Driver Interaction with Pedestrians at Intersections

Quantifying the influence of environmental factors on driver comfort boundaries

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Master's thesis in Engineering Mathematics and Computational Science

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Abstract

Active safety systems are constantly being enhanced, featuring more and more environmental factors and advanced algorithms. The system needs to be able to evaluate many different driving situations, and take appropriate action, at a safety critical moment. In this study, focus has been on quantifying factors' influence on driver comfort boundaries when interacting with pedestrians at intersections.

Seven factors, on two levels, were included in the study; *Car speed*, *Pedestrian speed*, *Pedestrian size*, *Crossing angle*, *Crossing presence*, *Crossing entry* and *Lane width.* The experiment was designed with a fractional factorial layout with the seven factors combined into 32 tasks. Additional 4 tasks were created, 3 to compare the study against two studies previously conducted, and another to analyze the learning/adaptation effect.

Participants were divided into two groups; Group 1, frequent drivers and Group 2, occasional drivers. Statistical analysis based on *Linear mixed-effects models* was carried out with a significance level of 0.01 for both group of drivers separately, and by combining the two groups. Factors *Car speed* and *Crossing entry* have a significant influence on Time To Collision (TTC) at brake onset for all group of drivers. The factors decreased TTC when changed from low to high level. Factors *Pedestrian size* and *Lane width* also had a significant influence on TTC at brake onset for all group of drivers. The factors increased TTC when changed from low to high level.

The study was conducted with a low-fidelity simulator available at SAFER. Limitations of the simulator included participants' lack of input from auditory and sensory sources and narrow field of view. Also, the expectancy of the pedestrian might have changed the comfort boundaries as there was only one pedestrian crossing the road in every scenario.

However, even though the simulator was developed with open source software, still nearly 90% of the participants stated they experienced the environment to be natural or sort of natural and more than 95% said they behaved, or sort of behaved, as normally as they would have in a real traffic situation.

Keywords: environmental factors, driver behaviour, pedestrian-crossing, intersection, comfort boundaries, driving simulator, brake onset, hypothesis testing

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Contents

1
Introduction

1.1 Background

The field of active safety systems is evolving fast, more and more car manufacturers decide to implement these systems in their cars. However, challenges still remain in perfecting the safety system's performance. Many studies have been searching for solutions to these challenges, for instance, how to define imminent, how to distinguish the difference between desired and undesired warnings, and how to decide when an active safety system should be activated.

Another important aspect to include is whom to warn. Lee et al. investigated attentive and distracted drivers' relation to warnings to an imminent collision. The study showed that both types of drivers benefit from the warnings, [1]. However, since the study was done in a simulator, Lee et al. concluded that the driver behaviour seen in the study might not entirely be adaptable to on-road driving. The test drivers were given many warnings during a short time to mostly severe situations, which may not present themselves that often in every day driving. Hence, when used on the road, the safety system could trigger many false alarms which later could prove to be more of a nuisance for the driver, resulting in distrust in the system.

System designers must therefore find a way to evaluate what is a desired system activation time, as a function of the driving situation, that will be accepted by the driver. Abe and Richardson found that it is undesired to activate safety systems either too early, which would be perceived as a nuisance by the driver, and late, which would not use the system's full safety potential, [2]. Timely interventions that will use the full potential of the system, while not be a nuisance for the driver, is to strive for.

Lubbe and Rosén investigated if there is a suitable measure for the quantification of comfort boundaries, [3]. To accomplish this they studied drivers' comfort boundary zone when they encounter a pedestrian crossing the vehicle's path. In the study the researchers analyzed the relationship between driving speed and TTC, longitudinal and lateral distance at brake onset. They found that TTC at brake onset is a suitable measure for the quantification of comfort boundaries and that this measure could guide system activation timing.

While Lubbe and Rosén investigated the dependency between comfort boundaries and vehicle speed, Lubbe and Davidsson investigated the dependency between comfort boundaries and pedestrian speed in [4]. Indication of discomfort from the drivers was measured for TTC at brake onset. The researchers made the assumption that drivers will brake if, and only if, they feel uncomfortable continuing driving as before and want to regain comfort by braking.

Bärgman et al. provided a complete definition of comfort zone saying; "The comfort zone is a dynamic spatiotemporal envelope surrounding the vehicle, within which drivers feel comfortable and safe.", [5]. It can be viewed as a threshold above which the driver feels comfortable and is engaged in normal driving and below the threshold the driver feels discomfort. Figure 1.1 is an illustration of the comfort boundary and its relation to a driver's perception of a situation.

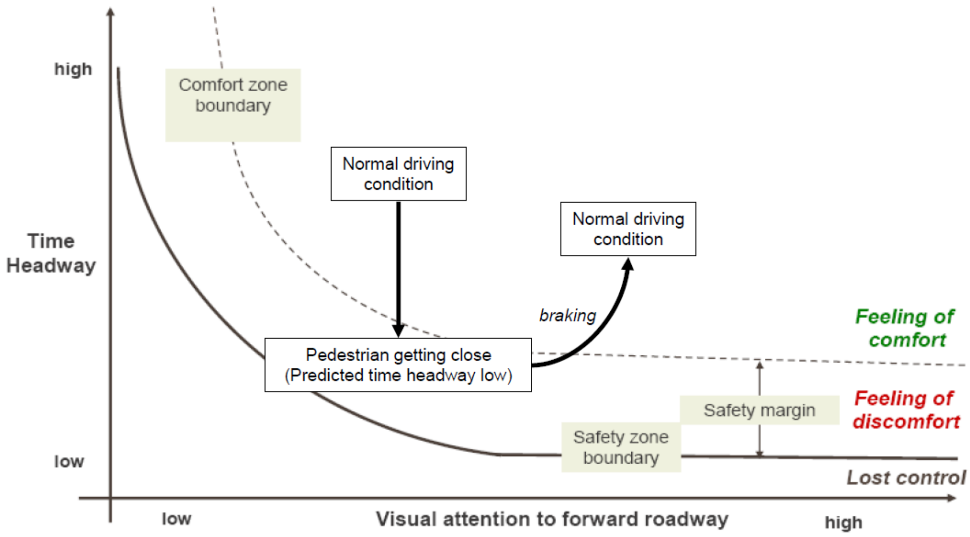

Figure 1.1: Comfort boundaries. Figure from [3].

The scenario illustrated in Figure 1.1 can be related to the study done by Lubbe and Rosén, though it describes a driver's interaction with a pedestrian. During the first phase, the driver is maintaining normal driving conditions. This phase is located above the *Comfort zone boundary* and here the driver feels comfortable. Suddenly, a pedestrian shows up unexpectedly, e.g. from behind a building with the intention of crossing the road. The driver sees the pedestrian and estimates the time headway. The predicted headway is low, and since the *Comfort zone boundary* has been crossed, the driver starts to feel uncomfortable. However, since the driver is still within the *Safety zone boundary*, they are still capable of maintaining control of the situation, even though the feeling of discomfort is strong. As Lubbe and Davidsson assumed in their study, drivers who are in this situation will try to resolve the discomfort by braking. Assumed that they reacted in time, the driver can avoid a collision and once again go back to normal driving conditions. If instead the driver reacted too late and braking cannot prevent a collision from happening, then the situation has crossed the *Safety zone boundary*. In this phase, the driver has lost control of the vehicle and a collision or out of control maneuver (e.g. the vehicle starts to skid from sudden steering movement) is inevitable.

1.2 Aim

The aim of the study is to quantify different factors' influence on driver comfort boundaries for drivers in interaction with pedestrians in crossing situations from data collected through volunteer test drivers.

1.3 Purpose

This study will contribute to the definition of *Requirements for vehicle safety systems* in the context of Vulnerable Road Users (VRU) safety. The study is a collaboration between Chalmers, Autoliv Research and Toyota Motor Europe.

2

Methods

2.1 Participants

2.1.1 Recruitment

The selection of the participants were based on a driver profile which included the following criteria:

- Participant must have a valid driver's license.
- Participant must be in the age group 25-60 years old.
- Possibly drive at least 3 days per week.

These criteria were chosen so to that the participants, besides having driving experience and are familiar with the Swedish traffic rules and regulations, could be divided into two groups: frequent drivers and occasional drivers. The frequent drivers' group included all participants in the specified age group who drove 3 or more days a week, and the occasional drivers' group who drove less than 3 days a week. Number of participants needed in the study was estimated by performing a power analysis, which will be described more in detail in Section 2.1.2.

The recruiting of the participants were done by advertising in SAFER events, on Lindholmen Science Park website and on social media (Facebook and Reddit), and also by putting up fliers at Ericsson, Chalmers Lindholmen, Fysiken and student apartments (Appendix A).

The interested volunteers were then sent a link to a Doodle form created for the study where they choose a time slot to participate in the experiment. The participants were contacted one day before the experiment as a reminder of their booking via mail, where also the location and access of the SAFER *Driving simulator room* was described.

In the end, 103 volunteers signed up for the study out of which 94 participated. From the exclusion criteria, described in Section 2.1.3, 87 usable data sets were obtained for analysis. The age range for all participants were 22-59 years old with mean of 33.6 years and standard deviation of 10.8 years. 19.5% of all participants were females with age ranging between 25-51 years old, mean of 32.5 years and standard deviation of 9.1 years.

Group 1, the frequent drivers, consisted of 47 participants with age range 25-59 years old, mean of 37.6 years and standard deviation of 11.5 years. The proportion of females in the group was 12.8% with age range 25-51 years old, mean of 36.2 years and standard deviation of 12.0 years. Group 2, the occasional drivers, consisted of 40 participants with age range 22-52 years old, mean of 29.0 years and standard deviation of 7.6 years. The proportion of females in the group was 27.5% with age range 25-46 years old, mean of 30.5 years and standard deviation of 6.9 years.

Data collected from Group 1, frequent drivers and Group 2, occasional drivers was analysed separately and also by combining the two groups. The steps followed in the data analysis is described in Section 2.8.

2.1.2 Power analysis

Power analysis is a method for estimating the sample size needed in order to detect any effect which is expected in the study. To be able to perform this analysis, one must estimate the difference in mean and standard deviation that can be expected in the experiment. For the current study, power analysis helped in estimating how many participants were needed in order to detect any significant influence from the factors on TTC at brake onset. The difference in mean and standard deviation for TTC at brake onset was estimated from papers [3] and [4] were the researchers had conducted a similar study to the current one. In both papers, the TTC for the two tested groups were calculated and plotted in a cumulative frequency graph. The mean TTC was found at 50%. One property of the normal distribution is that 68% of the data lays within one standard deviation, 95% within two standard deviations and 99.7% withing three standard deviations away from the mean. The standard deviation was calculated from this property. The difference in mean was then found by subtracting the two test groups' mean TTC from each other. This resulted in a range between 0.1 s and 0.21 s for the difference in mean and between 0.45 s and 0.5 s for the standard deviation of the TTC at brake onset.

The null hypothesis (H_0) is that the mean TTC at brake onset between the factors included in this study will not differ. The alternative hypothesis (H_A) is that the mean TTC at brake onset will differ. The power can be calculated with the following formula found in [6]:

$$power = 1 - \Phi\left[z(\alpha/2) - \frac{\Delta}{\sigma}\sqrt{\frac{n}{2}}\right] + \Phi\left[-z(\alpha/2) - \frac{\Delta}{\sigma}\sqrt{\frac{n}{2}}\right] \tag{2.1}$$

where α is the significance level, Δ is the difference in mean, σ is the standard deviation and n is the number of participants. $z(\alpha/2)$ indicate the Z-score (and Φ its inverse) found in a cumulative normal distribution table. The significance level was set to 5% in accordance with other studies, for instance [3].

From Equation (2.1) one can estimate the number of participants needed for a desired power. A realistic power to assume for the study is 80%. This means that the probability of a type II error is 20%, not rejecting the null hypothesis when it is wrong, [6]. With the assumed power and the different combinations of difference in mean and standard deviation of TTC at brake onset, Equation (2.1) resulted in total number of participants to be between 72 and 392. Detailed calculations can be found in Appendix B.

The power estimation of the minimum number of participants needed in the study was reasonable. However, the upper limit of 392 is too high. The maximum amount of participants that could be recruited for the study was instead estimated from number of days the simulator room was available for the study.

It was estimated that the information and test run would take 20-25 min, the main simulation 20 min and the break 10 min. Hence, the entire experiment would take approximately 50-55 min for each participant. Estimating in total of six hours/day on the experiment which will be carried out for four weeks with 1 hour/participant, yielded a maximum of 120 participants for the entire study.

Hence, recruiting 100 participants is sufficient to be 95% certain of not making a mistake when rejecting H_0 and 80% certain of not making a mistake when keeping H_0, if the difference in mean is at least 0.1 s and the standard deviation is maximum 0.5 s as assumed.

2.1.3 Exclusion criteria

Data collected during the experiment was analyzed and bad data was sorted out based on the following exclusion criteria:

- The participant was unable to complete the simulation task due to simulator sickness or discomfort.
- Participant answered “No” on the question: “Did you react like you would normally do in a real traffic situation?” asked in the questionnaire.
- Error during data collection.
- Scenarios including a crash between the car and the pedestrian as the study focuses on driver comfort boundaries in normal driving conditions.

2.2 Driving simulator

The driving simulation software for research purposes helps to analyze driving performance and driver interaction, in order to evaluate and study automotive applications. To evaluate selected factors' influence on TTC at brake onset, an open source software named OpenDS was used along with the basic set up of Logitech G27 steering wheel and pedals which were available in the SAFER *Driving simulator room*, see Figure 2.1. A Windows 7 Enterprise computer with Intel Core i7-3770 3.40 GHz processor, NVIDIA GeForce GT640 graphic card and 16 GB RAM was available for simulation at SAFER. The simulation was visualized with a Hitachi CP X1 LCD projector (1024x768 resolution) available in the *Driving simulator room*.

Figure 2.1: Driving simulator setup in the SAFER *Driving simulator room*.

The different components of the simulation environment were built up using open source software. The pedestrian models were created using MakeHuman, which were then manipulated and further developed using Blender, a 3D modeling software. Blender was also used to create the environment, which included streets, buildings and trees to make the simulation as realistic as possible. The different environment and pedestrian models were then combined into complete tasks in MATLAB and exported to OpenDS. The software used, and their purpose, is visualized as a flow chart in Figure 2.2.

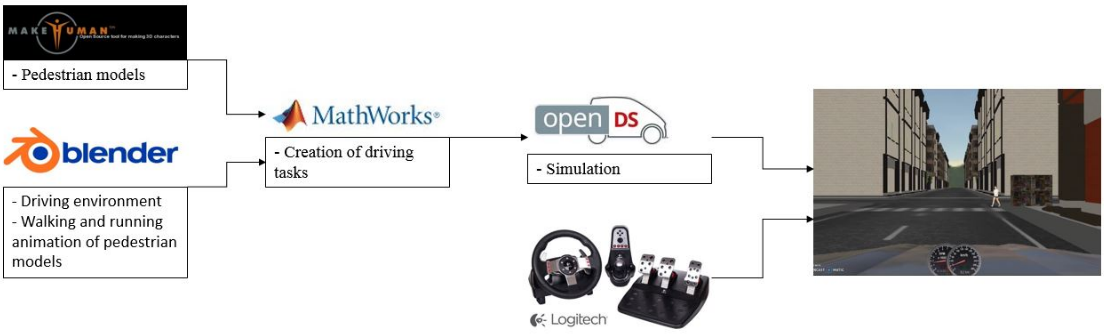

Figure 2.2: Schematic representation of software used to create the driving simulator. Images taken from [7], [8], [10], [11] and [12].

2.2.1 MakeHuman

MakeHuman is an open source 3D modeling software to create realistic humanoids of different size and shape. The software tool has a simple user interface in order to create different human models, mainly including four targets; baby, adolescent, adult and senior. The software is developed in Python and is specifically designed to create different virtual human models having a simple and complete pose system to simulate the muscular movements, [7].

MakeHuman was used to create the two different pedestrian models, child and adult, included in the study. The child model was created based on the low level of the factor *Pedestrian size* with height of 115 cm, and the adult was based on the high level, with height 175 cm.

The human models were then exported to Blender to develop further with complete animations using the exporter tool in MakeHuman. Key-framed animation tools in Blender, which includes inverse kinematics and rigging, are used to manipulate the muscles and skeleton. By doing this, different animation cycles of the human models namely, running and walking, are created. These cycles thus represent the different speed of the pedestrian models chosen in the factor *Pedestrian speed*. Finally, the complete child and adult model, with animations, are exported to OpenDS in a *.scene* format for scenario creation.

2.2.2 Blender

Blender is an open source software used for creating 3D models and also used to create animations, rendering and simulations, [8]. The software was used to create environments and to animate the human models, developed in MakeHuman, which are later used to create the different tasks in OpenDS.

The environment which includes the streets, buildings and surrounding (trees, bushes etc.) are also created using Blender. Different environment models were created in order to capture all levels of factor *Crossing presence* and *Lane width*. The building and tree models were downloaded from yobi3D, a free 3D model search engine, [9]. These models are then manipulated (size and color) and positioned to reassemble a realistic driving environment. Hence, four sets of environment models were created having a width of the road 2.5 m and 3 m respectively and with, or without, crossing markings. The placement of the buildings were further altered and manipulated to suit the pedestrian visibility. Finally, the environment models are also exported to OpenDS in a *.scene* format like the pedestrian models.

2.2.3 OpenDS

The pedestrian and environment models developed using MakeHuman and Blender are used to create different simulation tasks in OpenDS.

OpenDS is an open source driving simulator based on jMonkeyEngine (jME), a Java based game development tool, [10].

Different driving tasks can be loaded in the driving simulator. The driving task describes how a given map model will incorporate additional road objects, events and other parameters. It consists of three main components; scene, scenario and interaction, which are written in *.xml* format, the required format for OpenDS. A particular driving task contains in total of 5 different *.xml* files, each containing different models described as follows:

1. **Scene**
   Scene.xml file contains different models of buildings, trees, roads, roadsigns and car models, in *.scene* format, which are created using Blender and represent the driving environment. Along with these models, geometric objects such as box and sphere can be created using the preloaded models in OpenDS. These geometric shapes are used for triggering the specific events during the simulations. The light and shadow settings of the environment can also be described and modified based on the driving task.

2. **Scenario**
   Scenario.xml file contains and describes the role of dynamic models used in the Scene.xml. It mainly contains semantic information about the task created namely, weather condition, driving car specification and traffic. Traffic is the most important part of the driving simulation where the created pedestrian models are added along with the animation. There is also possibility to add other road users, like cars and pedestrians, and manipulate the traffic signs and signals.

3. **Interaction**
   Interaction.xml file mainly deals with changing the parameters during the sim-

ulation once the correctly specified conditions are met. In the simulation, the triggering of pedestrian is controlled.

4. **Setting**
   Setting.xml file contains particular settings specific to the task and can be customized upon request. It mainly contains the controller setting used for controlling the car model during the simulation.

5. **Task**
   Task.xml file combines all the above layers together and is executed as a simulation task in OpenDS.

As OpenDS is an open source driving simulator, the source code was available for modification to customize the simulator for the study. One of the modifications included a different trigger activation of the pedestrian model. As a default, OpenDS uses a static trigger which activates the pedestrian model when the car is a predefined distance from the collision point (independent of the car speed). Instead, a dynamic trigger was used which activates the pedestrian model when the car is at a predefined TTC value from the collision point (dependent of the car speed). Hence, TTC of the car was calculated at every time stamp and when it was equal to pedestrian visibility (4 s/8 s) the pedestrian was triggered to cross the street.

To simplify the task creation, a MATLAB *Scenario generator* script was developed to create different *.xml* files corresponding to different tasks with factors on either high or low level, based on the fractional factorial design described in Section 2.4.2.

2.3 Ethical approval

An ethical approval is needed when research involves human subjects, living or deceased, biological material from humans or sensitive information about people, [13]. An ethical board later decides to either grant the study the approval, that the study doesn't need an approval or to reject the approval because the researchers' proposed method to conduct the study doesn't follow the ethical guidelines.

For the study presented here, an ethical approval was filed but the board decided that the research could be conducted without an ethical approval.

2.4 Experimental design

The experimental design is a procedure for designing the experiment and it should contain the factor selection and design layout. The experiment should be designed in a way so that the response from the factors on TTC at brake onset can be measured.

2.4.1 Factor selection

Seven factors were chosen for the study during the literature study, having both a high and low level setting. The selected factors can be found in the list below, with motivation, and the different levels can be seen in Table 2.1.

Two different pedestrian visibilities were chosen for the study, 4 seconds TTC for near side crossing entry and 8 seconds TTC for far side crossing entry. 4 seconds pedestrian visibility was chosen in accordance with study [3] and [4]. Pedestrian visibility for the far side crossing entry was influenced by factors *Car speed*, *Pedestrian speed*, *Crossing angle* and *Lane width*. These factors were combined and evaluated for different pedestrian visibilities. In the end, 8 seconds TTC was found suitable for all combination of factors.

1. **Car speed**
   It was hypothesised in the study done by Lubbe and Rosén that driving speed, set to 30 or 50 km/h, has an influence on TTC at brake onset. Even though the study in the end revealed no significant influence, the researchers concluded that a larger speed range or different environment settings could potentially show different results, [3].

2. **Pedestrian speed**
   Lubbe and Davidsson's study regarding different pedestrian speed showed a significant influence on TTC at brake onset, [4]. The factor was chosen to compare the results of the current study with results in [4].

3. **Pedestrian size**
   Tanaka et al. study revealed that children are less prone to be involved in accidents, [14]. It was therefore hypothesized that children as more vulnerable and unpredictable road users might trigger specifically cautious driver behaviour.

4. **Crossing angle**
   Tanaka et al. found in the study that pedestrians crossing the road is a cause of many accidents, [14]. The crossing angle will mainly influence how a driver predicts the position of the pedestrian and estimate its path.

5. **Crossing presence**
   The study done by Lubbe and Rosén. were carried out in Sweden, with participants of mainly Swedish nationality, where the law states that pedestrians have priority at crossings, [3]. It was therefore thought to potentially be an influencing factor on TTC at brake onset.

6. **Crossing entry**
   Várhelyi discussed in his study the time it takes for a pedestrian to reach the

collision point when crossing the road from different directions, [15]. It will take a pedestrian longer time to reach the collision point when entering from the far side of the road, than the near side, which gives the driver more time to react.

7. **Lane width**
   The paper published by Shawky et al. analyzed the relation between the injury severity of pedestrians involved in crashes and the road width, [16]. It was found in the study that the injury severity level increased with increasing number of lanes (road width). By varying this factor, it might give an insight to how drivers' comfort boundaries are affected.

Table 2.1: Factors with levels

Factor	Low level	High level
1. Car speed	20 km/h	60 km/h
2. Pedestrian speed	1 m/s	2 m/s
3. Pedestrian size	Child	Adult
4. Crossing angle	45°	90°
5. Crossing presence	No crossing	Crossing
6. Crossing entry	Far side	Near side
7. Lane width	2.5 m	3 m

2.4.2 Fractional factorial design

Full factorial design helps in understanding the effects of factors with a fixed number of levels. However, in full factorial design, the experiment consists of all combination of factor levels, which can be time consuming to test. Therefore, by excluding repetitions in the full fractional design, a fractional factorial design can be used to observe any effect of factors, with less number of runs compared to a full fractional design, [17].

Fractional factorial analysis showed that the seven factors could be combined into 32 runs (2^{7-2}) resolution IV. In resolution IV, the main effects are not confounded by two-factor interactions, and two-factor interactions are confounded with other two-factor interactions, [17]. "Confounding is present when the difference in mean values of the outcome between populations defined by a potentially causal variable of interest is not equal to its causal effect on that outcome", [18]. In this study, the casual variable are the factors selected and "casual effect is defines as a difference in population mean", [18]. In fractional factorial design, higher order interactions between three or more factors are small enough to be neglected, [17].

Thus, (2^{7-2}) resolution IV was implemented to capture influence of factors on TTC at brake onset (Appendix C). The table in the appendix describes on which level each factor has to be in order to create 32 different tasks. To simplify the layout of the table, the two levels of each factor in Table 2.1 were assigned a dummy variable.

Factors on low level were labeled −1 and high level with 1.

Based on the fractional factorial design with resolution IV, the factor levels of *Crossing direction* and *Lane width* were generated using a combination of the other factors. *Crossing direction* was generated with *Car speed*, *Pedestrian speed*, *Pedestrian size*, *Crossing angle* and *Crossing presence*. *Lane width* was in turn generated with *Pedestrian size*, *Crossing angle* and *Crossing presence*. Since in fractional factorial design with resolution IV, main factors were not confounded with any two-factor interactions, it was therefore possible to estimate the main effect of all the factors.

Hence, 36 tasks were created, using a MATLAB *Scenario generator* script, consisting of 32 main tasks and 4 additional tasks, 3 to compare the study previously conducted by [3] and [4] and another to study the learning/adaptation effect. A detailed description of the additional tasks are explained below

- **Task 33**: A scenario where *Car speed* was 20 km/h, *Pedestrian speed* was 1 m/s and the pedestrian entered the intersection from near side with visibility 8 s TTC.
- **Task 34**: Based on [3] where *Car speed* was 30 km/h, *Pedestrian speed* was 1 m/s and the pedestrian entered the intersection from near side with visibility 4 s TTC.
- **Task 35**: Based on [3] where *Car speed* was 50 km/h, *Pedestrian speed* was 1 m/s and the pedestrian entered the intersection from near side with visibility 4 s TTC.
- **Task 36**: Based on [4] where *Car speed* was 30 km/h, *Pedestrian speed* was 2 m/s and the pedestrian entered the intersection from near side with visibility 4 s TTC.

Task 33 was chosen to study the learning/adaptation effect of the participant. The task was shown once in the beginning of the simulation and repeated 4 times, twice before the break and twice after the break.

2.5 Experimental procedure

Participants volunteering in the study as test drivers went through the following process during the experiment:

- The participant was given information about the study (background, aim and general information regarding the participation) and was then asked to sign a consent form if they understood and agreed to the terms. The information and the consent form can be found in Appendix D.
- The participant was introduced to the simulator and was given the possibility to adjust the seat. They were also given information regarding the controls of the simulator (steering, gas and brake pedal).
- The participant was asked to drive on a test track to get used to the controls

and to follow certain instructions. Instructions included rapid acceleration and braking to familiarize with the gas and brake pedals, driving over the pavement on left and right side of the road to get to know the width of the car and to drive close to a building wall, and stop as close to it as possible, to get the perception of how long the car front was.

- Once the participant was acquainted with the controls of the simulator, the actual experiment was conducted. The 32 tasks were run in random order. An additional 3 tasks were run to compare previous studies in [3] and [4], and 1 task was repeated 4 times to check for learning/adaptation effect. Hence, the main simulation experiment contained 39 tasks.
- After 20 tasks were completed, the participant was given a $5-10$ min break during which they were asked to fill in a questionnaire, detailed description in Section 2.7. The results from the questionnaire can be found in Chapter 3.
- After completing the experiment the participant was given two movie tickets as a compensation for their participation in the study.

2.6 Measurements

Gas pedal position, brake pedal position, car speed, car position and pedestrian position were collected for all participants. From the brake pedal, brake onset was extracted using MATLAB. Brake onset was defined as "Initiation of brake pedal to avoid potential collision with pedestrian". TTC at brake onset was calculated by measuring the longitudinal distance between the car position, at brake onset, and the predicted collision point, and dividing it by the car speed at brake onset.

2.7 Questionnaire

The questionnaire enquired detailed information about the participants, their driving habits and their simulator experience (Appendix E). The analysis of the questionnaire was divided into two parts, first part included the driver profile analysis and the second part, the simulator experience. The driver profile responses were analysed separately for each group and the simulator experience responses were analyzed for all drivers combined. The grouping was removed for the simulator experience questions as the feedback from participants were thought not to be influenced by if they were frequent or occasional drivers.

The driver profile questions included; age, gender, year the driver's license was issued, annual mileage and driving frequency. Questions regarding the simulator experience and environment included; if the traffic environment felt natural, if something in the scenarios did not feel natural, if the participant reacted normally, and reasons if they did not, and how the participant had heard about the study.

In Question 1 and Question 3, participants were given three options to choose from: *Yes*, *Sort of* and *No*. In Question 2, Question 3 and Question 4, participants were asked to leave their own comments. Hence, participants were given the opportunity to express themselves freely and leave several comments. Questions left unanswered were excluded.

2.8 Data analysis

Simulator studies generate a large amount of data. Statistical models are traditionally used to understand and analyze the different treatment conditions of simulator studies, [19]. With the use of statistical models it was possible to understand the influence of different factors on TTC at brake onset.

In [19] it was found that most of the simulator studies consists of mixed effect variables, which are a combination of both fixed and random effects of the factors. Therefore, a *Linear regression model with mixed effects* was used to evaluate factors' influence on TTC at brake onset.

The null hypothesis was rejected when the p-Value was below 0.01 by carrying out a significance test. The significance level in the data analysis differs from the value chosen for the power analysis because the experiments showed results which could be evaluated with an even lower significance level.

Along with statistical models, different graphical tools, such as histogram and box plot were used for each factor to visualize the collected data. The graphical tools helped in identifying the errors or anomalies in the data and to understand what distribution the data followed for each variable.

- **Histogram**
  Histogram of the responses gave an idea of the shape of the distribution and the location of the mean and grouping of the data. MATLAB was used to calculate the mean and standard deviation of TTC responses for all participants.
- **Box plot**
  Box plots were used to visualize the distribution of the data for each factor level. The bottom and top of the box corresponds to the 25^{th} and 75^{th} percentiles of the data, respectively. The box in the middle corresponds to the median, 50^{th} percentile. The whisker length is set to $\pm$ 2.7σ and data values beyond the whiskers are outliers.

2.8.1 Linear regression model with mixed effects

The main use of the *Linear regression model* was to estimate the variation of the average value of a response variable y given the value of a predictor variable x. The estimated average value of y was assumed to lie on the "regression line" or "line of mean", [20]. The general formula of the regression model was,

$$E[y|x] = predictors + e \tag{2.2}$$

where *predictors* are the predictor variable x and e is the random error.

Due to interactions, meaning a chosen factor's effect differs according to the level of another factor's effect [20], the predictor part, x, in Equation (2.2) consisted of 7 main effects and 15 two-factor interactions. These are the *fixed effects*.

Linear regression models are based on the main assumption that,

- The residuals are normally, identically and independently distributed, [19].
- The variance among the mean values are constant and the responses are statistically independent of each other, [20].

Since each participant is shown the same tasks, then the responses need to be grouped due to the fact that the responses vary for each participant. This violates the model assumption and introduces a new term in Equation (2.2), the *random effects*.

Knowing these two conditions, Equation (2.2) can be written as,

$$E[y|x] = fixed\ effects + random\ effects + e \tag{2.3}$$

where *fixed effects* consist of the main effects and the two-factor interactions, *random effects* which is the response variation for each participant and e is the random error.

2.8.2 Hypothesis testing - fractional factorial analysis

The fractional factorial analysis is carried out to test the significance of factors using *Linear regression model with mixed effects*. The steps taken are described below,

- Data is visualized using different graphical tools (histogram and box plot), which give an indication of what the final results might look like. The responses from the participants are separated per factor.

- Equation (2.3) is solved with *Linear mixed-effects models* function in MATLAB. Equation (2.4) represent the complete experiment model, where X_n, $n \in [1; 7]$, corresponds to the selected factors and gID represents the grouping variable of the participants.

- As described in Section 2.4.2 the fractional factorial design consists of 21 two-factor interactions, among which 6 two-factor interactions are confounded with other two-factor interactions. These confounded two-factor interactions cannot be evaluated separately and were therefore excluded. Hence, the formula used to fit the *Linear mixed-effect model* consists of 7 main factors and 15 two-factor interactions.

$$\begin{aligned} Formula = y \sim 1 + X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7 + \\ + X_1 : X_2 + X_1 : X_3 + X_1 : X_4 + X_1 : X_5 + X_1 : X_6 + \\ + X_1 : X_7 + X_2 : X_3 + X_2 : X_4 + X_2 : X_5 + X_3 : X_4 + \\ + X_3 : X_5 + X_3 : X_6 + X_3 : X_7 + X_4 : X_6 + X_5 : X_6 + (1|gID) \end{aligned} \tag{2.4}$$

- Columns *estimate* and p-Value in the resulting table determine which factor influences TTC at brake onset. Non-significant factors are removed by stepwise elimination. The removal of the non-significant factors is known as re-fitting of the statistical model to the observed responses. Re-fitting was done until all non-significant factors were removed.
- The goodness of fit of the *Linear mixed-effect model* after re-fitting was verified by looking at the *coefficient of determination* (R^2). R^2 gave an indication of how well the *Linear mixed-effect model* fit the observed responses.
- Residuals are plotted to verify the normality assumption and to give an indication of goodness of fit.

2.8.3 Analysis of additional tasks

Data collected from the 4 additional tasks (see Section 2.4.2 for detailed description) was analysed to compare previous studies and to check for learning/adaptation effect among participants. The grouping was removed for the analysis of the comparison tasks.

The influence of *Car speed* on TTC at brake onset was analyzed by comparing the cumulative frequency of the responses from Task 34 and Task 35 with results from [3], and also by conducting a t-test with a significant level of 0.05. Similarly, responses from Task 34 and Task 36 were compared with the results from [4] to analyze the influence of *Pedestrian speed* on TTC at brake onset.

Task 33 was repeated 4 times to check for learning/adaptation effect. The responses were visualized using box plots to detect any variation of the median due to learning/adaptation. If there was a variation then it was an indication of learning/adaptation among participants.

The pedestrian visibility in factor *Crossing entry* involved two different visibilities, 8 s and 4 s, for the low and high level, respectively. To analyze the influence of the different visibilities, Task 33 and Task 8 were compared as these tasks describe identical scenarios, except for the pedestrian visibility. The task responses were compared using box plot to see the variation of the median TTC at brake onset. If the median of the responses vary then the pedestrian visibility has a larger influence on TTC at brake onset than *Crossing entry*.

3

Results

3.1 Questionnaire analysis

The age distribution varied between the two groups (Figure 3.1). For frequent drivers, all age groups were represented more equally than for occasional drivers. However, the age group 22-29 years was overrepresented for both groups.

The gender distribution for both groups showed that for frequent drivers, only 12.8% of the participants were females and for occasional drivers, 27.5% (Figure 3.2).

For the study, it was also interesting to see for how many years participants have had their driver's license (Figure 3.3). It gave an indication about the driver experience for the two groups. The distribution for frequent drivers had peaks around 1980 and 2005, while for occasional drivers, majority of the participants received their driver's license between 2005-2010.

The annual mileage also gave an indication of how experienced the drivers were in the different groups. The distribution of the annual mileage for the two groups were as expected (Figure 3.4). Frequent drivers drove on average 21 700 km and occasional drivers drove on average 4 900 km.

The last question which concluded the driver profile was the question regarding driving frequency, how many days during the week the participant is driving. The distribution of the driving frequency can be seen in Figure 3.5. The distribution for frequent drivers was somewhat even around 3-7 days per week. Occasional drivers tend to drive once or less than once per week, which was expected. This question, together with number of years participants have had their driver's license and the annual mileage, gave a complete picture about the driver experience.

Majority of participants answered in Question 1 that the traffic environment *sort of* felt natural, 72% (Figure 3.6). In addition to this, 16% said that the traffic environment felt natural.

Nearly 25% of participants stated in Question 2 that they experienced difficulties handling the pedals, meaning they had difficulties adjusting the acceleration or brake level (Figure 3.7). Almost 20% would have preferred other road users on the roads to better replicate a real life environment. This also influenced the expectancy of the pedestrian, removing the element of surprise and increasing learning effect, as 10% of the participants noted.

45% said in Question 3 that they reacted normally and 51% said they *sort of* reacted as they would have in a real traffic situation (Figure 3.8). Only 4% said they did not react as they would normally do, hence these participants were excluded from the data analysis.

The most frequent issue influencing the participant's reaction was difficulties with the pedals (Figure 3.9). The expectancy of the pedestrian and difficulties judging the distance also seemed to be an influence on participant's behaviour. However, 20% of the participants stated they behaved as they would normally do.

Majority of the participants heard about the study through a colleague (co-worker or friend), Figure 3.10. The study was also advertised through SAFER events, hence it was no surprise that almost 20% of the participants volunteered from SAFER. The study also gained interest on social media (Facebook and Reddit).

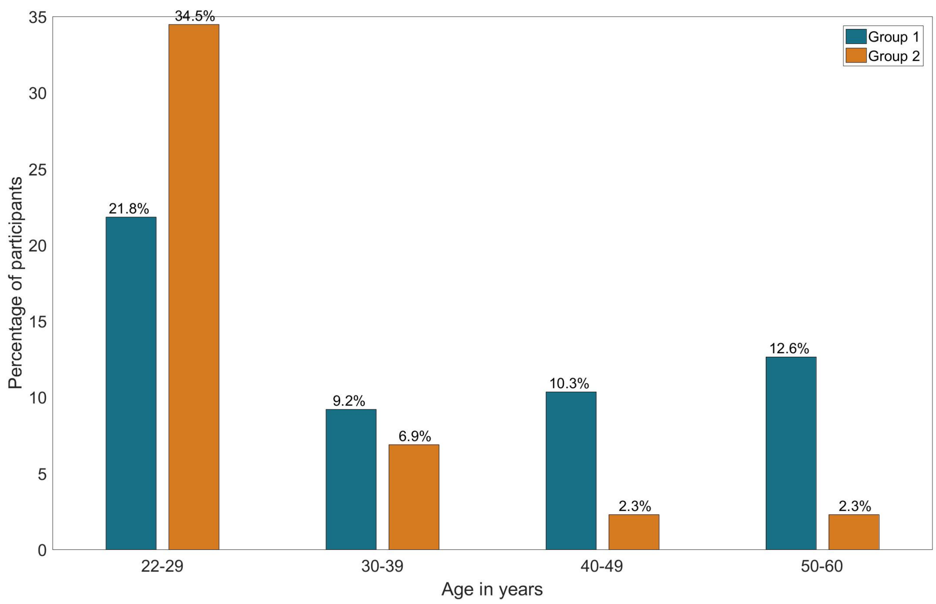

Figure 3.1: Age distribution for frequent (Group 1) and occasional (Group 2) drivers.

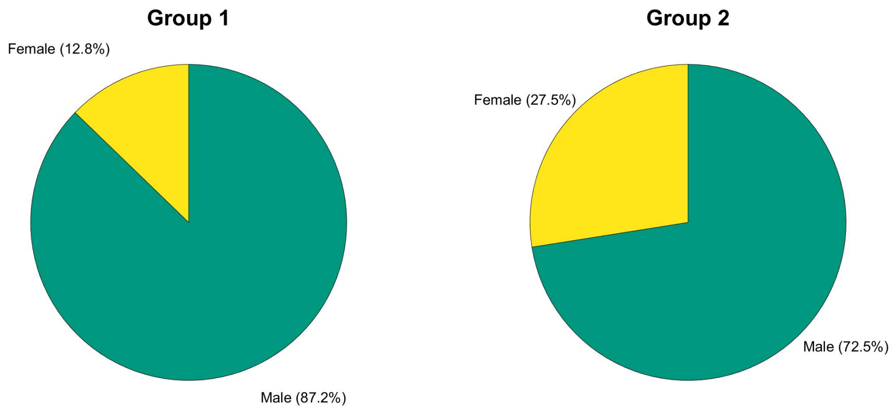

Figure 3.2: Gender distribution for frequent (Group 1) and occasional (Group 2) drivers.

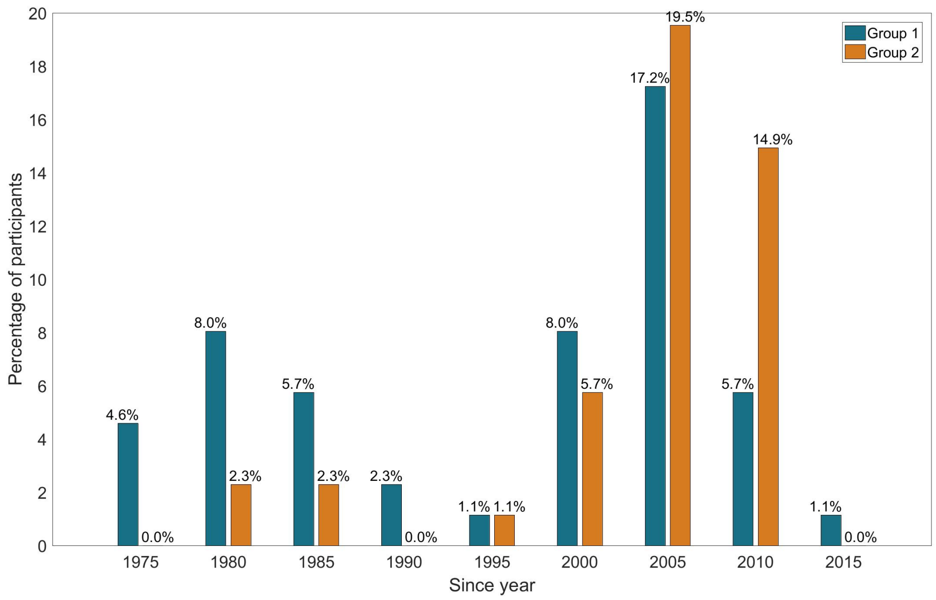

Figure 3.3: Year the participant obtained their driver's license for frequent (Group 1) and occasional (Group 2) drivers.

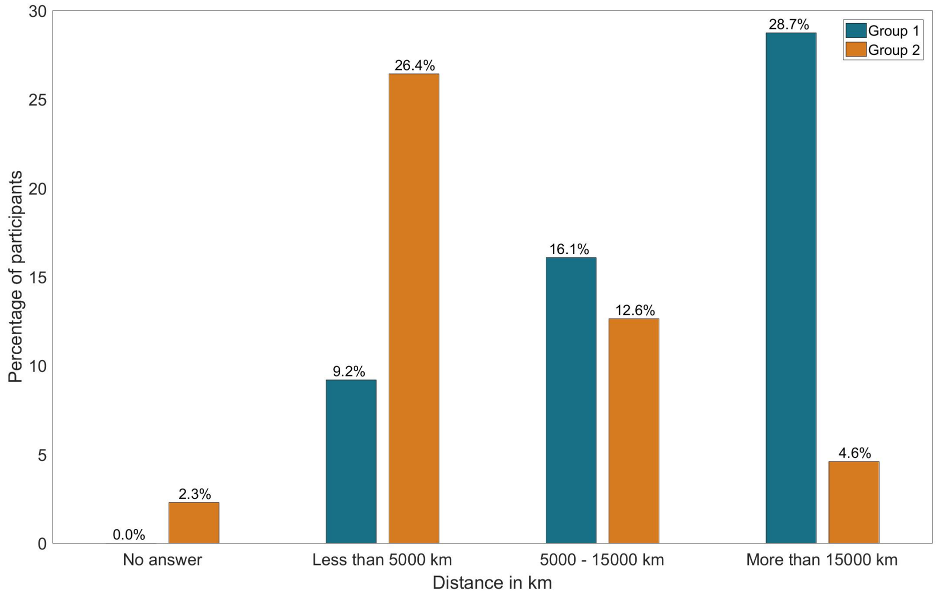

Figure 3.4: Annual mileage for frequent (Group 1) and occasional (Group 2) drivers.

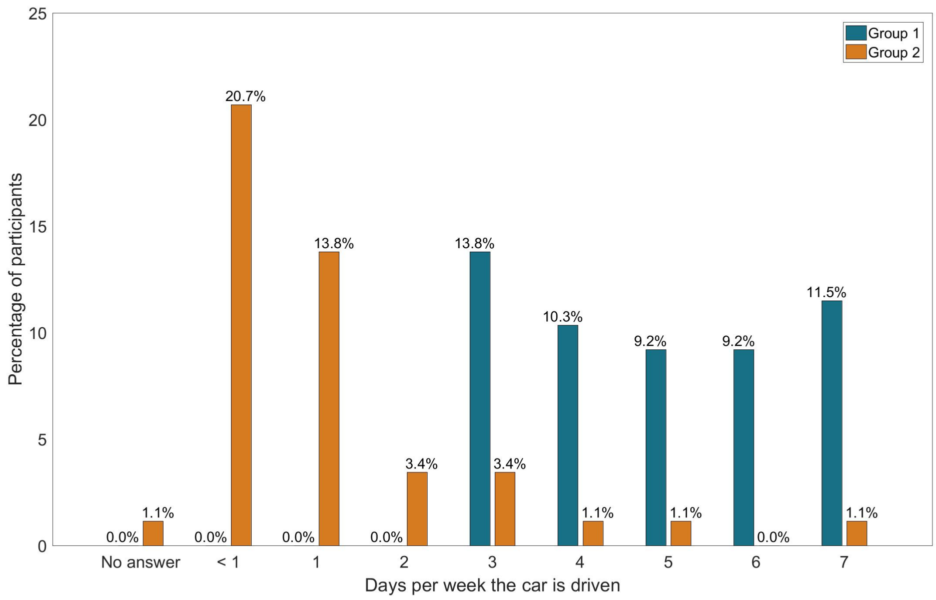

Figure 3.5: Driving frequency for frequent (Group 1) and occasional (Group 2) drivers.

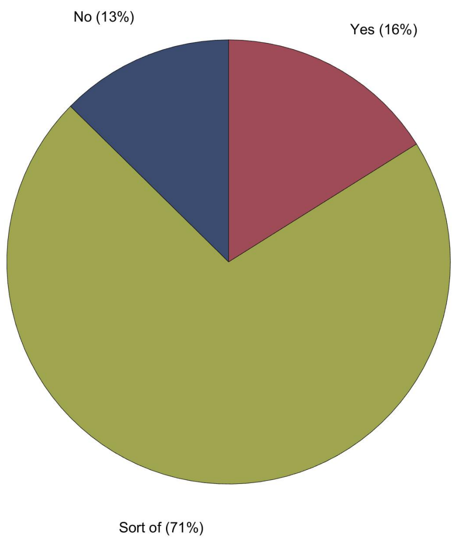

Figure 3.6: Question 1: "Did the traffic environment feel natural?"

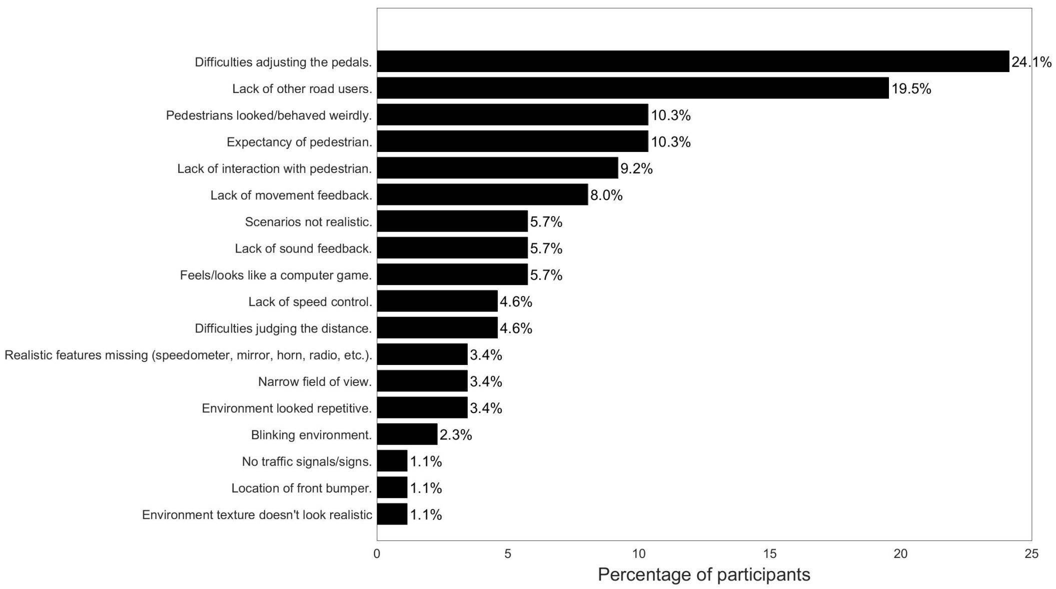

Figure 3.7: Question 2: "Cite the most notable thing that was not feeling natural in the experiment's scenario."

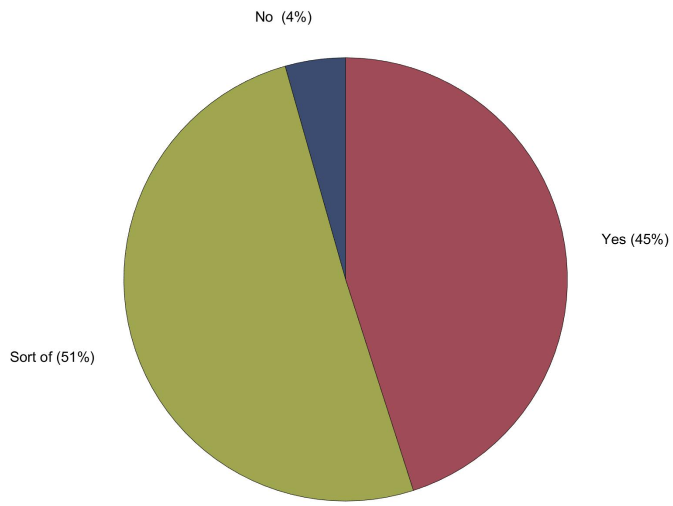

Figure 3.8: Question 3: "Did you react like you would normally do in a real traffic situation?"

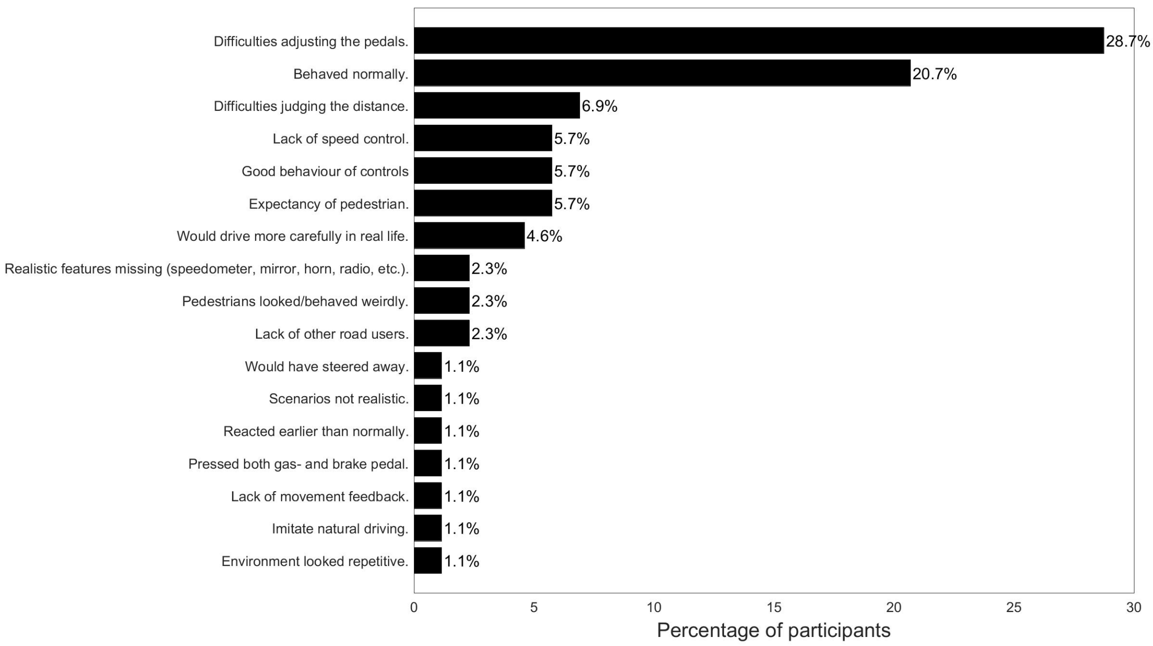

Figure 3.9: Comments to Question 3: "Did you react like you would normally do in a real traffic situation?"

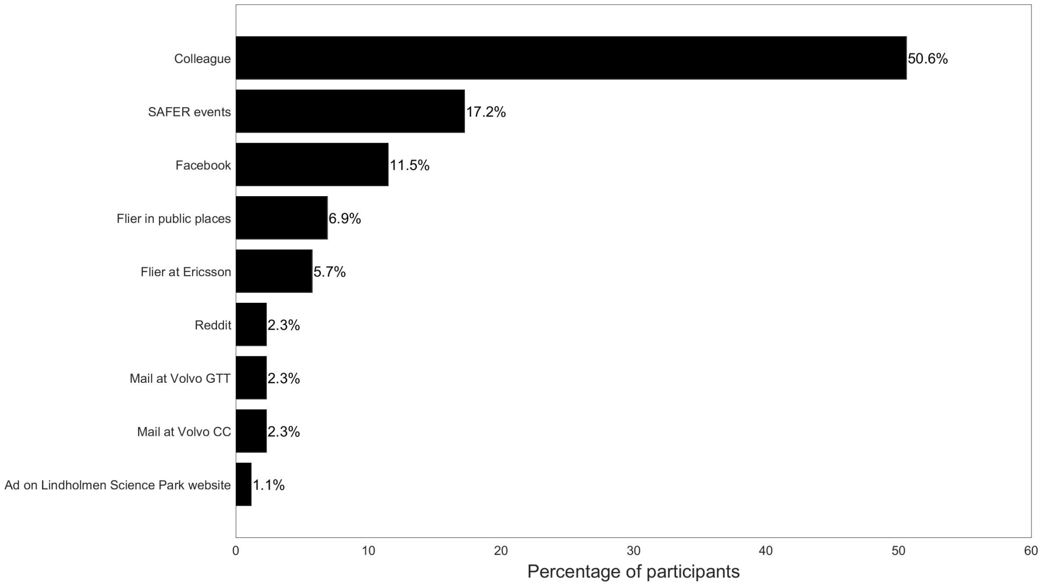

Figure 3.10: Question 4: "How did you hear about the study?"

3.2 Statistical analysis

Analysis of the groups described in Section 2.1.1 were analyzed separately and by combining the two groups to include all participants. Results of each group is presented in this section.

3.2.1 Preliminary data evaluation

The TTC at brake onset responses for frequent, occasional and all drivers were visualised using the graphical tools described in Section 2.8. In addition to the box plots, cumulative frequency graphs were also plotted of the TTC values (Appendix F).

3.2.1.1 Group 1 - Frequent drivers

TTC at brake onset, for all factors, was distributed as seen in Figure 3.11 with mean of 2.8 s and standard deviation of 1.8 s. A long tail to the right was also observed due to outliers. The box plots of the seven factors selected, plotted for the different levels, can be seen in Figure 3.12.

3.2.1.2 Group 2 - Occasional drivers

Same trend of the TTC responses was observed for occasional drivers, as for frequent drivers, with mean of 3.0 s and standard deviation of 1.5 s (Figure 3.13). The distribution also showed a long tail to the right due to outliers. The box plots of all factors selected, with the different levels, can be seen in Figure 3.14.

3.2.1.3 Group 1 and Group 2 combined

TTC at brake onset of all factors was evaluated by combining both frequent and occasional drivers (Figure 3.15). The combined group of drivers had a mean of 2.9 s and standard deviation of 1.7 s. The box plots of all factors selected, with the different levels, can be seen in Figure 3.16.

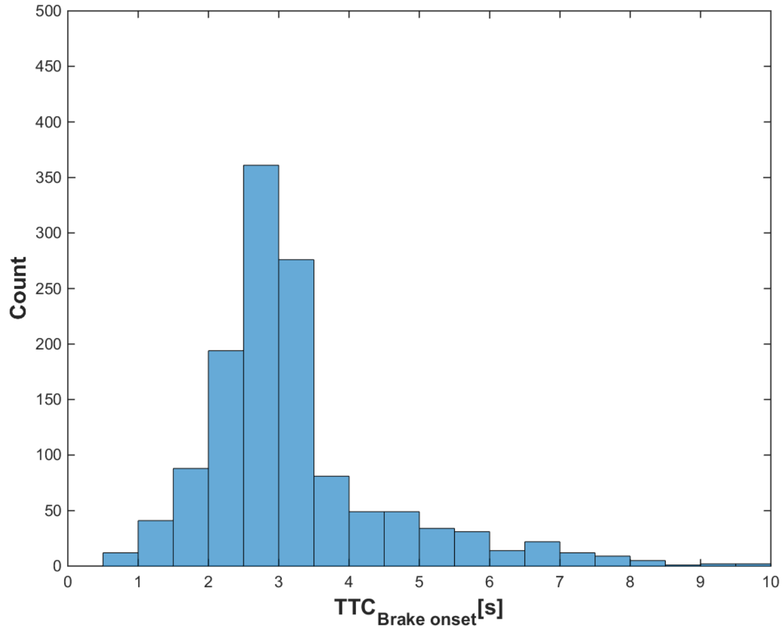

Figure 3.11: Histogram of TTC responses at brake onset for all factors for frequent drivers.

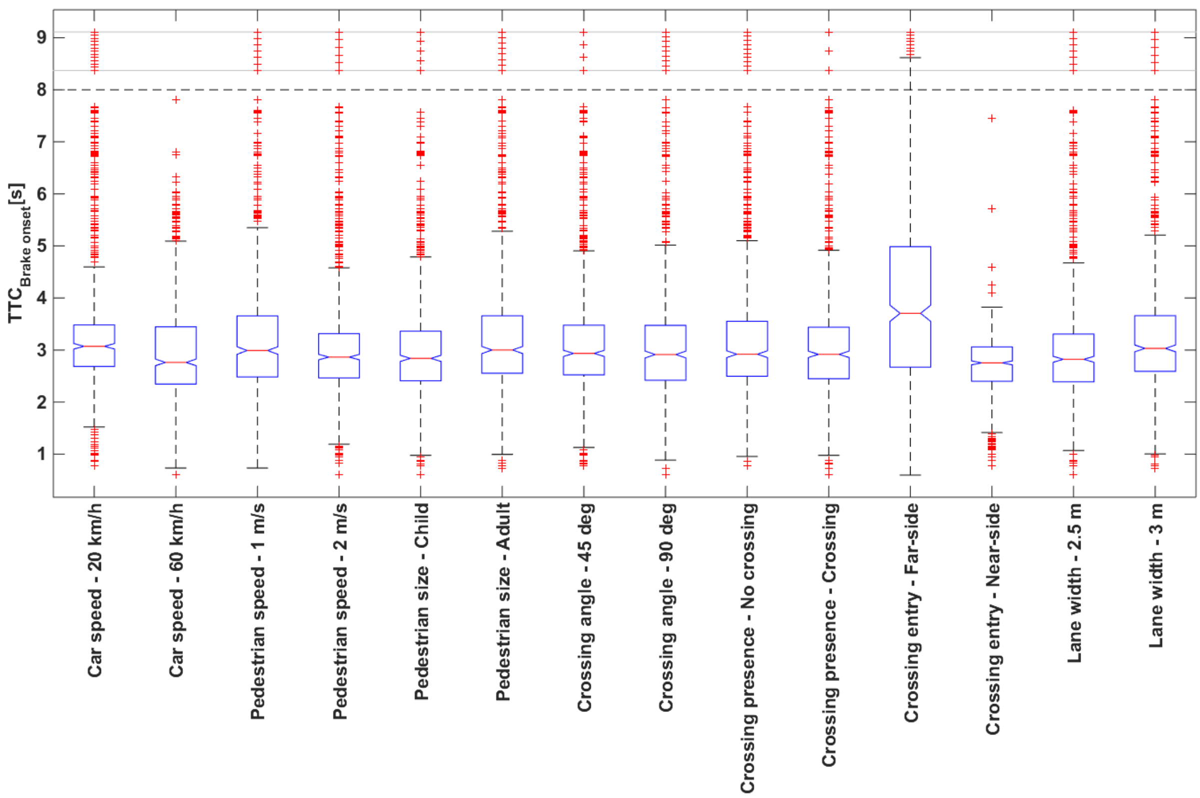

Figure 3.12: Box plot of TTC responses at brake onset for different factors for frequent drivers.

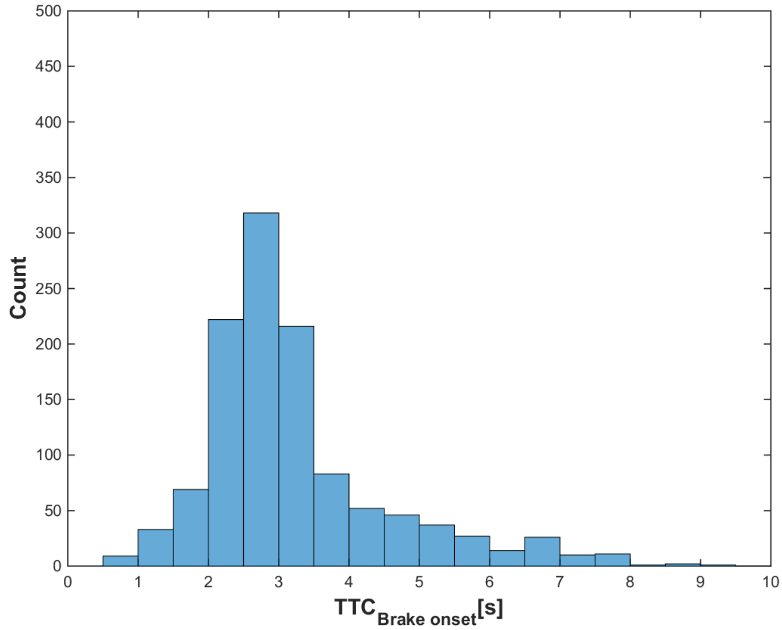

Figure 3.13: Histogram of TTC responses at brake onset for all factors for occasional drivers.

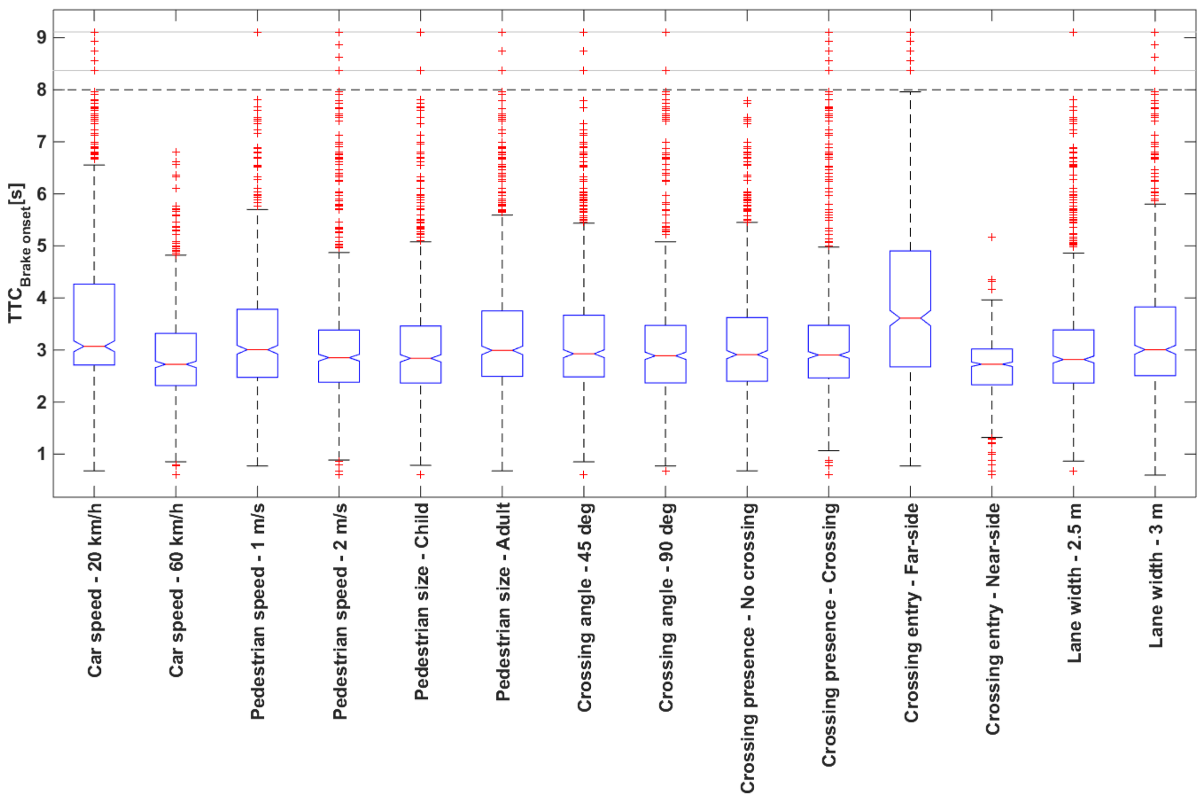

Figure 3.14: Box plot of TTC responses at brake onset for different factors for occasional drivers.

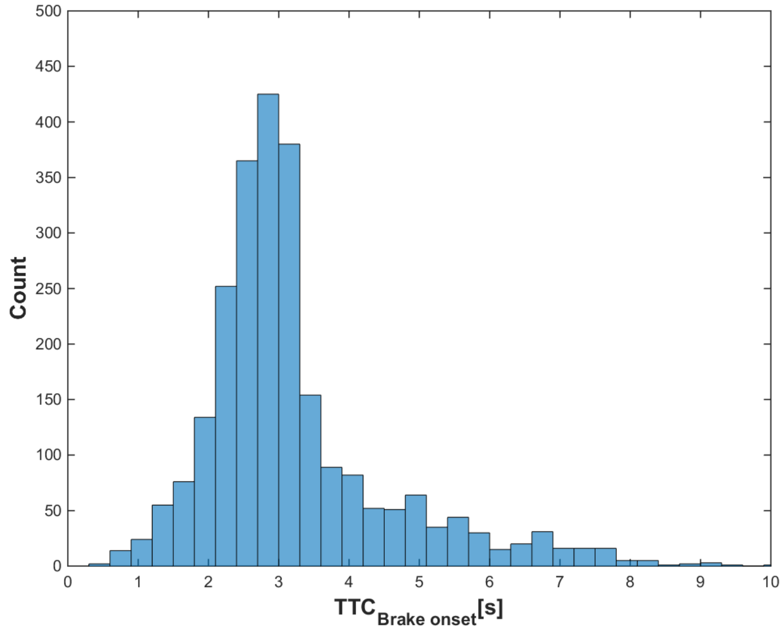

Figure 3.15: Histogram of TTC responses at brake onset for all factors for all drivers.

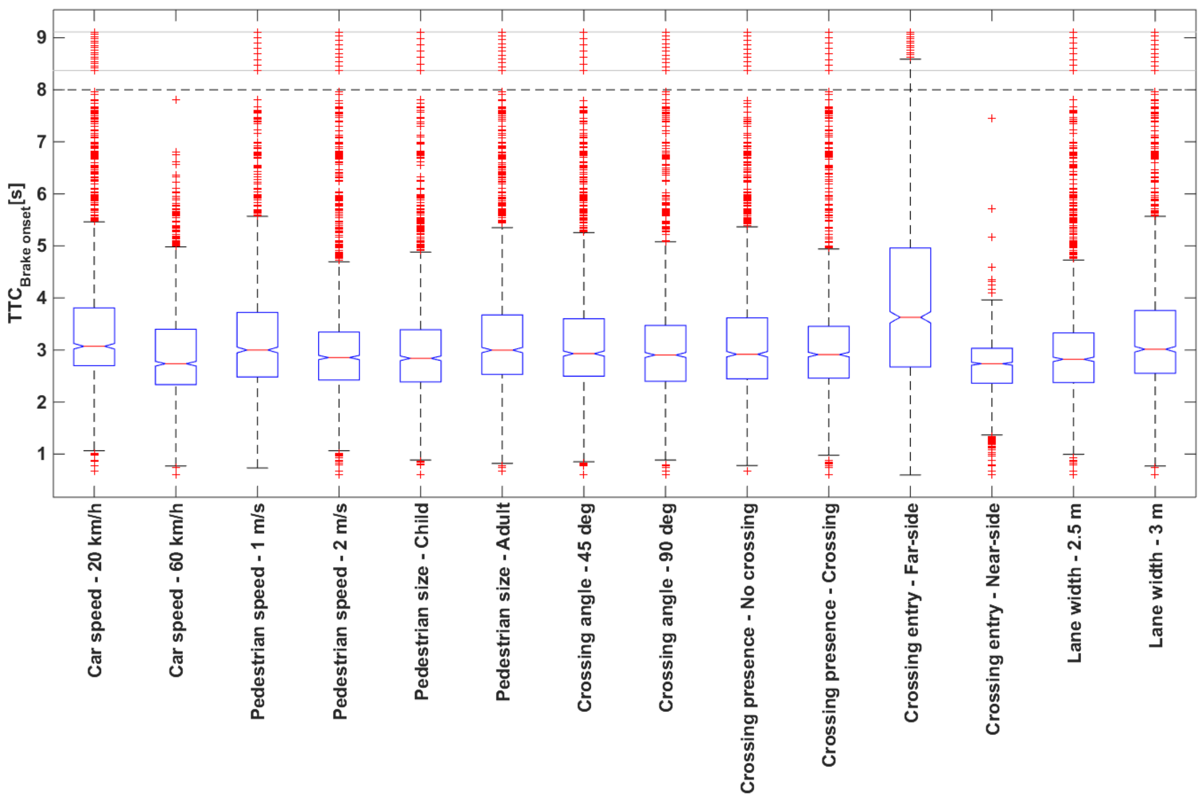

Figure 3.16: Box plot of TTC responses at brake onset for different factors for all drivers.

3.2.2 Theoretical linear mixed-effect models

The theoretical model contained the main factors, interactions and the grouping based on Equation 2.4 in Section 2.8.2. The fitting of the theoretical model was done for both groups separately and by combining the groups. MATLAB's *Fit linear mixed-effects model* (*fitlme*) function was used, and the output was evaluated, and used, as a reference for re-fitting the model for each group. It can be observed from Table 3.1 and 3.2 that more than one variable had a significant influence of less than 0.01 on TTC at brake onset. The term intercept in the tables refer to the mean value of the TTC response when all variables are zero.

Table 3.1: Theoretical linear mixed-effect model fit for frequent and occasional drivers.

	Frequent drivers		**Occasional drivers**	
Variable name	**Estimate**	***p*-Value**	**Estimate**	***p*-Value**
Intercept	3.51	0	3.35	0
Car speed	**-0.50**	**0**	**-0.45**	**0**
Pedestrian speed	-0.07	0.01	-0.05	0.04
Pedestrian size	**0.14**	**6.65**$*10^{-8}$	**0.11**	**2.19**$*10^{-6}$
Crossing angle	-0.02	0.44	-0.04	0.07
Crossing presence	**-0.09**	**3.12**$*10^{-4}$	5.00$*10^{-3}$	0.93
Crossing entry	**-0.84**	**0**	**-0.71**	**0**
Lane width	**0.10**	**1.24**$*10^{-4}$	**0.12**	**1.83**$*10^{-7}$
Car speed:Pedestrian speed	-0.03	0.28	**-0.08**	**5.45**$*10^{-4}$
Car speed:Pedestrian size	-0.02	0.49	-8.70$*10^{-3}$	0.76
Pedestrian speed:Pedestrian size	0.05	0.05	0.03	0.21
Car speed:Crossing angle	-0.02	0.36	-0.02	0.42
Pedestrian speed:Crossing angle	-0.01	0.51	0.01	0.65
Pedestrian size:Crossing angle	0.04	0.09	0.05	0.02
Car speed:Crossing presence	-0.02	0.53	**-0.08**	**3.85**$*10^{-4}$
Pedestrian speed:Crossing presence	**-0.09**	**6.44**$*10^{-4}$	-2.00$*10^{-3}$	0.87
Pedestrian size:Crossing presence	-0.02	0.40	-4.30$*10^{-3}$	0.93
Car speed:Crossing presence	**0.33**	**0**	**0.29**	**0**
Pedestrian size:Crossing presence	**-0.13**	**2.22**$*10^{-7}$	**-0.08**	**2.54**$*10^{-4}$
Crossing angle:Crossing presence	0.02	0.40	0.04	0.09
Crossing presence:Crossing entry	**0.15**	**6.60**$*10^{-9}$	0.05	0.04
Car speed:Lane width	0.06	0.02	0.04	0.07
Pedestrian size:Lane width	0.02	0.60	6.70$*10^{-3}$	0.66

Table 3.2: Theoretical linear mixed-effect model fit for all drivers.

	All drivers	
Variable name	**Estimate**	***p-Value***
Intercept	3.34	0
Car speed	**-0.47**	**0**
Pedestrian speed	**-0.05**	**2.60**$*10^{-3}$
Pedestrian size	**0.13**	**2.06**$*10^{-13}$
Crossing angle	-0.03	0.08
Crossing presence	**-0.04**	**0.01**
Crossing entry	**0.78**	**0**
Lane width	**0.12**	**5.46**$*10^{-11}$
Car speed:Pedestrian speed	**-0.06**	**9.53**$*10^{-4}$
Car speed:Pedestrian size	-0.01	0.55
Pedestrian speed:Pedestrian size	0.04	0.02
Car speed:Crossing angle	-0.02	0.23
Pedestrian speed:Crossing angle	0.60$*10^{-3}$	0.85
Pedestrian size:Crossing angle	**-0.04**	**7.50**$*10^{-3}$
Car speed:Crossing presence	**-0.05**	**3.70**$*10^{-3}$
Pedestrian speed:Crossing presence	**-0.05**	**5.80**$*10^{-3}$
Pedestrian size:Crossing presence	-0.01	0.50
Car speed:Crossing entry	**0.30**	**0**
Pedestrian size:Crossing entry	**-0.10**	**5.78**$*10^{-10}$
Crossing angle:Crossing entry	0.03	0.08
Crossing presence:Crossing entry	**0.10**	**2.17**$*10^{-8}$
Car speed:Lane width	**0.04**	**0.73**$*10^{-2}$
Pedestrian size:Lane width	0.01	0.50

3.2.3 Re-fitting of the linear mixed-effect models

The theoretical linear mixed-effect model was re-fitted by step wise elimination of non-significant variables whose *p-Value* was greater than 0.01. Tables 3.3, 3.4 and 3.5 represent the variables which have a significance level (*p-Value*) less than 0.01 for frequent, occasional and all drivers, respectively.

Table 3.3: Re-fitted linear mixed-effect model for Group 1, frequent drivers.

	Frequent drivers	
Variable name	**Estimate**	***p*-Value**
Intercept	3.50	0
Car speed	-0.50	0
Pedestrian size	0.14	$7.62{*}10^{-9}$
Crossing presence	-0.09	$2.55{*}10^{-4}$
Crossing entry	-0.83	0
Lane width	0.11	$6.15{*}10^{-6}$
Pedestrian speed:Crossing presence	-0.09	$2.70{*}10^{-4}$
Car speed:Crossing entry	0.32	0
Pedestrian size:Crossing entry	-0.12	$2.61{*}10^{-7}$
Crossing presence:Crossing entry	0.15	$4.67{*}10^{-9}$

From re-fitting the model, the main factors and the interactions which had a significant influence on TTC at brake onset for Group 1, frequent drivers, are listed in Table 3.3. Among the main factors, *Car speed*, *Pedestrian size*, *Crossing presence*, *Crossing entry* and *Lane width* had a significant influence on TTC at brake onset.

Table 3.4: Re-fitted linear mixed-effect model for Group 2, occasional drivers.

	Occasional drivers	
Variable name	**Estimate**	***p*-Value**
Intercept	3.35	0
Car speed	-0.44	0
Pedestrian size	0.10	$4.02{*}10^{-6}$
Crossing entry	-0.71	0
Lane width	0.13	$2.70{*}10^{-8}$
Car speed:Pedestrian speed	-0.08	$1.42{*}10^{-4}$
Car speed:Crossing presence	-0.08	$2.61{*}10^{-4}$
Car speed:Crossing entry	-0.28	0
Pedestrian size:Crossing entry	-0.08	$3.96{*}10^{-4}$

The model was also re-fitted for Group 2, occasional drivers (Table 3.4). Among the main factors, *Car speed*, *Pedestrian size*, *Crossing entry* and *Lane width* had a significant influence on TTC at brake onset.

Table 3.5: Re-fitted linear mixed-effect model for all drivers.

	All drivers	
Variable name	**Estimate**	***p*-Value**
Intercept	3.43	0
Car speed	-0.47	0
Pedestrian speed	-0.05	$3.00*10^{-3}$
Pedestrian size	0.12	$2.92*10^{-13}$
Crossing entry	-0.77	0
Lane width	0.11	$5.43*10^{-11}$
Car speed:Pedestrian speed	-0.60	$8.76*10^{-4}$
Pedestrian size:Crossing angle	0.04	$8.30*10^{-3}$
Car speed:Crossing presence	-0.06	$1.20*10^{-3}$
Pedestrian speed:Crossing presence	-0.05	$5.80*10^{-3}$
Car speed:Crossing entry	0.30	0
Pedestrian size:Crossing entry	-0.10	$7.35*10^{-10}$
Crossing presence:Crossing entry	0.09	$1.15*10^{-7}$
Car speed:Lane width	-0.04	$8.40*10^{-3}$

By combining the two groups, the re-fitting of the model yielded the factor list in Table 3.5 which had a significant influence on the TTC at brake onset. Among the main factors, *Car speed*, *Pedestrian speed*, *Pedestrian size*, *Crossing entry* and *Lane width* were shown to influence the TTC at brake onset significantly.

Along with the *p-Value*, *estimate* of each significant factor was observed for all three group of drivers. The *estimate* indicates the magnitude and direction of the factor's influence on TTC at brake onset when the factor is changed from low to high level. Hence, a negative *estimate* means that TTC at brake onset decreases when the factor changes from low to high level, while a positive *estimate* increases the TTC value. If the *estimate* value is in the interval $-0.1 < estimate < 0.1$ then the effect of the variable was considered to be low and was neglected.

3.2.4 Goodness of fit

The goodness of fit of the re-fitted model was determined by calculating the R^2. From Table 3.6 it can be observed that the model fits the observed TTC responses by 63% for frequent drivers, 67% for occasional drivers and 64% for all drivers.

Table 3.6: R^2 terms and adjusted R^2 terms for frequent, occasional and all drivers.

	Frequent drivers	**Occasional drivers**	**All drivers**
R^2	0.63	0.67	0.64
Adjusted R^2	0.62	0.67	0.64

By plotting the residuals after re-fitting the *Linear mixed-effect model* it was observed that the residuals are approximately normally distributed, thus satisfying the assumptions in Section 2.8.1 (Figure 3.17, Figure 3.18 and Figure 3.19).

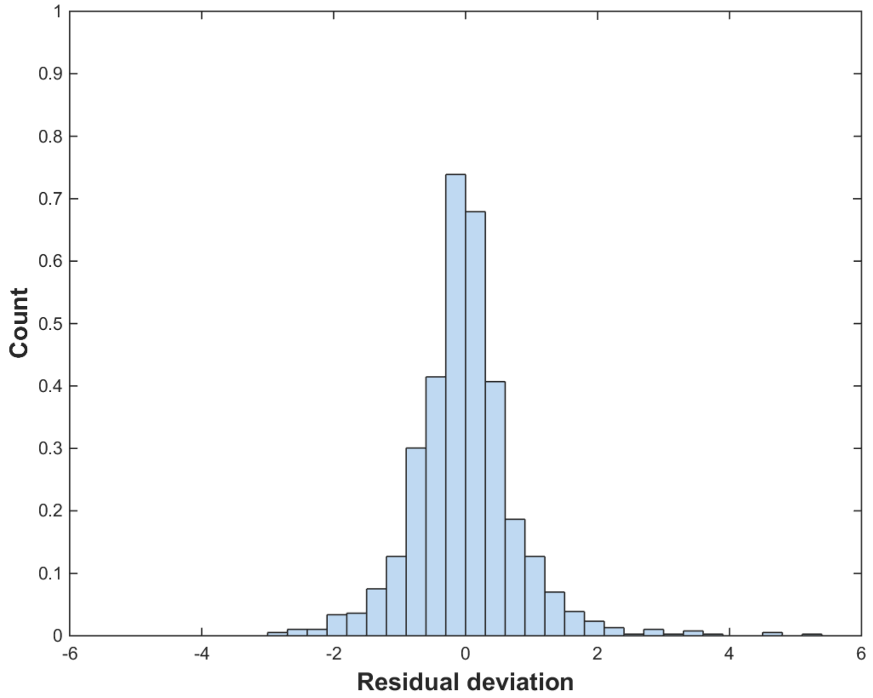

Figure 3.17: Residual plot of responses after re-fit for frequent drivers.

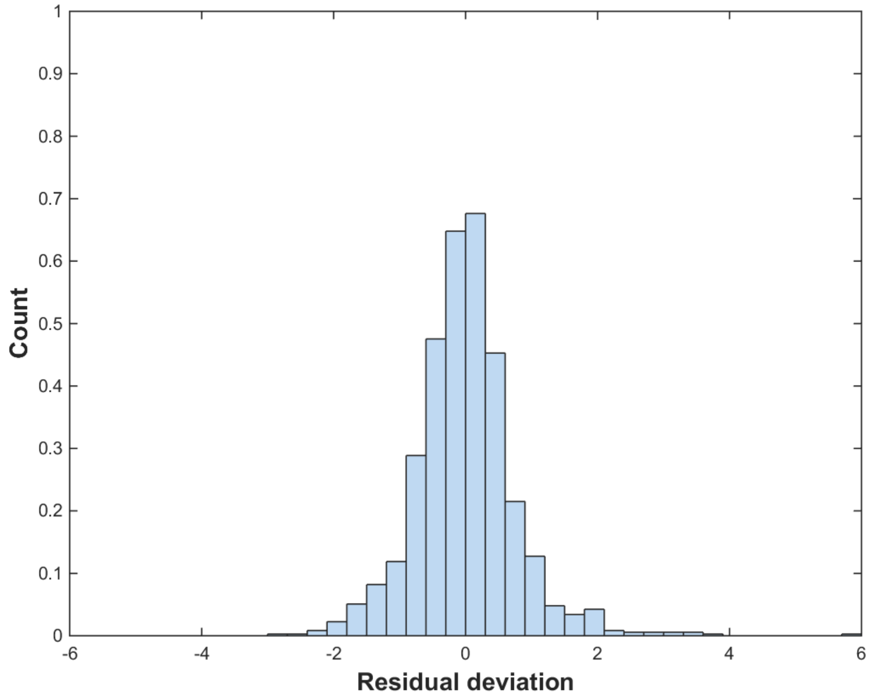

Figure 3.18: Residual plot of responses after re-fit for occasional drivers.

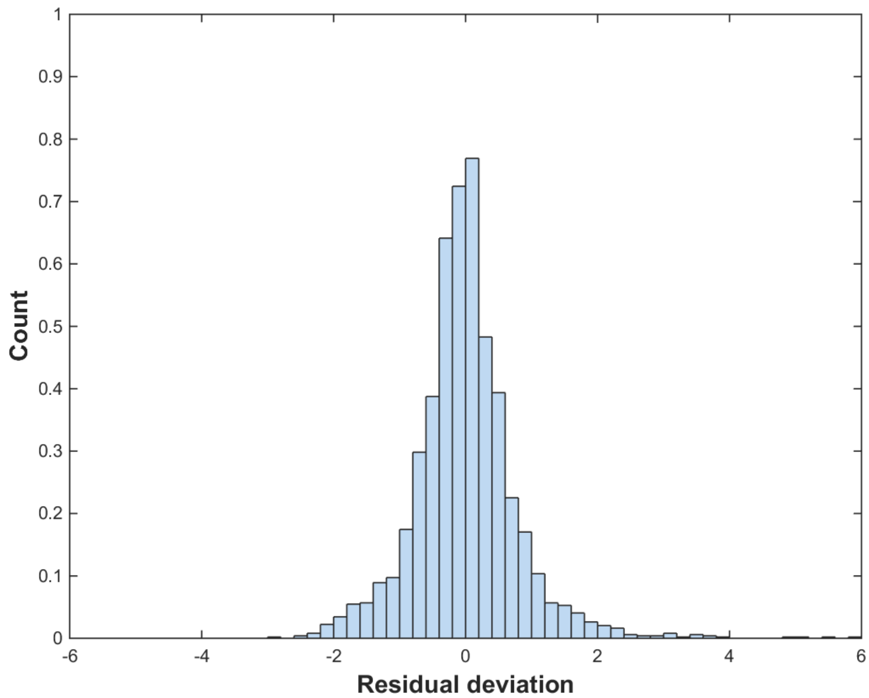

Figure 3.19: Residual plot of responses after re-fit for all drivers.

3.2.5 Analysis of additional tasks

3.2.5.1 Comparison tasks

The cumulative frequency of the responses from Task 34 and Task 35, variation in car speed, were plotted for comparison with study [3] (Figure 3.20). The comparison was done by combining all drivers.

Similarly, the cumulative frequency of the responses from Task 34 and Task 36, variation in pedestrian speed, was plotted for comparison with study [4] (Figure 3.21).

Two sample *t*-test was carried out using MATLAB to check the influence of *Car speed* and *Pedestrian speed* on TTC at brake onset. The analysis results obtained can be seen in Table 3.7. *Yes* indicates significant influence of factors on TTC at brake onset with a significant level of 0.05.

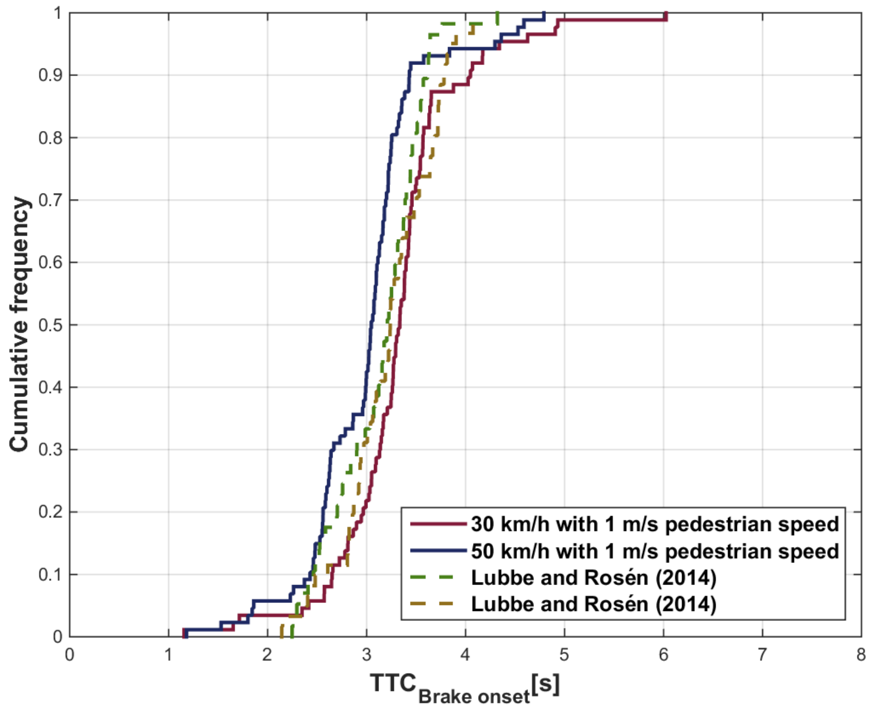

Figure 3.20: Cumulative frequency of TTC at brake onset responses from Task 34 and 35 compared with study [3] for all drivers.

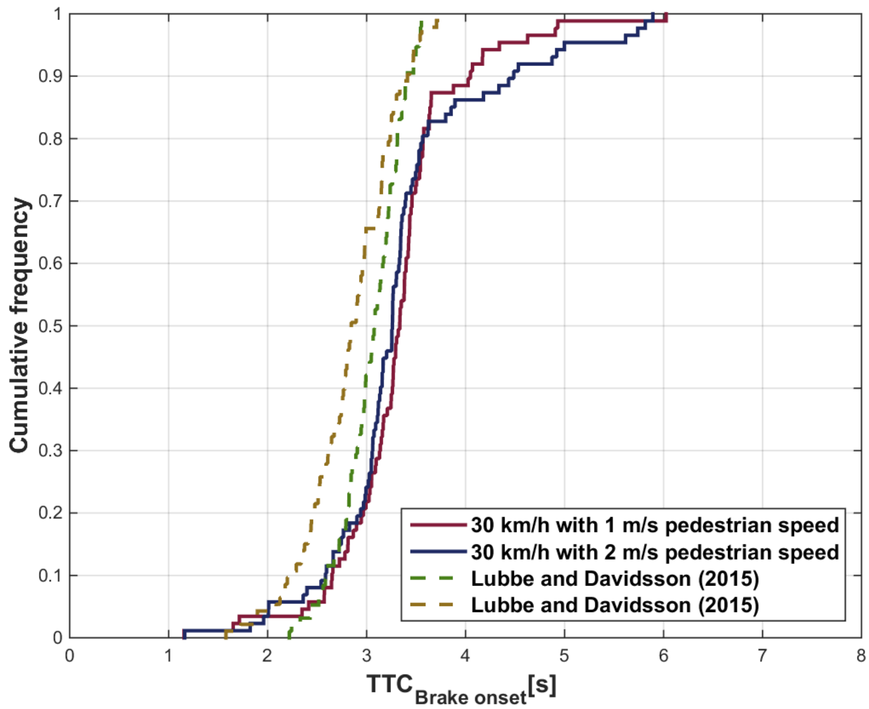

Figure 3.21: Cumulative frequency of TTC at brake onset responses from Task 34 and 36 compared with study [4] for all drivers.

Table 3.7: Results of two sample t-test showing the statistical significance of the comparison tasks.

	All drivers
Variation in car speed	Yes
Variation in pedestrian speed	No

3.2.5.2 Learning/adaptation effect

The repeated Task 33 was plotted using box plot for all three group of drivers (Figure 3.22, 3.23 and 3.24). The learning/adaptation effect on TTC at brake onset was observed by looking at the variation of the median between the repetitions. For frequent drivers and all drivers it was observed that the median TTC varied between the repetitions, indicating a learning/adaption effect. However, for occasional drivers, the variation of the median TTC was very small, thus no learning/adaptation effect was observed.

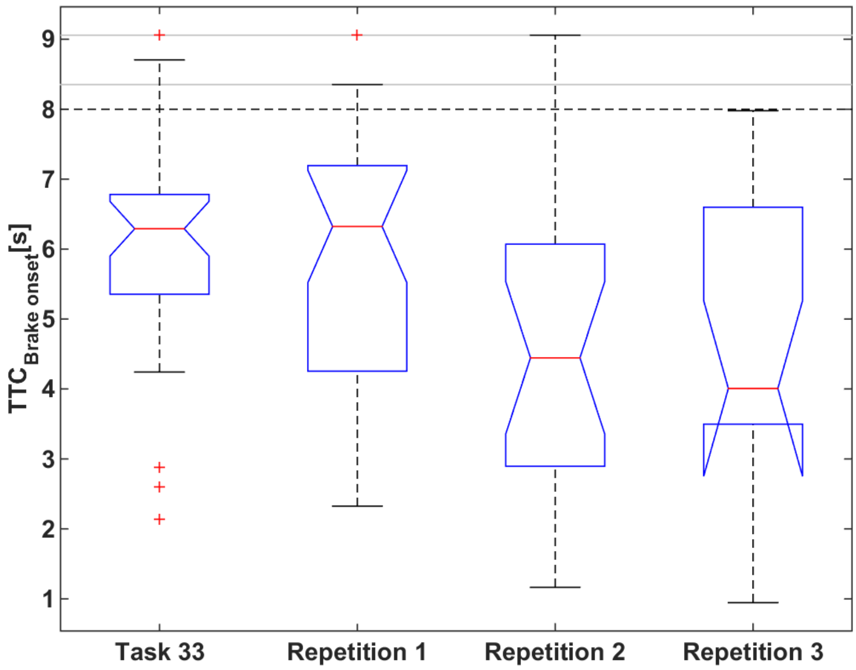

Figure 3.22: Box plot of TTC at brake onset for Task 33, frequent drivers.

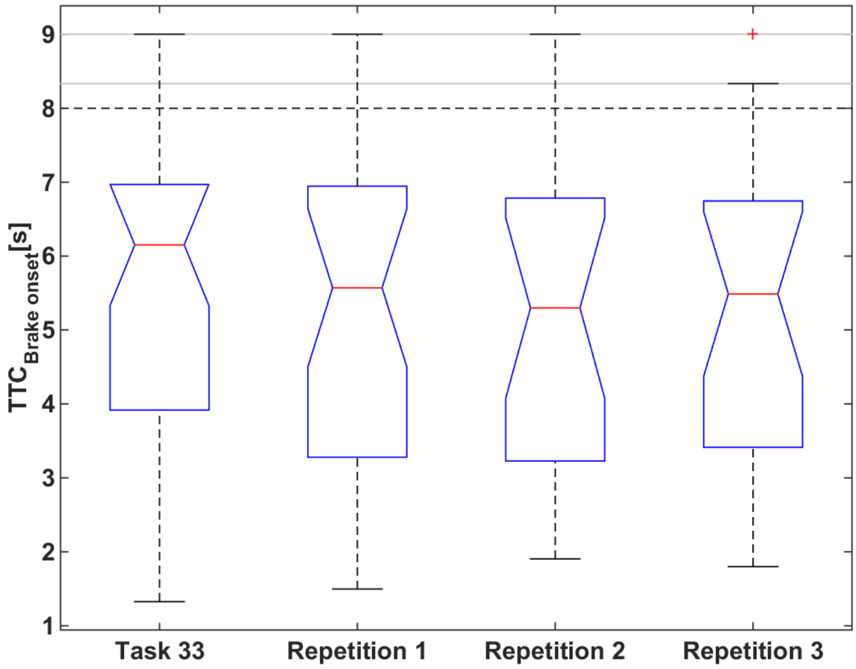

Figure 3.23: Box plot of TTC at brake onset for Task 33, occasional drivers.

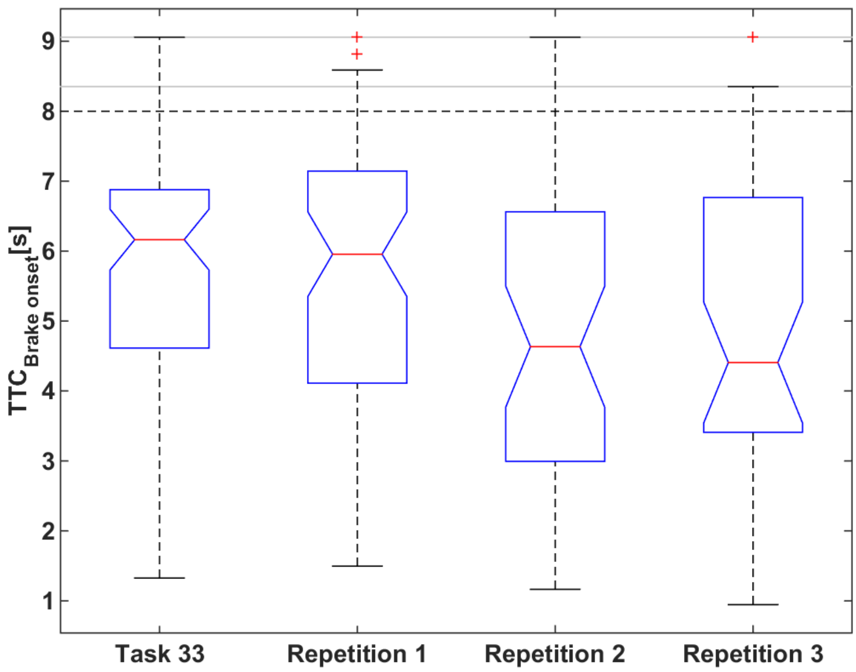

Figure 3.24: Box plot of TTC at brake onset for Task 33, all drivers.

3.2.5.3 Task 33 and Task 8 comparison

Analysis, comparing Task 33 and Task 8 was carried out to see the influence of pedestrian visibility on TTC at brake onset. Task 33 and Task 8 represent identical scenarios, with the exception of pedestrian visibility. Figures 3.25, 3.26 and 3.27 represent the box plot comparison of the TTC responses.

By comparing the median of the 4 repetitions of Task 33 with the median of Task 8 in the figures, a large variation of TTC at brake onset can be observed. Hence, participants in all three groups tend to brake earlier when the pedestrian visibility was 8 s (Task 33) than 4 s (Task 8).

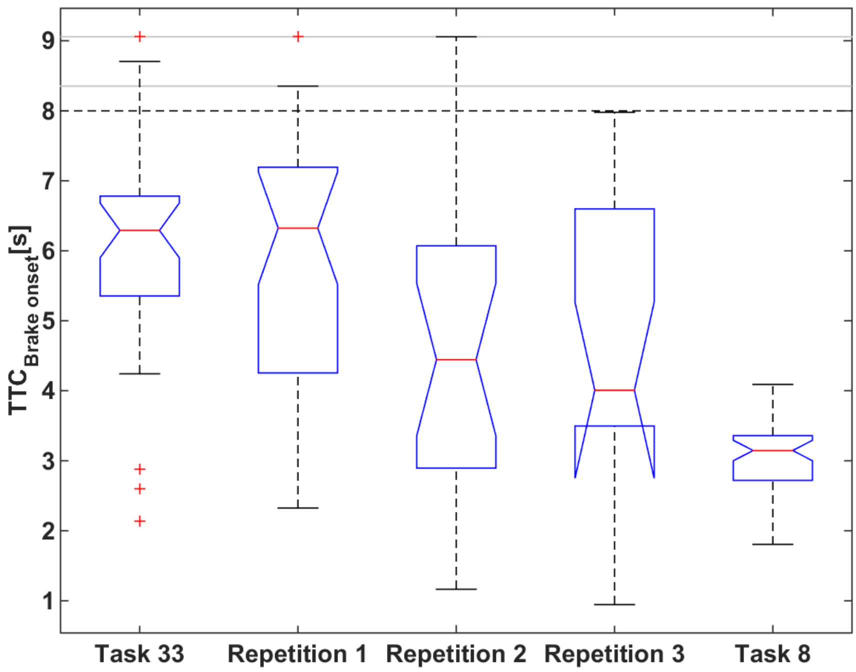

Figure 3.25: Comparison between Task 33 and Task 8 for frequent drivers.

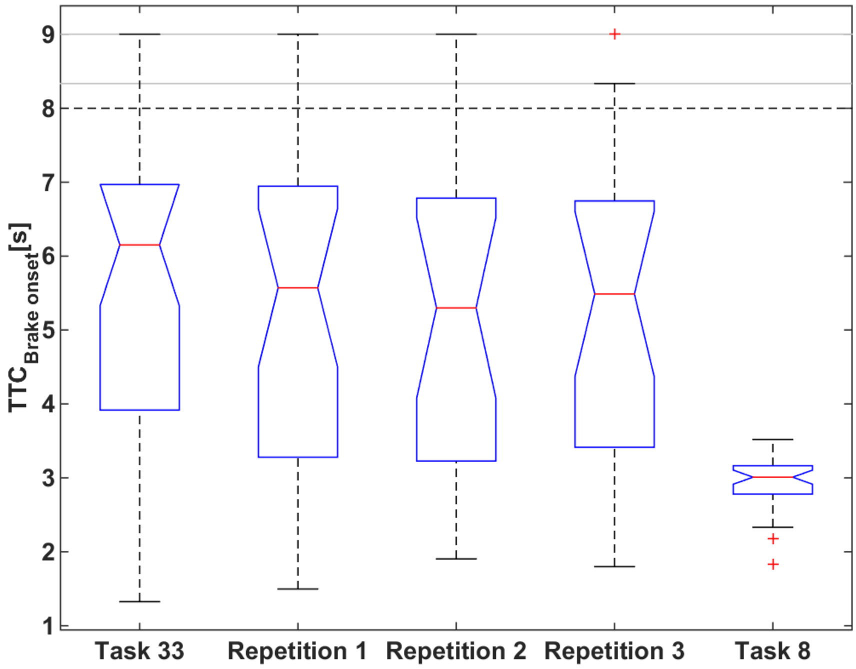

Figure 3.26: Comparison between Task 33 and Task 8 for occasional drivers.

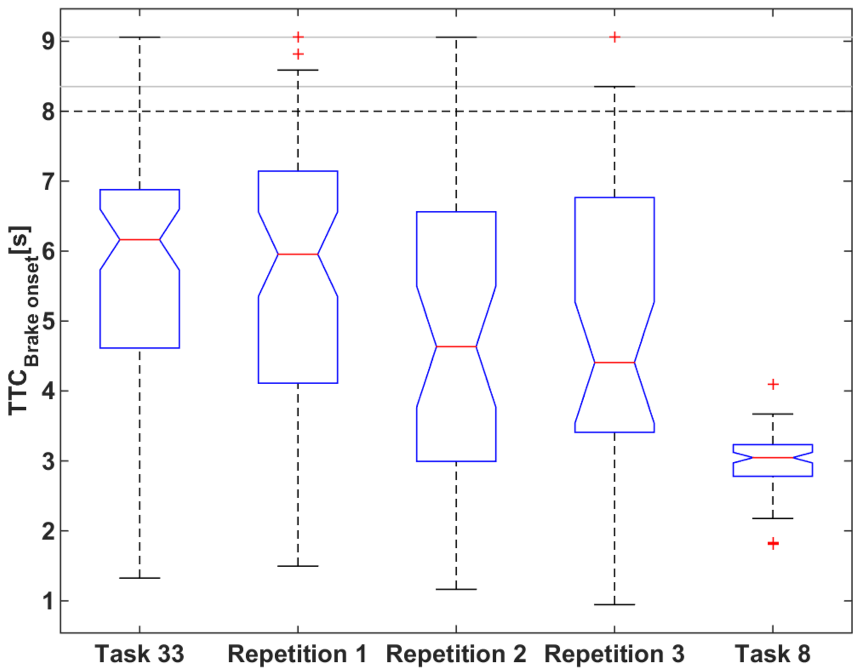

Figure 3.27: Comparison between Task 33 and Task 8 for all drivers.

4

Discussion

Questionnaire analysis

The questionnaire analysis showed that the collected data included many different variation of drivers, with varying driver behaviour, which is important to incorporate into the active safety systems. However, to be able to generalize the findings from the study on the whole population, both genders must be represented equally. From the gender distribution it was shown that only 13% and 28% of frequent and occasional, respectively, were females. These results imply that the findings only represent males' driver behaviour. Further analysis is required to investigate the difference between male and female behaviour in the study. The findings from the study can be generalized to the whole population only if the driver behaviour between males and females is not significant.

Question 1 showed that participants responded positively toward the traffic environment in the simulator. Nearly 90% of the participants stated they experienced the environment to be natural or sort of natural. These result show that even though the simulator environment was created with open source software, the outcome was still realistic enough to be used as a driving simulator. However, parts of the simulator set up might need to be changed as almost 25% of participants stated they experienced difficulties adjusting the pedals, which was discovered in Question 2. Participants expressed concern regarding the location of the pedals, that the gas and brake pedals were located to close to each other causing them to press the gas pedal while braking. Participants also had issues with the braking level, meaning they felt as if they were braking harder than they were pressing the pedal. The issue with the pedals might have influenced the driver behaviour.

Other features participants stated in Question 2 that they missed were sound and movement feedback and speed control. The latter originated from the fact that a speed limiter was used in every scenario, preventing the driver to exceed the levels of car speed chosen for the study, 20 and 60 km/h. The reason behind use of a speed limiter was that since the simulator does not provide neither sound nor movement feedback, participants would have spent more attention on maintaining the speed than focusing on the driving task. However, even though there were some issues with the simulator set up, more than 95% of participants still behaved, or sort of behaved, as normally as they would have in a real traffic situation according to Question 3.

From Question 2 it was also found that almost 20% of participants found it to be unrealistic that there were no other road users in the scenarios. The reason behind not including other road users was that if there would have been cars and/or pedestrians, these would also influence the driver behaviour. As the study only investigated the influence from the pedestrian crossing the street at the intersection, it would have been difficult to determine if it was the pedestrian or other road users who had an influence on the driver behaviour. This, however, contributed to enhance the expectancy of the pedestrian since there was only one pedestrian crossing the street in every scenario, which was also stated by participants in Question 2. Expectancy of the pedestrian was also observed from repetition of Task 33, where participants showed learning effect, even if not by much. Hence, since the lack of other road users contributed to defect the realism of the scenarios, different scenario construction might be used to include other road users.

Participants also expressed issues with the pedestrian's appearance and behavior in Question 2 (10%). Issues regarded the similarities between child and adult models, saying the child pedestrian moved much like an adult, making it difficult to believe it was a child. In general, participants also lacked the interaction with the pedestrians, for instance eye contact. Pedestrian behaviour such as seeking eye contact and slowing down before crossing the street was excluded from the animations due to difficulties animating these behaviors realistically. Hence, more attention needs to be paid to the differences between the two models and specific pedestrian behaviour, and how to incorporate these features into the models.

In Appendix E it can be seen that it was possible for participants to give comments in Question 1. However, it was decided during the questionnaire analysis not to analyze these responses as it was seen that they would mainly include the same comments as in Question 2.

Statistical analysis

It was observed during the analysis that TTC at brake onset was higher than pedestrian visibility. This was because when the pedestrian was visible to the driver (4 s/8 s TTC), they tend to react and reduce the speed by removing their foot off the gas pedal, and brake if necessary. In the simulator it was observed that the engine brake was higher than a real car, hence the speed reduced faster than in reality. So when the participant braked, the speed was very low. As TTC was computed by dividing the distance to the collision point at brake onset with car speed at brake onset, this value became higher than pedestrian visibility because of the low car speed.

Car speed
The variation in car speed from 20 km/h to 60 km/h had a significant influence on

both Group 1, frequent drivers and Group 2 occasional drivers. It was observed for both groups that *Car speed* had a decreasing effect on TTC at brake onset. Hence, variation of factor *Car speed* from low to high level decreases the TTC at brake onset. For these two groups, the two-factor interactions between *Car speed* and *Crossing entry* had a decreasing effect in TTC at brake onset. Similarly, variations in car speed was observed to have a significant influence on TTC at brake onset for all drivers. The two-factor interactions between *Car speed* and *Pedestrian speed* and *Car speed* and *Crossing entry* had a decreasing influence on TTC at brake onset. As the factor *Car speed* was thought to have an increasing effect on TTC in the beginning of the study, further analysis is needed to investigate reasons behind the obtained results. One possibility could be to look at gas pedal release, first instance participants start to regulate the speed, instead of brake onset.

Pedestrian speed
Pedestrian speed was observed to have a small effect on TTC at brake onset for all three group of drivers. However, the two-factor interactions between *Pedestrian speed* and *Car speed* had a decreasing effect on TTC at brake onset for all drivers. Results vary from initially expected, which could be due to low resolution output from the projector used for visualization which was available in the SAFER *Driving simulator room*. Hence, participants might not have been able to perceive different speeds of the pedestrians.

Pedestrian size
For all three group of drivers, factor *Pedestrian size* had a significant influence on TTC at brake onset, with an increasing effect. When size of the pedestrian was varied from child to adult, participants tend to initiate the brake earlier, which goes against expectations. As for the factor *Pedestrian speed*, also *Pedestrian size* could have been influenced by low resolution of the projector used for visualization, hindering participants' perception of the difference between the two sizes. The two-factor interactions between *Pedestrian size* and *Crossing entry* was observed to have a decreasing effect on TTC at brake onset for frequent and all drivers.

Crossing angle
It was observed that variation in crossing angle from 45° to 90° did not have any effect on TTC at brake onset for any of the groups. The two-factor interactions with *Pedestrian size* was observed to influence the TTC value for all drivers. This effect was however very low and was therefore neglected.

Crossing presence
It was interesting to find out from the results that factor *Crossing presence* did not have a significant influence on TTC at brake onset for any of the groups. It can be observed that even two-factor interactions with the factor had a low effect. Variation of the factor included either the absence, or presence, of a zebra crossing. It was expected that drivers would stop the car earlier when the pedestrian was crossing the road with a zebra crossing present, and later when it was absent. However the result showed no influence on the driver behavior. Reasons behind this might have been due to low resolution of the projector used for visualization, which made

it difficult for participants to observe the zebra crossing. Another reason might have been the lack of a pedestrian crossing sign which help direct the participants' attention toward the zebra crossing.

Crossing entry
Crossing entry was found to have a significant influence on TTC at brake onset for all three group of drivers. The two-factor interactions with other factors also had a high effect on TTC at brake onset. However, due to large variation in TTC at brake onset, factor *Crossing entry* was further investigated by comparing Task 33 with Task 8. It was observed that the visibility of the pedestrian had an higher influence on TTC at brake onset than the influence of *Crossing entry*. One explanation behind these finding could be that participants mistook it for a reaction test, and therefore braked as soon as they saw the pedestrian. Either a different scenario construction might be needed to make it possible to observe the pure effect of the factor, or analysis of a different moment might be better, for instance when participant realises the gas pedal.

Lane width
Lane width as a main factor was found to significantly influence the TTC at brake onset for all group of drivers. It was observed that change in lane width from 2.5 m to 3 m increased the TTC value at brake onset, meaning drivers tend to brake much earlier when driving on a 3 m wide lane. A wider road is commonly associated with higher speeds, like driving on a highway. Hence, drivers are more alert when driving faster and tend to brake, rather than engine brake, to reduce the speed.

Additional analysis

Comparison tasks
The statistical analysis conducted to compare study [3] and [4] resulted in a interesting observation. When Task 34 and Task 35 were analysed, the variation in *Car speed* had a significant influence on TTC at brake onset. The results were then compared to results from [3], which showed that *Car speed* had no significant influence on TTC at brake onset. Hence, the two studies resulted in a contradiction.

Similarly, analysis of Task 34 and Task 36 also resulted in contradiction when compared to the data from study [4]. In [4] *Pedestrian speed* had a significant influence on TTC at brake onset, which was not the case in the current study.

Difference in results between the current study and the two previously carried out might be explained by the difference in simulators, as study [3] was carried out on a test track and study [4] was carried out in a motion simulator. The simulator used in the current study was of low-fidelity, meaning there was neither movement nor sound feedback, and the field of view was narrow, only one screen. Hence, lack of input from auditory and sensory sources could have been a reason behind difference in results. Another reason might have been the difference in participants recruited for the studies and their behaviour toward the scenarios. Also, the experimental protocol was different for the studies, with difference in how the scenarios were displayed.

Learning/adaptation effect
Frequent drivers were found to adapted to the scenarios during the simulation. TTC at brake onset decreased from 6 s to 4 s during the test, indicating participants' learning of the events in the scenarios. The same trend was observed for all drivers. However, the trend was different for the occasional drivers, as analysis showed low learning effect compared to the frequent drivers.

Participants stated in the questionnaire that there was some expectancy to the events in the scenarios. However, since the learning/adaptation effect was mainly observed for the frequent drivers, it could be argued that as they drive more often, they are also more experienced with the different kind of events that might occur in an intersection, and can therefore adapt their driving style faster.

5

Conclusion

The aim of the study was to find influence of selected environmental factors' on driver comfort boundaries when interacting with pedestrians at intersections. The null hypotheses, (H_0), of the study was that the mean TTC at brake onset between the factors would not differ, and the alternative hypothesis, (H_A), was that the mean TTC at brake onset would differ.

Data from 87 participants were used for analysis. The participants were divided into two groups based on a driver profile. Group 1 consisted of frequent drivers, who drove 3 or more days per week, and Group 2 consisted of occasional drivers, who drove less than 3 days per week. In spite of recruiting these many participants, sample group was not representative of the entire population, as only 12.8% and 27.5% were females among frequent and occasional drivers, respectively.

Questionnaire analysis showed that participants responded positively toward the traffic environment in the simulator as nearly 90% stated they experienced the environment to be natural or sort of natural. Also, 96% of participants behaved, or sort of behaved, as normally as they would have in a real traffic situation. Considering that the simulator environment was created with open source software, the outcome was still realistic to be accepted by the participants.

The questionnaire analysis also revealed limitations with the simulator. Almost 25% of participants stated they experienced difficulties adjusting the pedals due to close proximity and high braking levels. Participants also lacked the movement and sound feedback from a high-fidelity simulator and the presence of other road users, cars and pedestrians.

Statistical analysis showed that for all group of drivers (frequent, occasional and combined), factors *Car speed* and, *Pedestrian size*, *Crossing entry* and *Lane width* had a significant influence on TTC at brake onset. *Car speed* and *Crossing entry* had a decreasing effect on TTC at brake onset, while *Pedestrian size* and *Lane width* had an increasing effect on the TTC value. Factor *Crossing presence* for frequent drivers and factor *Pedestrian speed* for all drivers had a small effect on TTC and was therefore neglected. Hence, frequent and occasional drivers can be combined into a single group as brake onset was found not to be influenced by driving frequency.

Analysis of the comparison tasks showed contradicting results for both study [3] and [4]. Difference in results could be explained by the low-fidelity of the simulator used in the study and narrow field of view (only one screen). Another reason might be the low definition projector available in the SAFER *Driving simulator room*. The experimental protocol varied between the studies which might also explain the difference in the results. The participants recruited for the different studies might have behaved differently toward the scenarios. Hence, the current study should be compared with more studies to determine the fidelity of the results.

Comparison between Task 33 and Task 8 showed that influence from factor *Crossing entry* on TTC at brake onset was due to pedestrian visibility not crossing entry. The two levels of the factor involved two different TTCs, 4 s near side and 8 s far side. When the pedestrian was entering from the far side, the participants had 4 s longer to react compared to pedestrian entering from near side. Hence, longer TTC gave the participants more time to react. However, as *Crossing entry* was found to have a significant influence on TTC at brake onset, other scenarios should be created where the pure effect of the factor can be observed and analyzed.

Participants' tendency to adapt to the scenarios in the experiments, based on the analysis of learning/adaptation effect, should be further investigated to understand its influence on the results. Further analysis is also needed to evaluate gender's influence on TTC at brake onset.

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Appendices

A

Advertisement

Participants required for driving simulator study

The Department of Applied Mechanics, Division of **Vehicle Safety**, at Chalmers University of Technology is looking for participants to take part in our new study.

The aim of the study is to better understand driver behavior at pedestrian crossings. You will be invited to drive in a simulator at Chalmers' campus Lindholmen.

The experiment will take place 14th of March to 8th of April. Total duration of the experiment is 1 hour.

Requirements for participation:
- Have a valid driver's license
- Be in the age group 25-60 years old
- Possibly drive at least 3 days per week

Request from participants:
- Drive in the driving simulator
- Fill in a questionnaire

Your participation will be rewarded with **two movie tickets**. If you would like to participate, please contact:

Leila Jaber
Chalmers University of Technology

Mobile: **072-3932478 (9:00 - 17:00)**
Email: **leilaj@student.chalmers.se**

Christian-Nils Boda (English contact)
Chalmers University of Technology
Department of Applied Mechanics

Phone: **031-7723577 (7:00 - 16:00)**
Email: **christian-nils.boda@chalmers.se**

CHALMERS

B

Power analysis

Difference in mean and standard deviation from [4].

Difference in mean was given, $\Delta = 0.21\ s$. Difference in standard deviation was calculated from the Empirical rule,

$$\sigma = \frac{0.4 + 0.5}{2} = 0.45\ s$$

Difference in mean and standard deviation from [3].

Difference in mean was calculated from the 50% values of the distribution,

$$\Delta = 3.2 - 3.1 = 0.1\ s$$

Difference in standard deviation was calculated from the Empirical rule,

$$\Delta = \frac{0.4 + 0.6}{2} = 0.5\ s$$

The power can be calculated from formula in [6],

$$power = 1 - \Phi\left[z(\alpha/2) - \frac{\Delta}{\sigma}\sqrt{\frac{n}{2}}\right] + \Phi\left[-z(\alpha/2) - \frac{\Delta}{\sigma}\sqrt{\frac{n}{2}}\right]$$

If the sample size is to be estimated, then it is enough to look at the dominant term,

$$power = 1 - \Phi\left[z(\alpha/2) - \frac{\Delta}{\sigma}\sqrt{\frac{n}{2}}\right]$$

where $\alpha = 0.05$, $z(\alpha/2)$=1.96 and $power = 0.8$. Solve for n gives,

$$n = \left[\frac{(1.96 + 0.84)\sigma}{\Delta}\right]^2$$

The sample size for different combinations of σ and Δ yields,

	σ=0.45	σ=0.5
Δ=0.1	318	392
Δ=0.21	72	89

Hence, $72 \leq n \leq 392$

C

Fractional factorial design

	Car speed a	Pedestrian speed b	Pedestrian size c	Crossing angle d	Crossing presence e	Crossing entry abcde	Road type cde
1.	-1	-1	-1	-1	-1	-1	-1
2.	-1	-1	-1	-1	1	1	1
3.	-1	-1	-1	1	-1	1	1
4.	-1	-1	-1	1	1	-1	-1
5.	-1	-1	1	-1	-1	1	1
6.	-1	-1	1	-1	1	-1	-1
7.	-1	-1	1	1	-1	-1	-1
8.	-1	-1	1	1	1	1	1
9.	-1	1	-1	-1	-1	1	-1
10.	-1	1	-1	-1	1	-1	1
11.	-1	1	-1	1	-1	-1	1
12.	-1	1	-1	1	1	1	-1
13.	-1	1	1	-1	-1	-1	1
14.	-1	1	1	-1	1	1	-1
15.	-1	1	1	1	-1	1	-1
16.	-1	1	1	1	1	-1	1
17.	1	-1	-1	-1	-1	1	-1
18.	1	-1	-1	-1	1	-1	1
19.	1	-1	-1	1	-1	-1	1
20.	1	-1	-1	1	1	1	-1
21.	1	-1	1	-1	-1	-1	1
22.	1	-1	1	-1	1	1	-1
23.	1	-1	1	1	-1	1	-1
24.	1	-1	1	1	1	-1	1
25.	1	1	-1	-1	-1	-1	-1
26.	1	1	-1	-1	1	1	1
27.	1	1	-1	1	-1	1	1
28.	1	1	-1	1	1	-1	-1
29.	1	1	1	-1	-1	1	1
30.	1	1	1	-1	1	-1	-1
31.	1	1	1	1	-1	-1	-1
32.	1	1	1	1	1	1	1

D

Information and consent form

Information and consent

Background and purpose

Technical systems in cars can detect pedestrians, estimate the probability of collision and if the probability is high enough, act by warning the driver or brake the car autonomously.
It is not desirable to act too early nor too soon. The later the action, the lesser the time to reduce the speed or steer away. The earlier the action, the greater the probability that the situation would not lead to an accident because the driver or the pedestrian has avoided the collision on their own. Early interference by technical systems can be annoying for the driver and could lead to it being turned off or ignored. Late interference might lead to the system's safety potential not being used to its maximum.
The purpose of this research is to define a time for system interference that will lead to highest possible safety and comfort of the driver. We would like to achieve this by finding the comfort boundaries of drivers when a pedestrian or a bicyclist is crossing the road, with variations on different factors, such as car speed. Comfort boundaries describe a threshold, above which the driver feels comfortable and is engaged in normal driving, and below which the driver feels some discomfort. According to current theories, drivers who feel discomfort want to get out of the hazardous situation and back to a normal situation. Depending on the driving situation, this could be achieved by for instance braking the car.

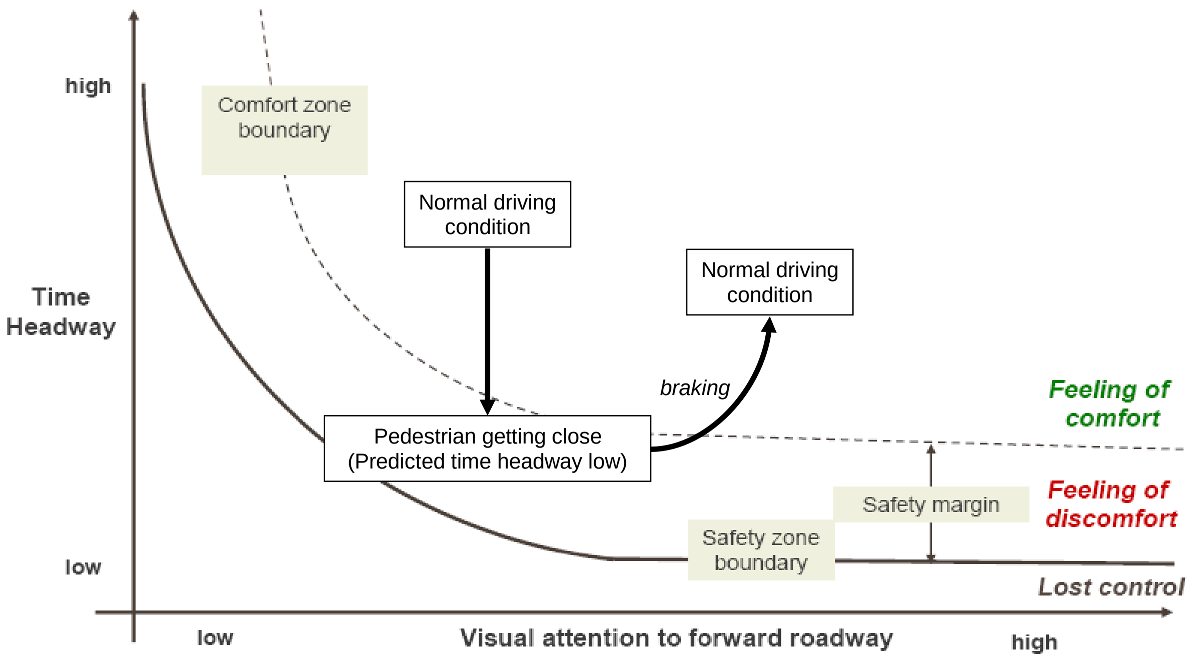

Figure 1: Comfort boundaries (from Ljung Aust, M. and Engström, J.(2011))

Inquiry concerning participation

You are participating in this study because you have contacted us through our ad and because your profile matches our requirements for the study.

How will the study be conducted?

Your task is to drive through an intersection in a virtual environment with a certain speed which you will be informed about in advance. A realistic traffic scenario will be "displayed" and we would like you to drive the car and react to any possible events as you would normally do. The car you are driving is an ordinary car without any additional equipment. There are pedestrian dummies, cyclist dummies and other obstacles in the testing area, try and treat them as regular cars and pedestrians.

What are the risks?

Several similar studies have been carried out before. Because you are sitting in a chair and steer with a fake steering wheel or brake with a fake brake pedal, the risks for physical harm are very limited. During the experiment you might virtually crash with a cyclist/pedestrian. This experience might upset you and cause you psychological harm, even though we have not been able to find any studies confirming this. During the experiment the test personnel will continuously judge how you feel and your wish to continue.

Are there any advantages?

You will be driving in a virtual environment and the results from the study will be used to improve implemented safety systems in cars.

Dealing with data and confidentiality

Data in your profile (age, gender, annual mileage, number of years you have had a driver's license, etc.) will be stored and connected to the experiment results. However, your personal information (name, address, phone number, etc.) will be removed from the dataset. Only an encrypted copy of the coding list (which connects your anonymous ID and your personal information together) will be saved. This list will only be handled by Christian-Nils Boda (see contact information below). The coding list will be destroyed within 5 years and the anonymous dataset will be erased within 10 years. Finally, your answers and your results will be handled so that unauthorized people cannot take part of it, according to personuppgiftslagen (PUL). Emma Didring, lawyer and personal data protection officer at Chalmers, is responsible that the data is kept confidential. She can be reached through mail (emma.didring@chalmers.se) or phone (031-772 1278).

How do I obtain information about the results of the study?

Results of the study will be published in a scientific journal. For more information or to review your personal dataset, please contact Christian-Nils Boda (see **Responsibility** part below).

Insurance, compensation

The insurance from Chalmers University of Technology cover any potential harm during the experiment.
Your participation will be compensated with two movie tickets.

Voluntarism

Participation in the study is voluntary and you have the right to at any moment withdraw your participation.

Responsibility

Responsible for the experiment data and personal information is Christian-Nils Boda.
Responsible for the study are Erik Rosén, Nils Lübbe and Christian-Nils Boda.
The experiment will be conducted by Christian-Nils Boda, Leila Jaber and Prateek Thalya.

All the contact information can be found below

Christian-Nils Boda	Nils Lübbe	Erik Rosén
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Leila Jaber	Prateek Thalya
Master student Chalmers University	Master student Chalmers University
leilaj@student.chalmers.se	thalya@student.chalmers.se

Consent form for

Comfort boundaries for drivers when pedestrians/cyclists are crossing the road in a virtual environment

I have received information, both orally and written, and had the possibility to ask questions and have them answered. I am aware that I can at any time withdraw my participation without giving any specific reason.

I also consent to have collected data being reused in other research projects focusing on traffic safety.

☐ Yes
☐ No

I consent to participate in the study

……………………………………. …………………………………….
Signature City and date

…………………………………….
Clarification of signature

Undersigned has given information about the study

……………………………………. …………………………………….
Signature City and date

…………………………………….
Clarification of signature

Roll in the study

…………………………………….

E

Questionnaire form

Interview questions during experiment

Personal-ID: ____________________ (day/round/person)

Ex. Person driving first in the group, during the third round on Tuesday is: 16/3/1

Age:__________ **Gender:**__________ **Driver's license since:**___________

Annual mileage:_____________

How many days during the weeks is the car normally driven? ______

1. "Did the traffic environment feel natural?"

O Yes **O Sort of** **O No**

Please explain

2. "Cite the most notable thing that was not feeling natural in the experiment's scenario."

Please explain

3. "Did you react like you would normally do in a real traffic situation?"

O Yes **O Sort of** **O No**

Please explain

4. "How did you hear about the study?"

____

F

Cumulative frequency graphs

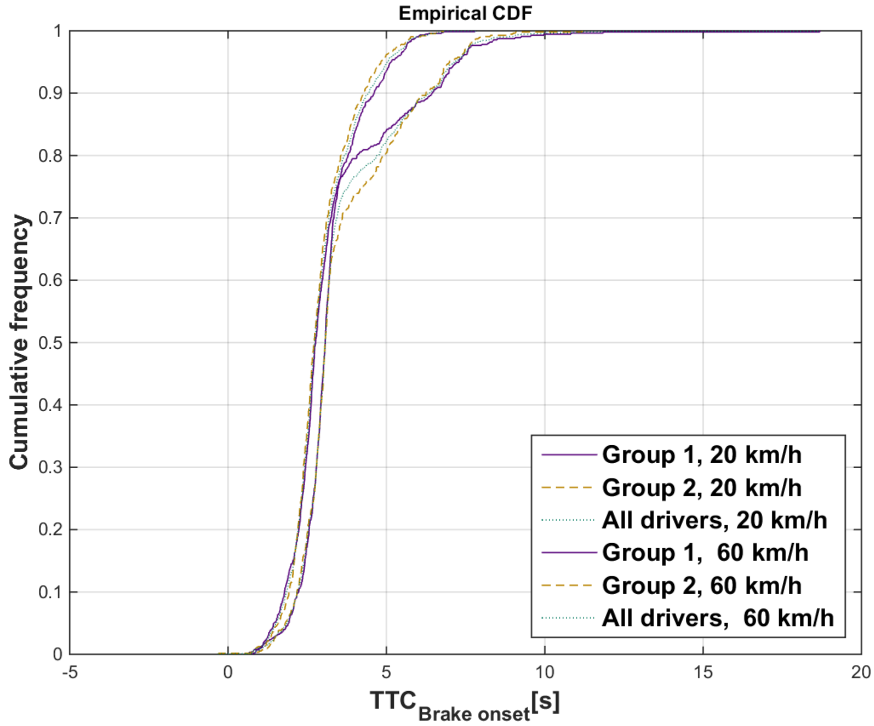

Figure F.1: Cumulative frequency distribution for factor *Car speed*.

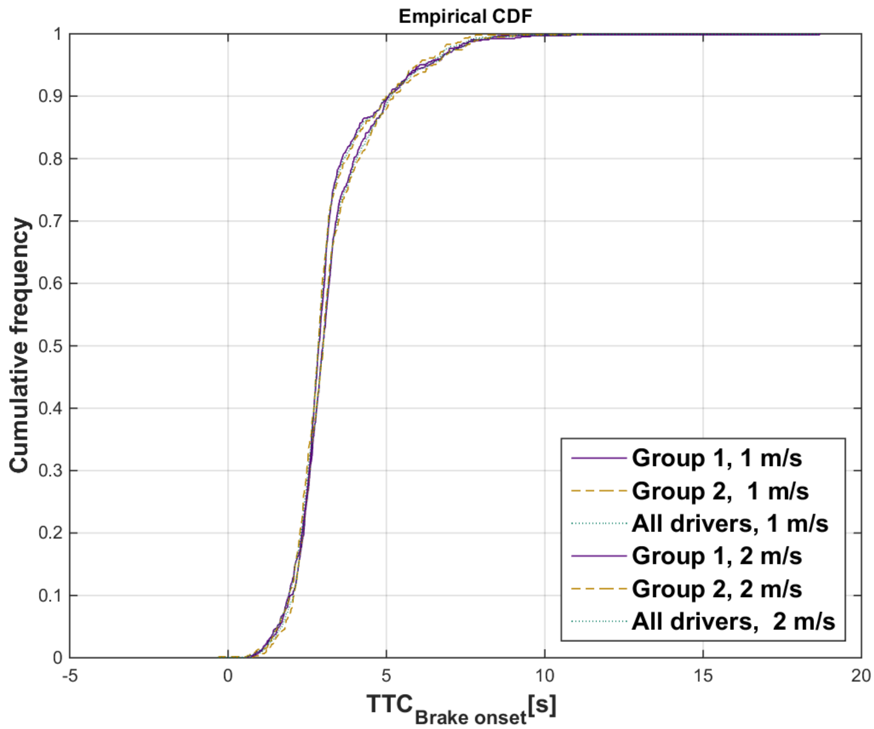

Figure F.2: Cumulative frequency distribution for factor *Pedestrian speed*.

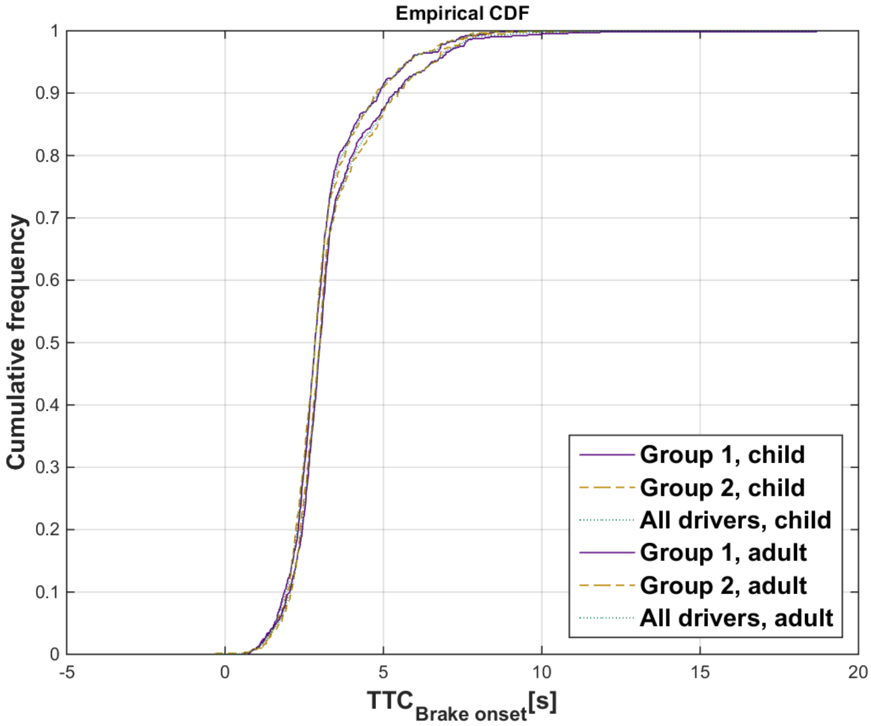

Figure F.3: Cumulative frequency distribution for factor *Pedestrian size*.

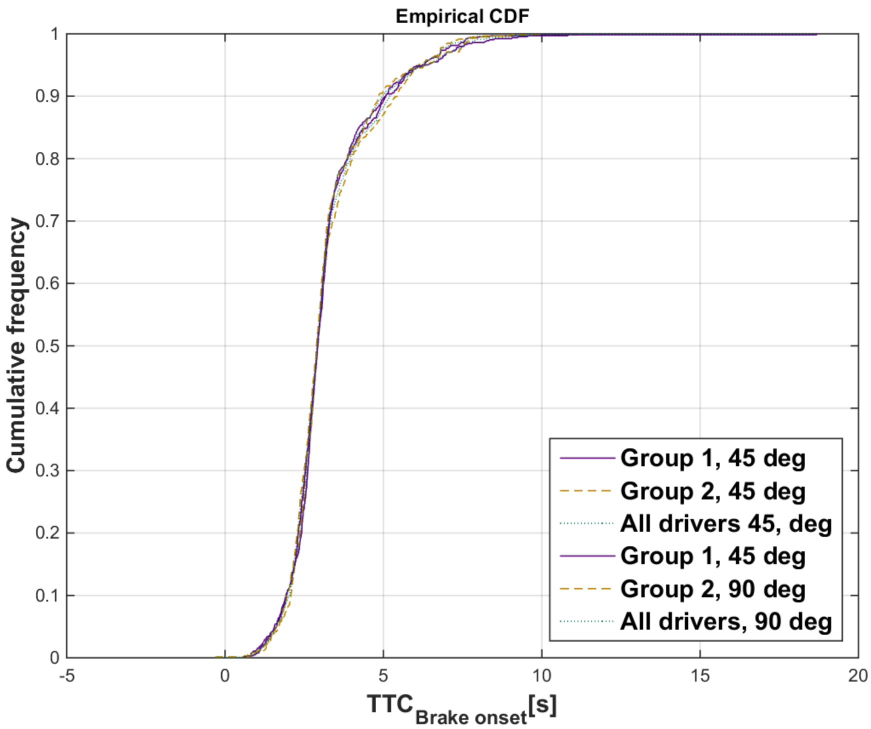

Figure F.4: Cumulative frequency distribution for factor *Crossing angle*.

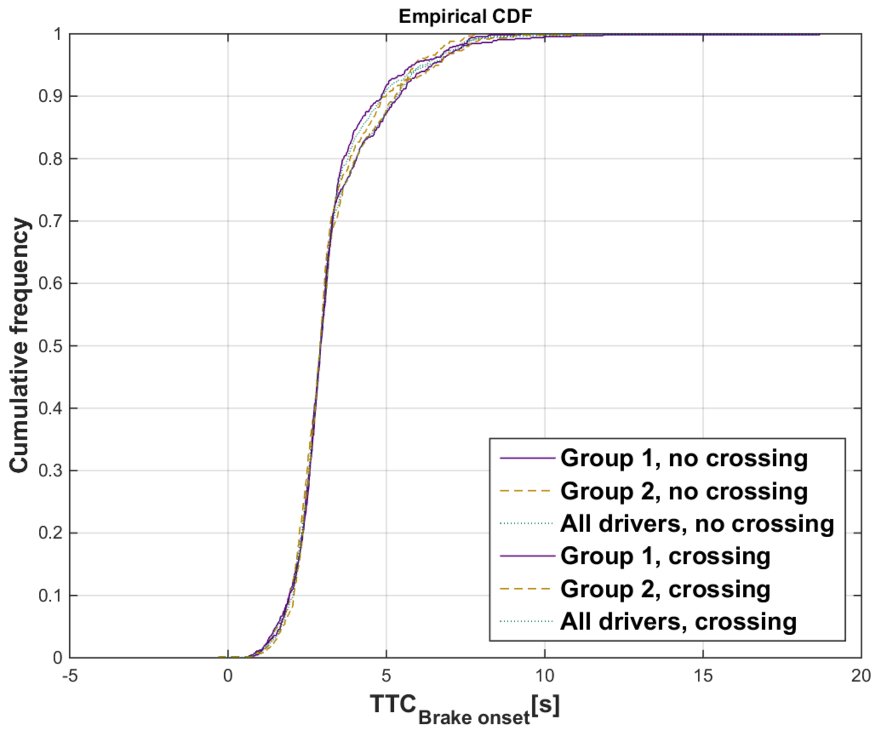

Figure F.5: Cumulative frequency distribution for factor *Crossing presence*.

entry.png

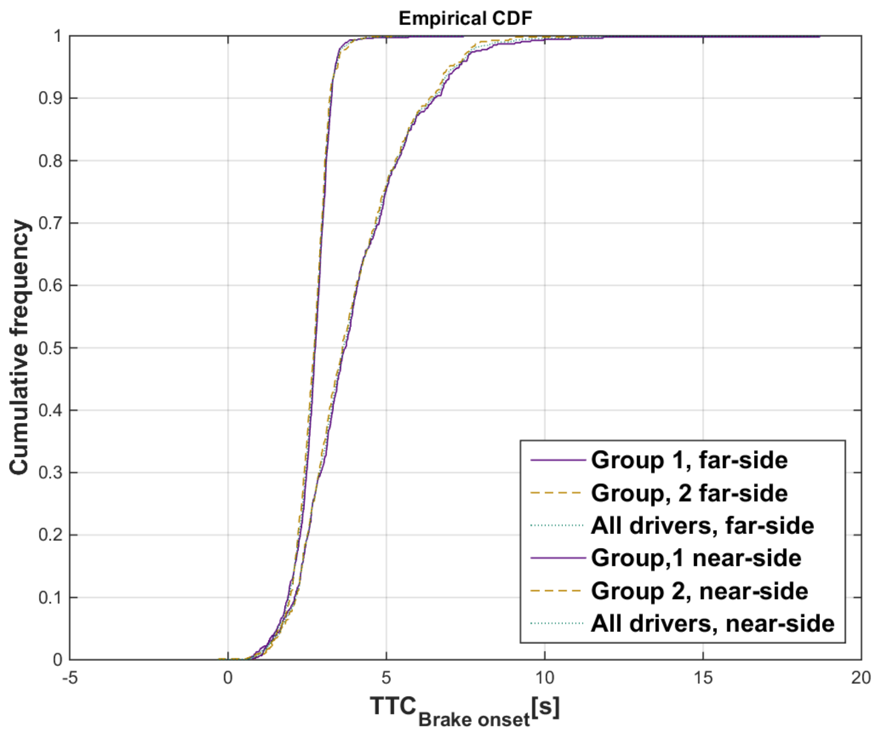

Figure F.6: Cumulative frequency distribution for factor *Crossing entry*.

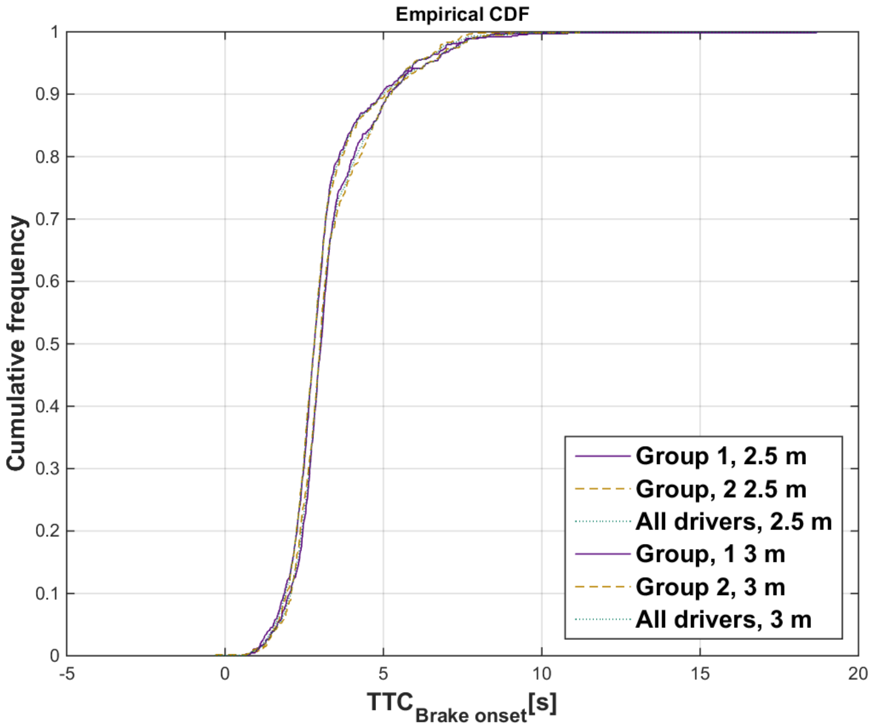

Figure F.7: Cumulative frequency distribution for factor *Lane width*.