story was not the actual subject of the study but that the focus was on the lights and how the participants driving behaviour is affected by the lights, and if the nudging measure was obvious. In addition to that the concept of nudging was explained so that the participants had an understanding of how the measure was supposed to work in the context of speed reduction.

After the clarification of the actual subject of the study the second part of the experiment started. The eye-tracker was removed and participants drove another set of trials, this time without performing the secondary task. Moreover the section of the road was much shorter, starting closer to the exit. The task was to pay attention to the nudging measure when taking the exit. After each trial the instructor asked questions referring the design of the measure and the participants filled out a survey themselves. After driving all trials the participants were asked to rank the different nudging measures from most to least effective in reducing driving speed. After the experiment participants were thanked for their participation and received a monetary compensation.

7.2.4 Design

The design of the experiment can be split into the two halves of the experiment as well. In the first part of the experiment the independent variable was the design of the nudging measure with a total of three levels including a baseline with no lights at all, a condition with static red lights and a condition with red light moving towards the driver. Every participant drove every condition only once because habituation effects were possible and the initial response to the nudging measure was of interest. The sequence of the conditions was balanced over all participants. The dependent variables in the first part of the experiment were quantitative aspects, such as velocity (average and local, in m/s), vehicle parameters (especially brake pedal onset), position on the road for trajectory (clearance to the left side of the road), eye movement, and experience was measured qualitatively by open question on people's impression after each of the three trials.

In the second half of the experiment a set of different factors as independent variables were manipulated: the colour in the static light condition and the colour in the towards moving light condition. The varied colours were white, orange or red lights that respectively turned off when the speed limit was reached and orange or red lights turning green when speed limit was reached. Another factor evaluated qualitatively in the second part of the experiment was movement, with lights moving towards the driver, lights moving with the driver and static lights. Also, the factor blinking was added to examine differences between blinking and non-blinking lights. The technology of the lights was tested as well using either spot or strips. As a last factor the location of the nudging measure was altered by presenting the lights either on the straight section of the exit or in the curve. Due to test economic reasons, the combinations were not fully crossed over all factors, resulting in a total amount of 28 conditions. Since one factor was assigned to each participant and each of them was composed of three to five different conditions, every participant underwent three to five of the 28 conditions. For example one participant compared the different colours of lights with all of the other factors staying the same over all trials. Furthermore the presentation sequence of the trials was incidental. The dependent variable in the second part was the experience described by the qualitative reports of the participants based on their perception and the assessment of the presented nudging measures in the context of driving speed reduction.

7.2.5 Analysis

MATLAB was used for the analysis of the quantitative data received from the simulator tests. The simulator logged various parameters during each test drive like the global position of the ego vehicle, ego vehicle velocities and accelerations in x-, y- and z- directions, and the lateral distance from the lane reference line. It also contained time stamps and distances from the scenario trigger point at each logged data point. The data was interpolated between logged datapoints to figure out parameter values at regular desired intervals of distance. Graphs plotting velocity, accelerations and brake-onset and gas-offset were plotted with respect to time and speed. The analysis was then continued further using IBM SPSS Statistics 23.

7.3 Results

In the following, the results are displayed. First, the quantitative results regarding velocity, brake pedal onset, lateral position on the street, and number of glances on lights stimuli and traffic signs (50 km/h-sign) are examined, before the qualitative part of the study is reported.

7.3.1 Quantitative Results

Due to elimination of statistical outliers or abortions of participants that perceived motion sickness, a final sample size of $N = 48$ participants remained. In order to remove participants from further analysis who did not understand or did not follow the instructions, statistical outliers in driving speed at the trigger point p0 were identified. Therefore participants exceeding or undershooting two standard deviations from the mean driving speed were excluded from further analysis.

In the following subchapters, the results of the first (quantitative) part of the study are given. These include the results of inferential statistics for the dependent variables velocity and brake pedal onset for speed, clearance to the left side of the driving lane for differences in trajectory, and number of glances for eye tracking to examine whether the lights and the 50 km/h-sign were seen by participants.

7.3.1.1 Velocity

In order to check whether entry speeds at light onset are comparable among the different nudging conditions, an ANOVA with repeated measures for the factor condition at p0 was calculated. Results showed no significant main effect for condition ($F(2, 94) = .90$, $p = .409$, $\eta_p^2 = .02$).

Concerning hypotheses **H1a** and **H2a**, an ANOVA with repeated measures with the factors nudging condition (3) and position (33) on the road from the trigger point p0 to p160 with data points every 5 meters, resulting in a total amount of 33 factor levels for position, was conducted. A main effect for the position ($F[1.55, 64.94] = 153.01$, $p < .001$, , $\eta_p^2 = .79$) was significant, as well as the interaction between the nudging condition and the position ($F[3.38, 141.74] = 2.90$, $p = .032$, $\eta_p^2 = .07$). Further effects did not show significance.

In order to examine the significant interaction between position and condition even further, three additional post hoc ANOVAs with repeated measures from p0 to p160 were calculated, comparing either the baseline with the static lights, the baseline with the towards moving lights or the static with the towards moving lights. This was done to rule out interaction effects of the three nudging conditions and examine differences between each pair of nudging conditions separately, in order to analyse the data regarding the hypotheses H2a and H2b and understand the interaction effect.

The post-hoc ANOVA comparing the velocity development with static and the lights moving towards the driver revealed a significant main effect for position ($F[1.32, 55.29] = 102.30$, $p < .001$, $\eta_p^2 = .71$). The interaction of condition and position revealed a tendency that did not reach significance ($F[1.58, 66.18] = 3.06$, $p = .065$, $\eta_p^2 = .07$).

Results of the ANOVA comparing the baseline with the towards moving lights revealed a significant main effect for position ($F[1.78, 74.70] = 126.54$, $p < .001$, $\eta_p^2 = .75$), but no significant interaction of position and condition.

Comparing baseline with the static lights, a significant main effect for position (F[1.73, 72.76] = 142.09, $p < .001$, $\eta_p^2 = .77$) and a significant interaction between condition and position (F[1.81, 75.80] = 3.81, $p = .31$, $\eta_p^2 = .08$) were found. As descriptive data shows, participants drove faster in the baseline initially but this changed 120 meters after the position of the light onset of the light conditions, which was p0 for all conditions. Contradicting, participants in the static lights condition drove faster for the rest of the relevant section of the course up to p160. The mean velocity depending on the position of the driver in the conditions lights moving towards the driver, static lights, and the baseline is illustrated by figure 7.3.

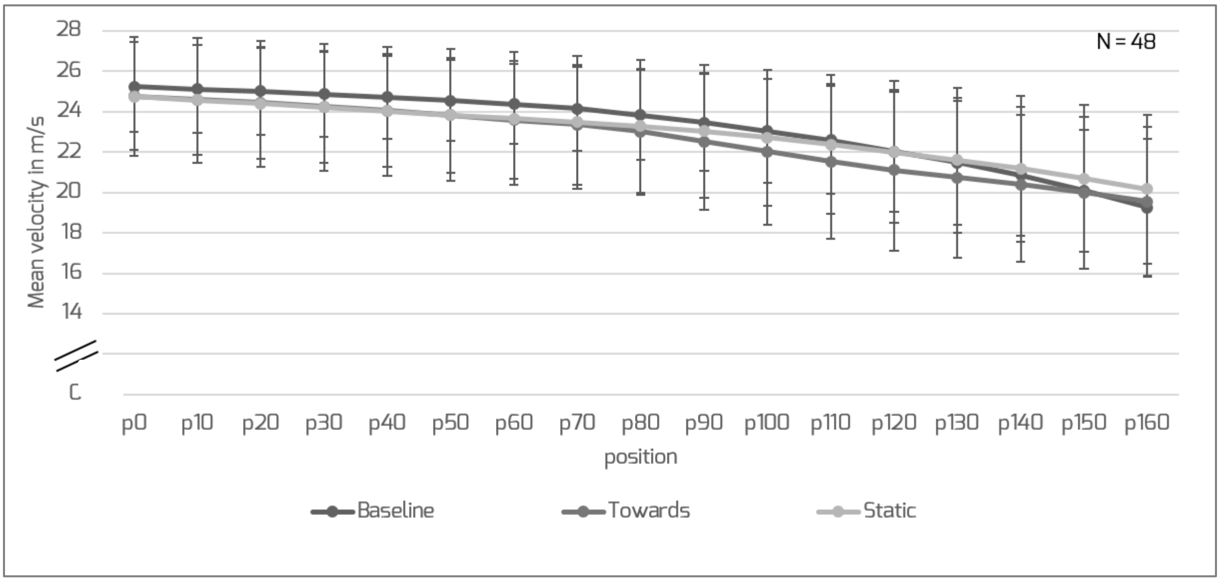


Figure 7.3: Mean velocity in meters per second depending on the position of the driver in the conditions lights moving towards the driver, static lights, and the baseline

7.3.1.2 Brake Pedal Onset

With respect to hypotheses **H1b** and **H2b**, the same ANOVA with repeated measures with the factors nudging condition (3) and position (33) was conducted with the only difference being the brake pedal onset as dependent variable. Analysis showed, besides a significant main effect of the position (F[2.64, 110.81] = 11.06, $p < .001$, η_p^2 = .21), a marginally significant main effect for the nudging condition (F[2, 84] = 3.11, $p = .050$, $\eta_p^2 = .07$). Moreover, a tendency in the interaction between position and condition was found that did not reach significance (F[4.37, 183.51] = 2.33, $p = .52$, η_p^2 = .05).

In order to examine the existent significant effects even further, again three additional post hoc ANOVAs with repeated measures from p0 to p160 were calculated, comparing either the baseline with the static lights, the baseline with the towards moving lights and the static lights with the towards moving lights.

When comparing baseline with static lights a significant main effect for position (F[2.93, 123.10] = 11.69, p < .001, η_p^2 = .22) as well as a significant main effect for condition (F[1, 42] = 6.58, p = .016, η_p^2 = .14) was found. No interaction of condition and position was revealed.

When comparing the development of the brake pedal pressure in the baseline with the braking pressure in the condition with the towards moving lights showed a significant main effect for position (F[2.53, 106.40] = 8.22, p > .001, η_p^2 = .16) and an interaction of position and condition (F[3.39, 142.15] = 3.27, p = .019, η_p^2 = .07).

The third post-hoc ANOVA comparing the velocity development with static and the lights moving towards the driver revealed a significant main effect for position (F[2.69, 112.83] = 5.46, p < .005, η_p^2 = .16). The results are illustrated In figure 7.4.

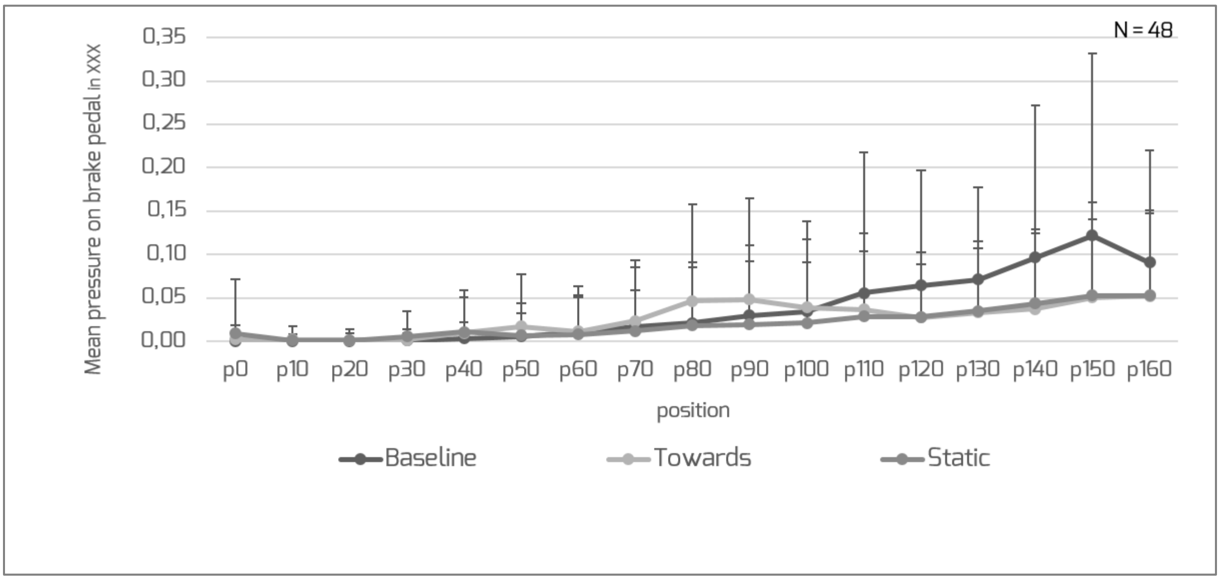


Figure 7.4: Mean pressure on brake pedal depending on the position of the driver in the conditions lights moving towards the driver, static lights, and the baseline

7.3.1.3 Trajectory

Trajectories were analysed with the distance between the car and the left edge of the road as dependent variable. For a better understanding of the results of the analysis, the respective values are explained in the following:

According to convention in automotive engineering [ISO 8855:2011(E)], values to the left of the reference are positive while the values to the right of the reference are considered negative. In case of the curve under consideration, the reference line to which the lateral offset of the ego is measured is at the outer edge of the curve. Hence, the negative value of the lateral offset (dy) indicate that the ego vehicle is to the right of the reference line. This means that the ego is to the right of the outer edge of the right-hand curve, i.e., inside the lane. The lane width in the curve is 5.5m and broadens to 6.5m between p200 and p300. All values of dy lie between -2.3m and -3.46m. This implies that no car is overshooting the lane boundaries.

The results of the analysis of the trajectory are presented in the following. An ANOVA with repeated measures with factors condition (3) and position (33) from p160 to p320 was calculated in order to examine the effect of the nudging measure in altering trajectory. Results revealed a significant main effect for position (F[3.69, 173.20] = 135.86, p < .001, $\eta p^2 = .74$) and a significant interaction between position and condition (F[6.40, 300.61] = 2.83, p = .009, $\eta p^2 = .06$).

In order to examine the interaction between position and condition further, additional ANOVAs with repeated measures were calculated, either comparing the baseline with the static lights, the baseline with the towards moving lights or the static lights with the towards moving lights. When comparing only the baseline and the static lights, results showed a significant main effect for position (F[3.61, 169.66] = 116.63, p < .001, $\eta p^2 = .71$), and a marginally significant interaction between position and condition (F[3.67, 172.34] = 116.63, p = .060, $\eta p^2 = .05$). Descriptive data showed that the distance between the car and the left edge of the road was larger in the baseline first, but this changes at p290. From this point on, the distance between the car and the left edge of the road is larger in the static light condition.

When comparing the baseline with the towards moving lights condition, a main effect for position (F[3.72, 174.60] = 116.11, $p < .001$, $\eta p^2 = .71$) was found.

When comparing static lights with the towards moving lights condition, results showed a main effect for position (F[3.60, 169.24] = 120.73, $p < .001$, $\eta p^2 = .72$) and an interaction between position and condition (F[3.48, 163.47] = 5.76, $p < .001$, $\eta p^2 = .11$). Descriptive data showed that the distance between the car and the left edge of the road is larger in the static lights condition of the first part of the exit up to p290. From p290 to p320 the distance between the car and the left edge of the road was larger in the towards moving lights condition. Descriptive results are displayed in figure 7.6.

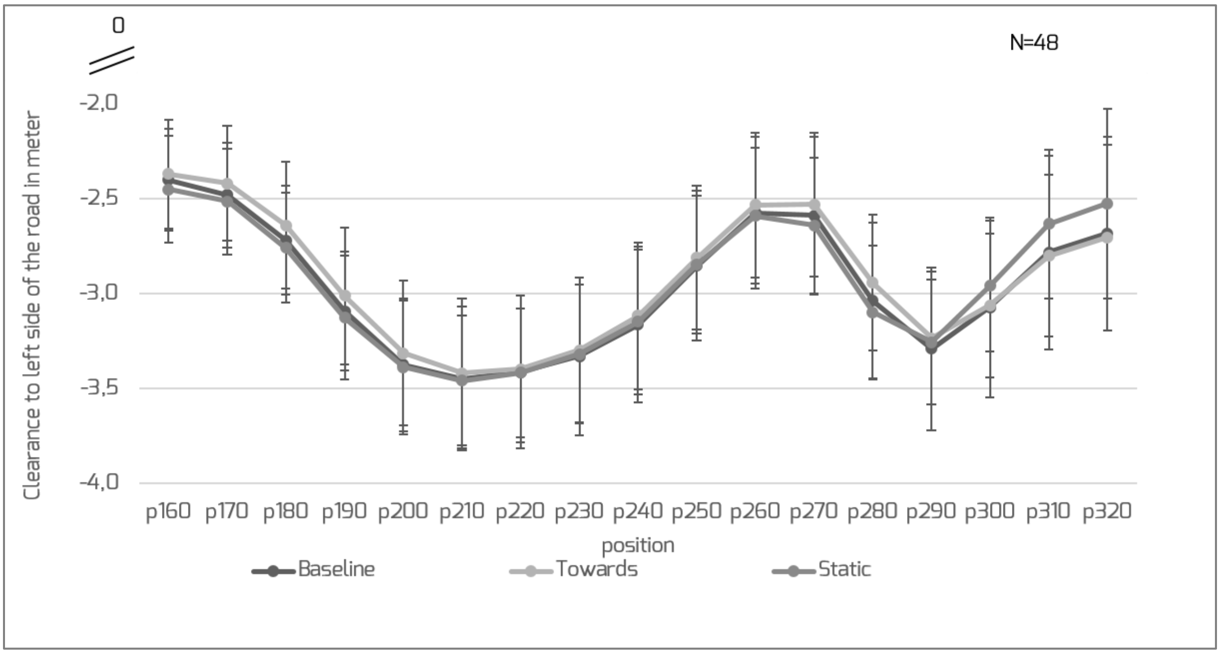


Figure 7.5: Clearance of the car to the left side of the road in meters depending on the nudging condition and the position of the driver. Negative values indicate the car driving left from the reference line. Since the reference line is the left edge of the road

In order to illustrate the trajectory of the drivers along the course of the curve, figure 7.7 shows a sketch of the driven mean trajectory over all nudging conditions. At p210 and p290, right before and after the peak of the curve, the distance between the car and the left edge of the road is the greatest, respectively the distance between the car and the right edge of the road is the smallest. In the peak of the curve, at p250 the distance between the car and the left edge car of the road decreases. This pattern can be seen in figure 7.7.

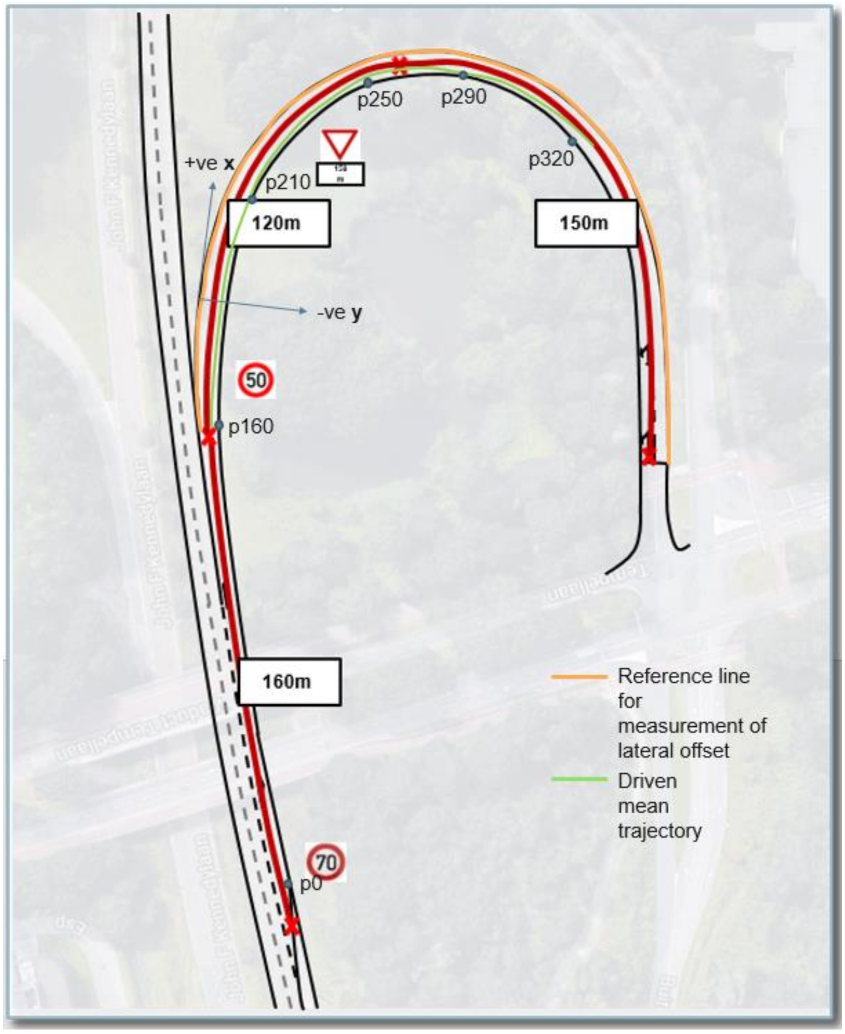


Figure 7.6: Reference line for measurement of lateral offset and driven trajectory throughout the course of the curve

Since the driven trajectory depends on the driven velocity, it is crucial to compare the mean velocities among the different nudging measures over the same stretch of the road from p160 to p320. The velocity among the conditions is depicted in figure 7.8.

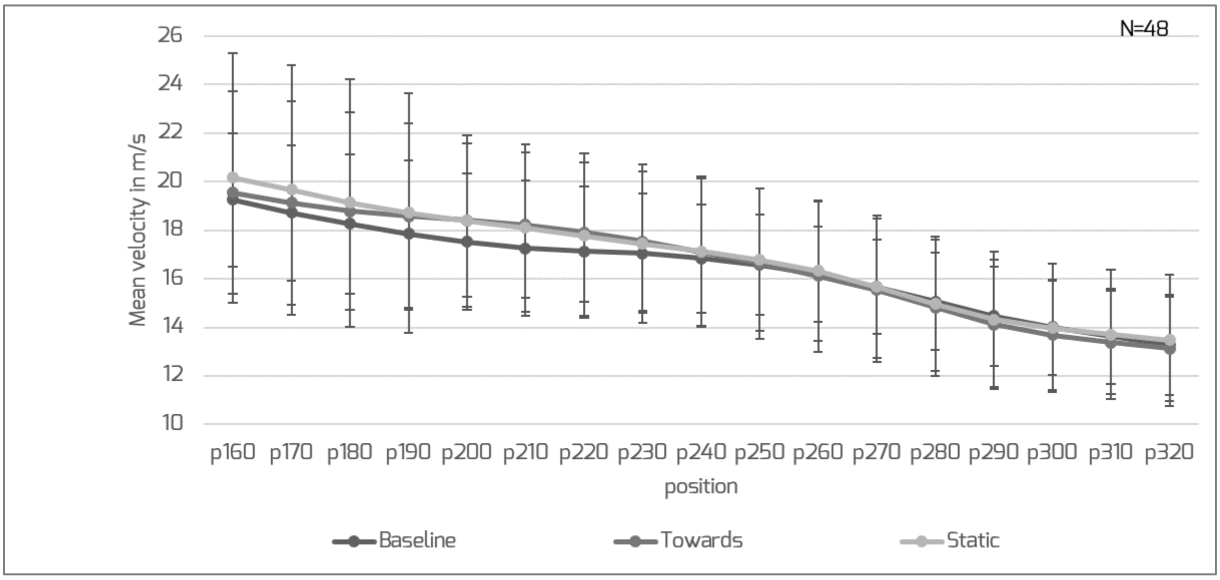


Figure 7.7: Mean velocity in m/s throughout the course of the curve from p160 to p320 among the different nudging conditions

When comparing the development of the trajectory throughout the curve with the velocity at the respective section of the exit, descriptive data shows slight differences in driving speeds from p160 to p240 among nudging conditions. From p240 on, which is right before the peak of the curve, the velocity does not differ among the conditions.

7.3.1.4 Eye Tracking

In order to check whether and how many times participants glanced at the lights of the nudging measure and the 50 km/h sign, eye-tracking data was analysed. Therefore, an ANOVA with repeated measures was calculated with the condition (3) and the object that was looked at (4), being (a) the light stimuli on the left side, (b) the light stimuli on the right side, (c) both stimuli and (d) the 50 km/h sign as independent variables and the number of glances as a dependent variable.

Data of $N = 16$ participants was feasible for further analysis. This was due to technical issues with the calibration of the eye-tracker. Results revealed a significant main effect for glances towards the light stimuli on the left($F[2, 30] = 10.16$, $p < .001$, $\eta p^2 = .40$) as well as glances towards the light stimuli on the right ($F[2, 30] = 15.74$, $p < .001$, $\eta p^2 = .51$), both sides of the light stimuli ($F[2, 30] = 20.09$, $p < .001$,

$\eta p^2 = .57$). A main effect of glances towards the 50km/h sign was not significant (F(2, 30) = .00, p = 1.000, $\eta p^2 < .01$). To examine the difference in the amount of glances between the static and towards moving lights conditions in more detail, several t-tests for dependent samples were conducted. Results revealed no significant difference between the two conditions when comparing amount of glances at left light stimuli (t(15) = -.34, p = .741), right light stimuli (t(15) = -1.06, p = .31), both sides (t(15) = -.77, p = .46) and the 50 km/h sign (t(15) = .00, p = 1.0).

Figure 7.9 depicts the amount of glances dependent on the condition and the target participants glanced at. The descriptive data shows that the amount of glances on the 50 km/h sign remained the same over all conditions. Since light stimuli were not available in the baseline condition, no glances at lights were recorded. Descriptive differences between the amount of glances of the static light and towards moving light condition exist but as reported, do not lead to a statistical difference.

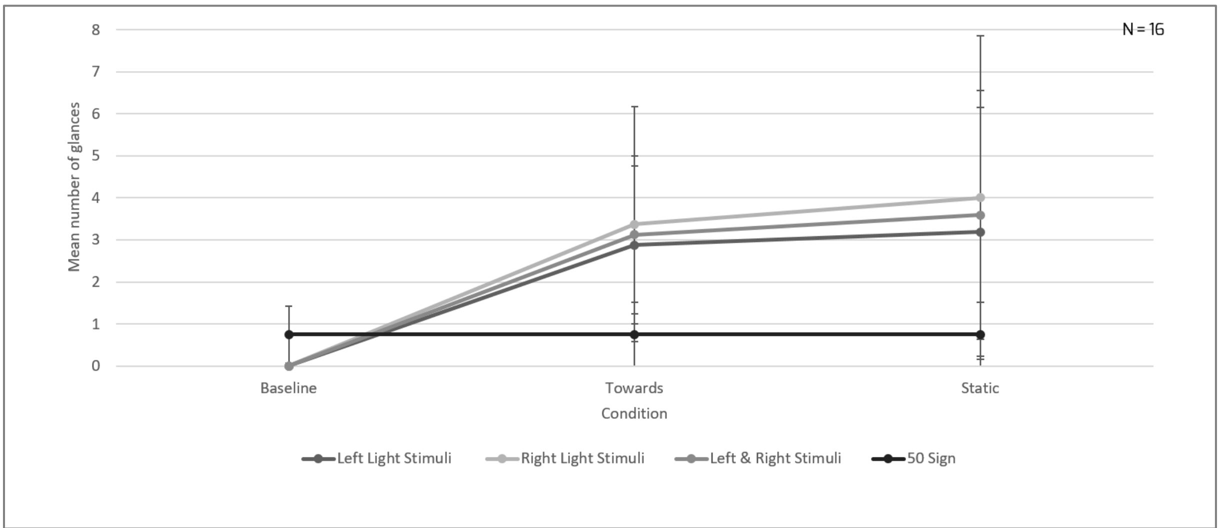


Figure 7.8: Number of glances depending on the condition and the target the participants glanced at

7.3.2 Qualitative Results

As explained in chapter 7.2.3 the study was split into two halves. The first part of the study was used in order to test the hypotheses H1a, H1b, H2a and H2b on a quantitative level and gather additional qualitative information, while the second part of the study was conducted in order to gather further information on other design aspects of the nudging measure. As this was done explorative, the gathered information was not used to test hypotheses but to get insights on how other aspects affect the perception of the nudging measure.

As described before in chapter 7.2, the test instructor asked questions after driving each of the three test trials of the first part of the study (quantitative study). These included what the participant might have observed during the drive. Results revealed that less than half of the *N* = 54 participants saw the lights (*N* = 20). *N* = 11 participants mentioned after the baseline that they did not see lights at the exit anymore.

As aforementioned, the second half of the study yields information on further possible design aspects in an explorative way. In the following, the advantages and disadvantages of the respective levels (see table 7.1 in chapter 7.2.2 for details) of the factors colour, movement, location, technology, and blinking named by participants are presented, as well as the ranking with regard to the subjectively perceived efficiency in speed reduction. The score was calculated based on the number of times a condition was named for the respective ranks. For example, if a total amount of three participants ranked the static red lights on first place, the number of times the red static lights were named on the respective ranks is *three*. This number is multiplied by five since there are five different ranks. This calculation was done for all different possible ranks of the static red lights. The results of these calculations are then summed up and represent the total score of the red static lights. A total amount of *N* = 9 participants was allocated to each factor.

7.3.2.1 Factor 1: Colour (red-off vs. amber-off vs. white-off vs. red-green vs. white-green)

When **lights moved towards the driver** and different colours were tested, some of the *N* = 9 participants reported to perceive the *red lights* (red-off) to have an alerting and warning character (*N* = 6), to target speed reduction (*N* = 3), and to be a safe measure (*N* = 2) with a clear message (*N* = 1). *N* = 2 participants felt no negative impacts because of the lights. As those aspects can be seen as advantages of the red lights, some disadvantages were named as well. *N* = 4 participants reported negative impacts, such as stress or distraction. Please note that these statements were replies to an open question and that multiple statements were possible per participant.

The *orange lights* (orange-off) were perceived as warning or alerting as well (*N* = 3) and were also seen to target speed reduction (*N* = 3). *N* = 1 participant mentioned that the orange lights had a guidance function as well. Moreover, *N* = 1 participant reported that the lights had no negative impact such as stress or distraction. The main disadvantage named by participants was that the lights do not have a clear message or signification (*N* = 5). In this context, *N* = 1 participant found the orange lights to be not alerting and too neutral.

Participants perceived the *white lights* (white-off) to have a warning or alerting character (*N* = 3). *N* = 1 participant reported the white lights to target speed reduction and *N* =3 participants perceived to lights to have a guidance function. Besides that, people mentioned a positive impact of the lights in terms of being pleasant and improving the driving feeling. Disadvantages of the white lights were that they did not have an impact on speed (*N* = 1), they were perceived as too neutral and not alerting enough (*N* = 1) or the message of the lights was not clear enough (*N* = 2). *N* = 1 participant reported negative impacts such as stress and distraction.

Lights that *turned green* when the speed limit was reached were perceived to reward the desired behaviour (N = 3). *N* = 2 participants saw no sense in this measure. *N* = 1 participant reported that lights that *turned off* when the driving speed was reached lack a guidance function in the moment of lights turning off.

Again as aforementioned the score of the structured questionnaire was calculated based on the number of times a condition was named for the respective ranks. The overall ranking in the structured questionnaire revealed that people prefer *orange-off* lights (score = 26) over *red-off* lights (score = 22), followed by red-green (score = 21) and orange-green lights (score = 21) for speed reduction. Participants found the white-off lights to be most ineffective for speed reduction (score = 15). The results of the structured questionnaire regarding the factor colour (F1) with lights moving towards the driver are attached in annex A.1.

When **static lights** and different colours were tested, of the *N* = 9 participants, some reported in response to the open question on their subjective opinion regarding the lights that the *red lights* had a warning and alerting character (*N* = 6) that they target speed reduction (*N* = 6), have a clear message (*N* = 4) and are seen as a safe measure (*N* = 2). One participant perceived the red lights to have a guiding function as well. Again, participants named negative impacts, such as stress and distraction (*N* = 4). Some participants criticized the red lights by reporting no guiding function (*N* = 1) and no clear message (*N* = 1). *N* = 1 participant saw no sense and necessity in the red lights.

Orange lights were found to have a warning and alerting function (*N* = 4) and target speed reduction (*N* = 3). Participants perceived a positive impact in terms of an improved driving feeling and experienced the orange lights as pleasant (*N* = 3). *N* = 2 participants reported the function of the lights as guidance. *N* = 1 participant considered the orange lights a safe measure. Moreover one participant mentioned that the lights have no negative impact. Disadvantages named by participants are negative impacts, such as stress and distraction because of to the orange lights (*N* = 1), no sense and necessity of the orange lights (*N* = 1).

Participants perceived a positive impact of the *white lights* (*N* = 2) and described a guidance function (*N* = 3). *N* = 2 participants liked that the white lights did not induce stress or distracted them. *N* = 1 participant found that the white lights were not necessary.

Advantages of the lights that *turn green* when the target speed is reached were reported to be a warning function (*N* = 1), a safe measure (*N* =1) and to have a positive impact on driving feel (*N* = 1). Participants reported also disadvantages like negative impact in terms of stress or distraction (*N* = 2) and the lack of a clear message (*N* = 3).

N = 1 participant reported that the lights that *turn off* when the target speed is reached have a clear message. *N* = 1 participant did not see a necessity in the measure. The results of the structured questionnaire regarding the factor colour (F1) with static lights are attached in annex A.2. A detailed interpretation of these qualitative and explorative results is given in chapter 7.4.

Again as aforementioned the score of the structured questionnaire was calculated based on the number of times a condition was named for the respective ranks. The overall ranking revealed that people prefer red-green lights (score = 35) over orange-green lights (score = 33), followed by red-off (score = 28) and orange-off lights (score = 25) for speed reduction. Participants found the white-off lights to be most ineffective for speed reduction (score = 14).

7.3.2.2 Factor 2: Movement (towards the driver vs. static vs. with the driver)

Of the *N* = 9 participants, few assessed the lights moving towards the driver as warning and alerting (*N* = 2) and effective for speed reduction (*N* = 4). Moreover, the towards moving lights were perceived to have a clear message (*N* = 1) and to have a positive impact in terms of being pleasant and calming (*N* = 2). Besides that, *N* = 1 participant reported a guidance function of the lights. While *N* = 1 participant experienced no negative impacts, such as stress, danger or distraction, *N* = 2 participants reported negative impacts because of the lights.

Lights moving with the driver were rated as warning and alerting (*N* = 3), effective in reducing driving speed (*N* = 2) and safe (*N* = 1). As disadvantages, few participants felt no or a reversed impact on speed acceleration (*N* = 2) and negative impacts, such as stress, distraction and alarm (*N* = 2). *N* = 1 participant reported no guidance function.

If addressed at all, the static lights were perceived as warning and alerting (*N* = 1) and effective in speed reduction (*N* = 1). Besides that, participants assessed the lights to have no negative impacts, such as stress, danger or distraction (*N* = 2) but to have a positive impact (*N* = 1), to be a safe measure (*N* = 1), and to have a guidance function (N = 1). Participants reported disadvantages such as no clear message (*N* = 2), no or a reverse impact on speed acceleration (N = 1) and negative impacts, such as stress, distraction or alarm (N = 2). N = 1 participant assessed the lights to be too neutral and not alerting. The results of the structured questionnaire regarding the factor movement (F2) are attached in annex A.3. A detailed interpretation of these qualitative and explorative results is given in chapter 7.4.

Again as aforementioned the score of the structured questionnaire was calculated based on the number of times a condition was named for the respective ranks. The overall ranking revealed that for speed reduction people prefer the lights moving towards the driver (score = 22) over static lights (score = 16), followed by lights moving with the driver (score = 10).

7.3.2.3 Factor 3: Blinking (blinking vs. no blinking)

The non-blinking lights were assessed by N = 9 participants and were reported to have no negative impact, such as stress, danger or distraction by some (N = 5) and to function rather as a road guidance (N = 5) than having different function. Moreover, participants assessed them to target speed reduction (N = 2), to be warning or alerting (N = 1), and to have a positive impact in terms of being pleasant or lead to an improved driving feeling (N = 1). Only N = 1 participant felt that the lights had no impact on driving speed.

On the one hand, blinking lights were reported as warning and alerting (N = 4) and participants named that they have a guidance function (N = 2) as well as a clear message (N = 1). On the other hand, participants reported negative impacts by the blinking, such as stress, distraction or the feeling of not being safe (N = 3), no clear message (N = 1), no impact on speed (N = 1) and no sense and necessity (N = 1). The results of the structured questionnaire regarding blinking (F3) are attached in annex A.4. A detailed interpretation of these qualitative and explorative results is given in chapter 7.4. A detailed interpretation of these qualitative and explorative results is given in chapter 7.4.

Again as aforementioned the score of the structured questionnaire was calculated based on the number of times a condition was named for the respective ranks. The overall ranking revealed that for speed reduction people prefer red blinking lights (score = 26) and red non-blinking lights (score = 26) equally over white blinking lights (score = 20), followed by white non-blinking lights (score = 18).

7.3.2.4 Factor 4: Technology (spots vs. strips)

For the comparison between the two technologies spots and stripes. Some of the *N* = 9 participants described the spots to have a warning and alerting character (*N* = 2), no negative impact, such as stress, distraction or danger (*N* = 1), a guidance function (*N* = 2) and a positive impact as the lights contribute to a pleasant and better driving feel (*N* = 1). *N* = 1 participant reported that the lights looked like regular street lights. *N* = 1 participant reported no or a reversed impact on driving speed. Another participant named negative impacts, such as stress, distraction and alarm.

Strips were experienced as warning and alerting (*N* = 1) with "no negative" (*N* = 3) but positive impact (*N* = 2). At the same time participants assessed the stripes to be too neutral and not alerting (*N* = 3) and to have negative impacts, such as stress, distraction, or alarm (*N* = 1). The results of the structured questionnaire regarding the factor technology (F4) are attached in annex A.5. A detailed interpretation of these qualitative and explorative results is given in chapter 7.4.

Again as aforementioned the score of the structured questionnaire was calculated based on the number of times a condition was named for the respective ranks. The overall ranking revealed that people prefer red-off strips (score = 14) over orange-green spots (score = 13), followed by orange-green strips (score = 12) and red-off spots (score = 11) for speed reduction.

7.3.2.5 Factor 5: Location (straight vs. curve)

Of the *N* = 9 participants, some reported the lights in the curve to be warning and alerting (*N* = 3) and to have an impact on speed reduction (*N* = 2), a guidance function (N = 4) and a positive impact in terms of a pleasant and better driving feeling (*N* = 5).

Few participants perceived no impact on speed (*N* = 1), felt negative impacts, such as stress, distraction or alarm (*N* = 2), or found the lights to have no clear message (*N* = 1).

The lights on the straight section of the exit were called warning or alerting (*N* = 3), a road guidance (*N* = 1), affect speed reduction (*N* = 3), and were reported to have a positive impact (*N* = 3). Some participants reported negative impacts because of the lights on the straight lane such as stress and distraction (*N* = 4) and no clear message (*N* = 3). *N* = 1 participant reported that the lights on the straight road induced habituation. The results of the structured questionnaire regarding different locations of the nudge display (F5) are attached in annex A.6. A detailed interpretation of these qualitative and explorative results is given in chapter 7.4.

Again as aforementioned the score of the structured questionnaire was calculated based on the number of times a condition was named for the respective ranks. The overall ranking revealed that for speed reduction people prefer towards moving lights in the curve (score = 25) over static lights in the curve (score = 24), followed by towards moving lights on the straight road (score = 18) and static lights on the straight road (score = 13).

7.4 Discussion

In this simulator study, we tested whether the nudging interventions derived as described in chapter 6 had an effect on altering the speed of drivers, measured by velocity and brake pedal onset. Furthermore, we explorative explored, whether an effect on the driven trajectory could be shown between the three tested nudging conditions and where the visual attention of drivers with regards to the light stimuli and the 50 km/h-sign was. Subsequent to this quantitative first part of the study, a qualitative part of the study followed, where participants were surveyed regarding their impression of different specification of the factors colour, movement, blinking, technology and location. This aimed at answering questions regarding the design of the nudging interventions in a goal-directed manner and reducing complexity of the quantitative part of the study, allowing for a systematic testing with the necessary power for a thorough statistical analysis in the first part of the study.

7.4.1 Results of the Statistical Assessment

Focusing on **velocity** data first it is worth mentioning that the entry speed did not statistically differ among the conditions, indicating comparable entry speeds at lights onset. This way differences in driving behaviour among nudging conditions are not moderated by different entry speeds. Looking at the development of the velocity the significant main effect for position shows that drivers reduce their speed in the course of the motorway exit. This can be firstly be moderated by the drivers approaching the curve and secondly by the 50 km/h-sign.

When comparing all three tested nudging conditions, the significant interaction between condition and position in the velocity data indicates that depending on the longitudinal position in the exit, a difference between conditions can be found. The descriptive data shows that with the nudging measures, the participants reduced the driving speed more; however, the main effect of condition is not significant. As the hypotheses indicate, this was not expected. ANOVA's compared the speed development and took the position of light onset into account. But according to our hypotheses, we expected the speed to develop differently over the course of the exit and not to be different in general. This result now indicates that the lights altered the driving behaviour over the course of the exit. This makes perfect sense when taking reaction times into account.

In order to examine the effects of the nudging measures in more detail and to be able to assess the hypotheses, additional ANOVAs were calculated, comparing either the baseline with the static lights condition, the baseline with the towards moving lights condition or the towards moving light condition with the static lights condition.

When comparing static lights with the baseline only in an additional ANOVA, the interaction between condition and position was significant, again indicating that a difference between nudging conditions in speed was found depending on driver's longitudinal position on the road. As descriptive values show, participants drove faster in the baseline initially, but this changed 120 m after the light onset and now participants drove faster in the static light condition than in the baseline condition. However, the difference is only few meters per second, indicating for the differences to be marginal. A possible interpretation could be that lights give the drivers a good overview of the curve, leading to a safer feeling. This is in line with the qualitative reports of the participants as described in chapter 7.3.2, including a guidance function of the lights. Moreover, qualitative data revealed that the lights were preferred when they were placed in the curve, indicating that drivers liked the additional support in the curve over the lights on the straight section of the exit. Participants named the lights in the curve in the context of guidance more often than the lights on the straight section. Moreover, they subjectively rated them to be most effective in speed reduction. This indicates that placing the lights in the curve until the vertex as done in the simulator study should be pursued further.

Next, baseline and lights moving towards the driver were compared. No statistically significant interaction between condition and position was observed. This could be due to descriptive values at p150, showing a similar pattern as the values of the static lights: After 150 m, drivers in the baseline were again slower than drivers in the towards moving lights condition by 0,6 m/s, which is slightly more than 2 km/h. It is possible that the interaction between position and condition was not significant because the crossing point of the velocity in the towards moving and baseline condition occurred at the end of the relevant section of the road, reaching up to p160. A possible explanation is that participants in the nudging conditions with lights moving towards the driver and static lights reduced their speed, so there was no need for further slowing down at later points, whereas in the baseline condition little decreasing in speed occurred, then followed by a harsher speed reduction. This could indicate a safer traffic behaviour when lights were present. This assumption is supported by the qualitative data, in which participants often mentioned that the nudging measures had a positive impact on their driving behaviour.

Looking at the results of the ANOVA comparing either the baseline with the static or the towards moving light condition, data did not reveal the expected pattern of driver decreasing the driving speed earlier in both conditions with the lights than in the baseline. Drivers did overall not slow down faster in the nudging conditions than in the baseline. Therefore **H1a**, saying that driver are going to decrease the driving speed earlier when seeing lights than in the baseline, has to be rejected. However as explained, data indicates other possible functions of the measures, such as a guidance function, leading to possibly safer traffic behaviour in itself.

In order the assess **H2a**, saying that the velocity decreases earlier in the condition with the lights moving towards the driver than in the condition with the static lights, velocities in the static light condition and the towards moving light condition were compared. Results revealed a tendency of the interaction between position and condition, indicating that the development throughout the exit differs between the two nudging conditions not significantly but marginally significant. Looking at the descriptive data, participants reduced their driving speed faster when seeing the lights moving towards the driver. Based on these results, **H2a** is conditionally accepted. Looking at the qualitative data, a similar pattern is found: Participants rated the lights moving towards the driver as most effective in reducing driving speed, followed by static lights and the lights moving with the driver as the least effective measure. This result supports **H2a** even further and indicates that the measures are most likely able to affect the optic flow.

The results of the **brake onset** give more insights and a better understanding on the results of the velocity and are discussed in the following. Brake pedal onset revealed a significant main effect for position in all analyses, indicating that participants pressed the brake pedal differently over the course of the exit. This development of the course of the motorway exit mirrors the one of the velocity.

When comparing all three tested variables besides the main effect of the position, a main effect of the condition and an interaction of position and condition can be observed. This indicates that, firstly, the brake pedal onset differs among the conditions in general. Secondly, the data reveals that participants showed different braking behaviours in the three experimental conditions, indicating a different development of braking behaviour over the course of the exit.

For the sake of further examination of the braking behaviour, additional ANOVAs were calculated as stated in chapter 7.3.1.2. Again, in all calculations, a significant main effect of position was observed. When comparing the baseline and the static light condition, only the additional main effect for condition was found. Descriptive data showed that this interaction is likely to be due to a more extreme brake onset in the baseline, starting at p80 and peaking at p150. Even though this results does not substantiate **H1b** the findings underpin the assumption that the static lights in comparison to the baseline might lead to a safer driving behaviour and save the driver from harsher braking at later points.

Looking at the comparison of the baseline and the towards moving lights, results revealed a main effect of the position and an interaction between position and nudging measure. Descriptive data showed that drivers started to brake earlier in the condition with the lights moving towards them than in the baseline condition, starting at p70 and peaking at p90. Other than the previous results of the static lights, the results of the towards moving lights substantiate **H1b**. Based on this pattern and the results of the comparison of the baseline with the static lights, **H1b** is accepted for the towards moving lights, but not for the static lights. This indicates that, based on the results of our study, the lights moving towards the driver have the largest effect on driver behaviour. As aforementioned this result is in line with the findings of the qualitative data.

In order to assess **H2b**, the brake pedal onset of both nudging conditions was compared. Results only reveal a main effect of the position, indicating that both, static lights and towards moving lights led to a similar braking behaviour throughout the course. Therefore **H2b** has to be rejected.

Since the second part of the simulator study reveals information on measures that go beyond the design of the first part of the study, the qualitative data reveal a lot of relevant information on how to improve the design of such nudging measures. Besides the aforementioned results, the qualitative data shows that participants preferred the amber and the red lights over all other colours. Since some participants criticized that the red lights are too harsh and warning as it suggests threat and danger, amber lights are seen as an effective and at the same time more moderate option. Other participants mentioned that the amber lights are ambiguous and the message is not as clear as with the unequivocal demand of the red lights. Because of this finding the effect of both, red and amber lights are examined in the field study in Eindhoven. Moreover static lights are more likely to be associated with a guidance function while blinking lights have a more alerting and warning character. This information is relevant when designing a nudging measure that targets both, speed and the trajectory. Since it was difficult to distinguish between the spots and the strips, which were used in the qualitative part as well, the results referring the technology need to be interpreted with caution.

7.4.2 Limitations and Outlook

Overall, the quantitative results indicate that nudging itself works, but the effects found in the static simulator were small. This might be due to simulator effects, such as the ceiling effect. This effect occurs when the driving situation felt too easy and safe, resulting in little perceived danger. It is possible that participants felt no real reason to slow down. Besides that it is possible that participants behaved socially-desired because they felt supervised. In order to test the effect in real-life situations, it is crucial to examine the nudging effect in the field. Moreover, the question remains whether the real benefit of this nudging solution is the speed reduction or the raised situational awareness. In order to examine this aspect a follow-up study was conducted, in which participants performed a secondary task while the nudging measures appeared. This study is illustrated in chapter 8.

When assessing where on the course the nudging effect was most prominent, it can be said that the nudging effect mainly happened between the light onset and the curve. This indicates that the absolute difference in velocity after the critical point at the 50 km/h-sign at the beginning of the curve is rather small. However, braking behaviour suggested that the nudging measure leads to a safer traffic behaviour by guiding drivers through the first part of the exit before the critical point of the 50 km/h sign, indicating the beginning of the curve. Drivers approached the exit slower and more cautiously and, if they decided that a higher speed would be safe, sped up again deliberately when they assessed the situation to be safe for it. Furthermore, with the nudging measures, drivers were not surprised by the curve, indicating that the original intention of the nudging measure in a traffic environment can be met: we want to target drivers' inappropriate traffic behaviour before the critical situation itself and before it can become critical. The testing location itself can possibly be mastered with higher speeds, but drivers slow down beforehand regardless. This is an even higher benefit of the nudging interventions: they have the potential to slow down drivers even if those do not see the immediate need for it. So the nudging interventions work at the exact location where they are intended to, which is to prevent a situation to become dangerous at all. This is in line with qualitative results, where participants mentioned to like the warning character of the interventions. As discussed, effects on situational awareness will be studied in the subsequent study described in chapter 8 to examine this indication further.

Looking at qualitative results, the qualitative questionnaires support the preference of the lights moving towards the driver as participants mentioned that they believe that the movement of the lights led to a higher speed perception. Besides that, the red colour of the stimuli was – as intended – perceived to have a warning and alerting character. Overall, the participant's assessment of the nudging measures generally showed acceptance of the nudging measure, which is a crucial factor for implementation in real-life traffic.

When asking the drivers to report what they observed during the first part of the experiment, only *N* = 20 out of *N* = 54 participants mentioned the lights on the exit. This result is interesting because even though more than half of the participants did not see the lights, change in behaviour over all participants was still found. This finding substantiates that the nudging measure is a true mindless measure that does not necessarily require attention in order to lead to a desired behaviour. Moreover since drivers had the exact same amount of glances at the 50 km/h sign among all conditions it can be assumed that the nudging conditions do not draw attention away from other important objects in the infrastructural environment, such as traffic signs.

Analysis reveal significant but at a descriptive level minor differences in trajectory among the condition. This might be due to the fact that the design on the nudging measure targets speed perception more than the trajectory. In order to examine a nudging measure that is specifically designed to target the trajectory, a follow-up study is planned in order to test the effects of a nudging measure focusing on trajectory. Therefore, chapter 9 describes this study to examine nudging drivers along a preferred trajectory further. As lights on the side of the road did not appear to have a systematic impact on the driven trajectory as reported in this simulator study, we conclude the following: a nudging measure targeting alteration of the driven trajectory should be in the driving lane itself in order to allow for a compatible spatial stimulus-response mapping, creating a dimensional overlap (type-II S-R ensemble), and leading to faster responses (Umilta & Nicoletti, 1990). Consequently, a nudge targeting the trajectory of drivers within their own lane should be displayed exactly at the position where the action is required, which is the middle of the street in this case. As nudges should be easy to avoid (see Karlsson et al., 2017) and should not contain any negative impact such as bumps, we conclude that current measures are technologically not fully developed yet (see chapter 6.1 for details). Therefore, the trajectory nudge will be specifically targeted in a simulator environment only. Please note that the development of measurement within WP3 includes the prerequisites for trajectory detection.

8 Simulator Study 2

Building on the derived nudging interventions described in chapter 6, the first simulator study was conducted as described in chapter 7. The second simulator study now focuses on the effects of the nudging measures on attention and workload of the drivers.

Paying attention to the driving task should be a driver's priority in order to avoid accidents. To carry out the driving task, many resources are needed, including perceptual and cognitive mechanisms such as working memory, executive functions and attention (Matas, Nettelbeck & Burns, 2014). In this vein, the concept of situation awareness should be taken into account. Described by Endsley and Jones (2016) situation awareness is "an operator's understanding of the situation as a whole, which forms the basis for decision making" (pp. 10-11). When the cognitive load is raised, for example by carrying out a secondary task while driving, the comprehension of the situation as a whole can be threatened. Such incomplete processing of situational components thereupon affects accurate action selection (Brown, 2002).

Lights presented in our nudging installation are likely to draw driver's attention to the road, the drivers' workload just can be raised enough to have them identify the road section as a critical situation. Based on this, desired behavioural changes can take place. However, aspects such as overstimulation can lead to dangerous consequences regarding the driving task and the driver's safety. At this point we aim at evaluating if the nudging intervention actually draws attention to the road and the driving task in order to result in safer behaviours without raising the workload more than necessary in terms of situation awareness, to prevent further unsafe behaviour.

Based on the results described in chapter 7, we evaluate the experimental conditions baseline, lights moving towards the driver and blinking lights. The latter follow the specifications of the static lights as described in chapter 7 but have the added component of blinking. This is done to control for movement effects between blinking and moving lights and have only movement added as factor to the lights moving towards the driver. Again, we choose red lights, based on the results of the qualitative study described within chapter 7. In order to evaluate the effect of attention and workload due to the light installation, a secondary task is used to determine information about the focus of attention. Platten (2012) states a reduction in secondary task activity to be a key strategy in order to reduce situational workload (see also Schwalm, Voß, & Ladwig, 2015; Voß & Schwalm, 2015). Thus, activity in a secondary task while driving can indicate how high the general workload is and therefore how much attention is needed for the driving task. We examine both a visual and an auditory secondary task, in order to rule out any modality effects. Additionally, measuring the Skin Conductance Response (SCR) may provide sensitive physiological information about the current workload while encountering the different light conditions or handling different secondary tasks (Verwey & Veltman, 1996). This spontaneous ectodermal activity measured in microsiemens (μS) is thought to reflect associated workload and the general level of arousal or effort (Edelberg, 1972).

The subsequent subchapters outline the hypotheses for testing based on the theoretical background given in chapter 3, chapter 4 and chapter 5, as well as based on the results stated in chapter 7. This is followed by the methodological approach of this second simulator study. Detailed results are given subsequently, which are discussed and interpreted in subchapter 8.4.

8.1 Hypotheses

We expect performance in the visual task to be lower when lights are present (moving and blinking) than in the baseline with no lights (**H1a**). We also expect performance on the auditory task to be lower when lights are present (moving and blinking) than in the baseline with no lights (**H1b**). We base our hypotheses on the fact that the lights would generally draw attention to the street and the driving task, away from the secondary task because stimulus driven or exogenous attention would be directed towards salient stimuli such as movements or pop-ups even when presented in periphery (Müsseler & Rieger, 2017). Further, the presence of lights creates a more complex environment that needs to be attended which would add to the perceptual load (Duncan, 1980; Lavie & Tsal, 1994). Therefore, the attention would be guided to the streets by the light intervention, because this is the location where attention for the primary task is needed. Furthermore, we expect performance on a visual secondary task to be lower compared to an auditory secondary task carried out while driving (**H1c**). This is due to multiple resource theory stating that mental resources for information processing are limited: When the same resources are shared in the same modality, this becomes more difficult (Allport, Antonis & Reynolds, 1972; Baumann, Petzoldt, Groenewoud, Hogema & Krems, 2008; Duncan, Martens & Ward, 1997).

As in the previous simulator study (chapter 7), the distinct perceptual components of the light installation are colour, blinking and movement. The red colour of the nudging measure is, like the qualitative results of the first simulator study show, commonly recognized as a major warning colour and can trigger physiological reactions and forceful actions regarding cognitive focus, emotions, and motoric behaviour which are evolutionarily rooted (e.g. Goldstein, 1942). This warning character and interpretation of both, the colour red and the blinking component, require expenditure of drivers' mental resources and would therefore be considered as system 2 nudges, according to Kahneman's (2011) nudge categorization. Hence, we assume these two components to be adding to the driver's workload. Speed perception however, occurs continuously while driving. Accordingly, the additional component of movement should not add to the driver's cognitive load when encountering the moving light condition, which is in line with the definition of a System 1 nudge. Based on this reasoning, we expect no difference between performances on the visual task while encountering blinking lights, as compared to performances on the visual task while encountering lights moving towards the driver (**H2a**). Likewise, we expect no difference between performances on the auditory task while encountering blinking lights as compared to performances on the auditory task while encountering lights moving towards the driver (**H2b**).

According to Lansdown, Brook-Carter and Kersloot (2002), mental workload is higher in dual task driving situations. Therefore, we expect the SCR to be lower when no secondary task is involved as compared to when a secondary task is carried out while driving (**H3a**). When carrying out more than one task at the same time, people are more likely to make mistakes or operate more slowly, so performance on one or more of the simultaneous tasks typically decreases. These output losses can be due to switching attention between tasks, resulting in so-called switching costs, which corresponds to higher cognitive load in dual-task compared to single-task situations (Allport, Styles & Hsieh, 1994). We further expect SCR to be lower when no lights are present than while encountering blinking and moving light conditions (**H3b**). Here, we apply the same support as for **H1a** and **H1b** including attention being drawn to the driving task (Müsseler & Rieger, 2017) and lights creating a more complex environment, leading to an increased need for attention on the driving task (e.g. Duncan, 1980; Lavie & Tsal, 1994). Similarly to **H2a** and **H2b**, we expect SCR while encountering blinking lights not to differ from SCR while encountering lights moving towards the driver (**H3c**). This is because the additional component of movement should not – compared to the components colour and blinking – add to the driver's workload (see Goldstein, 1942; Manser & Hancock, 2007; Triggs, 1986; Wertheimer, 1912).

8.2 Methods

8.2.1 Participants

N = 36 participants (18 female, 18 male) recruited in April 2019 took part in this experiment. Participant ages ranged between 18 and 39 years (*MW* = 24; *SD* = 4.73). Each received an expense allowance of 10 € for their participation of roughly 30 to 45 minutes. Participants were unaware of the experimental goals due to the recruitment under the pretext of a cover story that they would take part in a study for multitasking in road traffic. German language proficiency on mother-tongue level (C2) was confirmed by all participants, as was normal or corrected-to-normal vision and hearing. No colour vision defects were reported. Attendees received their driver's licenses between 1998 and 2018 and reported driving an average of 5991.94 kilometres (*SD* = 7104.59) per year. All participants had a valid driver's license. An average percentage distribution of driving on 39 % urban roads, 29 % rural roads and 32 % motorway was reported.

8.2.2 Apparatus, Task & Stimuli

As the simulator study described in chapter 7, the experiment took place in the static driving simulator of ika in Aachen. The experimental set-up and technical materials used was the same as described in chapter 7.2.2, added with the system for measuring the SCR and the equipment for the auditory secondary task. For efficiency reasons, we only mention the additional materials here. The simulation was the same as in the first simulator study, with the exception of blinking lights being included and static lights being excluded as independent variable.

For measuring SCR, the ProComp5 Infiniti™ (Biograph Infiniti Software Version 6.2 Deutsch run on Windows 10) with two electrodes attached to two fingers was used. Additionally, two speakers (Logitech S-100 Black, 2.6W RMS) attached left and right behind the driver's seat were used for the auditory secondary task. This task was modelled via PsychoPy 3.0 and operated on a Dell Latitude 3340 with Windows 10. The setup is illustrated in figure 8.1. Rees, Frith and Lavie (2001) served as the basis for this task. They used a similar task for attention evaluation purposes in dual-modality situations where visual stimuli were supposed to be ignored while carrying out the auditory task (see also Taylor & Thoroughman, 2007 for frequency discriminations in dual-task settings). Since a list of words in English and with varying syllable number was used by Rees et al. (2001), we randomly presented words from a self-compiled list of 105 German nouns containing five letters to standardize spoken word length. We chose a female voice for the verbal presentation of the words. A switch between male and female voices would have made it difficult to distinguish loud from quiet words, since male voices have been found to be lower in pitch on average (Simpson, 2009). Additionally, female voices have been shown to be generally more intelligible than male voices (Bradlow, Torretta & Pisoni, 1996).

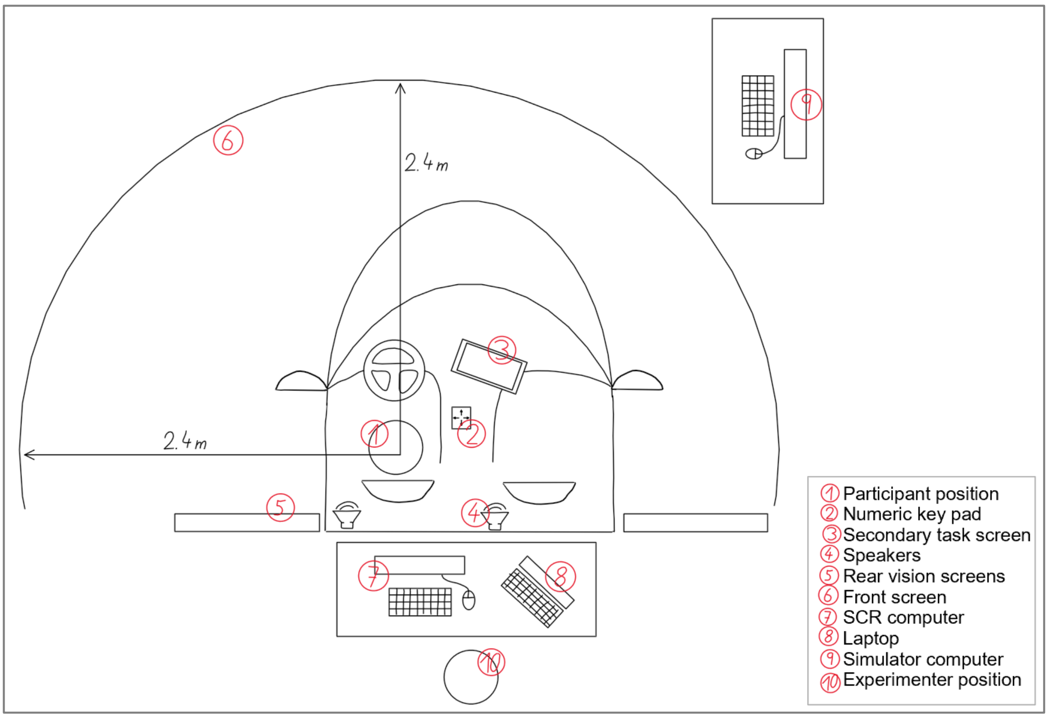


Figure 8.1: Sketch of experimental setup with the participant position, the numeric keypad and screen/speakers for the secondary task, SCR computer, and screens of the simulator setup

For the auditory secondary task, participants were asked to differentiate whether a five letter word was presented loudly or quietly. Participants were instructed to press the up arrow for a loud word (79.5 dB) and the down arrow and for a quiet word (67.5 dB) on the numeric keypad positioned next to the participant on the centre console (figure 8.1). For the visual secondary task we chose to use a simplified version of the Surrogate Reference Task (SuRT; Mattes & Hallén, 2009) modelled via VisualTask. For this visual search task, which was similar to the visual secondary task used for the cover story in chapter 7 and differed only in difficulty ("easy" task used here), 50 white circles (120 pixel circumference, 4 pixel line width) were randomly scattered across a black screen attached above the ventilation openings on the right side next to the driver's seat. One additional circle was presented larger (145 pixel circumference, 3 pixel line width) than the others. Participants were asked to determine, whether the larger circle was presented on the right or left side of the screen and enter their response by pressing the corresponding left or right key on the numeric key pad. A grey bar on the equivalent side appeared as feedback (see figure 8.2) and had to be confirmed by pressing the up-key. Although both tasks output modalities in which the secondary tasks were presented to the participant differed (visual vs. auditory), the input modality of how participants answered the trials, was kept consistent through participants responding manually using the numeric key pad. In addition, response compatibility was maintained through input keys corresponding to the input direction (up/down vs. left/right).

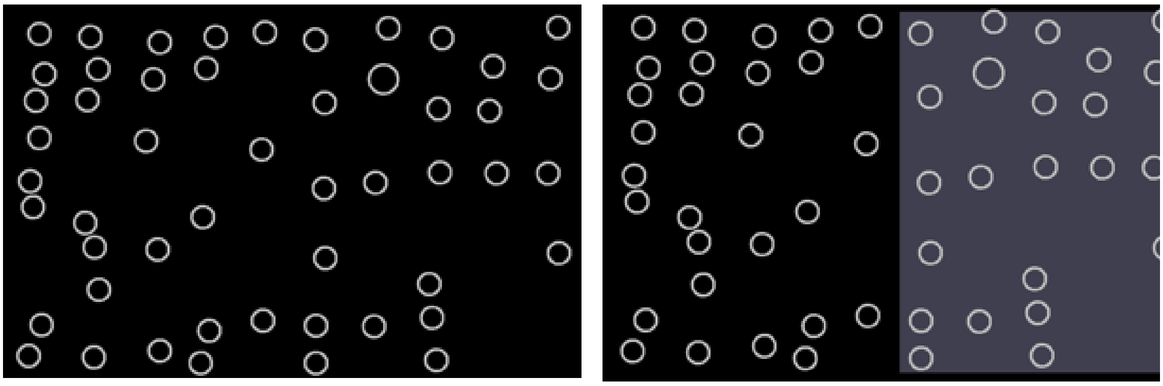


Figure 8.2: SuRT with and without key response

We formerly evaluated both tasks regarding workload using the NASA-TLX (Hart & Staveland, 1988; Appendix 2) by means of a ten-person sample (random sample of ten students). Interpretation of the NASA-TLX showed no noticeable differences in workload for the two tasks when carried out in a single-task situation. Additionally, both tasks were chosen because of their assumed realistic characteristics possibly comparable to tasks such as searching for a channel on the radio or answering phone calls via hands-free car systems.

8.2.3 Procedure

The experiment took place in April 2019. Participants were unaware of the experimental goals due to the recruitment under the pretext of a cover story that they would take part in a study for multitasking in road traffic.

Upon arrival, participants were greeted and asked to complete a pre-questionnaire regarding socio-demographic data and mobility habits. Subsequently, they were instructed to take a seat in the simulator and to adjust the seat into a comfortable driving position. We attached the two electrodes for measuring the SCR to the left hand's index and ring finger. All participants were instructed to only drive with the left hand, in order to free the right hand for multitasking situations in line with the cover story.

Participants buckled-up and had a test drive in the simulator for the purpose of familiarization with the road section and adhering to the 80 km/h speed limit, as well as the vehicle's behaviour on the simulated road. Route instructions included driving straight on the motorway until a bus stop appeared on the right, exiting the motorway right after the bus stop, which served only as a landmark, and to stopping the vehicle at the end of the curve in front of the stop sign. For both, test drive and experimental drives, a verbal reminder of the bus stop was given as it came into view (German equivalent of: "The bus stop becomes visible, remember to take the exit.") to ensure each participant took the exit as desired. Likewise, participants in the secondary task group practiced the according secondary task for about 30 s.

The testing situation required participants to complete both, driving task and secondary task (visual task, auditory task or no secondary task, depending on their assigned testing group) simultaneously, while they encountered all three light conditions in random order. Compared to the test drive, participants were directed to adhere to a speed limit of 130 km/h to ensure the driven speed was high enough to require behavioural adjustments when taking the motorway exit (e.g. slowing down or secondary task reduction) and to simulate a more risky driving situation. Each participant completed three experimental drives, encountering all three light conditions. As in experiment 1 (see chapter 7), experimental conditions with lights, the lights were always activated to ensure a controlled experiment. One drive took about 105 sec., depending on how fast drivers accelerated at the beginning and how fast the curve was taken. The experimenter sat out of participants' sight behind the simulator, controlling the SCR and secondary task programs. Recordings of SCR and secondary task data were initiated as soon as a participant began driving and terminated as soon as the participant had reached the stop sign at the end of the motorway exit. Subsequently, a post-questionnaire was administered, referencing all three driving situations and requesting reporting anything specifically noticed. The post-questionnaire was not completed after each drive, but only once at the end of the last drive to rule out priming of participants. Lastly, participants were asked to rate their subjectively perceived difficulty related to the completion of both tasks (driving and secondary task) separately on the different road sections (straight section and on the motorway exit) on a scale from 1 (German equivalent of: "not difficult at all") – 6 (German equivalent of: "very difficult").

8.2.4 Design

The independent variables in a 3 × 3 mixed design were light condition and secondary task. The three light conditions as within-subject factor comprised of no lights, blinking lights and lights moving towards the driver. For efficiency, the three secondary task conditions - no secondary task, an auditory secondary task, and a visual secondary task- varied between subjects. The dependent variables were activity in secondary tasks and SCR. Velocity measurement was researched in this simulator study as the focus of this experiment was on attention and workload based on the results of the study on velocity described in chapter 7. Participants were evenly distributed among the three different groups regarding secondary tasks, while light condition order was counterbalanced. Each experimental group included 50% male and 50% female participants.

8.3 Results

Sums of answered error-free trials per condition in the secondary tasks were calculated for each participant (count). An ANOVA with repeated measures was conducted in order to investigate **H1** and **H2**, which demonstrated a main effect of light condition, $F(2, 44) = 4.49$, $p = .009$, $\eta_p^2 = .17$. This revealed significant differences in secondary task activity between the conditions no lights ($M = 43.00$), moving lights ($M = 39.96$) and blinking lights ($M = 39.21$; see figure 8.3).

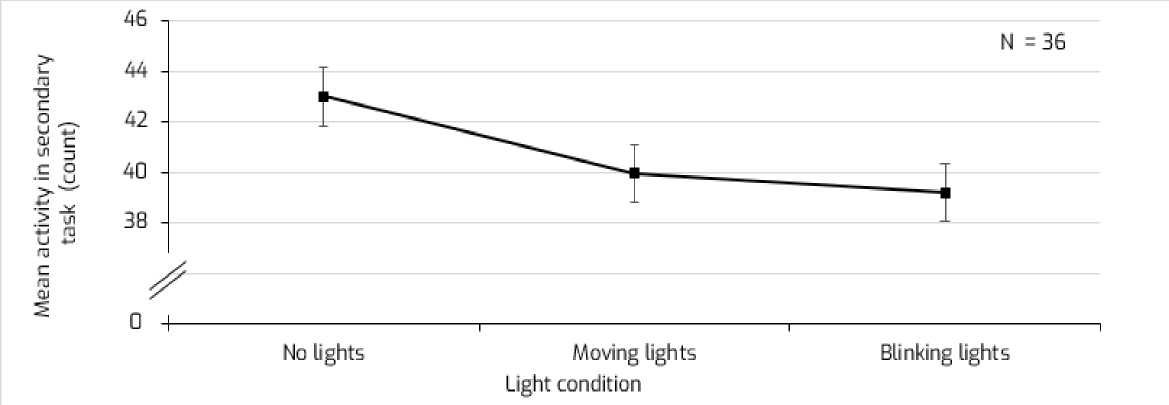


Figure 8.3: Mean activity in secondary tasks (count) as a function of light condition (no lights / moving lights/ blinking lights). Error bars depict standard error of means

Furthermore, a main effect of secondary task was found for **H1c**, $F(1, 22) = 65.86$, $p < .001$, $\eta_p^2 = .75$, pointing out lower activity in the visual ($M = 27.14$) compared to the auditory secondary task ($M = 54.31$; figure 8.4). An interaction between secondary task and light condition was not found, $F(1, 22) = 0.64$, $p > .05$.

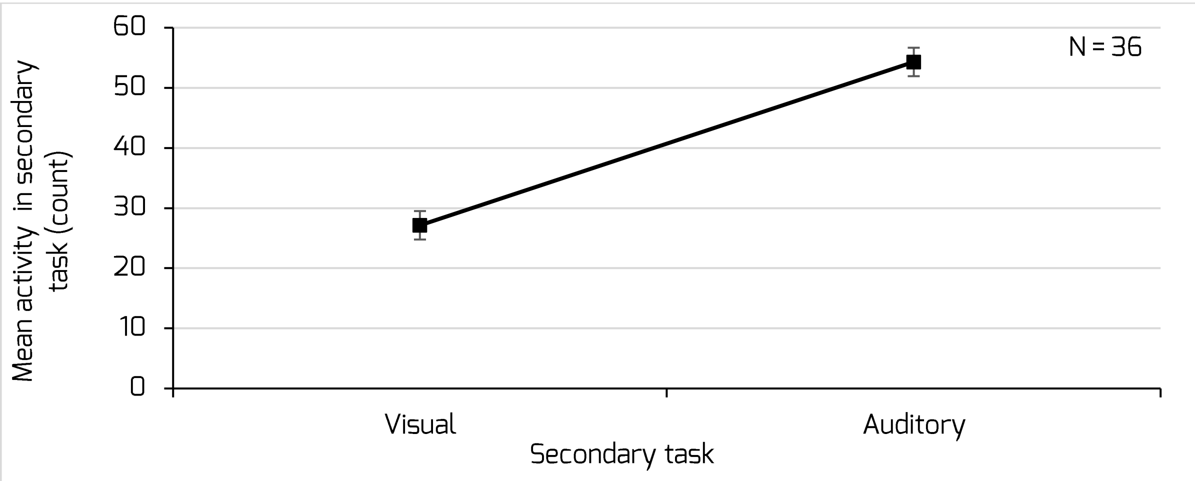


Figure 8.4: Mean activity in secondary task (count) as a function of which secondary task was carried out (visual vs. auditory). Error bars depict standard errors of means

Further analysis by T-tests for paired samples demonstrated no difference in activity between conditions with lights (blinking and moving) an no lights for the visual secondary task (**H1a**), $t(11) = 1.44$, $p > .05$. For **H1b**, a significant difference for the auditory secondary task, $t(11) = 2.36$, $p = .019$, revealed lower activity in conditions with lights ($M = 52.96$) compared to no lights ($M = 57.00$; figure 8.5). No differences in secondary task activity between the conditions of blinking and moving lights were found for the visual secondary task (H2a), $t(11) = 1.2$, $p > .05$, as well as for the auditory secondary task (H2b), $t(11) = -0.38$, $p > .05$.

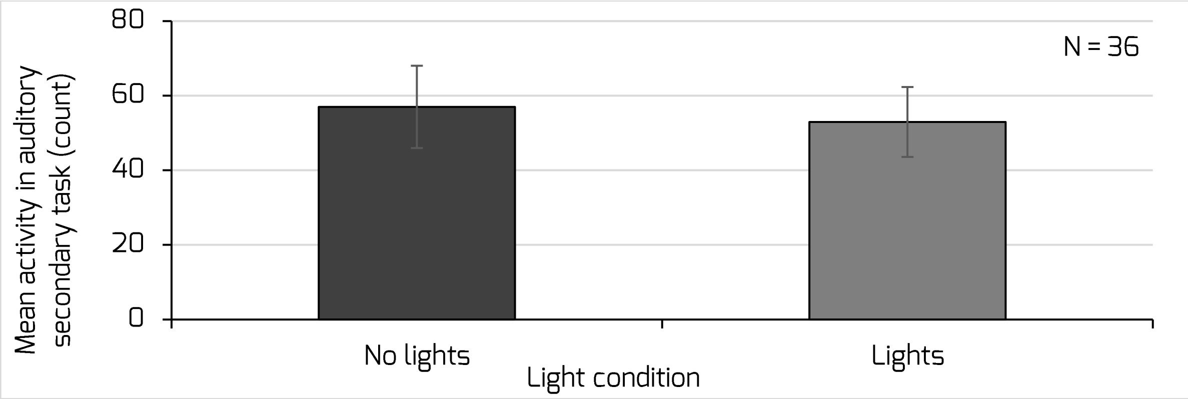


Figure 8.5: Mean activity in secondary task (count) as a function of light condition (no lights vs. lights). Error bars depict standard deviations

The SCR data was z-transformed, in order to make the data comparable between subjects, and corrected from testing situation artefacts by cutting out a small data time frame, where a loud noise popped up during one testing situation. Means for each light condition per participant in all three secondary task groups (visual secondary task, auditory secondary task and no secondary task) were calculated. We conducted an ANOVA with repeated measures to investigate **H3**, which did not demonstrate an effect of light condition (**H3b** & **H3c**), $F(2, 66) = 0.01$, $p > .05$. Further, no effect of secondary task was found (**H3a**), $F(2, 33) = 0.29$, $p > .05$. An interaction of light condition and secondary task could not be shown, $F(2, 66) = 0.41$, $p > .05$.

Further data analyses for **H3** in the form of an ANOVA with repeated measures did not reveal an effect of secondary task (with and without secondary task; **H3a**), $F(1, 34) = 0.47$, $p > .05$. T-tests for paired samples demonstrated no difference between conditions with lights and without lights (**H3b**), $t(35) = 0.03$, $p > .05$ and no difference between conditions with moving and blinking lights (**H3c**), $t(35) = 0.17$, $p > .05$.

We conducted post-hoc tests targeting further data insight for SCR. We analysed if the chronological order (driving sequence) and the different road sections affected the measurement. An ANOVA for repeated measures showed a significant main effect of driving sequence, $F(2, 66) = 50.35$, $p < .001$, $\eta_p^2 = .6$, with rising SCR from the first drive ($M = -0.68$ µS), to the second drive ($M = -0.01$ µS), until the third drive ($M = 0.72$ µS), regardless of light condition (figure 8.6).

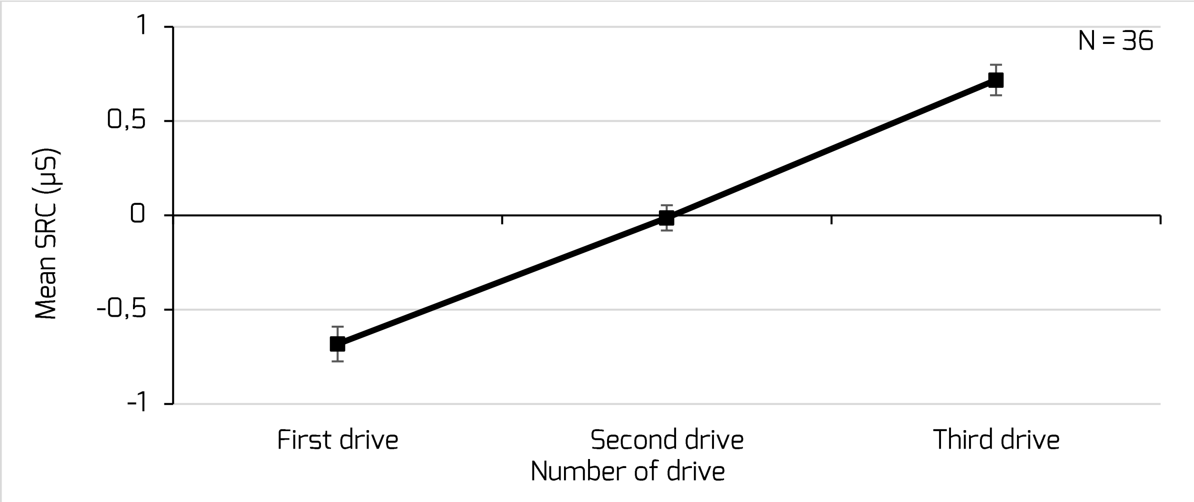


Figure 8.6: Mean SCR (skin conductance response in microsiemens) as a function of number of drive (first drive/ second drive/ third drive) in post-hoc evaluation. Error bars depict standard errors of means

A T-test for paired samples also demonstrated a significant difference in SCR, $t(35) = 3.93$, $p < .001$, showing lower SCR on the straight road section ($M = -0.09$ µS) compared to the motorway exit ($M = 0.26$ µS), regardless of light condition and secondary task (figure 8.7).

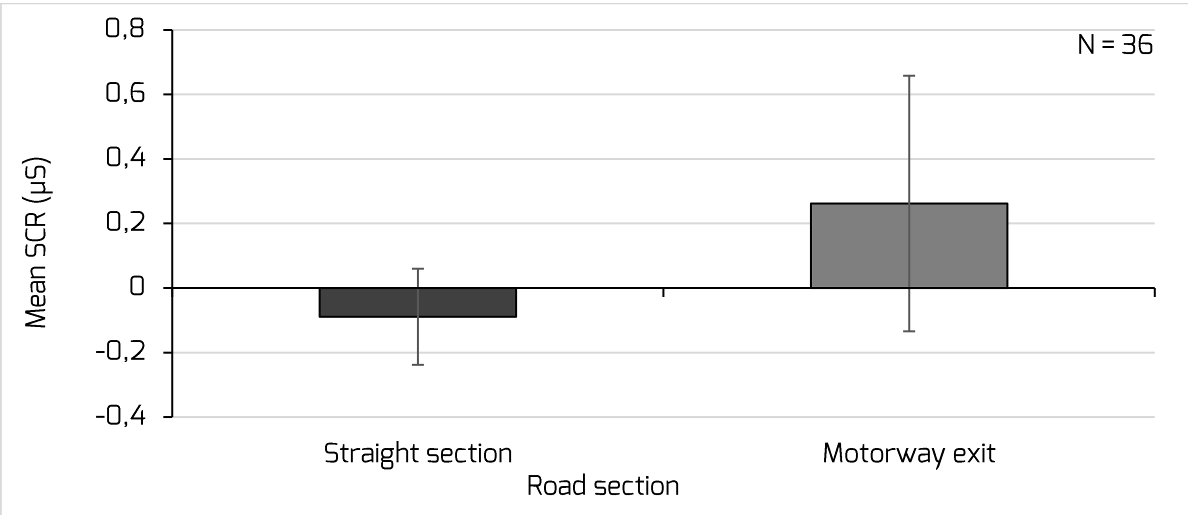


Figure 8.7: Mean SCR (skin conductance response in microsiemens) as a function of road section (straight section vs. Motorway exit) in post-hoc evaluation. Error bars depict standard errors of means

Post-questionnaire evaluations using the Kruskal-Wallis test for independent samples and ordinally scaled variables demonstrated an effect of perceived difficulty for the driving task on the straight road section, $\chi^2(2) = 5.21$, $p = .037$, between the groups with no secondary task (mean rank = 13.79), visual secondary task (mean rank = 22.96) and auditory secondary task (mean rank = 18.75; figure 8.8).

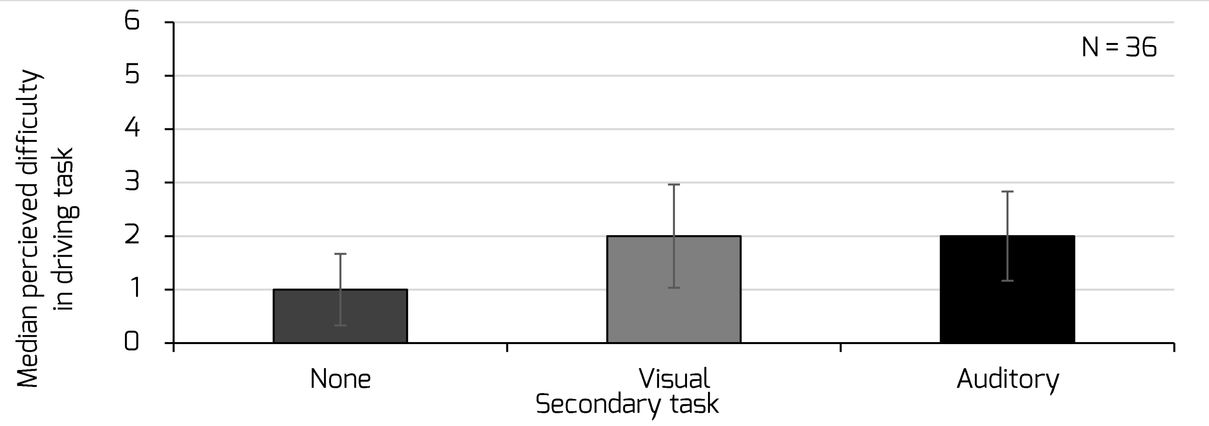


Figure 8.8: Rating of perceived difficulty of driving task of straight road section as a function of which secondary task was carried out (none/ visual/ auditory). Medians are displayed for the purpose of visualization. Error bars depict standard deviations

No effect of perceived difficulty was shown for the driving task on the motorway exit, $\chi^2(2) = 0.11$, $p > .05$. An effect of perceived difficulty was demonstrated for secondary task on the straight road section, $\chi^2(1) = 2.74$, $p = .045$, revealing higher values for perceived difficulty in the group with visual secondary task (mean rank = 14.79) compared to the group with auditory secondary task (mean rank = 10.21; figure 8.9). No effect of perceived difficulty was shown for the secondary task on the motorway exit, $\chi^2(1) = 0.3$, $p > .05$.

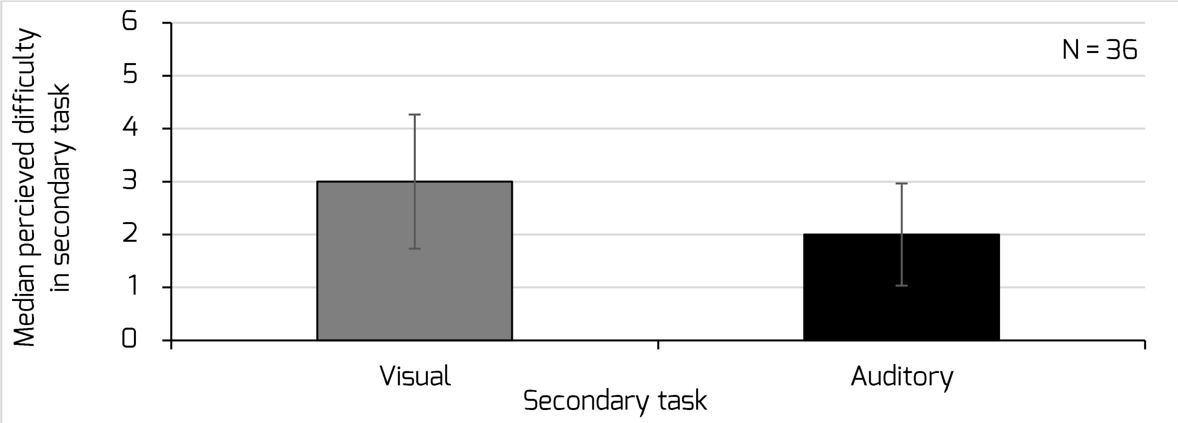


Figure 8.9: Rating of perceived difficulty of secondary task on straight road section as a function of which secondary task was carried out (visual vs. auditory). Medians are displayed for the purpose of visualization. Error bars depict standard deviations

8.4 Discussion

In this experiment we analysed the effects of a visual nudging installation regarding drivers' focus of attention and workload. Participants encountered three different light installations on a simulated motorway exit including no lights, blinking lights and lights moving along the side of the road, creating an illusion of moving towards the driver. In addition, participants either carried out no secondary task, a visual secondary task (SuRT) or an auditory secondary task (volume discrimination) while driving. Activity in secondary task was measured, targeting the evaluation of attentional orientation to the driving. SCR was measured to evaluate the workload based on physiological feedback.

H1a, expecting performance in the visual task to be lower when lights are present (moving and blinking) than in the baseline with no lights, was not confirmed by our data analysis, meaning we did not find performance on the visual task to be lower when lights were present as compared to performance when lights were not present. However, our findings did show lower performance on the auditory task when lights were present as compared to performance when lights were not present. This is in favour of **H1b**. In line with Müsseler & Rieger (2017), we can infer that the light installation in the motorway exit drew attention to the street because exogenous attention was directed to the salient stimuli away from the auditory secondary task.

Additionally, we found performance on the visual task to be lower as compared to performance on the auditory task (**H1c**). This supports our prediction that the visual secondary task would interfere more with the driving task as compared to the auditory secondary task because of modality interference (see Baumann et al., 2008; Duncan et al., 1997; Wickens, 1984). Likewise, evaluations of the participants' difficulty ratings in the post-questionnaire displayed that the visual secondary task was perceived significantly more difficult compared to the auditory secondary task on the straight road section. Taking findings from **H1c** and post-questionnaire ratings into account, we may not have found the same effect for **H1a** as for **H1b** because impairment between the visual secondary task and the driving task was too strong to reveal a relatively small effect between conditions with and without lights. Considering this along with the findings from **H1b**, it might also be the case that the visual nudging installation created a more complex environment, which needed to be attended compared to the condition with no lights (Duncan, 1980; Lavie & Tsal, 1994).

As for **H2a** (no expected difference between performances on the visual task while encountering blinking lights as compared to performances on the visual task while encountering lights moving towards the driver) and **H2b** (no expected difference between performances on the auditory task while encountering blinking lights as compared to performances on the auditory task while encountering lights moving towards the driver), no difference between performances on secondary task was shown when participants encountered blinking lights compared to lights moving towards the driver in both the visual and the auditory secondary task. Lower performance on secondary tasks in general when lights were present suggests a higher workload, resulting in a reduction in secondary task activity (Schwalm et al., 2015; Voß & Schwalm, 2015). Since no difference in performance was found between blinking and moving light conditions, we presume that a similar amount of mental workload was required for both. Therefore, the movement component in the moving light condition did not appear to add the driver's workload. This suggests that the moving light component could be seen as a System 1 component, resulting in automatic, quick and subconscious behavioural changes that did not add to the driver's cognitive load (Kahneman, 2011).

A categorization of responses from the post-questionnaire revealed that nearly all participants reported seeing the lights when asked about them. Very few people, however, were able to specify differences between the two different light conditions (blinking or moving towards the driver), suggesting that the moving component was not consciously processed (Manser & Hancock, 2007; Triggs, 1986; Wertheimer, 1912). Interestingly, participants reported their interpretation of the lights either as a guideline to help them stay on the path as directed, or correctly as a warning of driving too fast. Both interpretations suggest that participants interpreted the installation as a support to steer their driving behaviour because the installation drew attention to an inappropriate behaviour such as excessive speed (Goldstein, 1942; Sunstein, 2016). This again, supports our assumption that the components of colour and blinking may be categorized as System 2 nudges, which were actively interpreted by participants.

We did not find SCR to be lower in the group without a secondary task as compared to the groups with secondary tasks (**H3a**). We can therefore not confirm the dual-task situation involving higher cognitive load as compared to the single task situation based on the physiological data. **H3b** (we expected SCR to be lower when no lights were present than while encountering blinking and moving light conditions) was also not confirmed, as we did not find SCR to be lower when no lights were present compared to conditions with light installations. In line with **H3a** and **H3b**, we found no difference in the SCR measurements in the blinking light condition compared to the moving light condition (**H3c**). Since evaluations of SCR concerning a comparison of secondary tasks and presence of the light installation did not show any effect, we do not recommend a strong interpretation of **H3c**.

When taking a look at data trends outside of our hypotheses, post-hoc tests demonstrated rising SCR from the first to the third drive by a large effect. This effect of driving sequence may be due to several reasons. Feedback in the post-questionnaire revealed that many participants labelled the driving situation including driving with only one hand, visual analysis of the simulated environment, as well as the dual-task situation, as "demanding". It is therefore possible that anticipating a demanding task after the first and again after the second drive generally stimulated activation of the sympathetic nervous system, resulting in rising SCR with each drive (e.g. Botvinick & Rosen, 2009). The fixation of electrodes by a padded Velcro fastener could have also led to warming up of the fingers, resulting in sweat production and therefore higher SCR (Shibasaki & Crandall, 2010). Any of these or not yet considered confounding variables may have led to the SCR recordings and their analyses for **H3a** and **H3b** not being in line with effects shown for secondary task performances.

An additional post-hoc test also revealed SCR to be much higher while driving on the motorway exit compared to the straight section of the road. As mentioned before, this may be due to the generally more demanding situation of driving on a motorway exit rather than on a straight road. Similar findings were displayed by the difficulty ratings in the post-questionnaire regarding the motorway exit. Even though we did find differences in difficulty ratings concerning driving task and secondary task for the straight road section, no differences were demonstrated for the motorway exit. Another notable factor might have been the SCR electrodes' sensibility. For example, when applying pressure to the electrodes the SCR signal rises. However, this is a noise signal and no correct measurement of the persons SCR. Even though we instructed participants not to press their fingers equipped with electrodes to the steering wheel, it was neither not possible to control this behaviour while the driving task was carried out, nor to differentiate between actual and noise signal later. Participants might have unintentionally produced noise signals especially in the curve of the motorway exit, when driving with one hand became more challenging. Due to this, the SCR could have been much higher in the motorway exit. Under all these assumptions, a ceiling effect may have occurred, preventing other effects such as differences between light conditions or secondary tasks for the motorway exit to be demonstrated in data analyses (Bortz & Döring, 1995). Further studies on this topic should choose a less sensible SCR measurement technique. SCR could for example be measured at a stiller body part, which would then be less prone to noise signal compared to the hands.

With regards to testing the nudging system, the findings of this experiment regarding the focus of attention showed that encountering the visual nudging installation results in a reduction in secondary task activity in the auditory secondary task group indicating that attention was guided towards the driving task (Schwalm et al., 2015; Voß & Schwalm, 2015). In addition, no differences between performances on secondary task and SCR were found between the blinking lights and lights moving along the side of the road towards the driver. For situation awareness, this could mean that the additional component of movement did not take away further cognitive resources (Kahneman 2011). As post-questionnaire data confirmed, the light installation was interpreted as a critical signal, resulting in an observable reduction in secondary task activity for the auditory task group (Schwalm et al., 2015, Voß & Schwalm, 2015).

Concluding, we can state that, based on our findings in this simulator study, the visual nudging installation directs the driver's attention to the street. Moreover, no signs of raised workload between the two light conditions (blinking lights and lights moving towards the driver) were observed, indicating the additional component of movement does not take away cognitive capacity while ensuring situation awareness. This gives a strong indication for the system developed within MeBeSafe to be a reasonable means to nudge drivers towards adopting a safer driving behaviour by guiding their attention to the driving task.

9 Simulator Study 3

In order to examine the efficiency of a nudging measure explicitly designed for targeting trajectory, a third simulator study will be conducted. As described in detail in chapters 7.4.2 and 8.4, the trajectory nudge will be independent from the speed nudge due to workload reasons of drivers (see chapter 8) and due to observed trajectories not being affected by the speed-reducing nudging measures as researched and described in chapter 7.

In this simulator study, we will investigate the effect of a nudging intervention targeting only the driven trajectory by means of a simulated light solution creating a line to follow or to be avoided by drivers. This decision was based on the following assumption: A nudging measure targeting to alter the driven trajectory needs to be in the driving lane itself to allow for a compatible spatial stimulus-response mapping. Consequently, this creates a dimensional overlap (type-II S-R ensemble), and leads to faster responses (Umilta & Nicoletti, 1990). Consequently, a nudge targeting the trajectory of drivers within their own lane should be displayed exactly at the position where the action is required, which is the middle of the street in this case. This is strengthened by Müsseler, Aschersleben, Arning and Proctor's (2009) finding that the more peripheral the presentation of the relevant stimuli was, the less dangerous was the perception of the situation. As nudges should be easy to avoid (see Karlsson et al., 2017) and should not contain any negative impact such as bumps, we conclude that current measures are technologically not fully developed yet (see chapter 6.1 for details).

The design of the nudging measure is based on the findings of Müsseler et al. (2009), showing that in a natural (car-driving related) scene, people tend to avoid negatively valenced stimuli like e.g. a stimulus looking like a person/child to run onto the street any minute, since they lead to a dangerous perception of the situation. This is generally seen as a remarkable finding, since people usually tend to react faster and with less errors when the location of the stimuli and the location of the response overlap (reacting towards the location of the stimulus). This mapping is then called compatible. If no overlap exists, the mapping is called incompatible, resulting in more errors and longer reaction times. This phenomenon is called the *compatibility effect* (Kornblum, Hasbroucq & Osman, 1990). Against this backdrop, the results of Müsseler et al. (2009) show a reversed compatibility effect that exists when the stimuli has a negative valence.

As the colour red is frequently used in traffic in order to induce caution or to stop the driver (see e.g. stop-signs, red light in traffic lights), red can be seen as a predominantly negatively valenced stimuli. These associations are also found in the first simulator study (see chapter 7.3.2), in which participants assessed the red lights as warning and alerting, more than any other of the tested colours. Besides that, qualitative results of the first simulator study revealed that blinking lights are more likely to be associated with a warning function than static lights. Based on these findings, the colour and the blinking rate of the lights can be used in order to create an alerting and therefore negative valenced nudging measure.

We expect drivers to follow a certain trajectory more, based on their entry speed (pre-set via ACC). The faster the pre-set entry speed, the more likely are people to follow the race line, which cuts the curve and keeps radial forces as low as possible (**H1a**, for details please see chapter 4.2.2). The slower the entry speed, the more unlikely are they to follow any pre-set trajectory(**H1b**).

With respect to the results of Müsseler et al. (2009) and the findings from the first simulator study, three hypotheses are formulated: Since red lights on the road are associated with danger and are sometimes even perceived as threatening (see chapter 7.3.2) and people tend to avoid (such) negative valenced stimuli since it leads to a dangerous perception of the situation (Müsseler et al., 2009), it is expected that drivers will follow the green light stimuli and will avoid the red light stimuli (**H2**).

Once people have found an obstacle such as a construction site being on their driving lane, they will follow the trajectory nudge more often in subsequent trials than participants who have not encountered an obstacle as reason for the trajectory nudge

(**H3**). This explorative hypothesis is constructed due to the instruction of participants to drive as safe as possible and gives people a reason for their behaviour, creating a mindful or system-2 nudge (for details, see Karlsson et al., 2017).

9.1 Methods

9.1.1 Participants

A minimum of *N* = 36 participants is planned to be tested in this simulator study. It will be ensured that they have not participated in a MeBeSafe simulation before and have not been involved in the project in order to have the same starting conditions for every participant. As in the simulator studies described earlier in this deliverable, we will recruit a well-balanced sample.

9.1.2 Apparatus, Task & Stimuli

The planned study is going to be conducted either in the static simulator at ika with the same hardware setup as described in chapter 7.2.2, or in the dynamic simulator at ika, consisting of a hexapod on y-table an Nvidia 360° projection. The final decision on which simulator to use is made once the simulation itself is implemented.

The task of the participants will be to drive on the motorway and taking the same exit as used in the previous two simulator studies. Since the cruise control is activated to ensure the driver's speed is comparable among participants, their only task is to steer. The driving speed for all drivers is set to 60 km/h, 90 km/h, or 120 km/h (randomized over participants) in order to exclude any effects resulting from different driving speeds. They will be instructed to drive as safe as possible. In order to avoid possible simulator effects of driving more riskily in a simulator situation than in real traffic, drivers will be instructed that they will receive an additional financial reward when they belong to the safest drivers of the sample. This way, we expect them to be more likely to follow the trajectory nudge.

The stimulus will be a line on the road, simulating a line to follow, in three different curve radii (big radius on the outer edge of the curve, race line that cuts the curve, and following the middle of the road, resulting in higher lateral forces, which are controlled due to the set ACC). As an additional factor, the stimulus will be either red (negatively valenced stimulus) or green (positively valenced stimulus). Furthermore, some participants (between subject factor) will presumably see an obstacle in the curve, which is not interfering with the to-be-nudged trajectory.

9.1.3 Procedure

9.1.4 Design

The independent variables in a 3 × 3 × 2× 2 mixed design will be trajectory condition (within factor: big radius, race line, and following the middle of the road), entry speed (within factor: 60 km/h, 90 km/h, and 120 km/h), colour (within factor: red and green stimulus), and obstacle (between factor: obstacle and no obstacle)..

The dependent variable in this simulator study will be the lateral offset (dy) to the side of the road, steering wheel angle and brake onset.

9.2 Outlook

The simulator study will be conducted in September 2019 within WP3. The results will most likely be published as part of the subsequent deliverable 5.4. As described in this chapter and in chapter 7.4.2, the technology used for the trajectory nudge is not fit for field testing at this point but the results will provide valuable insights for future goal-directed product-development processes for enhancing road safety in certain locations.

10 Monte Carlo Simulation/Virtual Modelling

This subchapter presents the results of the computer simulations investigating the potential safety impact of an infrastructure nudge. The simulation follows the Monte-Carlo approach as described by (Kates, Jung, Ebner, Gruber, & Kompass, 2010; Helmer, Neubauer, Rauscher, Gruber, Kompass, & Kates, 2012; Luttenberger et al., 2014). The simulation is dedicated to the motorway exit in Eindhoven, for which the nudging system is going to be applied in the field test. The conducted simulation studies cover the deceleration before the motorway exit curve as well as driving in the exit curve. In the following, the method as well as the results are described.

It is important to note that all results presented in the following depend on the applied models and assumptions. The models and assumptions have been decided and implemented up to the best knowledge available at the point of time when the studies have been conducted. In the real world, the outcome might differ from the reported values in case assumptions are not met or the models turn out to be inaccurate. When referring to the results, the assumptions and limitations of the simulation studies must be taken into account.

10.1 Scope

The objective of the computer simulations is to investigate the potential impact of the infrastructure nudge in terms of traffic safety. The second objective is to provide information for the technical development of the infrastructure nudge. The first step for the computer simulation is to get a deeper understanding on the accident situation at motorway exits in order to set up the simulation in a correct manner.
Therefore, the German accident database GIDAS (Seek, Gail, Sferco, Otte, Hannawald, Zwipp, & Bakker, 2009) has been analysed. In order to identify the relevant accidents the following filter criteria have been applied:

- Road type: Motorway;
- Only passenger cars;
- Curve radius < 500 m;

- Consider only passenger cars build from 1990 onwards and equipped with ESC.

The filter criteria narrowed the 732 motorway accidents in GIDAS down to 20 cases. The 20 cases have been further analysed in detail regarding their relevance for the infrastructure nudges. Here, it must be taken into account that an accident is often not the result of one single cause but of several causes. This makes it sometimes difficult to decide whether the accident is of relevance or not. The detailed analysis has led to 14 accidents that are possibly relevant for the infrastructure nudge. Out of the 14 cases 10 accidents are considered as definitely relevant for the infrastructure nudge.

Figure 10.1 provides an overview of the reported accident causes for the identified relevant accidents found in the GIDAS accident database. For most of the accidents velocity in combination with the given environmental conditions is reported as the main cause of the accident. An error in the trajectory is only reported once as main accident cause. The same applies to driver impairment, technical failure or navigation failure.

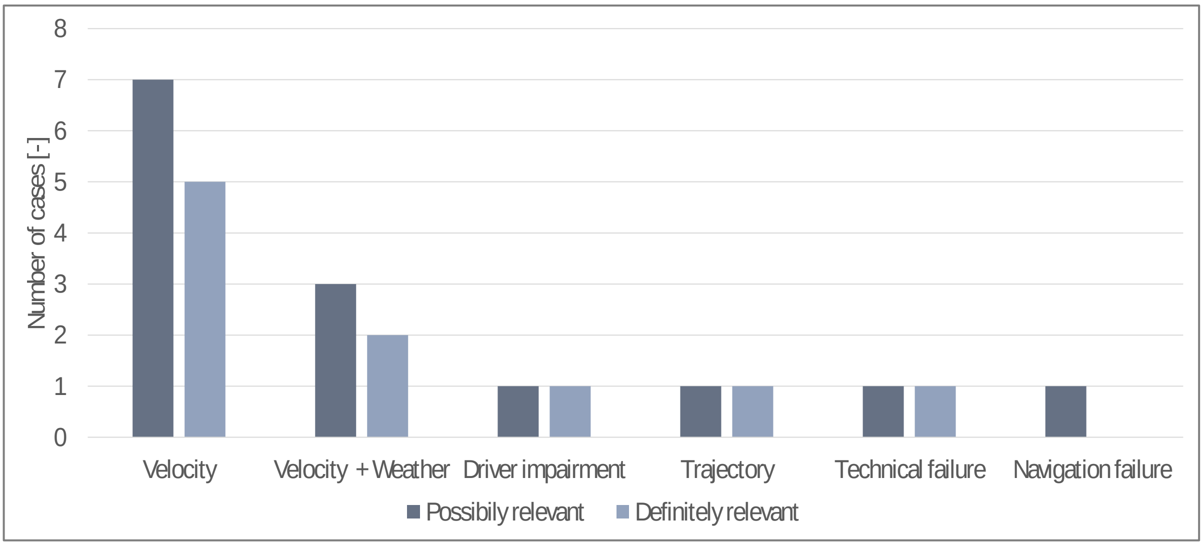


Figure 10.1: In GIDAS reported accident causes for accidents at motorway exits

The analysis of the reported accident velocity and the curve radius, at which the accident occurred, supports this finding. In at least 7 accidents, the calculated lateral acceleration is above 7 m/s² (see figure 10.2). This is, according to Schimmelpfennig and Nackenhorst (1985), above the driving experience of normal drivers.

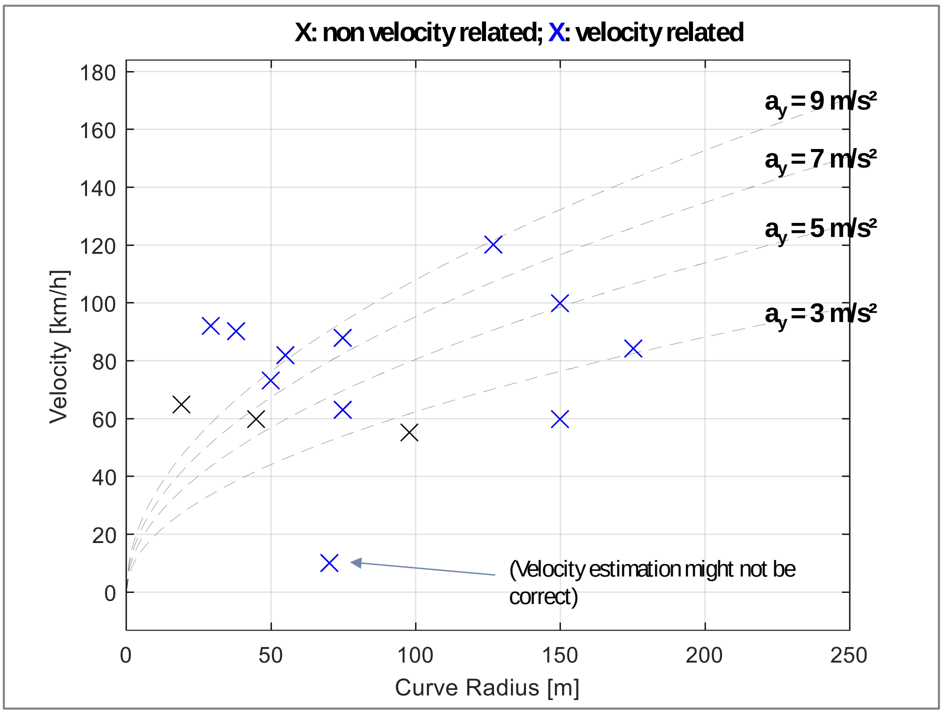


Figure 10.2: Overview on reconstructed accident speed and curve radius for motorway collisions in GIDAS

The analysis of the accident data implies that the focus of the simulation studies should be on speed related accident in the curve. This aspect is dealt in the main part of the computer simulation study.

Before the focus is set on the speed related accidents at motorway exit curves, the deceleration behaviour of vehicles prior to the curve is investigated. Here, the question is whether different deceleration profiles of a predecessor lead to more accidents with the following vehicle.

10.2 Simulation Approach

The taken approach follows the stochastic traffic based simulation approach for the impact assessment. In this approach, synthetic cases in the relevant conflict type are simulated in order to determine the likelihood of an accident. The starting conditions of each simulated case are randomly selected from pre-determined input distributions (see chapter 4.2.4.4) (Kates et al., 2010; Helmer et al., 2012;

Luttenberger, 2014). Afterwards the cases are simulated by means of a simulation tool. The simulation tool consists of different sub-models that are added and required in order to determine the vehicle movement, the driver reaction and to represent environment.

The effect of a technology is derived by means of a comparison between the baseline simulation and the treatment simulation(s). In the baseline, the infrastructure nudging system is not present, whereas for the treatment simulations the effect of the nudging system is taken into account. For both conditions at least 5 iterations à several thousand simulation runs are conducted. The exact number of simulation runs depends on the likelihood of the relevant events – in these cases collision with the predecessor or a road departure – as well as of the strength of the by the nudge induced effect.

A key component in the chosen simulation approach is the driver behaviour model. In contrast to the other impact assessment approach, which re-simulates real world accident situations, the chosen approach has no predefined trajectory for the traffic participant. Therefore, the trajectories must be determined by one of the models in the simulation. This model is typically the driver behaviour model, which defines how the virtual agent (combination of vehicle and driver) reacts towards a given situation.

In the following, the selected simulation tool, the applied driver behaviour model and the consideration of the infrastructure nudge in the simulation are described in more detail.

10.2.1 Simulation Tool

For the simulation of the infrastructure nudge two simulation tools have been considered. The first simulation tool is openPASS (Dobberstein, Bakker, Wang, Vogt, Düring, Stark, Gainey, Prahl, Müller, & Blondelle, 2017). The second simulation is a dedicated implementation in MATLAB 2015b. For both simulation tools the analysed motorway exit has been implemented (see figure 10.3) in order to investigate the advantages and disadvantages of each tool.

Figure 10.3: Visualization of curve in openPASS

The advantages of openPASS are that it offers a fast simulation, a 3D visualization, a sophisticated driver behaviour model with major focus on the longitudinal traffic and complex models for the environment and surrounding traffic. The advantages of MATLAB base on the fact that it can be used in the rapid prototyping tool. Therefore, this approach allows to adapt the simulation and / or the included models quite easily to a specific use case. However, the used driver behaviour model for the interaction between is less sophisticated. Furthermore, the applied MATLAB simulation tool focuses on simulation for a less complex traffic situation with only few traffic participants. Both tools use a single-track vehicle model. The parameters of the vehicle model are kept constant during the simulation in order to avoid additional parameters that influence the simulation outcome.

Considering the requirements of the analysis of the infrastructure nudging system in the end the MATLAB tool has been selected. The main criterion for this choice has been the flexibility of the tool, since different open issues regarding the best approach for the simulation and the driver behaviour model existed in the beginning of the project. The MATLAB tool allows to investigate different approaches in an easy and quick manner. The resulting drawbacks in terms of simulation time and limited complexity of the scenarios have been accepted. However, the simulated scenarios (deceleration behaviour on the straight and curve driving) are rather simple in terms of their design and consideration of surrounding traffic. Thus, the drawbacks are less relevant in this specific case. For a later and more extensive application of the simulation after MeBeSafe, a simulation dedicated Software like openPASS would be the better choice – in particular in terms of simulation time.

10.2.2 Driver Behaviour Model

The driver behaviour model has been selected according to the purpose of the simulated scenario. In the first study, which focuses on the deceleration behaviour, a driver behaviour model is required that focuses on the vehicle following behaviour. Here, the IDM driver behaviour model of Treiber (2000) is applied.

For the second study, the focus is on driving the curve and an adequate speed adaption related to curve. The basis for the applied model is the driver behaviour model for lateral control developed by Salvucci (2006). The Salvucci control model uses two points to determine the required steering angle. The first point is the "near point" in order to determine the vehicle's position relative to the centre of the lane. The "far point" is used to determine the curvature of the upcoming road section.

For the simulation in this study, the Salvucci model has been extended. The extensions are related to two aspects. The first aspect has been related to an improvement of the curve cutting behaviour of the simulation agents (combination of virtual driver and vehicle). The second aspect covers the longitudinal behaviour model, which controls the speed based on the expected lateral acceleration within a certain preview distance. Furthermore, the parameters of the Salvucci model were optimized by means of the available studies from RWTH Aachen (real world measures by ISAC and simulator study by ika). For this purpose, evolutionary optimization algorithms have been applied. By means of the optimization a similar flow of velocity over position could be achieved as measured in the driving simulator study, see figure 10.4.

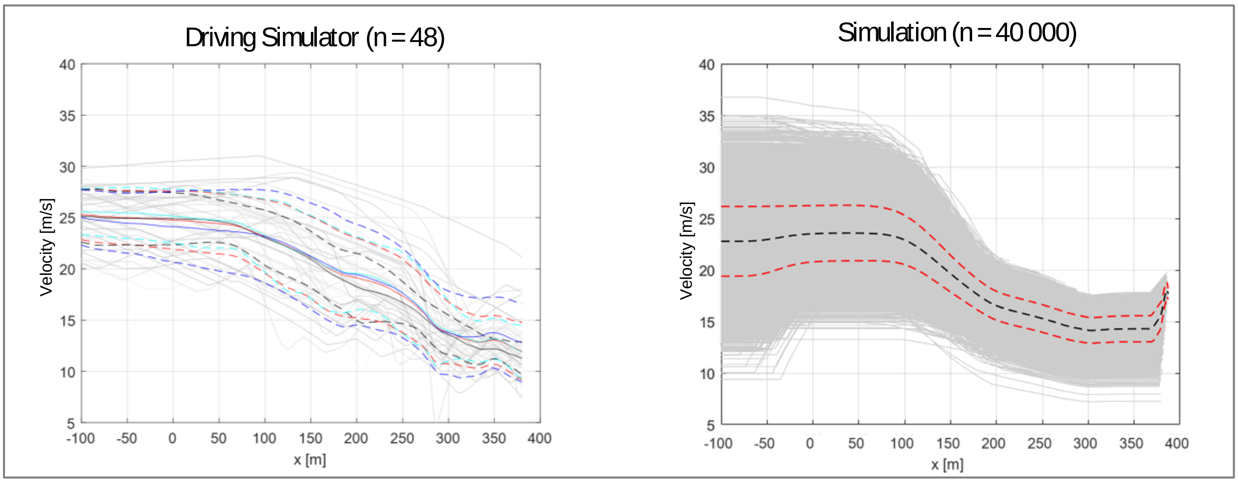


Figure 10.4: Velocity over position measured in the driving simulator and in the simulation

10.2.3 Implementation of the Nudge

The second important model next to the driver behaviour model for simulation is the infrastructure nudge. This model is in particular relevant for the second study, which analyses the effect in terms of traffic safety while driving through the motorway exit curve.

When simulations were started, the infrastructure nudging system that should be implemented at the motorway exit in Eindhoven had not been completely defined. Although studies had been conducted by the time, not all desired input parameters that would be required for impact assessment of the technology in question was available (e.g. final decision on the light colour or nudging threshold). For this reason, the applied simulation approach focuses rather on investigating the outcome of different potential nudging effects than a specific nudging system.

For the simulated scenario, the common assumption is that all drivers who are nudged respond to this nudge. The strength of the reaction to the nudge is pre-defined per scenario. It is expected that the infrastructure nudge will influence the driver behaviour in terms of driven speed as well as in terms of anticipation of the drivers to the curve. In order to model the earlier anticipation of the curve, the internal measure of the driver behaviour model "preview distance" is varied. A higher preview distance implies that the driver recognizes the curve earlier and can estimate the expected curve radius better respectively has more time to adjust the speed to the curve.

Next to the measures that are affected by the infrastructure nudge, it needs to be described how the measures are affected. The first approach is a simple shift of the mean value of the distribution. This means that the entire distribution is shifted to less critical values (i.e. in case of the velocity the velocity is shifted to a lower mean velocity and in case of the preview distance it is shifted to a higher mean value). This approach implies that all drivers are affected by the nudge.

However, considering the later in the field trial implemented technology, this not very likely, since only drivers who are considered too risky are going to be nudged. In order to cover this in the second approach, only a certain percentile of drivers is nudged. For those drivers that are nudged a new velocity respectively preview distance is determined, considering a less critical distribution compared to the one that is used for the baseline. Both approaches are given in figure 10.5.

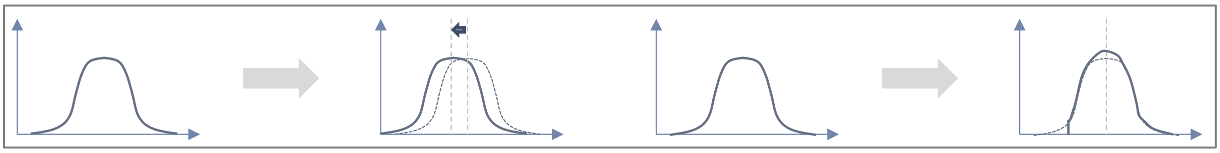


Figure 10.5: The two applied approaches to consider the infrastructure nudging in the simulation (left: shift of mean value; right: cut off at a certain percentile and redistribution around the mean value)

Due to their nature as described above, both approaches are intended to determine the maximum effect of the infrastructure nudge, since they neglect the point that not all drivers will respond to the nudge. Due to missing data, the likelihood of a reaction to a nudge could not be taken into account.

10.3 Simulated Scenarios and Input Data

For the simulated scenario and the input data a distinction needs to be made between the study looking at the deceleration behaviour and the study investigating the infrastructure nudge in the motorway exit curve. First, the study regarding the deceleration behaviour is described.

10.3.1 Simulation Study on Deceleration Behaviour

The scenario in the deceleration study is quite simple. It is a straight road with one lane considering two vehicles in a car following situation. The first vehicle (predecessor) drives at a constant speed. Behind the predecessor, the relevant vehicle follows with a predefined time headway. Both values – velocity of ego vehicle as well as the following time headway – are randomly selected from a distribution. Basis for the initial velocity distribution are the measures conducted by ISAC at the motorway exit beginning of 2018, see figure 10.6. Here, the speed distribution measured at the first point (exit lane) is used.

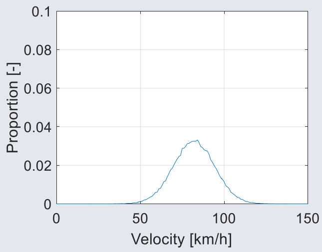
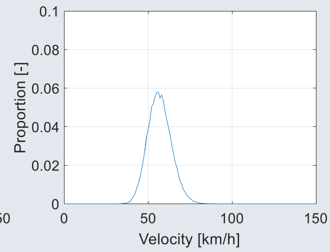
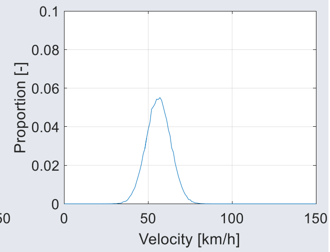
Measurement Location	1 (Exit Lane)	2 (Start of Curve)	3 (Curve)
Velocity			

Figure 10.6: Velocity distributions measured by ISAC in the motorway exit John F. Kennedylaan

At a certain point in time during the simulation, the predecessor starts to decelerate up to a pre-defined target velocity. The deceleration is preformed according to three different deceleration profiles, which are compared in the study:

1. Constant deceleration;
2. Constant linear decreasing deceleration (progressive);
3. Constant linear increasing deceleration (degressive).

All three deceleration profiles are set up in a way that they achieve the same target velocity in the same driven distance. Among the simulation runs, also the target velocity and the driven distance, in which it should be achieved, are varied. The target velocity is selected from a distribution, whereas the driven distance results from the delta between start and target velocity as well as from the different pre-defined constant deceleration scenarios. In the study, overall eight different deceleration profiles are analysed, see table 10.1.

Scenario ID	Mean Starting velocity (km/h)	Mean Deceleration Predecessor (g)	SD Deceleration Predecessor (g)
1	82.0	-0.20	0.05
2	82.0	-0.25	0.05
3	82.0	-0.30	0.05
4	82.0	-0.30	0.25
5	82.0	-0.40	0.25
6	82.0	-0.50	0.25
7	73.8	-0.50	0.25
8	90.2	-0.50	0.25

Table 10.1 Overview on relevant parameters for the simulated scenarios in the deceleration study.

In general, the simulations of this study have been set up with distributions that lead to a more critical driving situation as in the real world in order to reduce the amount of required simulation runs.

10.3.2 Simulation Study on Curve Driving Behaviour

In the second study, the effect of the infrastructure nudge on traffic safety shall be investigated. The motorway exit of the John F. Kennedylaan in Eindhoven, for which later the infrastructure nudge is going to be implemented in WP5, has been chosen as the location for the simulation study. For the simulation, the motorway exit has also been build up in the simulation tool, see figure 10.7. In each simulation run, one agent is driving through the motorway exit. There are no other traffic participants present during the simulation run.

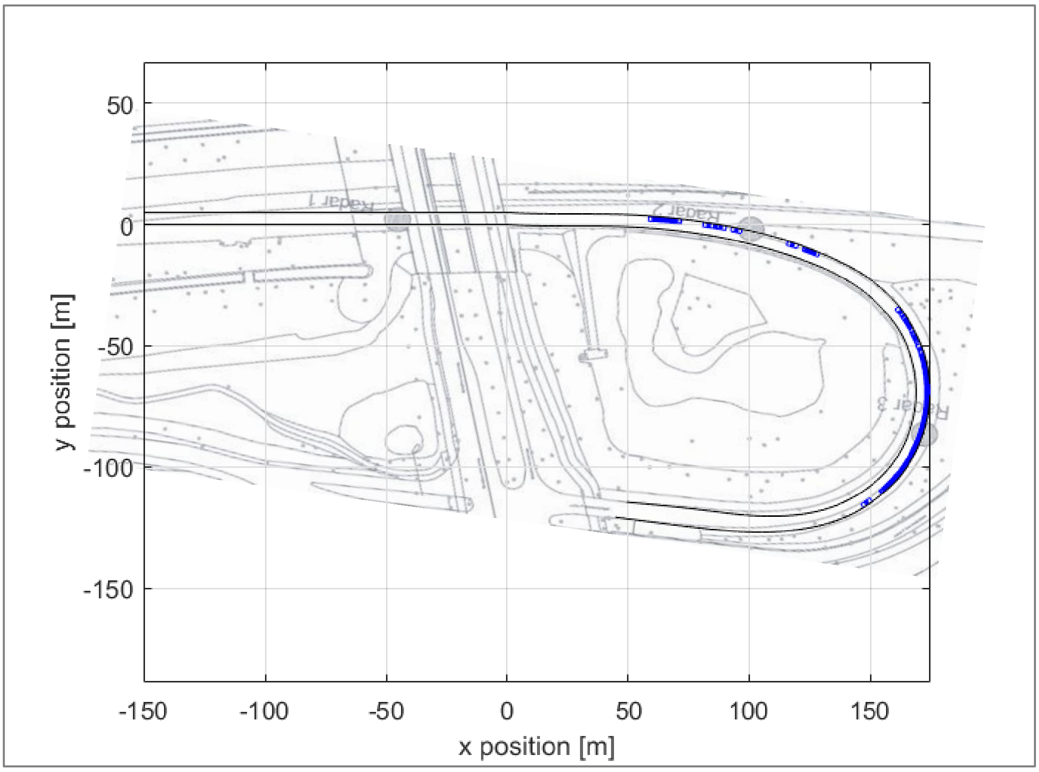


Figure 10.7: Overlay of motorway exit in the simulation (black) and original map (grey); blue: in the simulation detected collision points

The input distributions for this study are the velocities by ISAC measured in the motorway exit (see figure 10.6) and the lateral position in the lane, which have been measured by ika RWTH Aachen University in the driving simulator, see chapter 7. Regarding the velocity, further subdivision is necessary. For the first series of simulations, the distribution at location 1 (exit lane) is applied as initial velocity. In the second series of simulations, the initial velocity is defined by the distribution at location 2 (start curve). The speed distribution of two different locations are applied, since it has not been clear when conducting the simulations how early the vehicle is detected and the nudge is initiated in case the vehicle approaches the curve too fast. The first simulation series represents rather the ideal case without any limitation, whereas the second series represents a system that is only capable of initiating a nudge from the second location onwards. The lateral position in the lane is used to parameterize the distribution of the driver behaviour model's parameters. The parameters of the agent are randomly selected from this distribution in each simulation run.

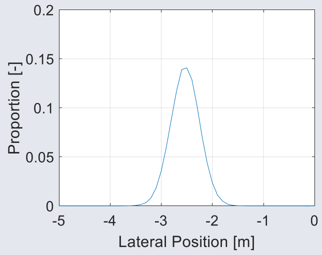
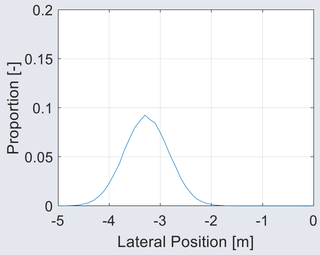
Measurement Location	1 (Exit Lane)	2 (Start of Curve)	3 (Curve)
Lateral Position In Lane	-		

Figure 10.8: Lateral position in the lane measured from the outer road boundary (positive to the left; negative to the right)

There is no clear indication by the driving simulator studies regarding how strong the infrastructure nudge will affect the driving behaviour, especially in the real world Therefore, different possible effects have been simulated in order to provide for wider range of possible impacts in terms of traffic safety. This results in a high number of different simulation scenarios that have been analysed for both simulation series. All analysed simulation scenarios are given in table 10.2 below:

Series of simulation	Type of Simulation	Type of Nudging Effect	By the nudge affected variable	New mean value / cut-off value	Simulation ID
1	Baseline 1	-	-	100 %	101
1	Treatment	1 (Mean value)	Velocity	99 %, 98 %, 95 %, 90 %	102-105
1	Treatment	1	Preview Distance	80 %, 90 %, 110 %, 120 %	106-109
1	Treatment	2 (Cut-off Value)	Velocity	99.5 %, 99 %, 98 %, 95 %, 92.5 %, 90 %	110-115
2	Baseline 2	-	-	100 %	201
2	Treatment	1	Velocity	99 %, 98 %, 95 %, 90 %	202-205
2	Treatment	2	Velocity	95 %, 90 %, 85 %, 80 %	206-209

Table 10.2 Overview on relevant parameters for the simulated scenarios in the curve driving behaviour study

Analogous to the procedure for the first study, the parameters of the driver behaviour model have been chosen a bit more critical compared to the real driving behaviour in order to ensure that a sufficient amount of accident for the evaluation is detected at reasonable effort of simulation runs.

In the following sub-chapters, the results of the simulation are presented. First, the results for the simulation study on the deceleration behaviour are presented. Secondly, the results of the simulation study on curve driving behaviour are presented

10.4 Analysis of Deceleration Behaviour

The main objective of the first simulation study on the deceleration behaviour is to investigate whether the deceleration profile does affect the likelihood of a rear-end accident and what kind of deceleration manoeuvre is preferred. Therefore, the three defined deceleration (constant, progressive, degressive) profiles have been analysed in the eight simulation scenarios with 5 iterations á 2'000 runs. Thus, overall 240'000 simulation runs have been conducted in this study. The results are given in figure 10.9 and figure 10.10. The detailed results are given in annex B.

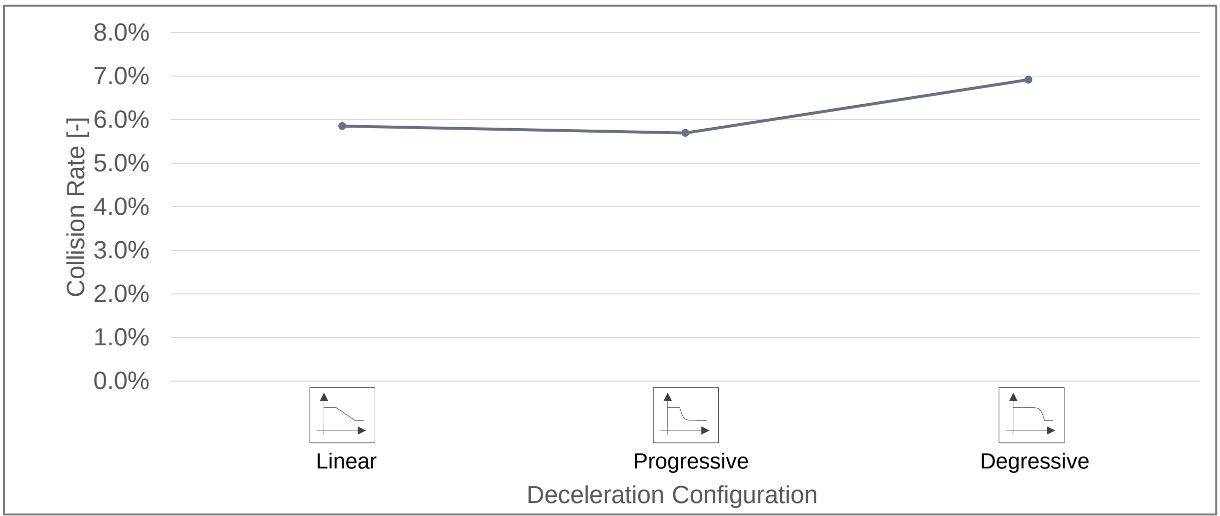


Figure 10.9: Mean collision rate for different acceleration profiles

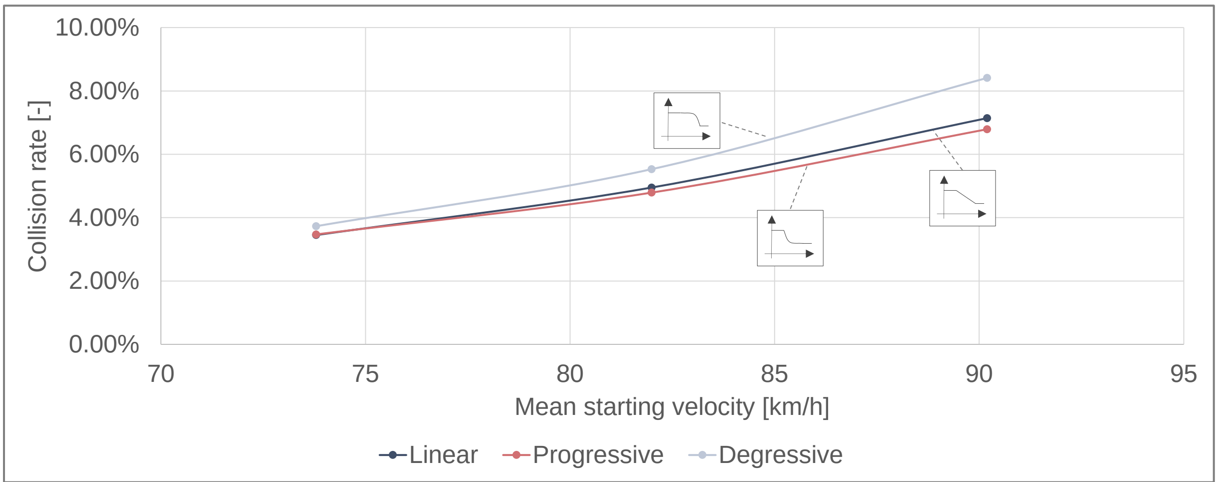


Figure 10.10: Collision rate for different acceleration profiles at different starting velocities

Both figures imply that the progressive deceleration profile has slight advantages in terms of traffic safety compared to the other deceleration profiles. However, there is nearly no difference to the linear deceleration profile. Also the effect size determines only a medium effect for velocity from 82 km/h onwards (|d (73.8 km/h)| = 0.08, |d (82 km/h)| = 0.44, |d (90.2 km/h)| = 0.45). The degressive deceleration results in a higher collision rate in all simulated scenarios compared to the other two deceleration profiles. The effect sizes comparing the degressive deceleration with the other deceleration profiles indicates at each velocity large effect (|d| > 0.8). An increasing starting velocity leads to larger absolute difference between the deceleration profiles.

Therefore, it is concluded that there is a difference of deceleration profiles in terms of the accident risk in car following scenarios. For the design of the infrastructure nudge, the simulation results imply that it should be prevented that the first vehicle, which is most likely nudged, starts to decelerate with a degressive brake manoeuvre.

10.5 Analysis of Curve Driving Behaviour

The second study investigates how the infrastructure nudge can affect the traffic safety presuming different effects. The relevant measure for traffic safety is the number of collisions in the curve. Every event is counted as a collision, in which any part of the vehicle hits the road boundary.

For the first simulation series 15 scenarios (101 – 115; see table 10.2) with 5 iteration à 8'000 simulation runs have been conducted. This means that overall 600'000 simulation runs have been conducted. The results are given in figure 10.11, figure 10.12, and figure 10.13. The detailed results can been found in annex B.

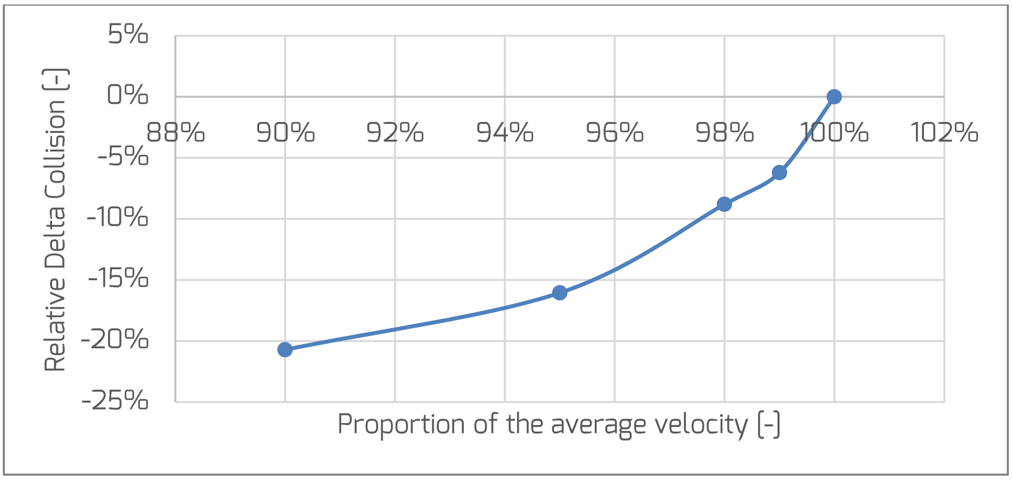


Figure 10.11: Relative delta in the collision risk compared to the baseline for a changed mean starting velocity

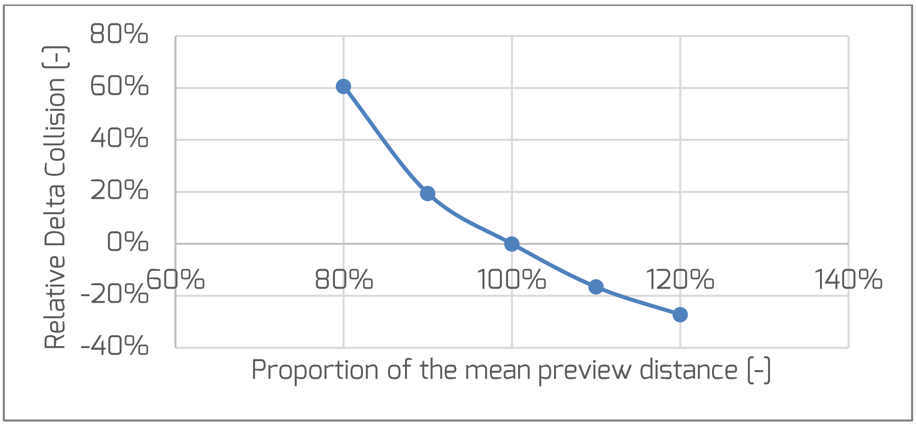


Figure 10.12: Relative delta in the collision risk compared to the baseline for a changed mean preview distance

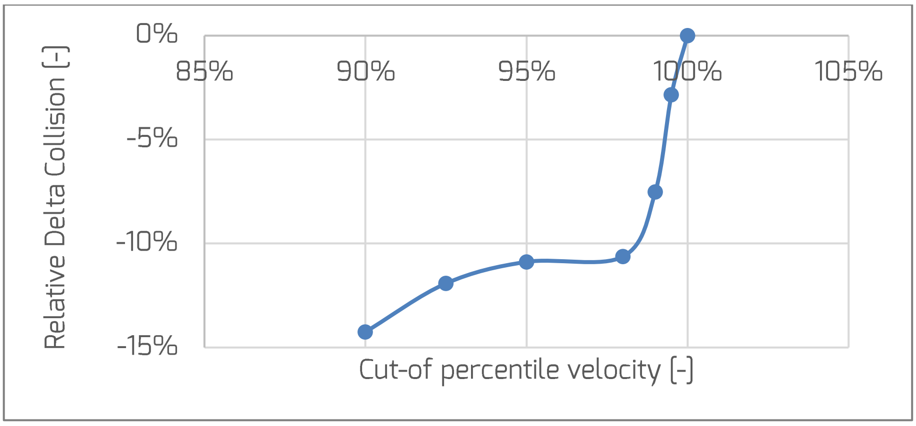


Figure 10.13: Relative delta in the collision risk compared to the baseline with defined nudging velocity

The three figures indicate both, a reduction of speed and an increased preview distance can lead to a reduction of the collision risk. On the other hand, a shorter preview distance can lead to an increase in the collision risk. How large the effect of the nudge is in the end has to be measured in the field trial. Furthermore, figure 10.13 indicates that most of the effect can be achieved if the fastest 2 % drivers are nudged. Of course it must be born in mind that in the simulation it is presumed that all drivers react to the nudge.

In the second series, when the initial velocity was set to the velocity that is measured at the curve entrance, 1'640'844 runs for eight simulation scenarios have been simulated and analysed. The results of this series are reported in figure 10.14 and figure 10.15. The higher number of simulation runs for the second series was necessary since in general the risk of a collision in the curve has been lower due to the lower starting velocity. In order to achieve a statistically relevant number of collisions the number of simulation runs has to be increased.

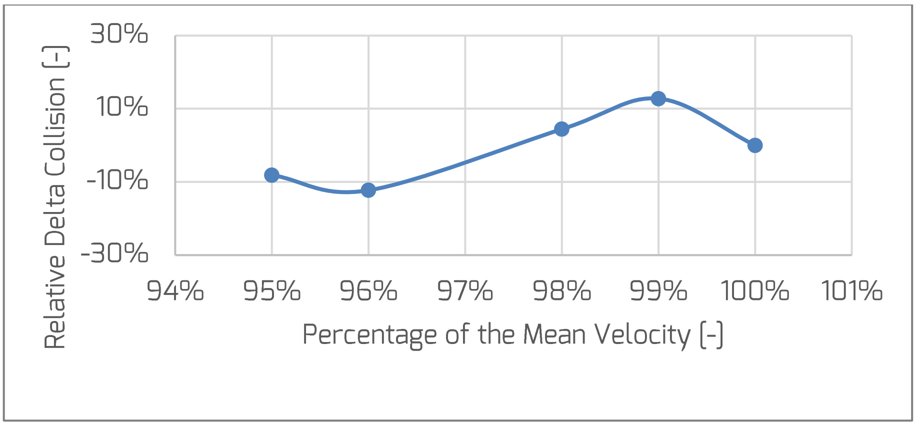


Figure 10.14: Collision risk for a changed mean starting velocity in the second series of simulation

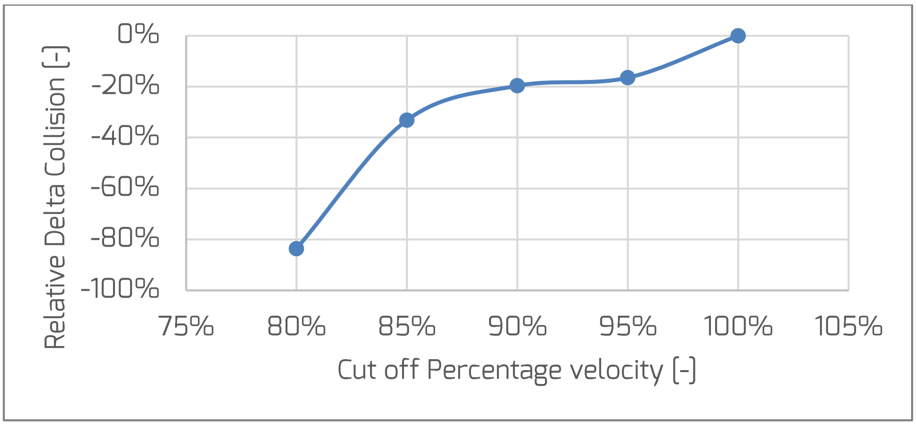


Figure 10.15: Collision risk at different nudging velocities in the second series of simulation

Although the number of simulations has be increased significantly, figure 10.14 shows no clear results, which might be related to the fact the results are influenced by the stochastics that are applied in the simulation. Nevertheless, in the second study the tendency of the first is confirmed. The accident risk is reduced in case a reduction of the mean velocity is achieved (figure 10.15).

For the second approach of the nudge the results show again that already a significant effect can be achieved for the 5 % fastest drivers. Afterwards the accident rate stay more or less constant. The even larger reduction of the accident rate between the 80 % and 85 % percentile cannot be explained at the moment and needs further investigation.

All simulation results show that an increase of the traffic safety by means of the infrastructure nudge is feasible. However, it must be taken into account that the reported values represent the maximum achievable effect, since the assumption for the simulation is that every driver who is nudged does also react to the nudge.

10.6 Discussion and Limitations of Study

The potential effect on traffic safety of the infrastructure nudge has been evaluated by means of computer simulations. In general, the results are as expected. A major finding of the studies, which is also relevant for the development of the nudge is that for large safety impact it should be aimed to nudge those drivers who are driving risky. Even if only a small percentage of the drivers is nudged, a safety benefit can be achieved, but this means that the right drivers must be nudged.

In terms of the achievable safety impact, it must be stated that the simulation can only give first estimations for different scenarios. A final indication on the achievable safety impact will only be possible once more data related to the effect of the infrastructure nudge on the speed and trajectory behaviour of the drivers in the real world are available. This will be the case once the field trail has been finished. Then it can be checked, which of the simulated scenarios is applicable and which is the associated expected safety benefit.

In general, it must be considered that every simulation is only as good as the models and tools used by it. Therefore, the simulation and its results include different constrains and assumptions that limit the analysis and its results. When referring to this result, these limitations must be acknowledged and reported.

Most of the constraints derive from the lack of relevant input data for this technology. Therefore, it has not been possible to build up a detailed model that derives reaction of the driver on the nudge. This means that only the effect of the nudge has been modelled in the simulation and not the direct nudge. Hence, the simulation cannot derive the difference between different implementations of the nudge (e.g. difference in terms of colour, flashing sequence, type of used signals). A second aspect is that by the taken approach it is unclear how many drivers are going to respond to the nudge. Therefore, the simulation can only provide maximum estimations on the effect of the nudge. If not all drivers who are nudged respond to the nudge, the effect in traffic safety will of course be lower. It is expected that the field trials conducted at a later stage in the project could provide valuable information regarding these aspects.

Next to the implementation of the nudging system, the applied driver behaviour model is a key aspect for the simulation and its results. This applies for both studies. For the study on the deceleration behaviour it must be taken into account that the result does depend on the applied driver model. Other driver behaviour models might lead to different results. However, it is expected that the tendency would be similar also for other driver behaviour models, since at least the rule based driver behaviour models rely on similar principles.

The quality of the applied driver behaviour model is also relevant for the studies regarding the curve driving behaviour. Therefore, a comparison with the data measured by ika in the simulator and measured by ISAC in the motorway exit in Eindhoven has been made. The results are given in figure 10.16.

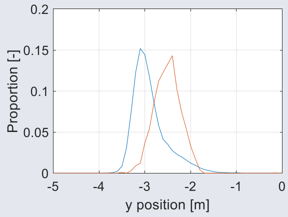
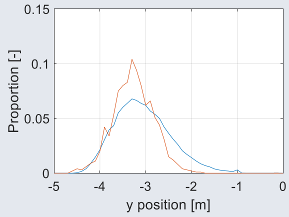
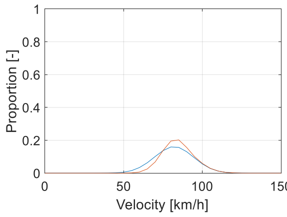
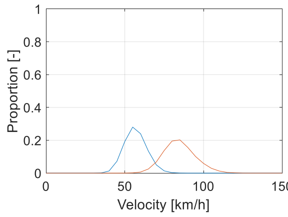
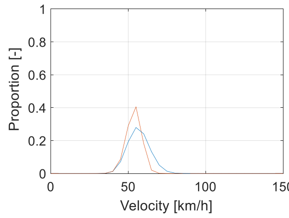
Measurment Point	1 (Exit lane)	2 (Start of curve)	3 (Curve)
Lateral Position (compared to simulator study by ika)			
Velocity (compared to real world measurment by isac)			

Figure 10.16: Comparison of the distributions measured by ISAC and ika (blue) with distributions resulting from simulation (orange) for the first series of simulation in the curve study

The comparison at the first measurement point (exit lane) is not of interest, since the approximated velocity distribution of the real world measurement has been used as an input for the simulation. At the second measurement point (start of curve), differences in the lateral position as well as in the velocity between real world measurement and simulation can be detected. Since the vehicles in the simulation are faster and closer to the left road boundary, the simulated scenario is more critical than the real world measurement. The reason for the difference is not entirely clear. One possible explanation might be the 50 km/h speed limit sign at the highway exit, which is not considered in the simulation. This might lead to an earlier deceleration of the drivers in the real world. At the third measurement point (curve), the distributions of the simulation for the lateral position and the velocity matches the one from the real world measurement quite well.

Potentially negative effects (e.g. due to glare) are not taken into account by the applied simulation tool. However, it is expected that these effects are neglectable small, since the lights applied in the field trial have already been used beforehand.

11 General Discussion

After the careful deduction and development of nudging interventions inside and outside the vehicle, the speed nudging stimuli, the measurement technology and the implemented decision control logic will be tested in the field to verify the effectiveness of nudging system.

For the intervention in the infrastructure aiming at speed reduction, it was possible to investigate the impact of various light scenarios on individual driving behaviour with the controlled set-up in the driving simulator in a virtual replication of the field test location in Eindhoven. Results of the first simulator study are promising and show that especially the lights moving towards the driver lead to a changed driving behaviour: Drivers did brake earlier in the condition with the lights moving towards them. Since participants assessed the towards moving lights as most effective in driving speed reduction, the finding is substantiated by the results of the structured interview. Moreover, both static and towards moving lights appeared to prevent the driver from harsh braking at later points close to the curve of the exit. This might be due to the guidance function of the lights that was frequently mentioned by the participants. The illuminated road might give the driver an improved view on the curve and the upcoming route. Therefore, participants have more reaction time to adapt to the demands of the curve. Besides that, red and amber coloured lights were rated as the best measure for driving speed reduction. While the red lights were found to be very warning or even threatening, orange lights were perceived to have a more moderate warning function to the driver. The field test in Eindhoven was conducted in order to examine the nudging measure and the effects of the two colours in general in a real life situation. The understanding of the lights moving towards the driver as a System 1 nudge is substantiated by the results of simulator study 2 (chapter 8) that revealed that the movement of the lights did not add to the workload, indicating an automatic processing.

As mentioned in the discussions of the first two simulator studies, the dynamic light system is implemented on a motorway exit in the city of Eindhoven. This location serves as field testing location for the initially developed and tested measures under real traffic conditions. Development and installation of the dynamic light system including the decision control logic has been provided by Heijmans. For the intelligent detection of vehicles throughout the curve, thermal cameras of ISAC are set up along the curve. The cameras detect approaching vehicles and track their movement and speed along the curve, and at the same time allow for data privacy of drivers. This enables us to analyse how drivers adapt their speed over almost the full length of the exit, which covers the road in front of, within, and after the nudging measure. The light system operates in real time, and is therefore able to provide light cues based on the behaviour of the car driver adjusted to the location of the vehicle. Details on this are described in D3.3. For the field test, a baseline measurement and several light scenarios will be tested in order to validate the behavioural effects found in the simulator test. Furthermore, different changing environmental conditions, such as day/night, or traffic density can be assessed. The behavioural effect of the nudging system is measured by recording the speed of all vehicles entering the exit, gaining more than sufficient data to study if and to what extent infra-structure can nudge drivers towards adopting a safe speed in order to increase safety margins during daily driving. Details on test design are reported in D5.1.

Based on the deduction of nudging interventions and the results of the first simulator study described in chapter 7, the Monte Carlo Simulation was conducted and revealed that especially those drivers who are driving riskily should be nudged. This implies that even if only a small percentage of drivers is nudged, a safety benefit can be achieved.

12 Conclusion

12.1 Deviations from Workplan

Due to the complexity of data in the simulator study, simulator study 3 as indicated in chapter 9 has not been finished until the due date of this deliverable. Ika is taking the remaining time within WP3 to finish this simulator study. Results will be delivered in D5.4 (results of field trials). There were no further deviations from the workplan.

12.2 Final Remarks

Summing up, this deliverable provides very detailed insights into the derivation of nudging measures based on previously conducted research, taking into account technical and perceptual mechanisms. The tested nudging interventions towards nudging drivers towards a desired speed (objective 6) showed promising results especially for lights moving towards the driver, which will be further elaborated in the field trials that are about to start. Potential simulator effects and open points from the simulation are expected to be solved with the setup of the field trials as described in deliverable D5.1. The results described in this deliverable provide direct input into expected behaviour of drivers in the naturalistic driving studies within WP5.

Regarding objective 7, which aims at guiding drivers along a preferred trajectory, results of the first two simulator studies revealed that targeting both objectives within one nudging intervention to be ineffective. Therefore, the final simulator study conducted within the duration of WP3 in September 2019 will provide valuable insights into developing this technology further.

12.3 Acknowledgements

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Annexes

Table of Contents in Annexes

List of Figures in Annexes

List of Tables in Annexes

Annex A: Results of Qualitative Questionnaire in Simulator Study 1

This annex contains the detailed descriptive results of a qualitative additional questionnaire as executed in study 1. The questions were asked to participants directly after they encountered every variation of the qualitative study as described in chapter 7.2. The results are only descriptive and serve the purpose to get deeper contextual insights on the attitude of participants towards the variations.

A.1Colour 1 (Movement: towards the driver)

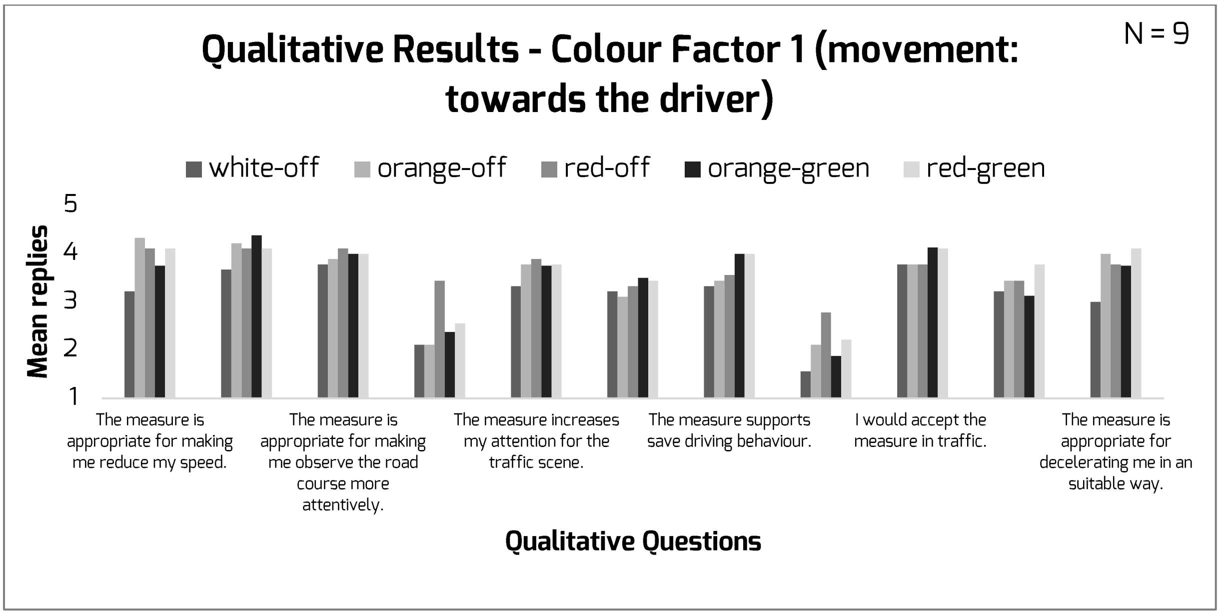

Figure A.1: Results of structured questionnaire of the qualitative study for the factor colour with movement towards the driver. Figure is descriptive and shows the mean replies to questions 1 – 11

"The measure is appropriate for making me reduce my speed."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	3.22	1.09	2 – 5	2, 4	
Colour "Orange Off"	4.33	.87	3 – 5	5	
Colour "Red Off"	4.11	1.05	2 – 5	5	.13
Colour "Orange Green"	3.75	1.04	2 – 5	4	
Colour "Red Green"	4.11	1.27	2 - 5	5	

Table A.1: Results of question 1 "The measure is appropriate for making me reduce my speed" of the qualitative study for the factor colour with movement towards the driver. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure is appropriate for alerting me more for the driving situation."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	3.67	.87	2 – 5	4	
Colour "Orange Off"	4.22	.67	2 – 5	4	
Colour "Red Off"	4.11	.78	3 – 5	4	.32
Colour "Orange Green"	4.38	.74	3 – 5	5	
Colour "Red Green"	4.11	1.27	2 – 5	5	

Table A.2: Results of question 2 "The measure is appropriate for alerting me more for the driving situation." of the qualitative study for the factor colour with movement towards the driver. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure is appropriate for making me observe the road course more attentively."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	3.78	1.09	2 – 5	4	
Colour "Orange Off"	3.89	.78	3 – 5	4	
Colour "Red Off"	4.11	.93	3 – 5	4	.95
Colour "Orange Green"	4.0	1.07	2 – 5	5	
Colour "Red Green"	4.0	1.0	2 – 5	5	

Table A.3: Results of question 3 "The measure is appropriate for making me observe the road course more attentively." of the qualitative study for the factor colour with movement towards the driver. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure distracts me."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	2.11	1.05	3 – 5	1, 2	
Colour "Orange Off"	2.11	1.27	1 – 4	1	
Colour "Red Off"	3.44	1.24	1 – 5	3	.25
Colour "Orange Green"	4.0	1.07	2 – 5	3	
Colour "Red Green"	2.56	1.13	1 – 4	3	

Table A.4: Results of question 4 "The measure distracts me." of the qualitative study for the factor colour with movement towards the driver. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure increases my attention for the traffic scene."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	3.33	1.0	2 – 5	3, 4	
Colour "Orange Off"	3.78	.83	2 – 5	4	
Colour "Red Off"	3.89	1.17	2 – 5	4	.88
Colour "Orange Green"	3.75	1.28	2 – 5	5	
Colour "Red Green"	3.78	.97	2 – 5	4	

Table A.5: Results of question 5 "The measure increases my attention for the traffic scene." of the qualitative study for the factor colour with movement towards the driver. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure makes me feel safer in traffic."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	3.22	1.2	1 – 5	3, 4	
Colour "Orange Off"	3.11	1.05	2 – 5	2, 3	
Colour "Red Off"	3.33	.71	2 – 4	3, 4	.42
Colour "Orange Green"	3.5	.53	3 – 4	3, 4	
Colour "Red Green"	3.44	.88	2 – 5	3	

Table A.6: Results of question 6 "The measure makes me feel safer in traffic." of the qualitative study for the factor colour with movement towards the driver. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure supports save driving behaviour."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	3.33	1.2	1 – 5	3, 4	
Colour "Orange Off"	3.44	1.01	2 – 5	4	
Colour "Red Off"	3.56	1.01	2 – 5	3	.35
Colour "Orange Green"	4.0	1.01	2 – 5	4	
Colour "Red Green"	4.0	1.12	2 – 5	5	

Table A.7: Results of question 7 "The measure supports save driving behaviour." of the qualitative study for the factor colour with movement towards the driver. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure seems stressful to me."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	1.56	.73	1 – 3	1	
Colour "Orange Off"	2.11	1.27	1 – 4	1	
Colour "Red Off"	2.78	1.39	1 – 5	1, 2, 3, 4	.07
Colour "Orange Green"	1.88	.83	1 – 3	1, 2	
Colour "Red Green"	2.22	1.09	1 – 4	1, 3	

Table A.8: Results of question 8 "The measure seems stressful to me." of the qualitative study for the factor colour with movement towards the driver. Table shows the descriptive values of the structured questionnaire with N = 9

"I would accept the measure in traffic."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	3.78	.97	2 – 5	4	
Colour "Orange Off"	3.78	1.09	2 – 5	4	
Colour "Red Off"	3.78	.83	3 – 5	3	.44
Colour "Orange Green"	4.13	.64	3 – 5	4	
Colour "Red Green"	4.11	.93	2 – 5	4	

Table A.9: Results of question 9 "I would accept the measure in traffic." of the qualitative study for the factor colour with movement towards the driver. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure explicitly shows which behaviour is demanded of me."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	3.22	.97	2 – 5	3	
Colour "Orange Off"	3.44	1.33	1 – 5	4	
Colour "Red Off"	3.44	1.33	2 – 5	2, 5	.92
Colour "Orange Green"	3.13	.99	2 – 4	4	
Colour "Red Green"	3.78	1.3	2 – 5	5	

Table A.10: Results of question 10 "The measure explicitly shows which behaviour is demanded of me." of the qualitative study for the factor colour with movement towards the driver. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure is appropriate for decelerate me in a suitable way."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	3.0	1.12	1 – 4	4	
Colour "Orange Off"	4.0	0.71	2 – 5	4	
Colour "Red Off"	3.78	1.48	2 – 5	5	.197
Colour "Orange Green"	3.75	.71	3 – 5	4	
Colour "Red Green"	4.11	.93	3 – 5	5	

Table A.11: Results of question 11 "The measure is appropriate for decelerating me in a suitable way." of the qualitative study for the factor colour with movement towards the driver. Table shows the descriptive values of the structured questionnaire with N = 9

A.2 Colour 2 (Movement: static)

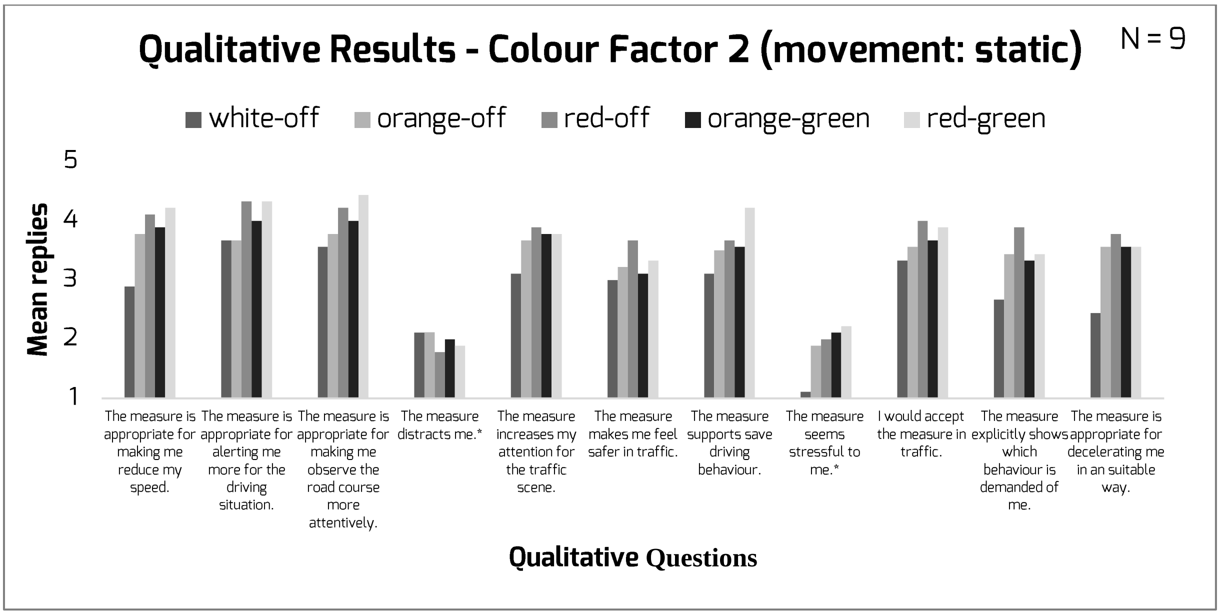

Figure A.2: Results of structured questionnaire of the qualitative study for the factor colour with static lights. Figure is descriptive and shows the mean replies to questions 1 – 11

"The measure is appropriate for making me reduce my speed."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	2.89	1.27	1 – 5	2	
Colour "Orange Off"	3.78	1.09	2 – 5	4	
Colour "Red Off"	4.11	1.05	2 – 5	5	.01
Colour "Orange Green"	3.89	1.05	2 – 5	4	
Colour "Red Green"	4.22	.97	2 – 5	4	

Table A.12: Results of question 1 "The measure is appropriate for making me reduce my speed." of the qualitative study for the factor colour with static lights. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure is appropriate for alerting me more for the driving situation."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	3.67	.71	3 – 5	3	
Colour "Orange Off"	3.67	1.0	2 – 5	3	
Colour "Red Off"	4.33	.71	3 – 5	4	.02
Colour "Orange Green"	4.0	.87	2 – 5	4	
Colour "Red Green"	4.33	.71	3 – 5	4	

Table A.13: Results of question 2 "The measure is appropriate for alerting me more for the driving situation." of the qualitative study for the factor colour with static lights. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure is appropriate for making me observe the road course more attentively."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	3.56	1.13	2 – 5	4	
Colour "Orange Off"	3.78	.83	2 – 5	4	
Colour "Red Off"	4.22	.67	3 – 5	4	.05
Colour "Orange Green"	4.0	.50	3 – 5	4	
Colour "Red Green"	4.44	.73	3 – 5	5	

Table A.14: Results of question 3 "The measure is appropriate for making me observe the road course more attentively." of the qualitative study for the factor colour with static lights. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure distracts me."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	2.11	1.45	1 – 5	1	
Colour "Orange Off"	2.13	.99	1 – 3	3	
Colour "Red Off"	1.78	.83	1 – 3	1	.62
Colour "Orange Green"	2.0	1.12	1 – 4	1	
Colour "Red Green"	1.89	1.17	1 – 4	1	

Table A.15: Results of question 4 "The measure distracts me." of the qualitative study for the factor colour with static lights. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure increases my attention for the traffic scene."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	3.11	.78	2 – 4	3	
Colour "Orange Off"	3.67	.87	2 – 5	4	
Colour "Red Off"	3.89	.93	2 – 5	4	.25
Colour "Orange Green"	3.78	.83	3 – 5	3	
Colour "Red Green"	3.78	1.2	2 – 5	4	

Table A.16: Results of question 5 "The measure increases my attention for the traffic scene." of the qualitative study for the factor colour with static lights. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure makes me feel safer in traffic."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	3.0	1.41	1 – 5	2	
Colour "Orange Off"	3.22	.67	2 – 4	3	
Colour "Red Off"	3.67	.71	3 – 5	3	.48
Colour "Orange Green"	3.11	.93	1 – 4	3	
Colour "Red Green"	3.33	.87	2 – 5	3	

Table A.17: Results of question 6 "The measure makes me feel safer in traffic." of the qualitative study for the factor colour with static lights. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure supports save driving behaviour."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	3.11	1.36	1 – 5	3	
Colour "Orange Off"	3.5	1.07	2 – 5	4	
Colour "Red Off"	3.67	1.0	2 – 5	3	.13
Colour "Orange Green"	3.56	1.01	2 – 5	4	
Colour "Red Green"	4.22	.44	4 – 5	4	

Table A.18: Results of question 7 "The measure supports save driving behaviour." of the qualitative study for the factor colour with static lights. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure seems stressful to me."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	1.11	.33	1 – 2	1	
Colour "Orange Off"	1.89	1.36	1 – 5	1	
Colour "Red Off"	2.0	1.22	1 – 5	2	.08
Colour "Orange Green"	2.11	1.54	1 – 5	1	
Colour "Red Green"	2.22	1.64	1 – 5	1	

Table A.19: Results of question 8 "The measure seems stressful to me." of the qualitative study for the factor colour with static lights. Table shows the descriptive values of the structured questionnaire with N = 9

"I would accept the measure in traffic."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	3.33	1.58	1 – 5	3	
Colour "Orange Off"	3.56	1.24	1 – 5	3	
Colour "Red Off"	4.0	1.22	1 – 5	4	.62
Colour "Orange Green"	3.67	1.5	1 – 5	5	
Colour "Red Green"	3.89	.93	3 – 5	3	

Table A.20: Results of question 9 "I would accept the measure in traffic." of the qualitative study for the factor colour with static lights. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure explicitly shows which behaviour is demanded of me."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	2.67	1.5	1 – 5	1	
Colour "Orange Off"	3.44	1.33	1 – 5	4	
Colour "Red Off"	3.89	.93	2 – 5	4	.09
Colour "Orange Green"	3.33	1.11	1 – 5	3	
Colour "Red Green"	3.44	1.13	2 – 5	3	

Table A.21: Results of question 10 "The measure explicitly shows which behaviour is demanded of me." of the qualitative study for the factor colour with static lights. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure is appropriate for decelerate me in a suitable way."

Colour	Mean	SD	Range	Modus	Friedman
Colour "White Off"	2.44	1.33	1 – 5	2	
Colour "Orange Off"	3.56	1.33	1 – 5	4	
Colour "Red Off"	3.78	.97	2 – 5	4	.013
Colour "Orange Green"	3.56	1.24	1 – 5	3, 4	
Colour "Red Green"	3.56	1.13	2 – 5	4	

Table A.22: Results of question 11 "The measure is appropriate for decelerating me in a suitable way." of the qualitative study for the factor colour with static lights. Table shows the descriptive values of the structured questionnaire with N = 9

A.3 Movement

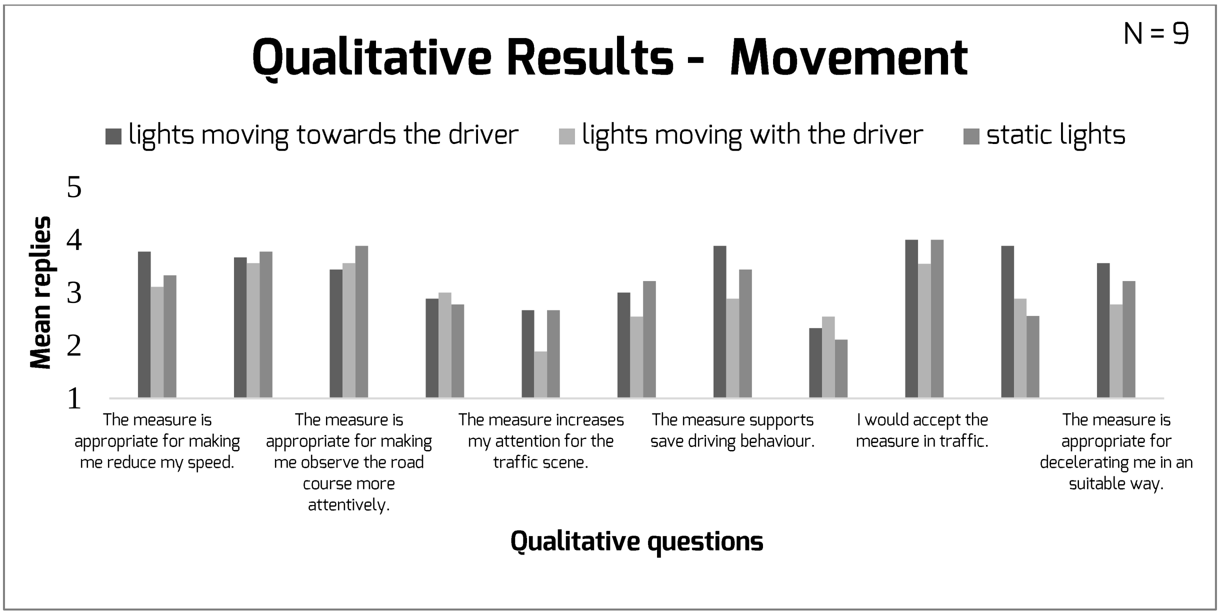

Figure A.3: Results of structured questionnaire of the qualitative study for the factor movement. Figure is descriptive and shows the mean replies to questions 1 – 11

"The measure is appropriate for making me reduce my speed."

Movement	Mean	SD	Range	Modus	Friedman
Movement „Lights moving towards the driver"	3.78	1.39	2 – 5	5	
Movement „Lights moving with the driver"	3.11	.154	1 – 5	1	.36
Movement „Static lights"	3.33	1.5	1 – 5	5	

Table A.23: Results of question 1 "The measure is appropriate for making me reduce my speed." of the qualitative study for the factor movement. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure is appropriate for alerting me more for the driving situation."

Movement	Mean	SD	Range	Modus	Friedman
Movement „Lights moving towards the driver"	3.67	.87	2 – 5	4	
Movement „Lights moving with the driver"	3.56	1.24	1 – 5	4	.89
Movement „Static lights"	3.78	.83	3 – 5	3	

Table A.24: Results of question 2 "The measure is appropriate for alerting me more for the driving situation." of the qualitative study for the factor movement. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure is appropriate for making me observe the road course more attentively."

Movement	Mean	SD	Range	Modus	Friedman
Movement „Lights moving towards the driver"	3.44	.88	2 – 5	3	
Movement „Lights moving with the driver"	3.56	1.42	1 – 5	5	.76
Movement „Static lights"	3.89	.93	3 – 5	3	

Table A.25: Results of question 3 "The measure is appropriate for making me observe the road course more attentively." of the qualitative study for the factor movement. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure distracts me."

Movement	Mean	SD	Range	Modus	Friedman
Movement „Lights moving towards the driver"	2.89	.93	2 – 4	2	
Movement „Lights moving with the driver"	3.0	1.41	1 – 5	2	.89
Movement „Static lights"	2.78	1.2	1 - 4	3, 4	

Table A.26: Results of question 4 "The measure distracts me." of the qualitative study for the factor movement. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure increases my attention for the traffic scene."

Movement	Mean	SD	Range	Modus	Friedman
Movement „Lights moving towards the driver"	2.67	1.0	2 – 4	2	
Movement „Lights moving with the driver"	1.89	.6	1 – 3	1.22	.14
Movement „Static lights"	2.67	1.22	1 - 5	2	

Table A.27: Results of question 5 "The measure increases my attention for the traffic scene." of the qualitative study for the factor movement. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure makes me feel safer in traffic."

Movement	Mean	SD	Range	Modus	Friedman
Movement „Lights moving towards the driver“	3.0	.87	2 – 4	2, 3, 4	
Movement „Lights moving with the driver“	2.56	1.01	1 – 4	3	.23
Movement „Static lights“	3.22	.83	2 – 5	3	

Table A.28: Results of question 6 "The measure makes me feel safer in traffic." of the qualitative study for the factor movement. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure supports save driving behaviour."

Movement	Mean	SD	Range	Modus	Friedman
Movement „Lights moving towards the driver“	3.89	.93	2 – 5	4	
Movement „Lights moving with the driver“	2.89	1.17	1 – 4	3	.03
Movement „Static lights“	3.44	.88	2 – 5	3	

Table A.2929: Results of question 7 "The measure supports save driving behaviour." of the qualitative study for the factor movement. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure seems stressful to me."

Movement	Mean	SD	Range	Modus	Friedman
Movement „Lights moving towards the driver“	2.33	1.32	1 – 4	1	
Movement „Lights moving with the driver“	2.56	1.24	1 – 5	3	.57
Movement „Static lights“	2.11	1.27	1 – 4	1	

Table A.30: Results of question 8 "The measure seems stressful to me." of the qualitative study for the factor movement. Table shows the descriptive values of the structured questionnaire with N = 9

"I would accept the measure in traffic."

Movement	Mean	SD	Range	Modus	Friedman
Movement „Lights moving towards the driver"	4.0	1.32	2 – 5	5	
Movement „Lights moving with the driver"	3.56	1.51	1 – 5	4	.55
Movement „Static lights"	4.0	1.32	2 – 5	5	

Table A.31: Results of question 9 "I would accept the measure in traffic." of the qualitative study for the factor movement. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure explicitly shows which behaviour is demanded of me."

Movement	Mean	SD	Range	Modus	Friedman
Movement „Lights moving towards the driver"	3.89	1.17	2 – 5	4	
Movement „Lights moving with the driver"	2.89	1.36	1 – 5	5	.16
Movement „Static lights"	4.0	1.32	2 – 5	5	

Table A.32: Results of question 10 "The measure explicitly shows which behaviour is demanded of me." of the qualitative study for the factor movement. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure is appropriate for decelerate me in a suitable way."

Movement	Mean	SD	Range	Modus	Friedman
Movement „Lights moving towards the driver“	3.56	1.01	2 – 5	4	
Movement „Lights moving with the driver“	2.78	1.39	1 – 5	1, 2, 3, 4	.45
Movement „Static lights“	3.22	1.2	2 – 5	2, 4	

Table A.33: Results of question 11 "The measure is appropriate for decelerating me in a suitable way." of the qualitative study for the factor movement. Table shows the descriptive values of the structured questionnaire with N = 9

A.4 Blinking

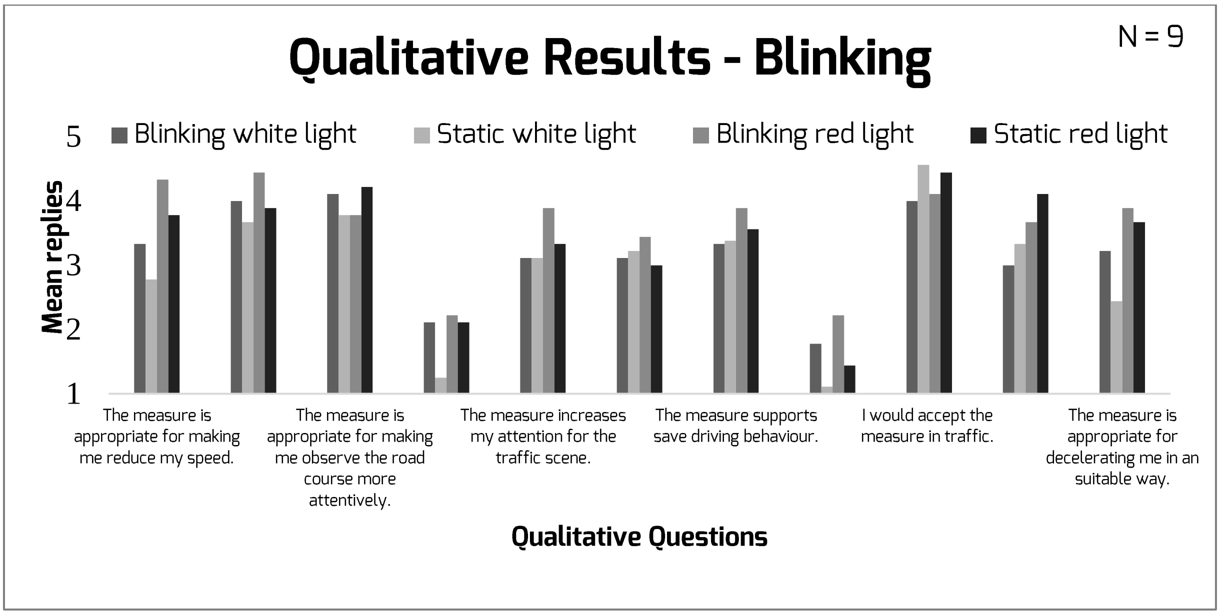

Figure A.4: Results of structured questionnaire of the qualitative study for the factor blinking. Figure is descriptive and shows the mean replies to questions 1 – 11

"The measure is appropriate for making me reduce my speed."

Blinking	Mean	SD	Range	Modus	Friedman
Blinking "white light"	3.33	1.5	1 – 5	4	
Static "white light"	2.78	1.64	1 – 5	1	.12
Blinking "red light"	4.33	.71	3 – 5	4, 5	
Static "red light"	3.78	1.2	2 – 5	4, 5	

Table A.34: Results of question 1 "The measure is appropriate for making me reduce my speed." of the qualitative study for the factor blinking. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure is appropriate for alerting me more for the driving situation."

Blinking	Mean	SD	Range	Modus	Friedman
Blinking "white light"	4	1.32	1 – 5	5	
Static "white light"	3.67	1.11	1 – 5	4	.29
Blinking "red light"	4.44	.53	4 – 5	4	
Static "red light"	3.89	.93	2 – 5	4	

Table A.35: Results of question 2 "The measure is appropriate for alerting me more for the driving situation." of the qualitative study for the factor blinking. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure is appropriate for making me observe the road course more attentively."

Blinking	Mean	SD	Range	Modus	Friedman
Blinking "white light"	4.11	1.17	2 – 5	5	
Static "white light"	3.78	1.48	1 – 5	5	.70
Blinking "red light"	3.78	1.09	2 – 5	3, 5	
Static "red light"	4.22	.44	4 – 5	4	

Table A.36: Results of question 3 "The measure is appropriate for making me observe the road course more attentively." of the qualitative study for the factor blinking. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure distracts me."

Blinking	Mean	SD	Range	Modus	Friedman
Blinking "white light"	2.11	1.05	1 – 4	1, 2	
Static "white light"	1.25	.46	1 – 2	1	.06
Blinking "red light"	2.22	1.48	1 – 5	1	
Static "red light"	2.11	1.05	1 – 4	1	

Table A.37: Results of question 4 "The measure distracts me." of the qualitative study for the factor blinking. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure increases my attention for the traffic scene."

Blinking	Mean	SD	Range	Modus	Friedman
Blinking "white light"	3.11	.78	2 – 4	3	
Static "white light"	3.11	1.05	1 – 4	4	.35
Blinking "red light"	3.89	1.05	2 – 5	4, 5	
Static "red light"	3.33	1.0	2 – 5	3, 4	

Table A.38: Results of question 5 "The measure increases my attention for the traffic scene." of the qualitative study for the factor blinking. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure makes me feel safer in traffic."

Blinking	Mean	SD	Range	Modus	Friedman
Blinking "white light"	3.11	.93	2 – 5	3	
Static "white light"	3.22	.83	2 – 4	4	.61
Blinking "red light"	3.44	1.01	2 – 5	3	
Static "red light"	3.0	1.11	1 – 5	3	

Table A.39: Results of question 6 "The measure makes me feel safer in traffic." of the qualitative study for the factor blinking. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure supports save driving behaviour."

Blinking	Mean	SD	Range	Modus	Friedman
Blinking "white light"	3.33	1.0	2 – 5	3, 4	
Static "white light"	3.38	1.06	2 – 5	4	.72
Blinking "red light"	3.89	.78	3 – 5	4	
Static "red light"	3.56	.73	3 – 5	3	

Table A.40: Results of question 7 "The measure supports save driving behaviour." of the qualitative study for the factor blinking. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure seems stressful to me."

Blinking	Mean	SD	Range	Modus	Friedman
Blinking "white light"	1.78	.97	1 – 4	1, 2	
Static "white light"	1.11	.33	1 – 2	1	.05
Blinking "red light"	2.22	1.39	1 – 5	2	
Static "red light"	1.44	1.01	1 – 4	1	

Table A.41: Results of question 8 "The measure seems stressful to me." of the qualitative study for the factor blinking. Table shows the descriptive values of the structured questionnaire with N = 9

"I would accept the measure in traffic."

Blinking	Mean	SD	Range	Modus	Friedman
Blinking "white light"	4.0	1.19	2 – 5	5	
Static "white light"	4.56	.73	3 – 5	5	.31
Blinking "red light"	4.11	1.05	2 – 5	5	
Static "red light"	4.44	.53	4 – 5	4	

Table A.42: Results of question 9 "I would accept the measure in traffic." of the qualitative study for the factor blinking. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure explicitly shows which behaviour is demanded of me."

Blinking	Mean	SD	Range	Modus	Friedman
Blinking "white light"	3.0	1.32	1 – 5	2, 4	
Static "white light"	3.33	.71	2 – 4	3, 4	.051
Blinking "red light"	3.67	1.22	2 – 5	5	
Static "red light"	4.11	.92	2 – 5	4	

Table A.43: Results of question 10 "The measure explicitly shows which behaviour is demanded of me." of the qualitative study for the factor blinking. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure is appropriate for decelerate me in a suitable way."

Blinking	Mean	SD	Range	Modus	Friedman
Blinking "white light"	3.22	1.2	1 – 5	3, 4	
Static "white light"	2.44	1.24	1 – 4	1, 3	.02
Blinking "red light"	3.89	1.05	2 – 5	4, 5	
Static "red light"	3.67	1.32	2 – 5	2, 4, 5	

Table A.44: Results of question 11 "The measure is appropriate for decelerating me in a suitable way." of the qualitative study for the factor blinking. Table shows the descriptive values of the structured questionnaire with N = 9

A.5 Technology

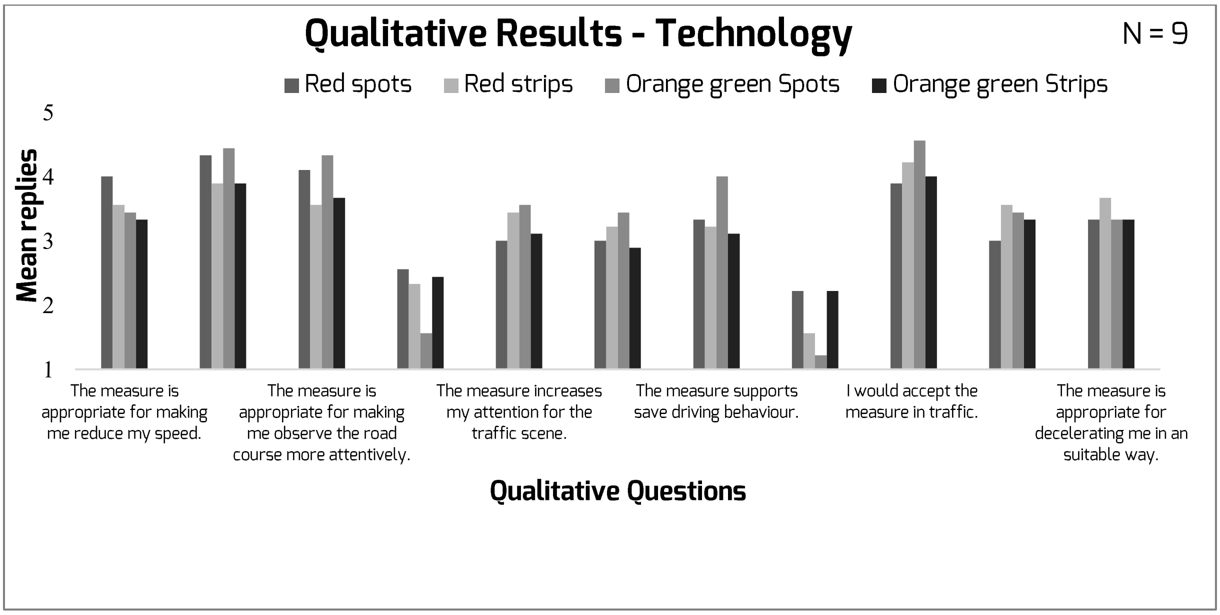

Figure A.5: Results of structured questionnaire of the qualitative study for the factor technology. Figure is descriptive and shows the mean replies to questions 1 – 11

"The measure is appropriate for making me reduce my speed."

Technology	Mean	SD	Range	Modus	Friedman
Technology „Red spots"	4	.87	2 – 5	4	
Technology „Red strips"	3.56	.88	2 – 5	4	.48
Technology „Orange green spots"	3.44	1.51	1 – 5	5	
Technology „Orange green strips"	3.33	1.12	2 – 5	4	

Table A.45: Results of question 1 "The measure is appropriate for making me reduce my speed." of the qualitative study for the factor technology. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure is appropriate for alerting me more for the driving situation."

Technology	Mean	SD	Range	Modus	Friedman
Technology „Red spots"	4.11	.93	2 – 5	4	
Technology „Red strips"	3.56	.73	3 – 5	3	.30
Technology „Orange green spots"	4.33	.71	3 – 5	4, 5	
Technology „Orange green strips"	3.67	1.41	1 – 5	4, 5	

Table A.46: Results of question 2 "The measure is appropriate for alerting me more for the driving situation." of the qualitative study for the factor technology. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure is appropriate for making me observe the road course more attentively."

Technology	Mean	SD	Range	Modus	Friedman
Technology „Red spots"	4.11	.93	2 – 5	4	
Technology „Red strips"	3.56	.73	3 – 5	3	.30
Technology „Orange green spots"	4.33	.71	3 – 5	4, 5	
Technology „Orange green strips"	3.67	1.41	1 – 5	4, 5	

Table A.47: Results of question 3 "The measure is appropriate for making me observe the road course more attentively." of the qualitative study for the factor technology. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure distracts me."

Technology	Mean	SD	Range	Modus	Friedman
Technology „Red spots"	2.56	1.24	1 – 4	2, 4	
Technology „Red strips"	2.33	1.41	1 – 5	1, 2	.20
Technology „Orange green spots"	1.56	.73	1 – 3	1	
Technology „Orange green strips"	2.44	.13	1 – 4	2	

Table A.48: Results of question 4 "The measure distracts me." of the qualitative study for the factor technology. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure increases my attention for the traffic scene."

Technology	Mean	SD	Range	Modus	Friedman
Technology „Red spots"	2.56	1.24	1 – 4	2, 4	
Technology „Red strips"	2.33	1.41	1 – 5	1, 2	.20
Technology „Orange green spots"	1.56	.73	1 – 3	1	
Technology „Orange green strips"	2.44	.13	1 – 4	2	

Table A.49: Results of question 5 "The measure increases my attention for the traffic scene." of the qualitative study for the factor technology. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure makes me feel safer in traffic."

Technology	Mean	SD	Range	Modus	Friedman
Technology „Red spots"	3.0	.71	2 – 4	3	
Technology „Red strips"	3.22	.97	2 – 5	3	.83
Technology „Orange green spots"	3.44	1.01	2 – 5	4	
Technology „Orange green strips"	2.89	1.05	1 – 4	3, 4	

Table A.50: Results of question 6 "The measure makes me feel safer in traffic." of the qualitative study for the factor technology. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure supports save driving behaviour."

Technology	Mean	SD	Range	Modus	Friedman
Technology „Red spots"	3.33	.71	2 – 4	3, 4	
Technology „Red strips"	3.22	.97	2 – 5	3	.053
Technology „Orange green spots"	4.0	.50	3 – 5	4	
Technology „Orange green strips"	3.11	.93	2 – 4	4	

Table A.51: Results of question 7 "The measure supports save driving behaviour." of the qualitative study for the factor technology. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure seems stressful to me."

Technology	Mean	SD	Range	Modus	Friedman
Technology „Red spots"	2.22	1.1	1 – 4	1, 3	
Technology „Red strips"	1.56	1.01	1 – 4	1	.03
Technology „Orange green spots"	1.22	.44	1 – 2	1	
Technology „Orange green strips"	2.22	.97	1 – 4	2	

Table A.52: Results of question 8 "The measure seems stressful to me." of the qualitative study for the factor technology. Table shows the descriptive values of the structured questionnaire with N = 9

"I would accept the measure in traffic."

Technology	Mean	SD	Range	Modus	Friedman
Technology „Red spots"	3.89	.93	2 – 5	4	
Technology „Red strips"	4.22	.83	3 – 5	5	.32
Technology „Orange green spots"	4.56	.73	3 – 5	5	
Technology „Orange green strips"	4.0	.87	3 – 5	3, 4, 5	

Table A.53: Results of question 9 "I would accept the measure in traffic." of the qualitative study for the factor technology. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure explicitly shows which behaviour is demanded of me."

Technology	Mean	SD	Range	Modus	Friedman
Technology „Red spots"	3.0	1.12	2 – 5	2	
Technology „Red strips"	3.56	1.01	2 – 5	4	.75
Technology „Orange green spots"	3.44	1.42	2 – 5	2	
Technology „Orange green strips"	3.33	1.58	1 – 5	2, 5	

Table A.54: Results of question 10 "The measure explicitly shows which behaviour is demanded of me." of the qualitative study for the factor technology. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure is appropriate for decelerate me in a suitable way."

Technology	Mean	SD	Range	Modus	Friedman
Technology „Red spots"	3.33	.87	2 – 4	4	
Technology „Red strips"	3.67	.87	2 – 5	4	.91
Technology „Orange green spots"	3.33	1.41	1 – 5	4	
Technology „Orange green strips"	3.33	1.32	2 – 5	2	

Table A.55: Results of question 11 "The measure is appropriate for decelerate me in a suitable way." of the qualitative study for the factor technology. Table shows the descriptive values of the structured questionnaire with N = 9

A.6 Location

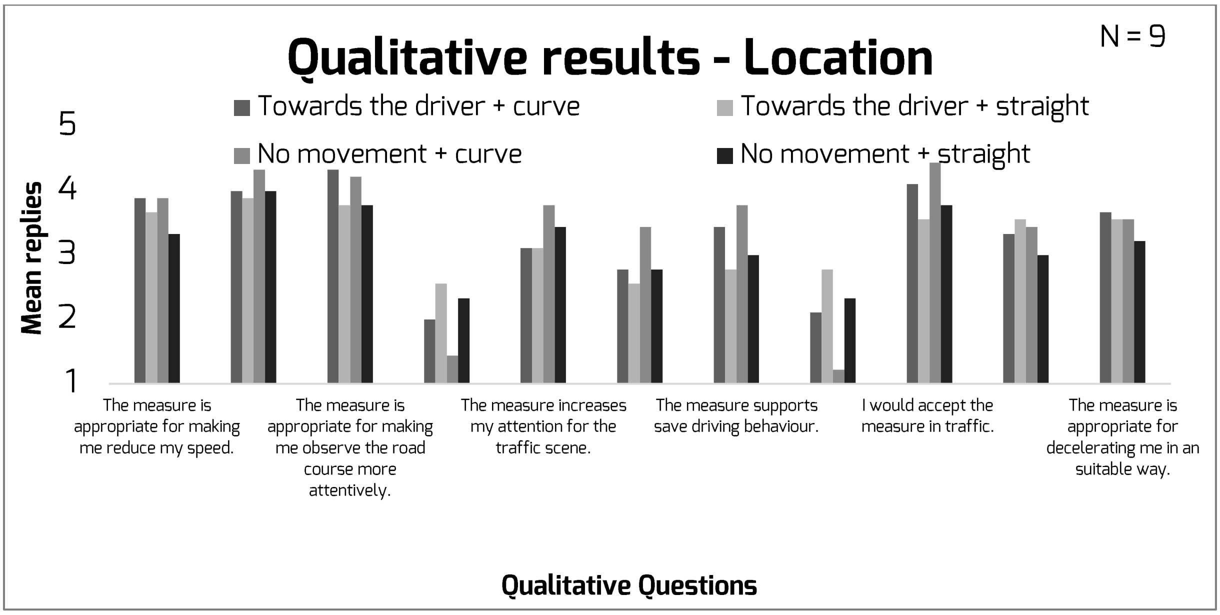

Figure A.6: Results of structured questionnaire of the qualitative study for the factor location. Figure is descriptive and shows the mean replies to questions 1 – 11

"The measure is appropriate for making me reduce my speed."

Location	Mean	SD	Range	Modus	Friedman
Location „Towards the driver + curve"	3.89	1.36	1 – 5	5	
Location „Towards the driver + straight"	3.67	1.0	2 – 5	3, 4	.20
Location „No movement + curve"	3.89	.93	2 – 5	4	
Location „No movement + straight"	3.33	1.22	2 – 5	2	

Table A.56: Results of question 1 "The measure is appropriate for making me reduce my speed." of the qualitative study for the factor location. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure is appropriate for alerting me more for the driving situation."

Location	Mean	SD	Range	Modus	Friedman
Location „Towards the driver + curve"	4.0	.87	3 – 5	3, 4, 5	
Location „Towards the driver + straight"	3.89	.78	2 – 5	4	.48
Location „No movement + curve"	4.33	.50	4 – 5	4	
Location „No movement + straight"	4.0	.71	3 – 5	4	

Table A.57: Results of question 2 "The measure is appropriate for alerting me more for the driving situation." of the qualitative study for the factor location. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure is appropriate for making me observe the road course more attentively."

Location	Mean	SD	Range	Modus	Friedman
Location „Towards the driver + curve"	4.33	.71	3 – 5	4, 5	
Location „Towards the driver + straight"	3.78	.83	2 – 5	4	.21
Location „No movement + curve"	4.22	.67	3 – 5	4	
Location „No movement + straight"	3.78	.97	2 – 5	4	

Table A.58: Results of question 3 "The measure is appropriate for making me observe the road course more attentively." of the qualitative study for the factor location. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure distracts me."

Location	Mean	SD	Range	Modus	Friedman
Location „Towards the driver + curve"	2.0	1.12	1 – 4	1	
Location „Towards the driver + straight"	2.56	1.01	1 – 4	2	.06
Location „No movement + curve"	1.44	.53	1 – 2	1	
Location „No movement + straight"	2.33	.71	1 – 3	2, 3	

Table A.59: Results of question 4 "The measure distracts me." of the qualitative study for the factor location. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure increases my attention for the traffic scene."

Location	Mean	SD	Range	Modus	Friedman
Location „Towards the driver + curve"	3.11	.93	1 – 4	3	
Location „Towards the driver + straight"	3.11	1.17	1 – 4	4	.33
Location „No movement + curve"	3.78	.83	2 – 5	4	
Location „No movement + straight"	3.44	1.24	1 – 5	4	

Table A.60: Results of question 5 "The measure increases my attention for the traffic scene." of the qualitative study for the factor location. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure makes me feel safer in traffic."

Location	Mean	SD	Range	Modus	Friedman
Location „Towards the driver + curve“	2.78	.67	2 – 4	3	
Location „Towards the driver + straight“	2.56	.88	1 – 4	3	.19
Location „No movement + curve“	3.44	1.13	1 – 5	4	
Location „No movement + straight“	2.78	.83	1 – 4	3	

Table A.61: Results of question 6 "The measure makes me feel safer in traffic." of the qualitative study for the factor location. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure supports save driving behaviour."

Location	Mean	SD	Range	Modus	Friedman
Location „Towards the driver + curve“	3.44	.88	2 – 4	4	
Location „Towards the driver + straight“	2.78	.67	2 – 4	3	.04
Location „No movement + curve“	3.78	.83	2 – 5	4	
Location „No movement + straight“	3.0	.87	2 – 5	3	

Table A.62: Results of question 7 "The measure supports save driving behaviour." of the qualitative study for the factor location. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure seems stressful to me."

Location	Mean	SD	Range	Modus	Friedman
Location „Towards the driver + curve"	2.11	1.27	1 – 5	2	
Location „Towards the driver + straight"	2.78	1.09	1 – 4	2, 4	.10
Location „No movement + curve"	1.22	.44	1 – 2	1	
Location „No movement + straight"	2.33	1.22	1 – 4	1	

TableA.63: Results of question 8 "The measure seems stressful to me." of the qualitative study for the factor location. Table shows the descriptive values of the structured questionnaire with N = 9

"I would accept the measure in traffic."

Location	Mean	SD	Range	Modus	Friedman
Location „Towards the driver + curve"	4.11	.78	3 – 5	4	
Location „Towards the driver + straight"	3.56	1.01	2 – 5	4	.01
Location „No movement + curve"	4.44	.73	3 – 5	5	
Location „No movement + straight"	3.78	.67	3 – 5	4	

Table A.64: Results of question 9 "I would accept the measure in traffic." of the qualitative study for the factor location. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure explicitly shows which behaviour is demanded of me."

Location	Mean	SD	Range	Modus	Friedman
Location „Towards the driver + curve"	3.33	1.12	2 – 5	4	
Location „Towards the driver + straight"	3.56	1.33	2 – 5	2, 5	.68
Location „No movement + curve"	3.44	.88	2 – 5	3	
Location „No movement + straight"	3.0	1.12	1 – 4	4	

Table A.65: Results of question 10 "The measure explicitly shows which behaviour is demanded of me." of the qualitative study for the factor location. Table shows the descriptive values of the structured questionnaire with N = 9

"The measure is appropriate for decelerate me in a suitable way."

Location	Mean	SD	Range	Modus	Friedman
Location „Towards the driver + curve"	3.67	.87	2 – 5	4	
Location „Towards the driver + straight"	3.56	1.13	1 – 5	4	.47
Location „No movement + curve"	3.56	.88	2 – 5	4	
Location „No movement + straight"	3.22	1.09	1 – 4	4	

Table A.66: Results of question 11 "The measure is appropriate for decelerating me in a suitable way." of the qualitative study for the factor location. Table shows the descriptive values of the structured questionnaire with N = 9

Annex B: Detailed results from the Monte-Carlo Simulation

B.1 Simulation Results of Analysis of Deceleration Behaviour

Scenario ID	Confi-guration	Number of runs	Mean v_0 [km/h]	Mean Acceleration Predecessor [g]	SD Acceleration Predecessor [g]	Mean Collision Rate [-]	SD Collision Rate [-]	Absolut Delta Collision	Relative Delta Collision
1	1	5 * 2000	81.9934	-0.2	0.05	2.56%	0.29%	0.37%	16.9%
	2	5 * 2000	81.9934	-0.2	0.05	2.19%	0.24%	0.00%	0.0%
	3	5 * 2000	81.9934	-0.2	0.05	4.67%	0.62%	2.48%	113.2%
2	1	5 * 2000	81.9934	-0.25	0.05	0.66%	0.18%	0.06%	10.0%
	2	5 * 2000	81.9934	-0.25	0.05	0.60%	0.10%	0.00%	0.0%
	3	5 * 2000	81.9934	-0.25	0.05	1.40%	0.26%	0.80%	133.3%
3	1	5 * 2000	81.9934	-0.3	0.05	0.78%	0.22%	0.25%	47.2%
	2	5 * 2000	81.9934	-0.3	0.05	0.53%	0.17%	0.00%	0.0%
	3	5 * 2000	81.9934	-0.3	0.05	2.08%	0.43%	1.55%	292.5%
4	1	5 * 2000	81.9934	-0.3	0.25	17.67%	0.64%	0.06%	0.3%
	2	5 * 2000	81.9934	-0.3	0.25	17.61%	0.74%	0.00%	0.0%
	3	5 * 2000	81.9934	-0.3	0.25	19.03%	0.77%	1.42%	8.1%
5	1	5 * 2000	81.9934	-0.4	0.25	9.61%	0.88%	0.04%	0%
	2	5 * 2000	81.9934	-0.4	0.25	9.57%	0.90%	0.00%	0%
	3	5 * 2000	81.9934	-0.4	0.25	10.50%	1.00%	0.93%	10%
6	1	5 * 2000	81.9934	-0.5	0.25	4.95%	0.36%	0.16%	3%
	2	5 * 2000	81.9934	-0.5	0.25	4.79%	0.37%	0.00%	0%
	3	5 * 2000	81.9934	-0.5	0.25	5.53%	0.23%	0.74%	15%
7	1	5 * 2000	73.79406	-0.5	0.25	3.45%	0.25%	-0.02%	-1%
	2	5 * 2000	73.79406	-0.5	0.25	3.47%	0.25%	0.00%	0%
	3	5 * 2000	73.79406	-0.5	0.25	3.73%	0.23%	0.26%	7%
8	1	5 * 2000	90.19274	-0.5	0.25	7.14%	0.84%	0.35%	5%
	2	5 * 2000	90.19274	-0.5	0.25	6.79%	0.70%	0.00%	0%
	3	5 * 2000	90.19274	-0.5	0.25	8.41%	1.07%	1.62%	24%

Table B.1: Simulation results of simulation regarding likelihood of rear-end accidents and preference of deceleration manoeuvres

B.2 Simulation Results of Analysis of the Motorway Exit

Simulation ID	Number of Simulation Runs [-]	Mean velocity [-]	Mean preview distance [-]	Mean target lateral acceleration [m/s²]	Cut-off distance [m] / percentile velocity [%]	Comment	Relative delta collision [-]	Mean collision [-]	SD collision [-]
101	5 * 8 000	100%	100%	4	0	Baseline	0%	0.97%	0.01
102	5 * 8 000	99%	100%	4	0		-6%	0.91%	0.009
103	5 * 8 000	98%	100%	4	0		-9%	0.88%	0.009
104	5 * 8 000	95%	100%	4	0		-16%	0.81%	0.008
105	5 * 8 000	90%	100%	4	0		-21%	0.77%	0.008
106	5 * 8 000	100%	80%	4	0		61%	1.55%	0.016
107	5 * 8 000	100%	90%	4	0		19%	1.15%	0.012
108	5 * 8 000	100%	110%	4	0		-17%	0.81%	0.008
109	5 * 8 000	100%	120%	4	0		-27%	0.70%	0.007
110	5 * 8 000	100%	100%	4	99.5%	Velocity	-3%	0.94%	0.009
111	5 * 8 000	100%	100%	4	99%	Velocity	-8%	0.89%	0.009
112	5 * 8 000	100%	100%	4	98%	Velocity	-11%	0.86%	0.009
113	5 * 8 000	100%	100%	4	95%	Velocity	-11%	0.86%	0.009
114	5 * 8 000	100%	100%	4	92.5%	Velocity	-12%	0.85%	0.009
115	5 * 8 000	100%	100%	4	90%	Velocity	-14%	0.83%	0.008

Table B.2: Simulation results with the matched initial velocity for the start of the motorway exit

Simulation ID	Number of Simulation Runs [-]	Mean velocity [-]	Mean preview distance [-]	Mean target lateral acceleration [m/s²]	Cut-off distance [m] / percentile velocity [%]	Comment	Relative delta collision [-]	Mean collision [-]	SD collision [-]
201	5 * 41 769	100%	100%	4	0	Baseline	0%	0.012 %	
202	5 * 40 000	99%	100%	4	0		13%	0.014 %	8.02E-05
203	5 * 40 000	98%	100%	4	0		4%	0.013 %	5.86E-05
204	5 * 40 000	96%	100%	4	0		-12%	0.011%	5.42E-05
205	5 * 40 000	95%	100%	4	0		-8%	0.010%	7.62E-05
206	5 * 40 000	100%	100%	4	95% (65.89 km/h)	Velocity	-16%	0.010%	6.37E-05
207	5 * 23 200	100%	100%	4	90% (65.85 km/h)	Velocity	-20%	0.010%	11.78E-05
208	5 * 40 000	100%	100%	4	85% (64.00 km/h)	Velocity	-33%	0.008%	6.71E-05
209	5 * 23 200	100%	100%	4	80% (62.52 km/h)	Velocity	-84%	0.002%	2.69E-05

TableB.3: Simulation results with the matched initial velocity for the curve entrance