CHALMERS
UNIVERSITY OF TECHNOLOGY

Drivers’ comfort boundaries when overtaking a cyclist

Set-up and verification of a methodology for field data collection and analysis

Master Thesis in Automotive Engineering

Ron Schindler, Viktor Bast

Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2015

MASTER THESIS IN AUTOMOTIVE ENGINEERING

Drivers' comfort boundaries when overtaking a cyclist

Set-up and verification of a methodology for field data collection and analysis

Ron Schindler, Viktor Bast

Department of Applied Mechanics
Division of Vehicle Safety
Accident Prevention Group
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2015

Drivers’ comfort boundaries when overtaking a cyclist
Set-up and verification of a methodology for field data collection and analysis
Ron Schindler, Viktor Bast

Master Thesis 2015:02
ISSN 1652-8557
Department of Applied Mechanics
Division of Vehicle Safety
Accident Prevention Group
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Vehicle overtaking a cyclist

Chalmers Reproservice / Department of Applied Mechanics
Göteborg, Sweden 2015-06-15

Drivers' comfort boundaries when overtaking a cyclist
Set-up and verification of a methodology for field data collection and analysis
Master Thesis in Automotive Engineering
Ron Schindler, Viktor Bast
Department of Applied Mechanics
Division of Vehicle Safety
Accident Prevention Group
Chalmers University of Technology

Abstract

In the past years, the global movement of people and goods has been increasing. Especially for personal transports, cars are the most frequent choice, resulting not only in a high market share, but also in problems such as pollution, traffic jams and congestion. However, there are alternatives; for instance cycling, which is a healthy, economical and environmentally friendly solution. For these reasons, the number of cyclists is in fact growing very rapidly in Europe.

Nevertheless, this modal shift might rise unforeseen concerns. In particular, cycling safety has drawn the attention of many researchers worldwide. While cycling, the interaction with motorized vehicles deserves a special attention, as crashes with motorized vehicles are responsible for the most severe cycling injuries. Among the possible scenarios where vehicles and cyclists may encounter, overtaking maneuvers are of exceptional concern, as they happen at speeds that are usually higher than in other scenarios.

In an overtaking scenario, the assessment of drivers' comfort zone boundaries is a crucial aspect. Driver comfort boundaries are often used to investigate whether or not a situation feels safe and comfortable for the driver. Comfort zone boundaries are also used to determine when to trigger warnings or initiate autonomous interventions for active safety systems. In overtaking situations, comfort zone boundaries allow for an estimation of safety distances between the involved actors. Although research has been conducted on car-to-bicycle overtaking maneuvers, especially on what influences these safety distances, previous studies have mainly been limited to assess the lateral clearance between the bicycle and vehicle.

Within this thesis, a new framework to enable field research of car-to-bicycle overtaking is presented. After providing a theoretical model for different phases of an overtaking maneuver, a field experiment was performed using an equipped bike and an equipped car. In these experiments, an electrical bicycle which had been equipped with sensors, cameras, a data logger and a LIDAR, was ridden on two roads in Västra Götaland, Sweden. In addition, an equipped car with a CAN logger, GPS and eye tracking system was used for the experiments. Data from the experiment were analyzed to determine the sensor performance and the extent to which data from the instrumented bicycle and the instrumented car were able to identify the phases of an overtaking maneuver and their corresponding comfort zone boundaries. This thesis also discusses the results in terms of the factors which may influence an overtaking maneuver and provides suggestions for future research on car-to-bicycle overtaking.

Keywords: electric bicycle, instrumented vehicle, human factors, traffic safety.

Contents

Table of Figures

Preface

In this thesis, experiments with an equipped bicycle and car have been conducted for a methodology development. The tests have been conducted in April 2015 in Västra Götaland, Sweden. The thesis is part of the studies to achieve a Master's Degree in Automotive Engineering at the University of Chalmers. The project is carried out at the Department of Applied Mechanics, Division of Vehicle Safety, within the Accident Prevention Group at Chalmers University of Technology, Sweden.

This thesis has been carried out with Giulio Piccinini as a supervisor and Marco Dozza as examiner, to both of which we are grateful for the support and advice. Furthermore, Johan Karlsson from Autoliv Development has provided helpful support for which we would like to thank him as well. The thesis has been supported by SAFER, providing an equipped bicycle as platform to further add equipment to, and by Autoliv Development Sweden, providing an equipped car for the experiments.

We also would like to thank our families and colleagues for the support and help during our thesis work.

Göteborg, 2015-06-15

Ron Schindler, Viktor Bast

Notations

Roman upper case letters

CAN	Controller Area Network (bus standard to enable control unites inside a vehicle to communicate)
GPS	Global Positioning System
HMI	Human Machine Interface
IMU	Inertial Measurement Unit (consists of accelerometers, gyroscopes and magnetometers)
LIDAR	Light Detection and Ranging
RADAR	Radio Detection and Ranging
SH	Space Headway
TH	Time Headway
VRU	Vulnerable Road User

Roman lower case letters

d	Lateral distance between vehicle and bicycle
v_b	Velocity of the bicycle
v_1	Velocity of the following vehicle
v_2	Velocity of (possible) oncoming traffic
a_1	Acceleration of the following vehicle

1 Introduction

As the population is growing, the global movement of people and goods is expected to increase accordingly. As a consequence, the need for personal mobility is becoming stronger, considering also that individuals live longer. Today, in economically developed countries, cars are the solution that people normally select to move from one location to another. This choice results in a high mode of transportation share for cars (Buehler, 2011), leading to traffic jams, pollution and space problems (e.g. finding a parking spot). Alternative solutions for mobility exist and among those, the bicycle is an environmentally friendly, economical and healthy mode of transport with increasing numbers of users (Pucher et al., 2011).

Despite the increase of bike usage could be a positive step to reduce pollution and to increase the mobility of people, the resulting modal shift might give rise to unforeseen safety concerns. Cyclists often share the road with other vehicles (usually bigger and heavier) and cannot rely on active (e.g. Anti-lock Braking Systems and Electronic Stability Control) or passive safety systems (e.g. airbags and seat belts) as they are installed in vehicles to mitigate the outcome of a crash. Although some cyclists wear a helmet, this protection equipment addresses only a small number of crashes (Williams, 1991). Besides, the helmet only protects the head, leaving other body parts exposed to a high risk of severe injuries.

Lately, the safety of cyclists has drawn the attention of researchers worldwide, focusing on the usage of helmet (Zibung et al., 2014, Ohlin et al., 2014), the interaction with other road users (Silvano et al., 2004; Petzoldt et al., 2014) and how to improve safety (Schramm & Haworth, 2014; Niska et al., 2014).

In this context, an aspect that deserves special attention is the interaction of cyclists with motorized vehicles during specific maneuvers. Among those, the overtaking maneuvers are notably interesting since studies have shown that accidents with motorized vehicles and bicyclists moving in the same direction have an increased likelihood to lead to severe injuries (Stone and Broughton, 2003). An explanation for the increased risk, is that "The high level of severity in incidents between pedal cyclists and drivers travelling in the same direction presumably derives from velocities being greater than in junction accidents, where vehicles have slowed down to manoeuvre" (Walker, 2007).

In the context of autonomous driving, this aspect is also becoming a challenge for the vehicle and its systems. Especially for the first autonomous cars, it is necessary to make them “behave” like a human driver would to not scare other road users.

The present work will investigate a methodology to measure comfort zone boundaries of drivers and cyclists during overtaking maneuvers as well as the definition and variables of the maneuver itself. In order to familiarize with the topic, in the next chapter, a literature review is presented to introduce and explain overtaking maneuvers and comfort zone boundaries.

2 Literature Review

This chapter gives an overview over the relevant literature on overtaking maneuvers (Section 2.1) and comfort zone boundaries (Section 2.2).

2.1 Overtaking Maneuver

The Oxford dictionary (2014a) and the Cambridge dictionary (2014) provide general definitions of the verb "to overtake”, not necessarily in the context of traffic. On the other hand, the Collins dictionary (2014) gives a specific definition of the noun “overtaking”, defining it as "an act or the process of moving past another vehicle or person travelling in the same direction".

A more scientific definition is used by Richter and Ruhl (2014), defining overtaking as the maneuver of a vehicle passing a leading vehicle which is slower, using another lane than its own. This overtaking process can be further divided into one vehicle overtaking one other vehicle, one vehicle overtaking multiple other vehicles in a row or vice versa as well as a double overtaking, where someone who is overtaking gets overtaken himself. Usually, the first described case is the most common one on roads, but the other cases might occur, especially on high standard roads (e.g. highways), where there are at least two lanes in each direction.

Although these definitions provide a general framework, overtaking maneuvers present a huge variety and can be described through several variables and parameters. In this work, the focus will be on cars overtaking cyclists, since, to present, there has only been little research on this specific topic (Chapman & Noyce, 2012). In particular, only few attempts have been made to obtain objective data on how motorized vehicles overtake bicycles and about subjective information (e.g. workload, feeling of comfort) of drivers and riders during the overtaking maneuvers. The so far conducted studies have mainly focused only on lateral clearance between the vehicle and the bicycle during the overtaking maneuver (Llorca et al., 2014; Mehta et al., 2014; Walker, 2007).

Before describing the experimental design for the study, it is relevant to provide a classification of the overtaking phases and identify the factors that could influence the overtaking maneuver. Those aspects are addressed in the following sections.

2.1.1 Overtaking Phases

In general, an overtaking maneuver can be divided into different phases (defined time frames), containing several basic control tasks, situational behaviors and general driving tasks (Hegeman et al., 2005). This division is useful to identify actions and variables that change over the progress of the maneuver.

As a starting point, the overall process of overtaking maneuvers can be divided into three phases (Shamir, 2004; Petrov & Nashashibi, 2011):

1) Diverting from the lane
2) Driving straight in the adjacent lane
3) Returning to the lane

This classification of the phases was used to describe and define overtaking maneuvers for autonomous vehicles, but it can be also useful as a first and general description of overtaking behavior. In the first phase, the vehicle is leaving its original position in the lane and starts moving away from the curb, following a given reference trajectory for a specific time period. In other words, a lateral movement (y-direction) is added to the forward movement (x-direction) of the overtaking vehicle until the latter reaches a preselected position behind the overtaken vehicle. In the second phase, the vehicle has left its original lane and is continuing its drive parallel to the driving direction of the overtaken vehicle at a selected lateral distance, preferably at a significantly higher speed than the vehicle that is about to be overtaken. In the case of a car overtaking a bicycle, this definition needs to be refined, as vehicles do not necessarily leave their own lane to overtake a bicyclist due to the significantly smaller width of the bicycle compared to motorized vehicles. The last phase of an overtaking maneuver is the returning of the vehicle into its original lane, coming back to a more or less equal y-coordinate as before starting the maneuver, reaching a preselected position in front of the overtaken vehicle. There may be cases, especially on multi-lane roads, where the last phase does not need to be performed, since the vehicle can continue in the passing lane for a longer time. Overall, the desired position and velocity of the overtaking vehicle at the end of every phase, as well the phase duration, are related to the requirements of the overtaking maneuver itself (Petrov & Nashashibi, 2011).

Chuang et al. (2013) presented another classification in three phases (t_1 to t_3), putting focus on a time wise differentiation. The authors assumed a duration of one second for an overtaking maneuver. The variable of interest was then the lateral distance, being the smallest perpendicular distance from the ego vehicle travelling direction to any object next to it. To divide the maneuver into three phases, the authors started by defining the point in time, when the overtaking starts (t_2) as the point when the measured lateral distance from the ego vehicle overtaken suddenly decreases due to an overtaking vehicle appearing next to the ego vehicle. From this time t_2, 0.5 s were subtracted to get to the phase “before passing”, t_1. By adding 0.5 s, the phase “after passing” t_3 is reached.

Hegeman et al. (2005) used a more detailed description of the overtaking maneuver. First of all, four overtaking strategies were defined, distinguishing between an accelerative, a flying, a piggy backing and a 2+ overtaking maneuver.

The accelerative overtaking occurs when the overtaking vehicle has no sufficient gap to immediately overtake and therefore has to adjust the speed to follow the lead vehicle and later, accelerate during the overtaking maneuver. The flying overtaking takes place when the overtaking vehicle is at the desired speed and has immediately the possibility to overtake without adjusting speed. The piggy backing overtaking happens when the ego vehicle is following the lead vehicle which overtakes another vehicle (see also Wilson and Best, 1982). Finally, the 2+ overtaking maneuver is when the overtaking vehicle passes two or more vehicles in a row at once.

After describing the overtaking strategies, Hegeman et al. (2005) divided the actual overtaking maneuver into five phases. The first phase is the one in which the driver decides whether there is a need to overtake or not. This need is depending on the desired speed of the driver as well as the speed of the preceding vehicle, but it is also influenced by behavioral factors (e.g. being in a hurry). In this step, the driver verifies and continuously checks only more or less static factors (e.g. infrastructural limitations) that influence the overtaking possibility.

The second phase is the one in which the driver prepares for the overtaking. This is the verification of the dynamic factors (e.g. potential opposing traffic). The distance to the next oncoming vehicle has to be judged constantly, and when there is a sufficient gap, the driver starts to observe the surrounding traffic. The final task of the driver in this phase is the use of the indicators. It is worth noting that not every driver uses the indicators as it is demanded by law, showing the limitations of this theoretical description. Time wise, this phase lasts from when the last oncoming vehicle has passed the ego vehicle until the front left wheel of the ego vehicle touches the center line, and is also referred to as the "perception reaction time" (perceive that there is a big enough gap to overtake and react, starting the overtaking maneuver).

The phase number three describes the drivers' lane change and it starts with the driver steering and accelerating in order to get to the center of the passing lane. This phase lasts from when the left front wheel touches the center line to when the right back wheel has crossed the line and, at the end of this phase, the indicator should be switched off.

The second to last phase is the actual passing maneuver, where the overtaking vehicle is in the overtaking lane and passing the formerly lead vehicle. In this phase, the driver is continuously monitoring the gap to possible oncoming traffic.

Finally, in the fifth and last phase, the vehicle returns to the original lane. The indicators should be used and the steering action may start when the headlights of the overtaken vehicle appear in the mirrors. Back in the right lane, the driver controls his own speed and adjusts it to the desired value. This period lasts from when the right front wheel touches the center line until the left back wheel has crossed the line.

The classification of phases proposed by Hegeman et al. (2005) is not only very detailed, but also gives a clear definition of the time frame as well as the actions and tasks that are performed within each phase. The consideration of different overtaking strategies is furthermore a very important aspect that needs to be considered when planning an experiment as it might have a significant influence on the overtaking maneuver.

The classifications earlier reported were generally defined for overtaking between vehicles and did not specifically refer to bicycles. Despite overtaking maneuvers are generally expected to be as described above, some minor changes have to be made when a bicycle is the overtaken "vehicle". A factor that needs special consideration is the lateral displacement of the overtaking car, which is expected to be smaller due to a smaller width of the bicycle, compared to cars or trucks. As well, for the overtaking of a bicycle, the oncoming traffic might not be as relevant as for the overtaking of another vehicle (e.g. truck or car). In the next section, the other relevant variables that need to be considered will be introduced.

2.1.2 Relevant Variables during the Overtaking Maneuver

For overtaking maneuvers involving bicyclists, the main variable generally taken into account in recent studies is the lateral clearance (Walker, 2007; Chapman & Noyce, 2012; Mehta et al., 2014), which is the distance between the two vehicles involved in the overtaking maneuver. Nonetheless, Llorca et al. (2014) have shown, that for bicyclists, there are more variables of concern, like the speed difference (between the car and bicycle) and the size of the overtaking vehicle. Those variables are especially important for an overtaken cyclist as the force that the bicyclist is subject to during an overtaking maneuver is of greater extent compared to cars and it may lead to wobbling or falling of the bicyclist. As Llorca et al. (2014) stated, this force is proportional to a combination of lateral distance and the speed difference between the cyclist and car, both of which variables together also typically correspond well to the subjective risk perception of the cyclist. However, so far only a few amount of general studies have been conducted in this field, merely using models and simulations (Kato et al., 1981; Corin et al., 2008).

The different speeds and lateral clearances in every overtaking maneuver highly depend on some confounding factors that are presented in the following chapter.

2.1.3 Confounding Factors on Overtaking Behavior

In the present work, the expression “confounding factors” will be used to describe those factors that influence the behavior of drivers and cyclists during the overtaking maneuver. As mentioned earlier, the confounding factors have an impact on the relevant variables to be used for describing the overtaking maneuver (e.g. lateral clearance, speed difference). The most important confounding factors and variables and their influence on the overtaking maneuver are presented in this section.

An important factor that has been considered in research is the presence or absence of dedicated bike lanes. Mehta et al. (2014) used an instrumented bike to measure passing distances on different roads with and without bicycle lanes. The authors concluded that the number of unsafe passages, which means overtaking the cyclist too close (at less than 1 m), are quite rare (in their study, they account for 3.9%), however occurring more often on streets without bike lanes. As a conclusion, bike lanes were shown to provide a statistically significant reduction in the number of unsafe passing maneuvers by motorized vehicles. In contrast, Frings et al. (2014) found in their study that bicycle lanes do not affect the behavior of the driver of the motorized vehicle, however, the cyclists perceived the overtaking maneuvers as less risky when they were riding on a bicycle lane. In their work, Chapman and Noyce (2012) found that some drivers even committed a centerline violation (crossing a solid centerline which in most countries is prohibited) to keep enough distance to the cyclist when overtaking, supporting the postulate that drivers generally leave large enough passing distances.

Considering the general position of a bicyclist on the street, Walker (2007) showed that the further away from the curb the cyclist rides, the smaller the lateral clearance is. Nevertheless, the subjective perception of those overtaking maneuvers may differ significantly, as cyclists felt safer when riding further from the curb. Walkers’ explanation is that riding further away from the curb makes motorized vehicles generally increase their distance to the curb as well, however not by the same amount as the cyclist, leading to less leeway for the cyclist (e.g. a cyclist riding 50 cm further away from the curb would make a car drive 35 cm further away from the curb, resulting in a by 15 cm reduced lateral clearance between both).

Another factor that may influence drivers' behavior during the overtaking maneuver is the appearance of the cyclist, especially the outfit worn and the presence or absence of a helmet. This has been studied twice by Walker (2007) and Walker et al. (2014), with focus on different influences. According to his first study, drivers left more space when overtaking riders that seemed to be female. He explained this behavior not only considering that drivers are polite, but more by an unconscious risk compensation as female bicyclists may be seen as more frail. Furthermore, cyclists wearing a helmet were overtaken with less lateral clearance, which again could be explained by risk compensation, or drivers believing that helmet riders were more experienced and less likely to act "irrationally" (Walker, 2007; Basford et al., 2002).

In his most recent study, Walker et al. (2014) described how different outfits of the cyclist might influence the overtaking behavior of drivers, in addition to the helmet influence described above. Although it could be expected that cyclists in "racer" clothes would be perceived much more experienced than "novice" riders, the study could not show any significant difference in overtaking behavior. This suggests that other factors than perceived experience might have triggered the behavioral changes in the earlier helmet study by Walker.

An aspect that has also been investigated by Walker (2007), is the influence of the vehicle type on the overtaking behavior. He concluded that the heavier and larger in length and width a vehicle is (as it may be the case for heavy duty trucks and buses), the longer its overtaking maneuver will take. This situation is aggravated by the small accelerations that those vehicles can achieve. A longer overtaking maneuver then leads to less leeway being left for the cyclist, as those vehicles try not to drive too far in the adjacent lane. And the consequent objective increase in risk is supported by the study of Llorca et al. (2014), showing that the more trucks traveled on the street, the more dangerous it felt for the cyclists.

In his analysis of overtaking distances, Mehta et al. (2014) also took into consideration the traffic volume. This variable might also be an influencing factor on how drivers chose to overtake a bicyclist. For measuring the traffic volume, the author used the occupancy time of the ultrasonic sensor and compared it to average vehicle dimensions that were obtained from researching different types of vehicles (average values were used to make the procedure easier instead of identifying each vehicle separately and then calculate its speed). The method of the sensor occupancy allowed to estimate the time headway (time gap) between the vehicles overtaking the cyclist. The results showed that a higher traffic volume leads to more restrictions onto the drivers (as there are more vehicles around and the free space for every vehicle is reduced), resulting in reduced lateral clearance during the overtaking maneuver. This method further enabled an indirect measurement of the vehicles speed and position on the street (e.g. if it crossed the center line). The results showed that there is no strong relationship between the speed of the vehicle and the lateral distance drivers keep to the cyclist during the overtaking maneuver, as the latter varies randomly across all different passing speeds.

Another significant influence on initial passing distance between vehicles and bicycles is the surface condition of the road. Chuang et al. (2013) found in their study that poor surface conditions (e.g. snowy, wet) reduced the lateral clearance to the cyclist to a value of 134.5 cm compared to 161.5 cm under good surface conditions. This shows a significant reduction of leeway for the cyclist in poor road conditions. That behavior not only makes cycling more dangerous due to the reduced leeway, but also by the poor road conditions (e.g. slippery, wet, icy) that may increase the risk for the cyclist to lose control of the bicycle.

Chuang et al. (2013) found that also the cyclists' behavior before and during the maneuver could have a relevant impact on the overtaking. Depending on how "stable" the bicyclist is, based on cyclists' speed, steering angle and speed variation control, overtaking lateral distance adopted by drivers vary. Chuang et al. (2013) found in their study that smaller wheel angles, lower speeds and smaller speed variation of the cyclist led to smaller initial lateral passing distances.

But how can the relevant variables and influencing factors be obtained during an overtaking maneuver? All presented studies used similar techniques to record data. A bike equipped with GPS, cameras and ultrasonic sensors has proven its feasibility in many studies (Mehta et al., 2014; Walker, 2007; Walker et al., 2014; Chuang et al., 2013). A laser can be added to the handlebar, helping the cyclist to keep a quite constant distance to the curb when collecting the data (Llorca et al., 2014; Walker, 2007). However, improvements by including other sensors and cameras can still be made to acquire new variables and enhance the data quality. In alternative to the research performed so far, a new approach would result in equipping cars with sensors and data logging systems to obtain information about the driver and about the rider from a drivers' perspective to better understand the overtaking maneuver.

Finally, a fact that should be taken into account for this study is brought up by Walker (2007). Based on his experiments, especially considering the position of the bicyclist on the road, he drew the conclusion that drivers are generally following the same path when overtaking, irrespective of where the bicyclist is located. This behavior might represent a relevant concern for cyclists that ride in the middle of the lane compared to those riding close to the curb, but from an experimental point of view, it may enable to draw a general description of driver behavior when overtaking bicyclists.

As reported in the first part of the literature review, the behavior of drivers during overtaking maneuvers can be influenced by several factors. Those factors, together with other important aspects (e.g. drivers' individual characteristics) determine the choice of comfort zone boundaries during overtaking maneuvers. What these comfort zones are is explained in the next Section.

2.2 Comfort Zones

This chapter provides general information about what comfort is as well as putting it into the context of traffic.

2.2.1 Definition of Comfort

As the Master Thesis addresses the so-called "comfort zone boundaries", it is first necessary to define what "comfort" actually is. By definition, "comfort" is a state of convenience, ease, consolation and feeling of security. Hence, a person that feels "comfortable" feels both mentally free from stress, affliction and anxiety and physically free from pain and tension (Oxford dictionaries, 2014b). Furthermore, “comfort” is distinguishable in three different types: physical, physiological and psychological (Slater, 1986). During driving, physical and physiological comfort is achieved by the design of the vehicle and is addressed by the different subassembly groups: soft and supportive suspension system, adjustable seats, adjustable steering wheels, a quiet, low vibration and well air-conditioned interior are only few elements that can improve the physical and physiological comfort of passenger cars (Porter, 1998; da Silva, 2002; Heißing & Ersoy, 2011).

Psychological comfort – a state of mind of perceived convenience and ease - however, is a more complex issue. In the context of the driving task the driver feels comfortable when he is in a so-called "comfort zone" (Summala, 2007). This means, referred to the definition of “mental”, or psychological comfort, that drivers strive to remain within distance margins to other road users and obstacles and choose velocities that allow them to feel both safe and satisfied. The choice of specific comfort zones can result in a specific driving behavior, as it will be introduced in Section 2.2.2.

2.2.2 Comfort Zone Boundaries

Driving can be seen as a control task with continuous adaptation to the environment by different drivers’ actions (e.g. changing speed, turning, applying brakes). The control task serves the fulfillment of several goals, which are hierarchically ordered (Engström & Hollnagel, 2007). High-level goals could be reaching the destination unharmed and in time and low-level goals could be staying in the lane. Those goals could be achieved acting at different levels of the driving task as shown in Figure 1, where the classification between strategic, tactical, and operational level is presented (Michon, 1985). The strategic level specifies everything involved in planning the trip, such as determining a goal, route, and way of transport as well as risk and cost estimation related to the trip. The maneuvering/tactical level includes tasks of maneuvering the vehicle in the environment in order to meet the strategic plans, e.g. turning, overtaking, lane selection, and obstacle avoidance. The operational level is the area of vehicle-control processes, such as turning the steering wheel, actuating the pedals, and gear-selection. Environmental inputs influence the maneuvering/tactical and control level which then again directly affect the next higher level.

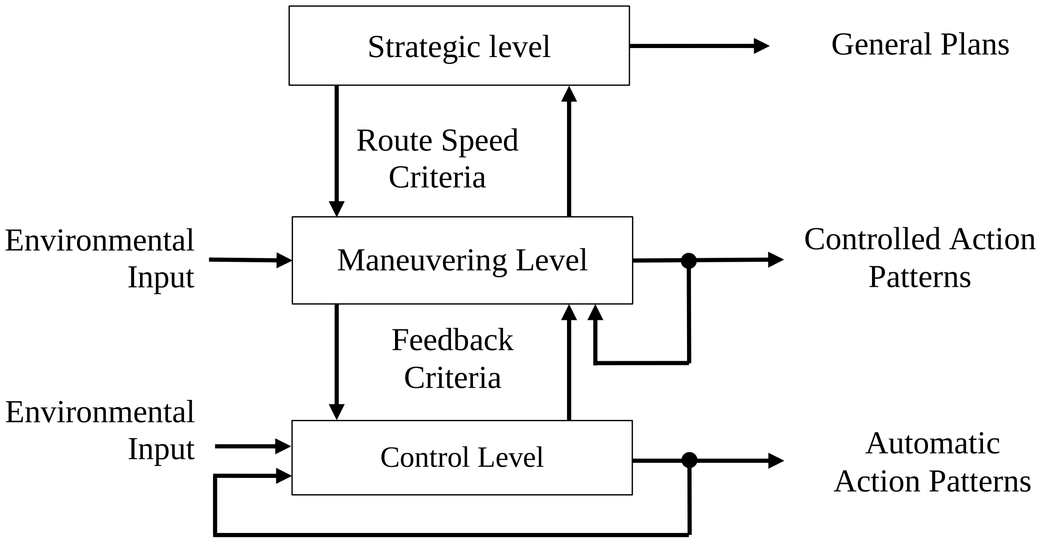

Figure 1: Hierarchical structure of the road user task

Driving tasks seen as control processes need to be complemented by a model that describes the motivations behind the drivers' behavior. The zero-risk theory (Summala, 1976) illustrates that the drivers' adaptive behavior on all control levels is a balance of excitatory and inhibitory forces, as illustrated in Figure 2.

Excitatory forces motivate the driver in the driving task and animate him in participating actively in the environment, e.g. expediency reasons such as arriving at the destination in time and as quickly as possible, reasons of rule-following, aggression, behavioral norms, etc. These motives entail the increase of vehicle speed, reduction of Time Headway and Space Headway (further on referred to as "TH" and "SH"), overtaking slow vehicles, and actively looking for gaps in traffic in order to go faster than other road users. On the other hand, inhibitory forces cause risk aversion and a more defensive driving behavior. Common indicators for inhibitory motives are comfort and subjective perception of risk which are also closely linked to exposure to risk: according to the zero-risk theory, drivers usually tend to avoid risks entirely in order to feel comfortable.

In Figure 2, speed is used as an indicator of comfort: if it is too low, it may result in arriving too late at the destination. Hence, the speed has to be increased in order to leave the feeling of discomfort caused by the fear of arriving too late (excitatory motives). However, in a curve, if the speed is too high for example, the driver will strain to avoid skidding by intensive steering wheel movement and will perceive discomfort in taking this action because the increased steering activity is an unusual behavior and beyond his or her comfort zone. In this case, the countermeasure is to reduce the speed in order to return within the drivers' comfort zone (inhibitory motives). Balancing all driving parameters between goal fulfilment and comfort zone compliance is a control task and the comfort zone the control variable to be strived towards.

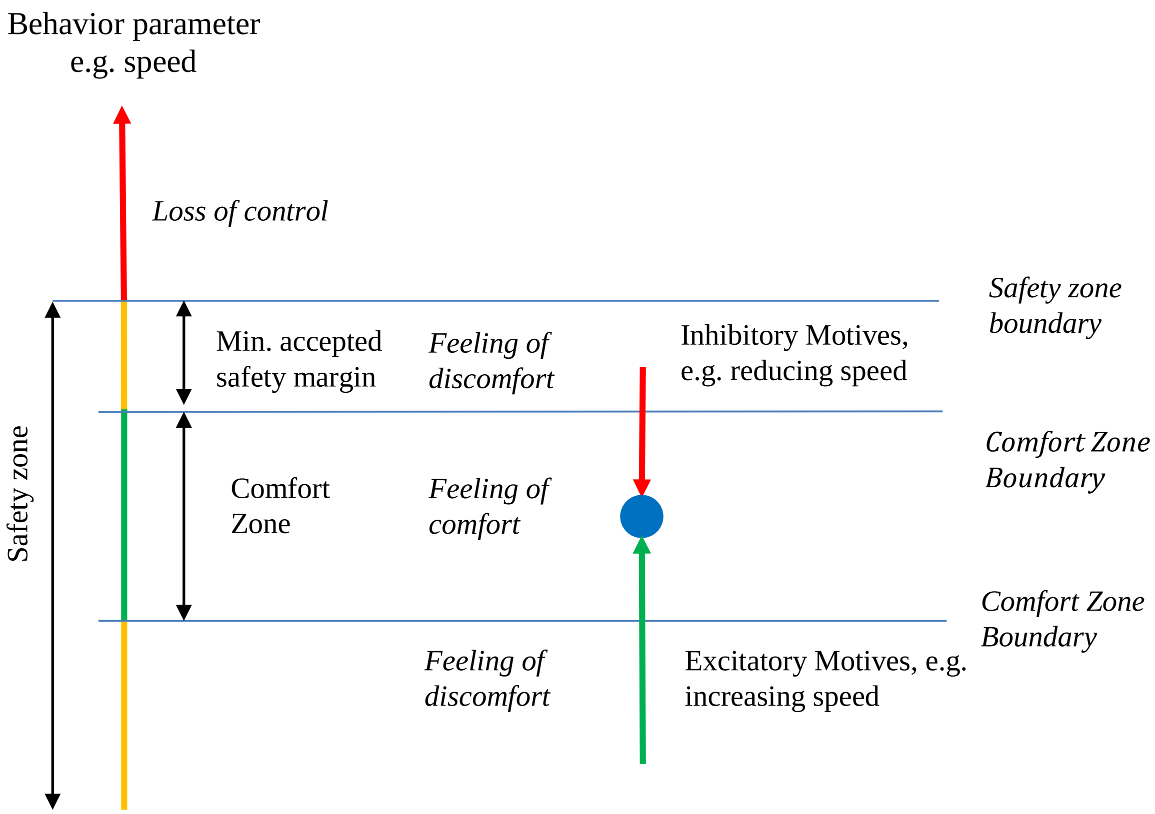

Figure 2: General safety margins and comfort zones

This comfort zone is individually dependent on a set of driver, vehicle and environment (DVE) parameters required for the driving task (Ljung Aust & Engström, 2011):

- Driver: physical and psychological condition, drowsiness, confidence, familiarity with vehicle, personality, etc.
- Vehicle: type and size, performance margins, ergonomics, etc.
- Environment: surrounding area, traffic conditions, time of day, season, weather conditions, etc.

Drivers usually seek the fulfillment of goals moving within their safety zone, which is dependent on the status of the variables belonging to the DVE space (Summala, 2007). The safety zone reported in Figure 2 is the region where vehicle control is still maintained but where the driver does not necessarily feel comfortable. As a consequence, the driver tends to move towards a region defined by the driver's comfort zone boundaries. A detailed description of comfort zone boundaries during overtaking follows in the next section.

Another concept of experiencing and striving after comfort while driving is described by the concept "comfort through satisficing" (Summala, 2007). Satisficing is the portmanteau word from the words satisfying and suffice in the decision theory created by Herbert Simon. It explains the strategy for finding a solution in a situation of decision-making: the search will not continue until the optimal solution is found but rather until the first option meeting the need is found (Simon, 1956). The "comfort through satisficing" could be a strategy used by the drivers to minimize the driving effort while keeping the performance within the comfort zone boundaries. On the other hand, professional drivers (e.g. race drivers, ambulance drivers and truck drivers) might strive for the optimal solution to each DVE state.

2.2.3 Comfort Zone Boundaries during Overtaking maneuvers

As described in Section 2.1.2, two variables were analyzed in previous studies of overtaking maneuvers: the lateral clearance of the car to the cyclist and speed difference between car and cyclist. However, other variables could be considered to describe comfort zone boundaries during overtaking maneuvers: lateral or longitudinal distances, velocities and accelerations maintained by the parties involved in the maneuver. The vehicle approaching faster will – in case of an accelerating overtake maneuver - decelerate until a certain space headway (SH) to the road user in front is reached. The SH is the sum of a minimum safety margin and an additional space and represents the drivers' own comfort zone. This SH and therefore $v_1 \approx v_B$ will then be maintained as long as the oncoming traffic is passing or as long as there is no time gap in the oncoming traffic sufficient for an overtaking maneuver (see Figure 3). Space headway to the oncoming traffic can also be divided in a safety margin, which is the minimum distance for a safe overtaking maneuver and an additional distance estimated by the driver. It is worth noting that the safety margin just as well can be violated by aggressive drivers and the additional space the drivers leave might become negative, meaning that the safety margin is violated. Then the safety margin becomes the drivers' own comfort zone and is not an actual safety margin anymore.

The acceleration (a_1) and the speed (v_1) of the vehicle can be seen as an indicator of drivers' comfort before and during the overtaking maneuver. In case of a hard acceleration, it can be assumed that the driver is either in a hurry or that he perceives discomfort in the current situation and strives to pass the cyclist as quickly as possible (see also Figure 4).

On the other hand, the lateral offset to the curb could be an indicator of the comfort zone boundary for the bicyclist during the overtaking maneuver. In this case, the cyclist will try to keep a compromise between a safe distance from the curb on the one hand and the lateral clearance from the car on the other hand.

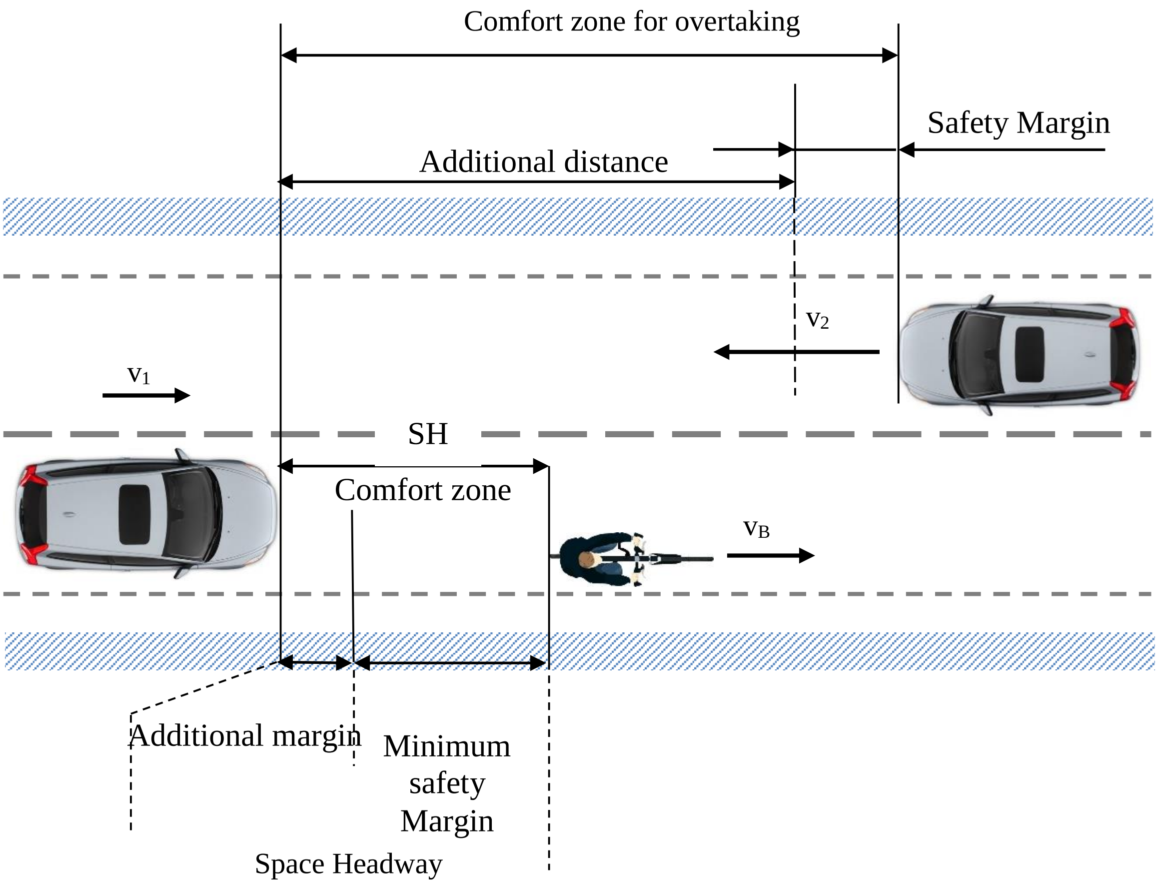

Figure 3: Comfort zone boundaries and safety margins before an overtaking maneuver [1], [2]

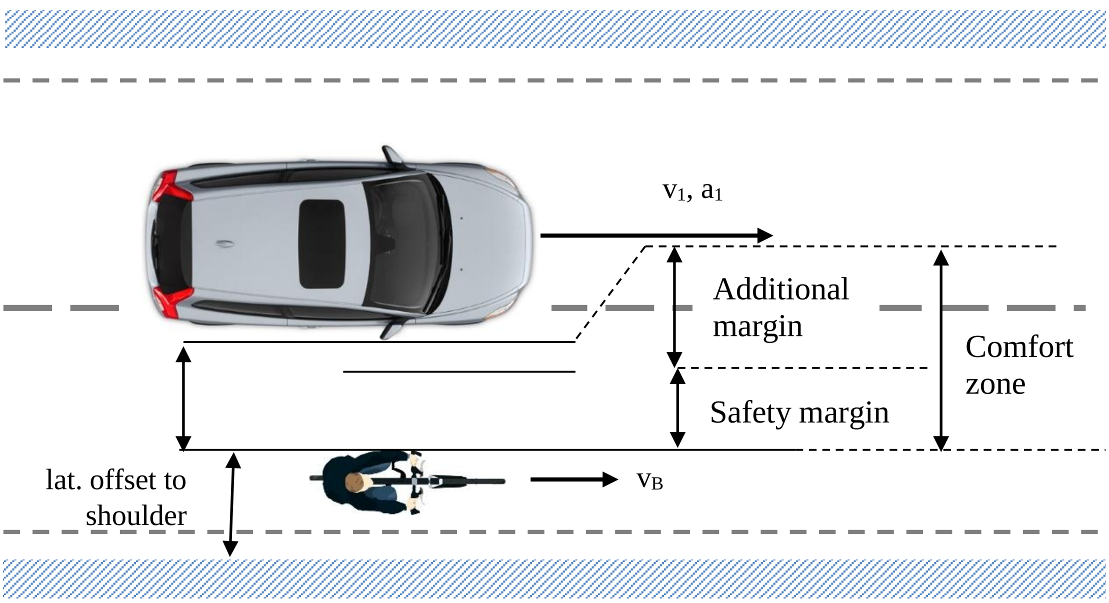

Figure 4: Comfort zone boundaries and safety margins during an overtaking maneuver [1], [2]

2.3 Discussion of Literature Review

As reported in the literature review, there are some research gaps regarding the comfort zone boundaries during the overtaking maneuver of a cyclist. First of all, the force that a cyclist experiences from air pressure variations during an overtaking maneuver has been classified as important by previous studies, but has not been deeply investigated so far. This force is strictly connected to the perceived risk during the overtaking maneuver, and might therefore be relevant to estimate the "comfort" of a cyclist when he or she is overtaken.

From a methodological point of view, previous investigations only equipped bikes to have a better understanding of the overtaking maneuver. However, it might be interesting to get also an insight from the drivers' perspective, equipping a car and using prepared questionnaires. This thesis will also investigate how those data could contribute for the development of a sound methodology to investigate the comfort zone boundaries during the overtaking maneuver, which may then be used when designing active safety systems.

For this purpose, a definition of overtaking phases suitable for the research needs to be provided, as the ones found in the literature seem to be not appropriate. Furthermore, indicators for the comfort zone boundaries need to be identified for each of those phases. Afterwards, it is necessary to evaluate how to measure and analyze the obtained data. The methodological approach to this problem is presented in the next chapter.

3 Approach and Methodology

This chapter describes the approach and the methodology used in this thesis. It starts by providing a tentative definition for the phases that constitute the vehicles' overtaking of a bike. Afterwards, variables of interest are derived from those definitions. Those variables are then used to define the equipment and sensors needed for the data acquisitions. The chapter ends by presenting the site chosen for the acquisitions in real road traffic and the final experiment set-up as well as confounding factors that need to be controlled.

3.1 Proposal for Overtaking Phases

As presented in the literature review (Chapter 2), previous researchers mainly have proposed a classification of an overtaking maneuver into three or five phases. However, both classifications seem to be missing important phases or focusing on phases that might not be applicable to the overtaking of bicycles.

In order to overcome the limitations of previous research, this thesis work proposes a new classification of the overtaking maneuver into four phases, as it is presented in this section.

The first phase is the "*Approaching Phase*" and describes the vehicle approaching the bicycle from behind (Figure 5). Especially for an accelerative overtaking maneuver (see Section 2.1.1), this phase is expected to be of interest, whereas it may be hard to identify for flying overtaking maneuvers. The main variables that may be used to describe this phase are the longitudinal distance between the vehicle and the bicycle (or described as TH, see Section 3.2.1), the lane position maintained by the vehicle (measured from the curb) as well as the speed of the vehicle.

As mentioned earlier, for a flying overtaking maneuver, this phase might not be clearly distinguishable from phase two, as cars would not have to slow down and stay behind the cyclist before overtaking. In fact, the overtaking maneuvers may start more or less already in the second phase which is described in the next paragraph. This is especially important for the data analysis, as it shows the importance to distinguish between different overtaking strategies.

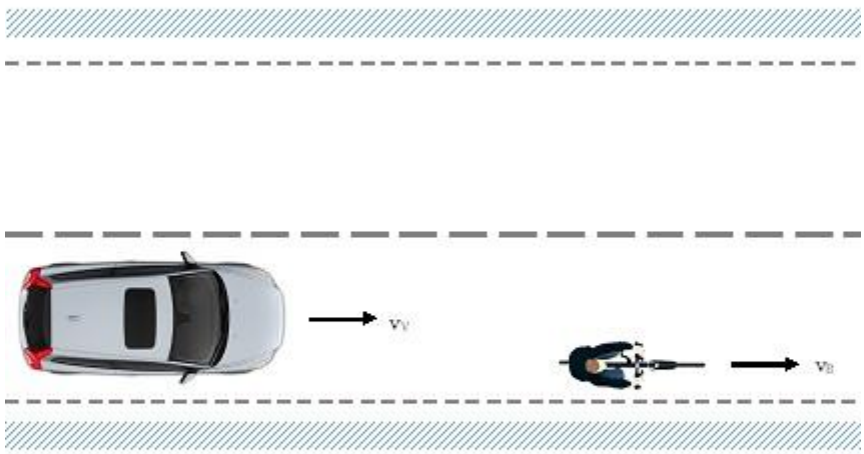

Figure 5: Schematic representation of Phase 1 [1], [2]

The second phase is called the “*Pull Out Phase*” and begins when the vehicle initiates the passing maneuver (Figure 6). This means that the vehicle leaves its position in the lane and increases its lateral distance to the curb in order to overtake the cyclist. The variables describing this phase might adopt different values depending on the driver and the situation. The increasing distance to the curb is the result of steering actions of the driver and, for accelerative maneuvers, may be accompanied by an acceleration of the vehicle. According to Swedish law, before overtaking, the indicators should be used by the driver to show his intention to other vehicles around.

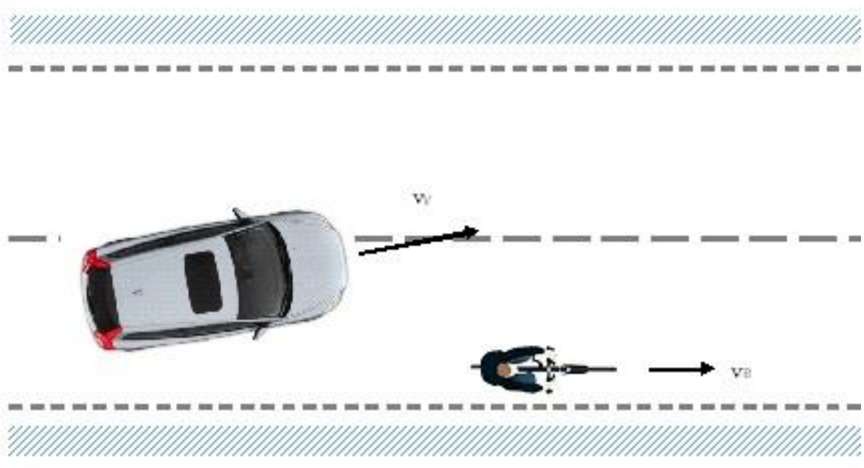

Figure 6: Schematic representation of Phase 2 [1], [2]

The third phase is the “*Passing Phase*” in which the vehicle is next to the bicycle and overtakes it (Figure 7). This phase starts when the front of the vehicle enters a defined “virtually extended passing zone” around the bicycle and is characterized by the speed of the vehicle and the lateral clearance between the vehicle and the cyclist. The characterization of the “virtually extended passing zone” is one of the objectives of the thesis in order to provide guidelines for future studies. The lateral clearance from the cyclist maintained by the drivers depends on the driver and the driving situation and represents a measurement of the drivers’ comfort zone.

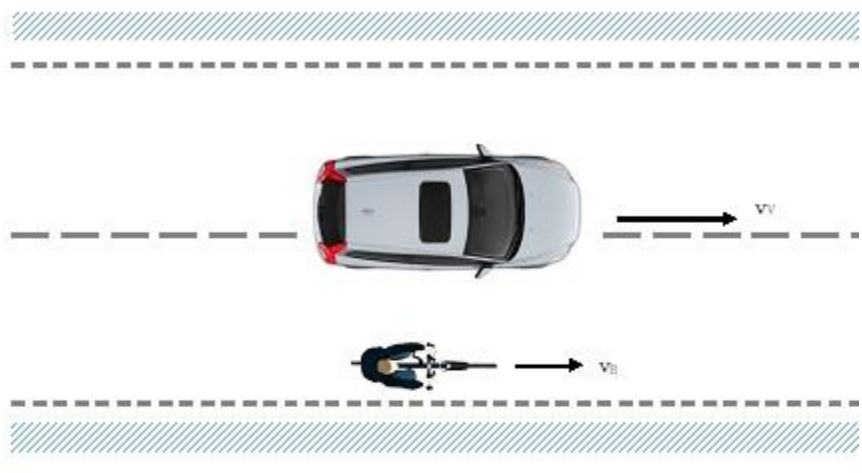

Figure 7: Schematic representation of Phase 3 [1], [2]

The fourth and last phase is the "*Returning Phase*" (Figure 8). It starts when the back of the vehicle leaves the "virtually extended passing zone" and is characterized by the vehicle returning to values of speed and lateral distance to the curb similar to the ones kept by the vehicle before the overtaking maneuver (during the "Approaching phase"). It might furthermore be of interest to characterize the leeway that the drivers leave for the cyclist when returning in the lane, which again can be approximated by the time headway between the bicycle and the car. According to Swedish law, also in this phase the indicators should be used by the drivers. Phase four and the complete overtaking maneuver end when the vehicle has reassumed its position in the lane and desired speed.

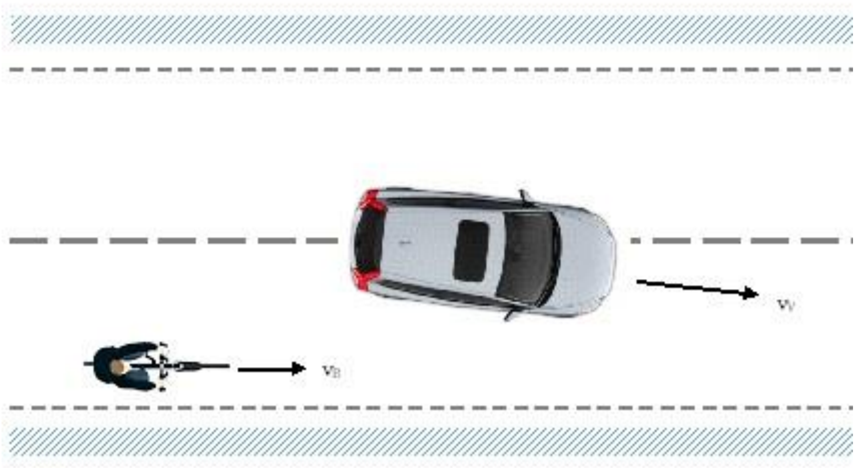

Figure 8: Schematic representation of Phase 4 [1], [2]

3.2 Variables Describing the Overtaking Phases

The previous classification of phases illustrates an ideal overtaking maneuver performed by a vehicle. Each phase is described through some variables as reported in this section and in the Appendix A.

3.2.1 Phase One

As mentioned earlier, phase 1 is characterized by the vehicle approaching the cyclist from behind and, for accelerative maneuvers, even slowing down and following the cyclist. As seen from the literature review, research has heavily focused on what happens next to the bicycle, especially on the lateral clearance between the bike and the vehicle during the overtaking maneuver in phase three. However, other parts of the overtaking maneuvers are relevant as well and it is also important to obtain information on what is happening behind the bicycle as vehicles approach it. A variable relevant for the "Approaching Phase" which is often used in traffic safety related fields, is the time headway (TH) (Dragutinovic et al., 2005; Piccinini et al., 2014). The TH represents the time gap between two following vehicles. Since this time gap is related to the temporal velocity, it can be the same "time" for different speeds other than a distance, which should increase with speed (e.g. a safe TH is recommended to be 2 seconds, which at 70 km/h would result in a distance of 39 m that should be kept between two vehicles. However, at 30 km/h, a safe TH of 2 seconds would result in a distance between the vehicles of only 17 m).

The TH is usually approximated using the distance d between the two vehicles and the velocity v_v of the following vehicle (Equation 3.1).

$$\mathrm{TH} = \frac{\mathrm{d}}{\mathrm{v_v}} \quad (3.1)$$

Colbourn et al. (1978) report a safe TH to be about 2s between vehicles in a following scenario. It is interesting to check if this TH will be the same when the vehicle follows a cyclist, or if it changes when encountering another “type of vehicle”. This might then also be an indicator for different comfort zones that each driver has for different types of “vehicles”. Safety critical TH are usually reported between 1 and 2 seconds with a variance from country to country (in Sweden, 1s is the critical value under which fines may be imposed, and 0.9s in Germany (Vogel, 2003)).

If there is a distinct phase one, the vehicle may have to follow the cyclist for some time and wait for a possibility to overtake. This requires for the vehicle to slow down to the speed of the cyclist. How early and hard this braking maneuver is performed by the driver might enable conclusions about his comfort zones and awareness of the VRU.

To distinguish between phase one and two, it is then important to keep track of the position of the vehicle in the lane. The interim from phase one to phase two can then be measured either by checking the drivers steering actions or by constantly observing the position of the vehicle in the lane. The later analysis of the data will search for ways and obvious patterns to detect the change between phase one and phase two.

3.2.2 Phase Two

In phase two, the following vehicle is leaving its position in the lane to initiate an overtaking maneuver. This starts at a certain TH to the cyclist, which is representative of the drivers comfort zone. Due to the character of the maneuver, it is likely that the vehicle will come closer to the bicycle when initiating the overtaking maneuver. It is therefore also important to measure the minimum distance between the vehicle and the cyclist during phase two, as this is another variable needed to describe the drivers’ comfort zone.

In addition to those distances, there are more behavioral variables of the vehicles’ driver that might be relevant for an analysis. The use of the accelerator pedal, or in other words, how strongly a driver choses to accelerate, might support assumptions about how safe and comfortable drivers feel in a certain situation. Short and strong accelerations for example might indicate that a driver wants to “leave” a situation as quickly as possible and therefore indicate a feeling of discomfort. Variables with similar properties are the steering angle and the yaw rate. The steering actions of the vehicles’ driver are furthermore the reason for the vehicle to move away from the curb. So higher steering angles which are kept longer might allow the conclusion that the cyclist was given more space (longitudinally and laterally), which resulted in a more comfortable situation for both, driver and cyclist.

Another important variable in phase two is the presence of oncoming traffic. It might be difficult to measure how close or far oncoming traffic is, but the presence or absence is a variable that may highly influence the behavior of the overtaking driver (not only which strategy is chosen, but also the leeway left for the cyclist). It is therefore an important influence on his comfort zone boundaries and should not be neglected.

3.2.3 Phase Three

In phase three, the vehicle has reached its position next to bicycle and is performing the passing maneuver. The most important variable in this phase is the lateral clearance between the vehicle and the bicycle. It is mainly determined by the vehicles' driver, as the cyclist will not change his distance to the curb (in this experimental set-up). This distance can be used not only to identify the comfort zone boundaries of the driver, but is also a value to assess the safety of the maneuver. It is furthermore rather easy to obtain and has been mainly used in research (see Section 2.1.2).

Another important variable is the relative speed between the vehicle and the cyclist. As reported in the literature review, not only the lateral distance is an indicator for how safe a cyclist feels, but the combination of distance and relative speed gives the best estimation on how comfortable an overtaking maneuver is for the bicyclist. A measurement that could combine both variables is the aerodynamic force experienced by a cyclist during the overtaking maneuver. To current knowledge, no set-up has tried to obtain values for this, although it has been identified as important (Llorca et al.; 2014). Since the measurement of the aerodynamic force presents methodological issues, the air pressure may be used as a surrogate measurement. Recording changes in pressure caused by passing vehicles may enable conclusions on how safe an overtaking maneuver is.

In this phase, no extensive steering actions by the drivers are expected. High changes in steering angle in this phase might be indicators for problems during the passing phase and therefore indicate a feeling of discomfort of the driver. The use of the pedals might also be considered as an indicator for critical situations, especially the braking pedal (as this likely indicates that the driver aborts the maneuver because he feels uncomfortable or unsafe to continue it). During accelerative maneuvers, it can be expected that the accelerator pedal is used due to the character of the maneuver.

3.2.4 Phase Four

In phase four, the comfort zone of the driver can again be measured by the minimum distance to the bicycle as well as the TH at the end of this phase. The minimum distance depends on how early a vehicle returns to its original position in the lane and is comparable to the minimum distance in phase two (see Section 3.2.2). The TH between the car and the bicycle is another indicator of the comfort zone of the driver.

Furthermore, the pedal use and steering behavior may be used to analyze the comfort zone boundaries, similar to phase two. The pedal use may also be important as drivers might need to slow down (since they exceeded the speed limit for a quicker overtaking maneuver) or accelerate further (as they have not reached their desired speed yet), the latter especially of interest for an accelerative overtaking maneuver. In addition, the change in steering angle might be an indicator of drivers' comfort.

The speed of the car and the distance to the curb are the variables needed to determine when this phase ends. The distance to the curb would indicate when the car has reassumed the position in the lane prior to the overtaking maneuver. For flying overtaking maneuvers, this can be considered the end of the overtaking maneuver. For accelerative maneuvers, it might be that drivers are back in the lane, but still have not reached their desired speed and are therefore still accelerating. The steering angle is a measurement that could also be used. When the car has reassumed its position in the lane, the steering angle should go back to around zero. But things like curves may distort this data to some extent and therefore maybe falsify data.

Note: In real-life traffic, the reported comfort zone boundaries are the ones of the driver <u>and</u> the cyclist, as the distances between them are determined by both to some extent. In this experimental set-up however, the influence of the cyclist was eliminated, since the cyclist was riding at a constant speed and constant distance to the curb, and had therefore no possibilities to maintain his own safety margins. In a non-experimental situation, a cyclist might brake or maneuver when feeling uncomfortable, which results in recorded comfort zones of both, driver and cyclist.

3.3 Confounding Factors during Overtaking Maneuvers

For an experimental set-up to define drivers' comfort zone boundaries, there are several factors that might influence the driver behavior. Some of them were described in the literature review (e.g. cyclist appearance, bike lanes) but others pertain to the driver, vehicle and environmental related influences.

The behavior (and comfort zone boundaries) are likely depending on gender, age and personality of the driver. They should therefore be considered when choosing test subjects and analyzing data and can be gathered by questionnaires, filled in by every participant. In addition, drivers might be influenced by the goal of their trip (e.g. being in a hurry to reach work) or by the type of trip (e.g. commuting, shopping, leisure activity). Those aspects would become very relevant when conducting naturalistic experiments on open roads.

Regarding the influence of the vehicle, there are several aspects that may influence the road users' behavior. The size of the car and its acceleration are of special interest, as they are influencing how an overtaking maneuver can be performed. Besides, the type of bicycle may also influence behavior. Although studies have shown that it is very hard to distinguish e-bikes from normal ones (Petzoldt et al., 2014), this fact should be kept in mind.

Finally, the environment is also an important factor to be taken into account in the experiment. Similar conditions during all experiments should be kept to be able to draw conclusions and compare data. Among the environmental aspects, the most relevant are light, weather and road surface conditions. As a matter of fact, behavior on sunny days with dry surface conditions might differ significantly from the behavior on dark days with snowy or icy roads.

With respect to overtaking maneuvers, the road geometry itself is also very important. Roads are expected to have changing properties such as lane width, shoulder width and road markings. This may influence behavior as much as the roadway profile (e.g. curves, hills) or road type (e.g. highway, rural, city) might do. It is therefore necessary to analyze the test sites in detail (see Chapter 3.5).

3.4 Sensors and Systems for Data Acquisition

In Chapter 3.2, the variables of interest have been identified for each phase. This section will describe the relevant sensors and systems needed to measure the variables previously explained. For each variable, there are different ways to actually measure it. The decision about which sensor or system to use is not trivial, as every possibility has its advantages and disadvantages.

In order to decrease the weight of the equipped bike and reduce the costs, it is useful to obtain as many variables as possible with a single sensor. So, instead of using a tape measure to measure a distance and light barriers to measure the velocity of a moving object, a radar might be the better choice as this sensor can perform both simultaneously. The process to find the optimal solution for the sensors has been performed for all variables of concern and the results are presented within this section.

3.4.1 Bicycle

Section 3.2 has shown that there are several distances that need to be measured. All studies conducted so far have focused on the lateral clearance between the vehicle and the bicycle during the passing phase. This variable only requires to measure one distance next to the cyclist and, therefore, an ultrasonic sensor is the easiest and cheapest device for this purpose.

However, in the experimental set-up chosen for this thesis, other distances need to be measured around the bike. Although more ultrasonic sensors could be used, a better solution would be a sensor that could scan the complete surrounding of the bicycle and enable the measurement of different points at different distances. The current technology provides two sensors that could serve for this purpose: the LIDAR (the word stands for "Light Detection and Ranging") and the RADAR (the word stands for "Radio Detection and Ranging") system. Both systems use the principle of sending out waves and measuring the time until the waves are received back at the sensor, allowing for the calculation of distances as the travel speed of the wave is known. The main difference between the two sensors is that the LIDAR uses light waves whereas the RADAR uses radio waves.

In automotive applications, RADARs usually consist of several beams that have a fixed orientation in space, like using multiple ultrasonic sensors on one plate. A RADAR would therefore allow the measurement of the needed distances in every phase, but not by using a single RADAR unit. In fact, at least three RADAR units would be needed around the bike to cover everything. On the other hand, a LIDAR would be able to cover the area of interest with just one unit. Although LIDAR systems typically only use a single beam, they have a wide field of view, up to 360 degree if necessary. This is achieved by a rotating mirror inside the LIDAR that can send out the one laser beam to different angles. A LIDAR seems therefore to be the most reasonable solution, although not the cheapest one.

In addition, the bicycle should be equipped with at least two cameras. Although most variables can be obtained by the other sensors, it is always useful, especially for the analysis, to have video data. This might be useful when it is difficult to give a reasonable explanation to parts of the sensor data. In addition, the cameras may be adopted to identify the use of the indicators. Depending on the camera system used, other redundant measurements such as the distance to the curb of the car might be derived.

An important part of this set-up is the evaluation of how to measure the aerodynamic force which the cyclist is exposed to. As proposed before, a pressure sensor seems the most promising way to quantify this influence on the cyclist. Therefore, at least one pressure sensor should be added to the instrumentation of the bike.

To determine the speed of the overtaking vehicle, it is not only necessary to obtain the relative speed between vehicle and bicycle (e.g. from the LIDAR), but also to exactly know the speed of the bike. For this purpose, a GPS system should be used, as this has the highest accuracy and is easier to handle than e.g. calculating the speed from the wheel rotation. It furthermore allows to track where the bike has been riding, and even to easily show where overtaking maneuvers took place.

Some additional factors need to be controlled during the experiment, as they may influence the drivers' behavior (see Section 2.1). One of them is the speed of the cyclist that should be kept constant during the experiment to avoid a confounding factor in the experiment. Although it is recorded with the GPS data for later analysis, a bike computer should be included in the instrumentation to enable the cyclist to keep a constant speed during the experiment. Finally, in order to keep a constant distance to the curb, the usage of a laser pointer was considered the best solution (see also Llorca et al., 2014)

3.4.2 Car

In addition to the equipped bicycle, it was investigated within this study if an equipped car is needed to identify the drivers' comfort zone boundaries, or if an equipped bicycle alone would be sufficient.

As mentioned in Section 3.2, apart from the minimum distances that the vehicle keeps to the bike in each phase, driver behavior such as steering or indicator use could also be an indicator of the drivers' comfort. These variables may be measured through the camera or LIDAR, but better information would be provided by a data logger inside the car. On the other hand, behavioral data such as gaze direction of the driver or the use of the pedals cannot be recorded by the bicycle but only by a logging system inside the car. In addition, the usage of an instrumented car might allow to compare between the measurements obtained from the bike and the car.

For the equipment of the car, three systems seem to be the most promising. First of all, a CAN logger will provide most of the data needed, being able to record, speed, steering angle, pedal use and accelerations for example. The main drawback associated to the usage of the CAN is that the retrieval of the data might be difficult (the CAN is a manufacturer specific system and understanding the data on this system is often not appreciated by manufacturers).

The second system that could provide relevant data is a GPS system, as mentioned earlier for the bicycle. The GPS would provide information about the position and the speed of the vehicle. The GPS data could also be used to compare the speed recorded by the GPS to the speed logged from the CAN. This is a quite easy way to check the data quality, as significant differences would imply problems within at least one of the systems.

Finally, an eye tracking system would be essential to detect the drivers' gaze location before, during and after the overtaking maneuver. This information could be an indicator of the drivers' awareness of the cyclist.

3.5 Experimental Road Choice

This experiment was conducted on two sites in Västra Götaland, Sweden. In order to collect data about overtaking maneuvers, it was necessary to avoid roads where a bicycle lane is present on the road or close to it, e.g. on a footpath next to the street. The first one would separate the cyclist so far from the motorized traffic that no clear overtaking maneuvers might be recorded and the latter one might influence the driver behavior (as they might expect a cyclist to use the bike lane). Due to the good bicycle infrastructure in Göteborg, the requirements for the selection of the road drastically reduced the list of candidates. Furthermore, only rural type roads with one lane per direction were taken into account for good data recording possibilities (as mentioned in Section 2.1, overtaking maneuvers may differ significantly having two lanes per direction, since people may not move back to the right lane immediately).

The first data collection site is an 11 km long stretch in the north of Göteborg, as this route was fulfilling the set requirements and easily reachable by the authors to conduct the experiments. As this road has not the same properties on its whole length, it was divided into 6 sections. Those sections range from wide lanes (3.8 m) and good sight conditions to very narrow ones (2.8 m) with curves, hills and sight restrictions by vegetation close to the road. The general speed limit was 70 km/h, whereas some strips had a higher limit of 90 km/h and one a lower of 50 km/h. Especially between sections 3 and 4, a longer way has to be cycled to get from one section to the next as there is a major crossing in between and a construction site, both of which might influence driver behavior and therefore distort the data. The detailed description of the sections is reported in the Appendix B.

The second data collection site is a 9 km long rural road west of Vårgårda, which in turn is located 70 km north-east of Göteborg and headquarter of Autoliv, the supporter of this thesis. This route was divided into 5 sections, with sections 1 to 4 having a lane width of less than 3 m and a speed limit of 80 km/h. Sight conditions along those sections are changing from straight roads with very good sight conditions to curvy ones with vegetation close to the road and a highly obstructed. The last section had a wider lane and higher speed limit with good sight conditions (also see Appendix B).

3.6 Experimental Equipment

The final set-up of the bicycle that was used in the experiment can be seen in Figure 9. From previous instrumentation (see Dozza & Fernandez, 2012; Dozza et al., 2013), this bike is already equipped with two brake force sensors and two IMUs, but their data was likely to be irrelevant for the present work. The used data logger is a Phidgets SBC3, which was placed in a water proof box in the front of the bike and logged data from all sensors that were fitted to the bike, especially the pressure sensors (Phidgets 1140 & 1141), GPS (Phidgets 1040) and a push button (see also Appendix C). As no experiments on recording pressure changes during an overtaking maneuver have been conducted before, no information on what pressure changes to expect were available. Therefore, two pressure sensors with different characteristics were chosen. The first sensor had a range from 20 kPa to 400 kPa (0.2 bar to 4 bar) with a resolution of 0.413 kPa (Phidgets 1140). The other one had a more narrow range (15-115 kPa) but higher resolution of 0.111 kPa (Phidgets 1141). The data from all sensors was logged 100 times per second, except for the GPS which was logged at 10 values per second.

Figure 9: Final bike set-up

In addition, the bike was equipped with a LIDAR system (Hokuyo UXM-30LXH-EWA laser range finder), mounted on the back of the bike. The LIDAR has a maximum range of 120m and a field of view of 190 degree and was logging data at 20 Hz. With this set-up, it is possible to measure distances to the side and the back of the bike as well as to the front to some extent.

Furthermore, two GoPro Hero cameras were used for video capturing (in this experiment one facing forward and one backward). They were recording videos in 1080p at 30 frames per second. On the handlebar, a simple human-machine-interface (HMI) was placed, containing a red LED that showed that the system was running and a push button used by the cyclist to flag events.

Unfortunately, no laser pointer could be used in the experimental set-up. Especially under sunny conditions, a laser pointer of class 3 or higher would be needed to see the laser on the road. But operating such a laser requires a special permission in Sweden, which could not be obtained due to time and resource restrictions.

The equipped car was provided by Autoliv and was a Volvo S60 with a CAN logger and GPS system onboard (see Figure 10 and Figure 11). In addition, the car was equipped with an eye tracking system from "SmartEye". All of this data was stored on a computer inside the car and could be extracted after the experiments.

Figure 10: Equipped car, provided by Autoliv

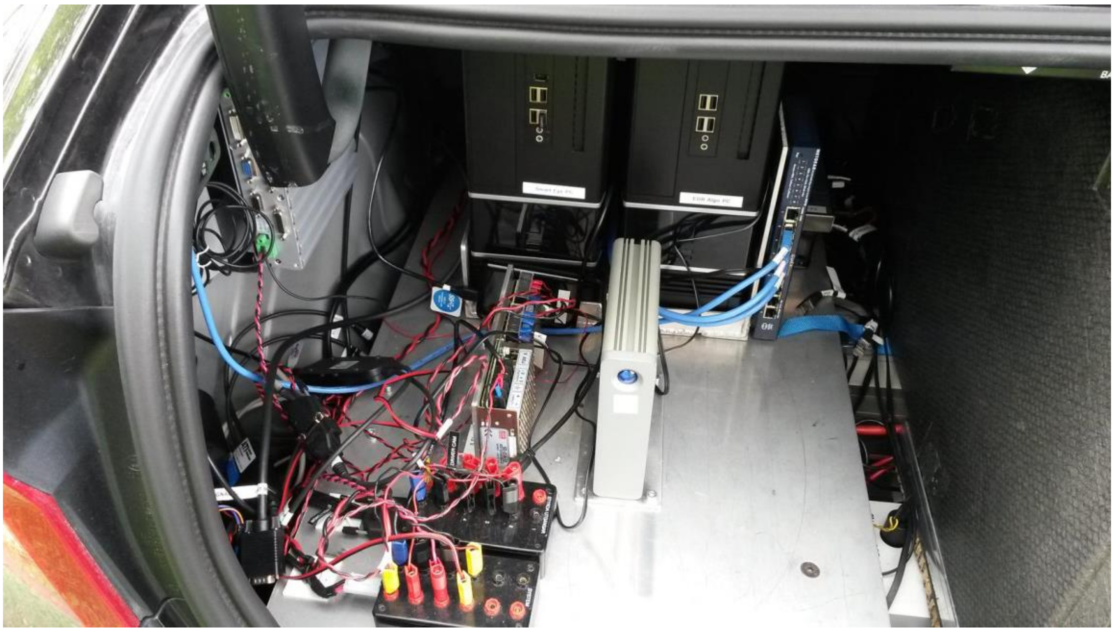

Figure 11: CAN and SmartEye logger in the trunk of the car

The "SmartEye" is an eye tracking system from a Swedish company. This system uses four infrared cameras, installed on the dashboard of the car (Figure 12), to capture the drivers gaze direction. From all the outputs delivered by this system, the focus in this set-up has been the gaze heading and gaze pitch as well as the quality of these signals.

Figure 12: SmartEye set-up inside the passenger cabin

3.7 Pilot Test

In order to use the capabilities of the LIDAR effectively, it should be mounted on the side (see Figure 13 right) to enable a view not only to the side of the bike, but also to the back and front. Since this mounting is very conspicuous, it might influence the driver behavior during the overtaking maneuver and therefore create a bias in the experiment. This should be avoided by any means. To ensure that the LIDAR positioning does not change the driver behavior, a first pilot experiment was run, comparing the two set-ups shown in Figure 13. For the first ride of this pilot test, which was conducted on section one of the route of Göteborg, the LIDAR was mounted on the back of the bicycle, being in a rather unobtrusive position (see Figure 13 left). Section one was ridden twice in each direction and overtaking maneuvers were recorded by the LIDAR. For the second test ride, the LIDAR was moved to its position on the side, being mounted at the same height as before, but in a presumably more obtrusive way. Then the same route was ridden under the same conditions, again recording the overtaking maneuvers with the LIDAR.

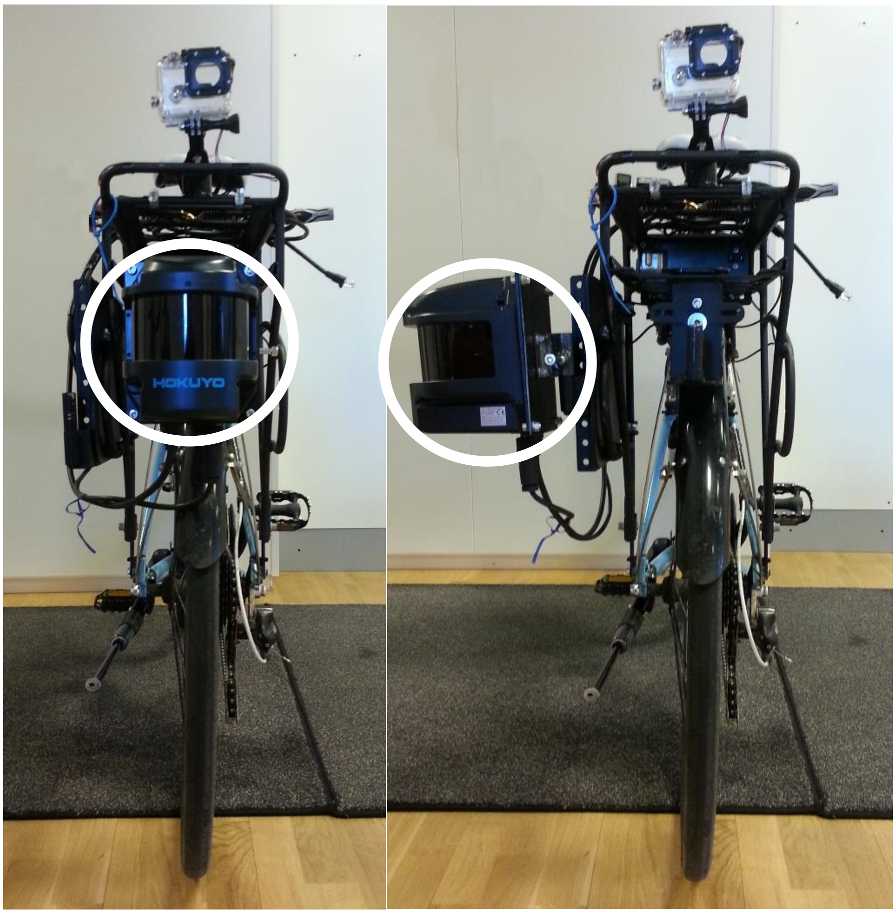

Figure 13: LIDAR mounting positions for pilot test

Since one of the main variables is the lateral clearance (during the overtaking maneuver, phase three), this was used as a representative to analyze the influence of the LIDAR position on the overtaking behavior of drivers. From both test rides, the lateral clearance was calculated from the LIDAR data and corrected by the lateral offset between the two LIDAR positions (the reported distances from this experiment are measured from the center of the bike).

For statistical analysis, the independent t-test was used since two independent samples were collected. Before applying the test, it was verified that the sampling distributions were normally distributed and had the same variance as well as that they were measured at the interval level. The one-sample Kolmogorov-Smirnov test was used to get information about the distribution of the lateral distance values and it showed that the two samples were normally distributed. Afterwards, the Levene's Test for Equality of Variances showed a significance of 0.465, so equal variances could be assumed. This enabled the use of the independent t-test to check for significant differences in the lateral clearances, which would be an indicator for a change in driver behavior. The t-test for Equality of Means compared the lateral overtaking distances with the LIDAR mounted in the back ($M=1849$mm, $SE=89.3$) to the mounting on the side ($M=1918$mm, $SE=103.5$). This difference was not significant $t(45)=0.483$, $p>0.05$ ($p=0.631$), representing an irrelevant effect $r=0.07$. All tests were performed using SPSS. The same tests were performed in Matlab and brought up the same conclusions. It can therefore be assumed that the LIDAR position has no significant influence on the driver behavior and the set-up with the LIDAR mounted on the side can be used as described in previous sections.

The data collected in this pilot test was also used to get a first estimation of the dimensions of the “virtually extended passing zone”. This estimation is then used for analyzing the data obtained in the actual experiments. This will enable a better analysis as well as the possibility to verify the assumption. From the data collected, an extension of 2 m to front and 2 m to the back seems the most reasonable since, on average, no significant change in speed or distance to the bicycle can be observed within this zone. It is therefore not too large and covering parts that should belong to another phase, but also not too short to not get enough data. The capability of this zone will be further evaluated with the data from the experiment runs.

3.8 Final Field Test

The experiments have been conducted on three weekdays in mid-April 2015. The first day, the bike and car have been at the test site at Vårgårda (see Section 3.5), conducting experiments in the morning and around lunchtime. They have been operated by both of the authors (one riding the bicycle and the other one driving the car) alternately. In addition, an employee from Autoliv was driving the instrumented car for the second test run at Vårgårda.

The other two days were spent at the test site at Göteborg conducting experiments, also around morning and lunch time. Again, the bicycle and car were operated alternately by the authors.

All experiments were conducted under sunny weather conditions and on dry road surfaces. The bike was continuously logging data during those test runs, not only recording the maneuvers of the equipped car but also naturalistic overtaking maneuvers of all other vehicles that passed the cyclist during his ride. The logging system of the car was also continuously logging data, but from those only the moments of overtaking maneuvers where of interest (as the rest of the time the car was waiting for the cyclist to pass by).

4 Results

This chapter presents the results of the experiments. This includes general observations about driver behavior as well as an analysis of the sensor performance to enable the provision of some guidelines for experiments aiming to measure comfort zone boundaries (CZB). Those results are presented in the following sections.

In total, 373 overtaking maneuvers were recorded, of which 132 (35.4%) took place on the test site at Vårgårda and 241 (64.6%) on the test site at Göteborg. For this purpose, 100 km were ridden and driven and about five hours of data collected. Of the overall 373 overtaking maneuvers, about one third was conducted by the instrumented car, driven by one of the participants of this thesis and their supervisor.

From a general point of view, two observations could be made regarding the overtaking maneuvers. First of all, most of the drivers seem to feel comfortable and safe enough overtaking the cyclist with oncoming traffic. This in fact is not only very dangerous for the driver himself, but even more for the cyclist. Due to the oncoming traffic, the overtaking vehicle cannot maneuver sufficiently far away from the curb, which then leads to a small lateral clearance to the cyclist during the overtaking maneuver. Although drivers generally left more lateral clearance than the generally recommended 1.5 m (with an average lateral clearance of 1.8 m), especially in maneuvers with oncoming traffic, many violations of this recommendation were observed. Those situations were very critical for the cyclist, as cars came very close to the cyclist, often less than a meter away. The closest maneuver was at a distance of 60 cm, and not only felt uncomfortable for the cyclist (marked by the push button), but was also very dangerous. From the video, some maneuvers could be identified where the overtaking drivers even forced the oncoming traffic to evade to their right.

Figure 14 shows the lateral clearance vehicles left to the cyclist in each section. It is distinguished between situations with (green bars on the left) and without (blue bars on the right) oncoming traffic. This boxplot shows the clear tendency that oncoming traffic reduces the lateral clearance between vehicles and the bicycle in phase three. Additionally, two lines were added to the plot for each section. Depending on the lane width, it has been calculated at which passing distance an average car would have crossed the center line. Points that are below the red line represent overtaking maneuvers where the vehicle was still completely in its own lane. This resulted in dangerously close overtaking maneuvers, as they did not leave the cyclist enough leeway (because they simply could not). On the other side, points that are above the green line represent maneuvers where vehicles have completely left the lane, which means even the right wheels of the vehicle have crossed the center line and that it was moving in the adjacent lane.

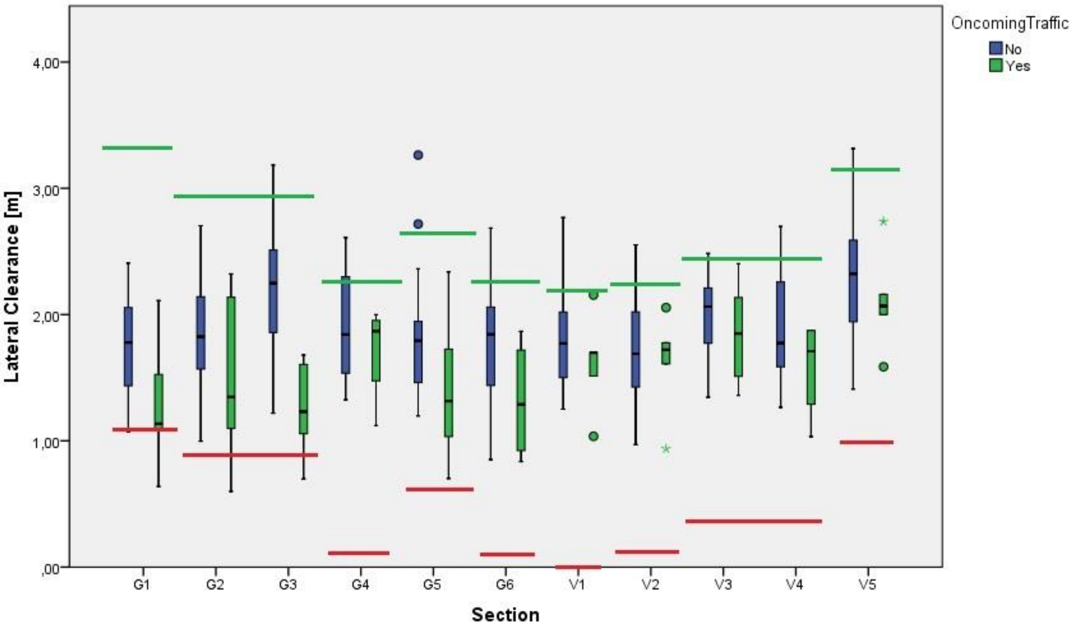

Figure 14: Plot of Lateral Clearance over Sections with regards to presence of oncoming traffic

This critical behavior of overtaking even at the presence of oncoming traffic, sometimes forcing those vehicles to evade, is also represented by the distribution of overtaking strategies (for definitions, see Section 2.1). Only 10% of the overtaking maneuvers were "accelerative". The low traffic volume may explain this to some extent (often, there was no oncoming traffic, so drivers could just overtake on the fly), but also the fact that drivers were overtaking with the presence of oncoming traffic (this happened in roughly 21% of the cases) influences this distribution, resulting in mainly flying maneuvers performed. Furthermore, some more accelerative maneuvers were expected due to bad sight conditions in some sections. However, no driver waited behind the cyclist in those areas until he could assure better sight conditions to perform a safe overtaking maneuver.

Note: The representation in Figure 14 *is produced by the software SPSS and is called boxplot or box-whisker diagram. It is a way to display where values of big datasets lie. They are represented in a box with two extensions called whiskers. The box represents the middle 50% of all values. The thick black line inside the box represents the median value of the dataset. The lower whisker extends to the smallest value and represents the area of the lower quartile (0-25%), whereas the upper one extends to the highest value and represents the upper quartile (75-100%). If there are more extreme values (e.g. one of 400 values is significantly smaller than all the others), those outliers are represented outside this structure by dots or stars.*

4.1 Bike Equipment

This chapter will present the data that was obtained from the bicycle during the experiments. The used sensors will be evaluated and the general data they record presented.

4.1.1 LIDAR

The data obtained from the LIDAR primarily provide a measurement of distances around the bicyclist (see also Section 3.4.1). However, the specifications of the LIDAR could not fully be used under the experimental conditions (e.g. reflectivity of objects, road geometry, movement of the LIDAR).

The biggest issue was the wobbling of the bicycle due to the pedaling and wind on the road. This resulted in odd looking data, as detected objectives move up and down rather than in a straight line behind the bicycle. On a straight road, someone would expect a car that approaches the cyclist from behind to also move in a straight line in the recorded data. However, the path a detected vehicle behind the bicyclist follows sometimes more resembled a sine wave, making the measurement of the distance to the curb impossible.

One indication for the distance to the curb that could be obtained from the data already available might be marker posts on the side of the road, which are visible on the LIDAR recordings. The difficulty lies in the gap of 60 m between the posts on the one hand and quite irregular distances to the actual curb or lane marking on the other. The gap between the posts is a difficulty because the lateral distance from the marker post to the vehicle can be measured only at one point. After the vehicle passed one certain post, it might have changed its position in the lane significantly within the 60 m to the next post. The marker posts could serve as a reference at a 350 m long strip near the airfield in section 5 of the route in Göteborg, as they are aligned at an interval of 5 m there. This can give a good estimation of the position of the car during the approaching phase, see Figure 15.

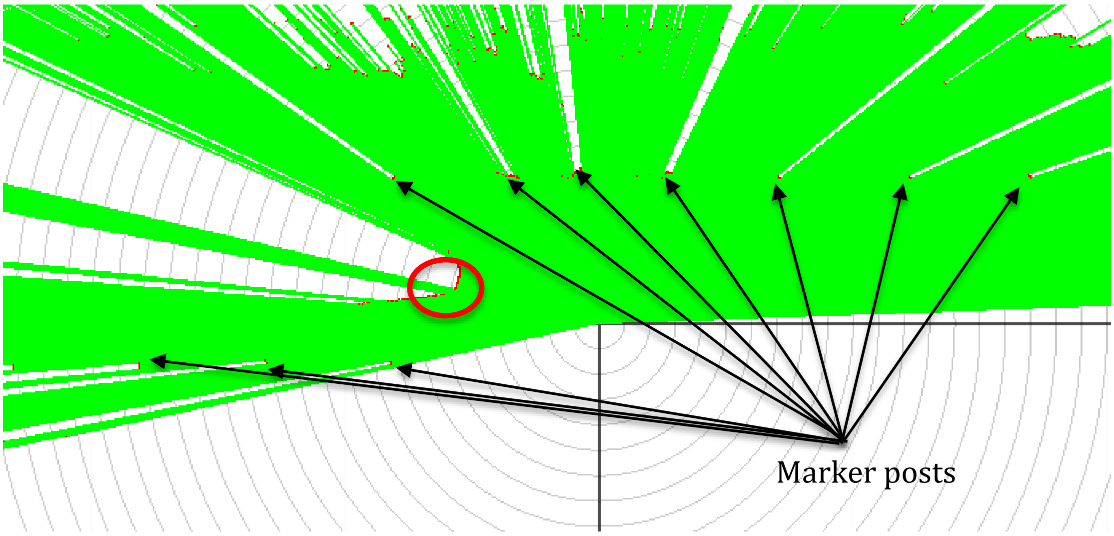

Figure 15: LIDAR representation with highlighted marker posts and reflectivity problems

Figure 15 shows also another problem of the LIDAR system: the reliable detection of obstacles, especially moving vehicles (red circle). The shape of a vehicle is detected, but some of the beams seem to go through the vehicle, likely because they have not been reflected back to the LIDAR. The specifications of the LIDAR guarantee a reflection back to the sensor of a black background only up to 30 m and of a white sheet up to 80 m (size of the obstacle 500 mm x 500 mm and 1000 mm x 1500 mm respectively). But the detection reliability decreases with brighter surrounding light conditions, just as they were during all the experiments. Highly specular parts such as reflectors and lenses of headlights and shiny decorative parts of a vehicle also tend to scatter the light and not reflecting it back to the LIDAR. Car windows were found generally unreflective, resulting in the low placement of the LIDAR, at the height of a passenger cars' front bumper.

Another problem that makes the measurement of the distance to the curb unreliable are curves. The geometry of the road is not recorded in the LIDAR. If measuring the distance to the curb might theoretically be possible on straight road sections, it is not possible even in an ideal world in a curve. These two issues together make it unreliable to measure the distance to the curb with the LIDAR.

4.1.2 Pressure Sensor

For this experimental set-up, two pressure sensors from Phidgets were used (see Section 3.6). Both sensors were mounted in a 90 degree angle to each other. One of them was facing backwards to the direction of travel. The second one was facing to the left in the direction of travel, perpendicular to the one before (Figure 16). However, those different directions had no influence on the recorded pressures, as the values are similar, being the only difference that the second sensor has a higher resolution (Figure 17).

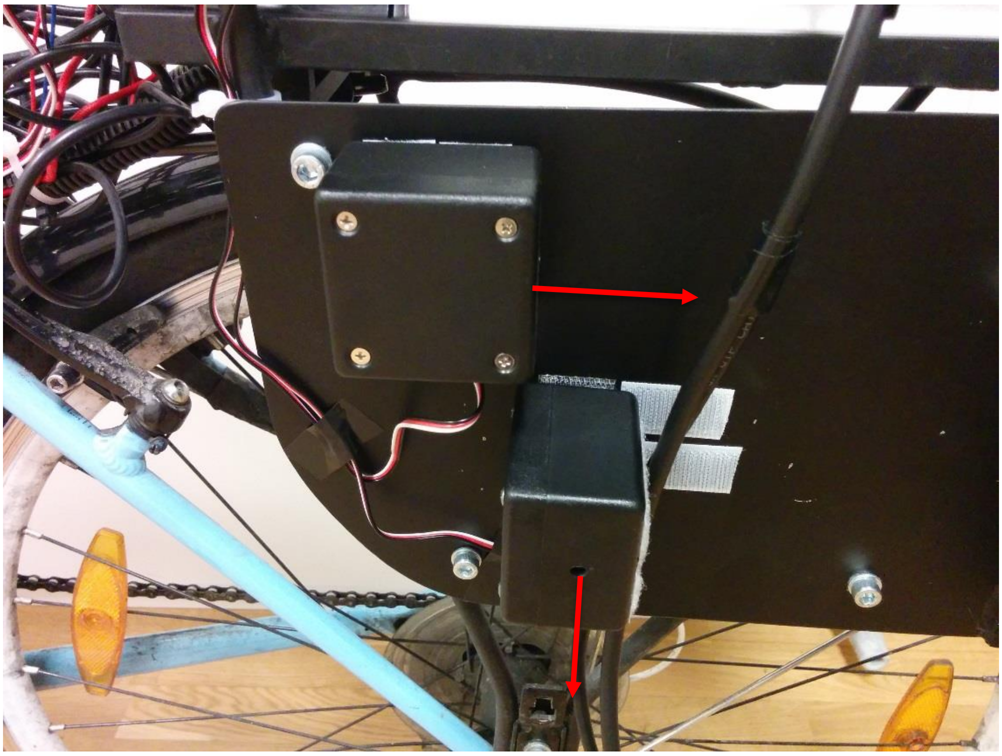

Figure 16: Mounting positions and directions of measurement of the pressure sensors

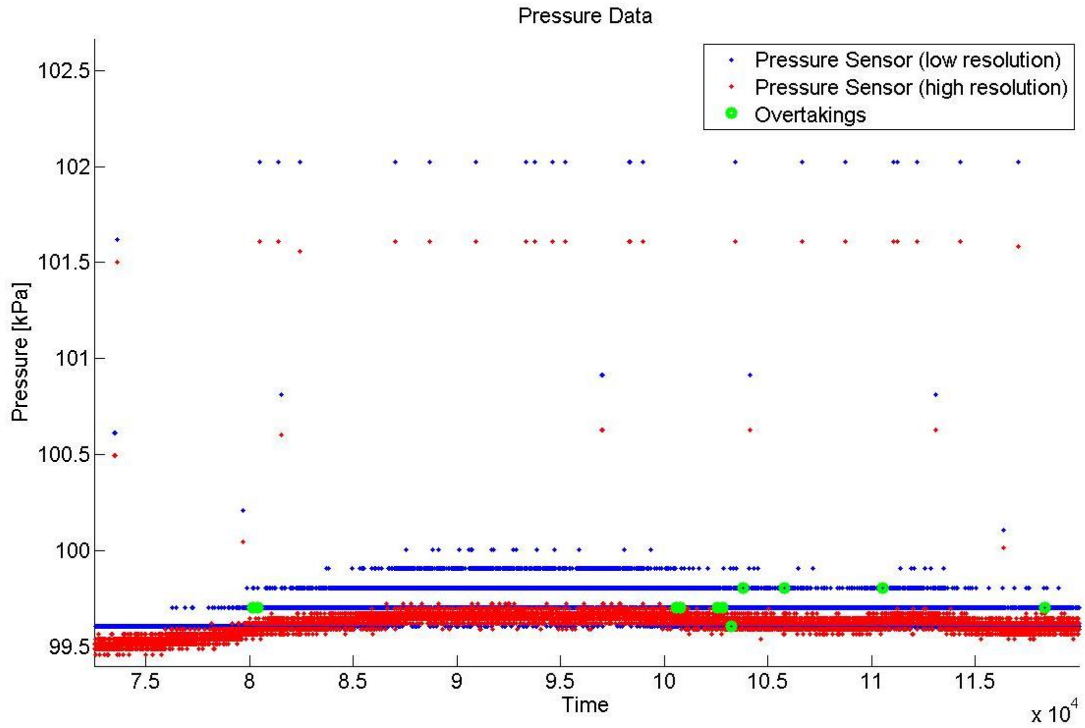

Figure 17: Example pressure sensor data

Both sensors work very good as barometers since changes in altitude, e.g. when crossing a bridge, were recorded and can be seen clearly. However, during the experiments, the cyclist experienced several times the force of air displacement, mainly by trucks passing close to the cyclist, but no meaningful peaks or drops in pressure could be observed (see Figure 17). Looking at the overall data, no change in values of pressure can be clearly associated to overtaking maneuvers. Figure 17 shows the recorded data, where a maneuver happened that felt very uncomfortable for the cyclist due to the air displacement. All overtaking maneuvers around that time are represented by green circles in the plot. But no significant changes in pressure close to those green circles can be observed. Overall, no changes in pressure could be associated to the air displacement by passing vehicles.

The used pressure sensors are therefore not able to record the variable of interest, which are the aerodynamic forces related to the overtaking of cyclists by passing vehicles. Although not certain, the recorded peaks were probably produced by the wind.

Note: This in fact does not mean that the aerodynamic force cannot be measured. The authors have experienced lateral displacement due to aerodynamic forces several times, so it is certainly present. There just needs to be another way to measure this properly. It can only be stated that the used sensors are not capable to record it, and not that it is generally impossible to measure the air displacement and that future research on this is required.

4.1.3 GPS

Regarding the GPS data, the precision of the sensor, especially in open field, was very good. The acquired data allow not only to see on which road the cyclist was riding, but also on which side of the road (see Figure 18). The accuracy of the signal became slightly worse in areas with a lot of vegetation close to the road (and the same might apply for city areas), but the overall accuracy and precision were satisfactory.

Figure 18: Example GPS data

Furthermore, the GPS produced reliable information for the speed of the bike, which are very important when analyzing the data (e.g. to calculate the speed of the vehicle overtaking the cyclist). On the other hand, equipping the bike with a wheel rotation sensor and calculating speed from this data might be an alternative, but more laborious and less accurate solution.

Based on the collected data, the GPS system from Phidgets can be recommended for further experiments, also because it is very small and easy to handle. The, GPS sensor should be generally preferred to other data sources providing speed information in similar experiments.

4.1.4 Camera

For the experiment, the bicycle was equipped with two GoPro cameras, one facing backward and one facing forward (Figure 19). The main purpose of the cameras was to identify the use of indicators by the overtaking vehicles, when an equipped car is not available. The discernment of the indicator use from the backward facing camera highly depends on weather conditions: under sunny conditions, the use of indicators in phase 2 is rarely well discernible. Under foggy weather conditions and cars using their headlights, the visibility gets even worse as the light gets scattered. As a result, it is impossible to discern the use of the indicator in phase 2.

In the conducted experiments, in some cases the use of indicators in phase 2 can be discerned. However, some cases have occurred (e.g. in right curves), where the indicator itself is not visible in the camera, because it is already covered by the vehicle. In most of the cases, the position of the indicator can be seen in the video, but it cannot be clearly seen if the driver uses the indicator or not. In fact, most of the cases are more guessing than being sure about whether the indicators were used or not. If the use of the indicator can be seen, obtaining timestamps is possible, but a lot of manual work.

Figure 19: Example for camera data

In the adopted set-up, the forward facing camera has, in theory, the same specifications as the backward facing one, but in reality (due to being an older model), the quality of the images was slightly worse, especially against the light. As a consequence, the ability to see the indicators was often compromised, although here it is better visible under low light conditions.

Overall, the use of indicators in phase 4 is usually even harder to obtain from the forward facing camera. Using a camera with a better quality might partly solve this issue. In the recorded data, it is not only very difficult to tell when someone used the indicator in phase 4, but also if at all. In some situations, the indicator was already blinking to the right when it appeared in the field of view of the camera, which makes it impossible to get the timestamp when the indicator was used.

Apart from the use of the indicators, the camera images are a powerful support for the analyst. Although the LIDAR data itself is very clear, in some situations, the video data has been very useful to support the analysis of the data. Finally, the camera is the only way to surely identify type and size of the passing vehicle, although the LIDAR data allows for a good estimation.

4.1.5 Human-Machine-Interface

The used human-machine-interface (HMI) was very useful during the experiment and for later analysis. The red LED that was indicating the status of the system was relevant during the experiment to ensure the system was still running and did not encounter any problems. For example, during the first experiment run, some issues made the system stop working and this problem could be easily detected through the HMI, allowing for abortion of the experiment and consequent saving of time.

Furthermore, the push button proved helpful for the analysis since it was used during the experiments by the cyclist to mark overtaking maneuvers in the datasets. This procedure made it easy for the analyst to recognize the overtaking maneuvers among the overall set of data. Besides, critical events (e.g. strong air movement, close overtaking maneuvers, uncomfortable feeling of cyclist) were marked as well by pushing the button twice. The only side effect of this procedure was that, in several occasions, pushing the button provoked a strong wobbling of the bike. Indeed, to reach the push button, the cyclist had to release the handlebar with his right hand, which made the cycling more unstable. For further experiments, the push button should be moved closer to the location of the cyclists' hands, so that there is no need to release the handlebar to push it.

4.2 Car Equipment

The logged data from the car was stored on a computer in the trunk and, after the experiment, the data could be extracted and converted to a Matlab file. Since the recording was performed in a binary way, some conversions needed to be done. The main issue about the data collection from the car was related to the synchronization with data acquired by the bicycle (the synchronization was needed due to the two different loggers used). Although the time of day can be used for a rough synchronization, no exact match can be guaranteed and, therefore, another solution had to be found.

A very good way of doing that would be using wireless communication and only one logger. Although this is not trivial, it would provide the best synchronization in the end. However, due to time and resource restrictions within this thesis, a wireless communication set-up could not be installed and alternative solutions had to be investigated. Among those, a not ideal, but practical solution was found.

To synchronize the data, it needed to be known which timestamp in one dataset (e.g. from the car) matches to which from the other dataset (e.g. from the bike). In order to get this, recognizable signals had to be produced and recorded by one party, but also needed to be clearly recorded by the other party. In this case, the hazard warning lights of the car (both indicators blink at the same time) were used in the beginning of each experiment. This blinking was recorded on the CAN logger, so the timestamp from the car data was known. On the other side, the camera of the bike recorded this blinking as well. Analyzing the video later frame by frame enabled finding the same very moment when the indicators started flashing up. From this, the timestamp of the car could be matched to the timestamp of the bike. Although there is still remaining an offset, it is so small that it could be neglected.

4.2.1 CAN Logger

The used CAN logger provided all the needed data, except for the brake pedal position, as there was an issue that could not be solved before the starting of the experiments. The quality of the measurements seems reasonably good, e.g. the speed logged from the GPS and the one recorded from the CAN are very similar.

Analyzing the steering angle and yaw rate, a typical pattern for overtaking maneuvers was found. Besides, the steering angle could even be used to distinguish between accelerative and flying overtaking maneuvers (see Figure 20 and Figure 21). For both accelerative and flying maneuvers, a clear steering action similar to a sinus wave could be observed. However, for flying maneuvers, a smaller steering angle amplitude was shown, and therefore also a smaller amplitude in yaw rate, as the steering is generally smoother when the car is driving faster.

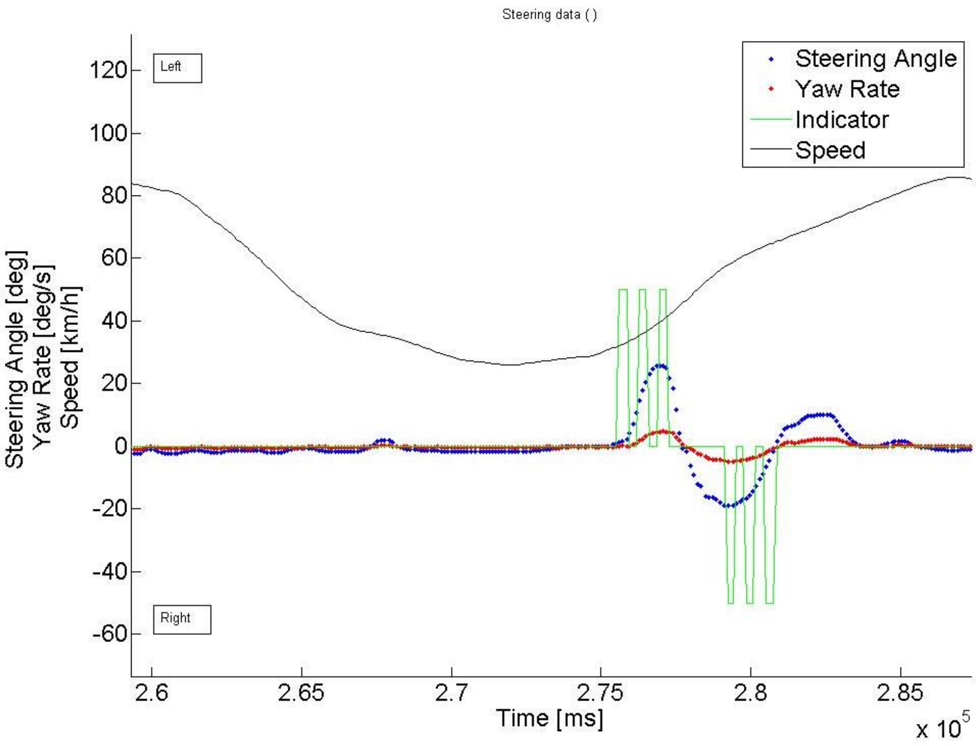

Figure 20: Lateral dynamics data car (accelerative overtaking maneuver)

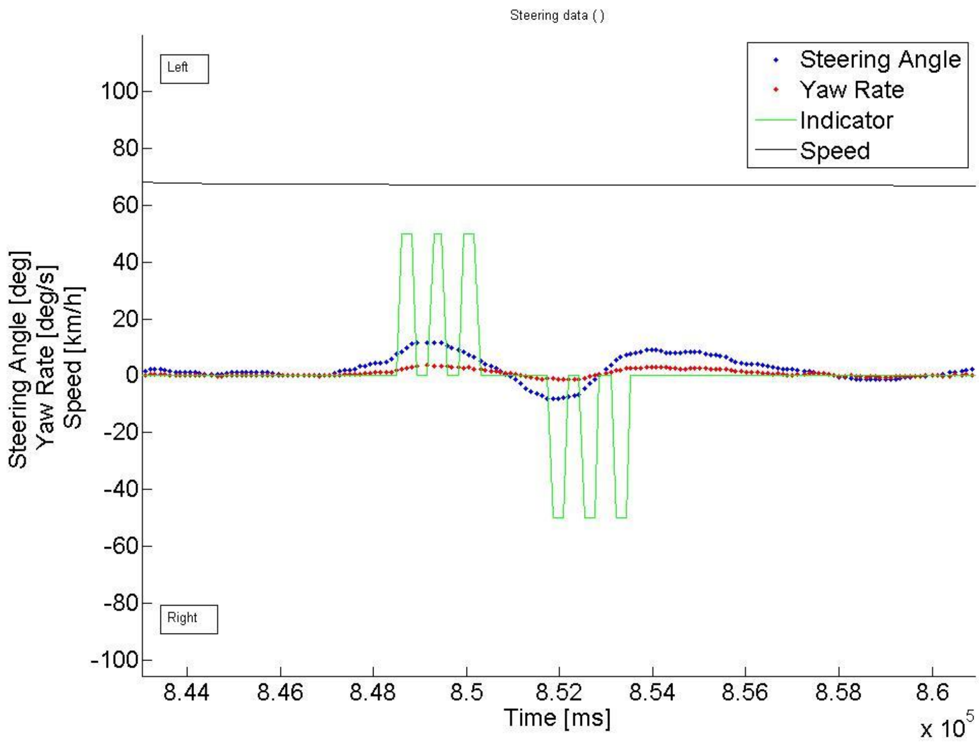

Figure 21: Lateral dynamics data car (flying overtaking maneuver)

4.2.2 GPS

The GPS system of the car delivered similar results as the one of the bike. From the data collected, it is possible to conclude that the accuracy is high and that the provided speed can be used to synchronize the CAN data with the GPS data, as they have a constant offset of about two seconds in the used set-up (see Figure 22). The GPS speed data can be furthermore used to verify the recorded speed on the CAN, as the speed curves should be very similar. This has been the case for all experiments.

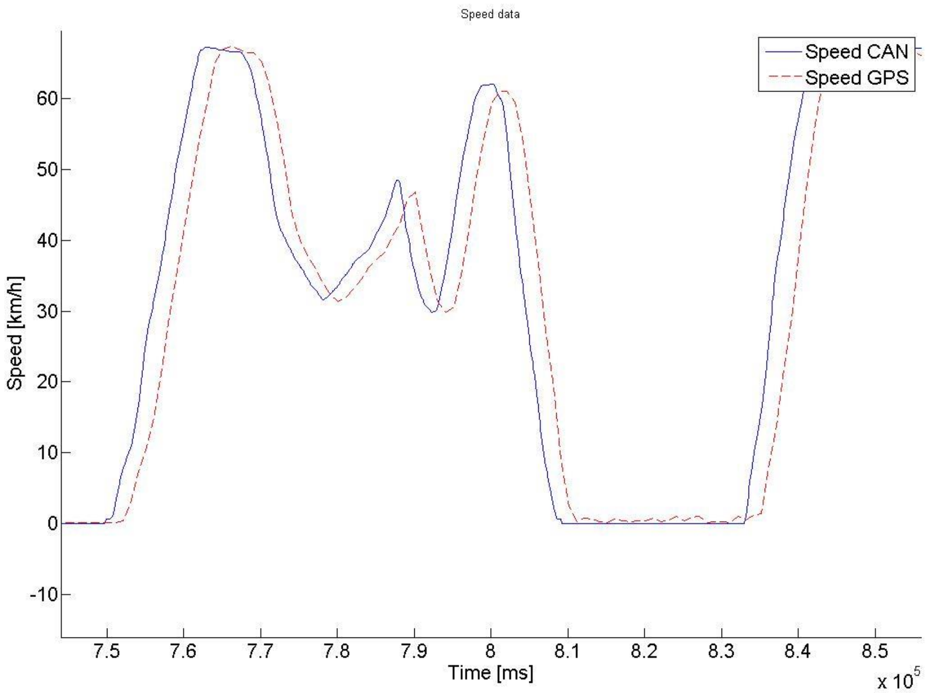

Figure 22: Compared speed data from CAN and GPS (raw data)

4.2.3 SmartEye

The most important data recorded by the SmartEye system have been gaze heading, gaze pitch and their quality. The gaze heading is a value in radians, reported by the system and it represents the yaw movement of the head (looking left or right). In addition, the system stores values for the quality of these values, indicating how sure the system is about where the driver is actually looking. Furthermore, the gaze pitch was obtained from the system and represents the pitch movement of the head in radians as well (looking up or down). Transforming those values to degree and taking into account the quality of the data allows to analyze where the driver was looking during overtaking maneuvers (as well as before and after).

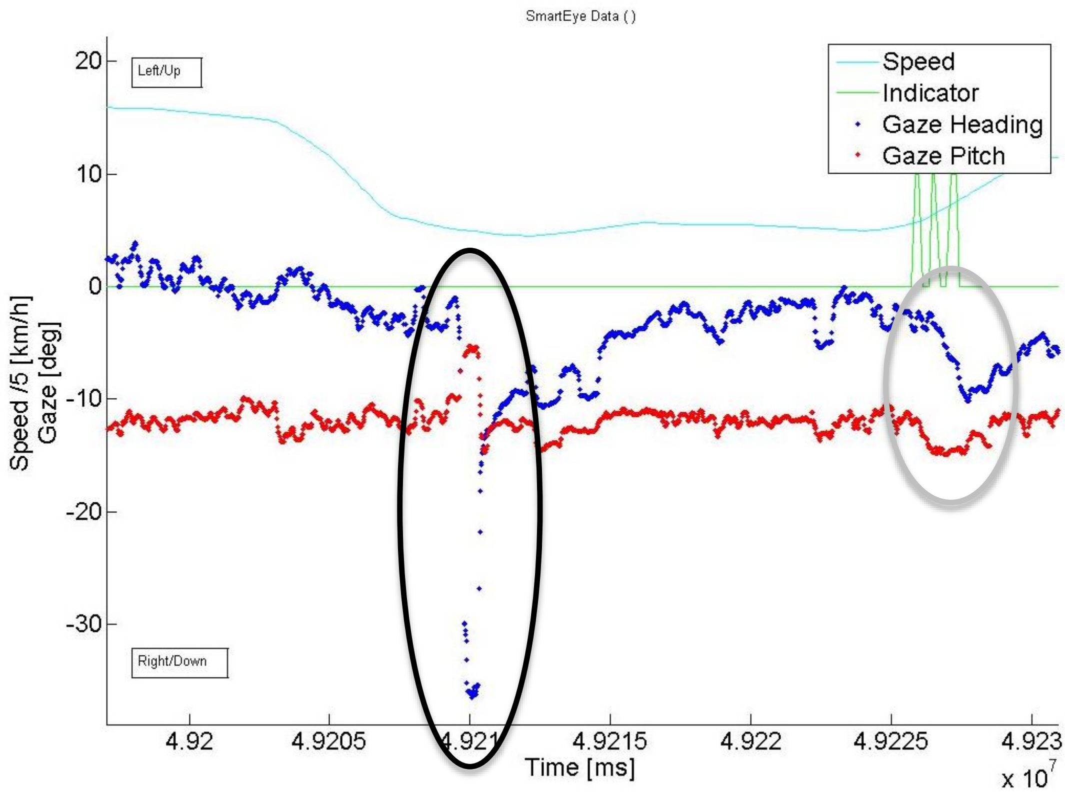

Figure 23: SmartEye data (accelerative maneuver)

Figure 23 shows an example of SmartEye data for an accelerative maneuver. The blue points represent the drivers' gaze heading (looking left or right), whereas the red points represent the drivers' gaze pitch (looking up or down). In this dataset, two significant areas can be found. The one highlighted in black shows the moment in which the driver looks about 40 degree to the right (change in gaze yaw) and upward (change in gaze pitch). At this moment, the driver is looking to the inside rearview mirror.

However, the more interesting moment is the one highlighted in grey that represents a tracking movement of the driver. The area in grey also shows the point when the passing maneuver starts (phase 2). Compared to looking into the rearview mirror, no sudden change in gaze direction is recorded. This typical pattern can be clearly distinguished for some overtaking maneuvers, but not for all. Besides, when this pattern is observed, it is usually the same for accelerative and flying maneuvers.

An issue that was known before and was confirmed during the data collection concerns the calibration of the system. The system has been calibrated at the beginning of every experiment but, if done after every overtaking maneuver, data quality is improved. The main cause of this "problem" is related to the heating up of the dashboard by the direct sunlight and consequent expansion. As a conclusion, the best solution is to calibrate the system as often as possible to obtain the best data quality possible.

4.3 Phase Definitions

Based on the data collection, when using the LIDAR, the phases can be identified. Phase one starts when the LIDAR makes the first contact with the approaching vehicle. At this time, especially for accelerative maneuvers, the LIDAR usually only sees the front of the vehicle (see Figure 24). When, later, the LIDAR also sees the side of the vehicle, the end of phase one and beginning of phase two is identified since the vehicle has started to leave its position in the lane to initiate a passing maneuver (see Figure 25).

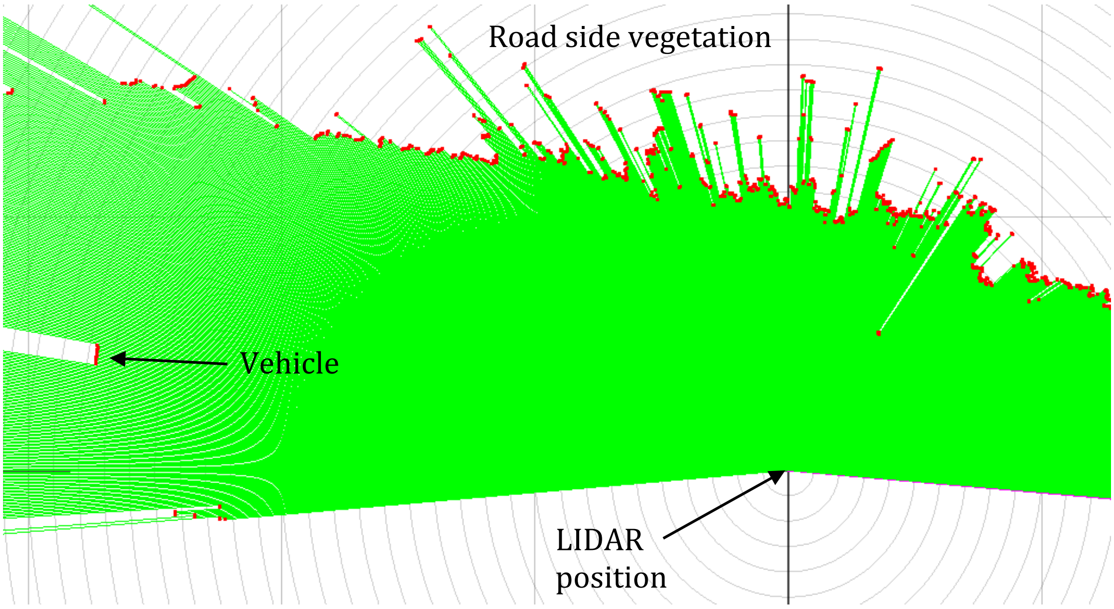

Figure 24: LIDAR data to identify phase one (red dots: spotted object; green area: no object spotted)

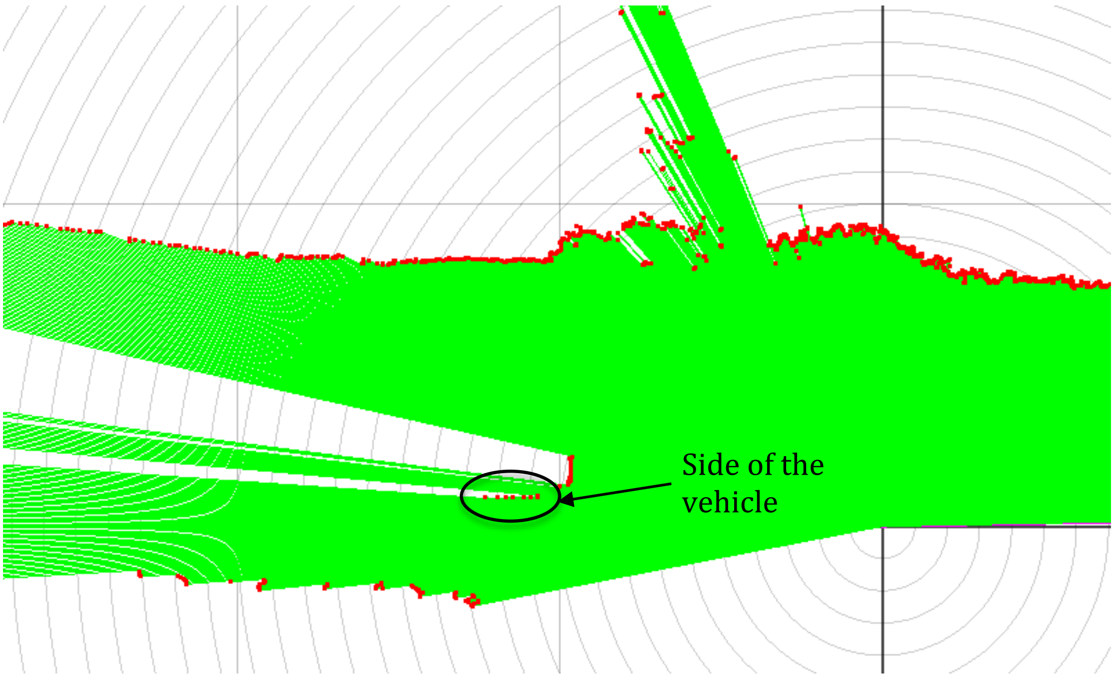

Figure 25: LIDAR data identifying the transition from phase 1 to 2

The end of phase two coincides with the start of phase three and can be identified by the vehicle entering the "virtually extended passing zone" of the bike (Figure 26). Due to the comparable low acquisition frequency of the used LIDAR system, the exact moment might not always be captured.

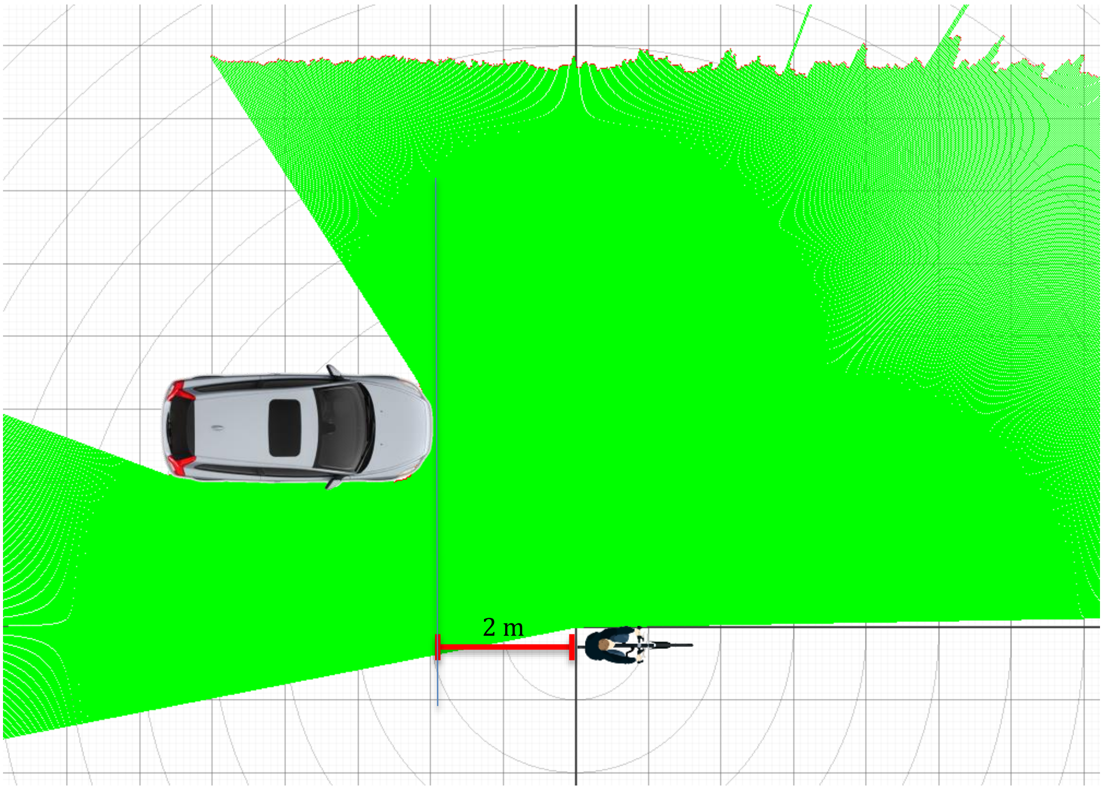

Figure 26: LIDAR data identifying the transition from phase 2 to 3 [1], [2]

Phase three ends and phase four starts when the very last point of the vehicle has left the "virtually extended passing zone" (Figure 27).

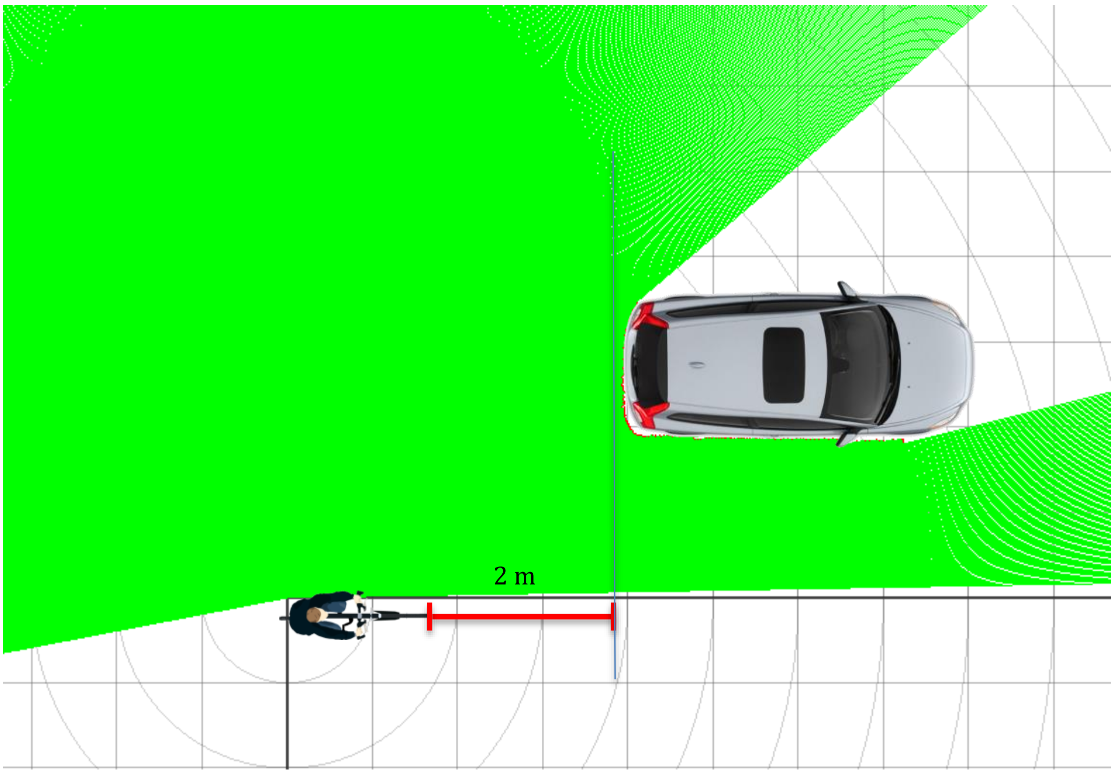

Figure 27: LIDAR data identifying the transition from phase 3 to 4 [1], [2]

By definition, phase four should end when the vehicle is back into its lane. However, due to methodological limitations, this occurs at the same time as the LIDAR loses contact to the vehicle or even later and, therefore, it is often not possible to identify the end of phase four (Figure 28).

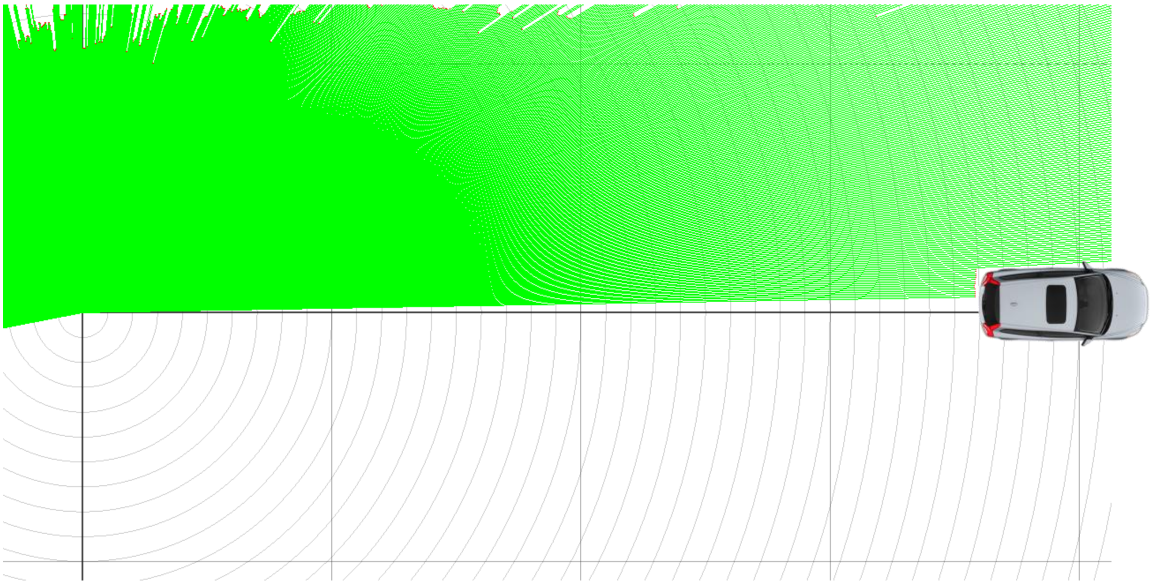

Figure 28: LIDAR data identifying the end of phase 4 [1], [2]

Having identified the start and end of each phase, it is now possible to measure the drivers comfort zone boundaries. They are represented in each phase by the minimum distance that the vehicle keeps to the cyclist. A schematic representation of those distances for each phase can be seen in Figure 29.

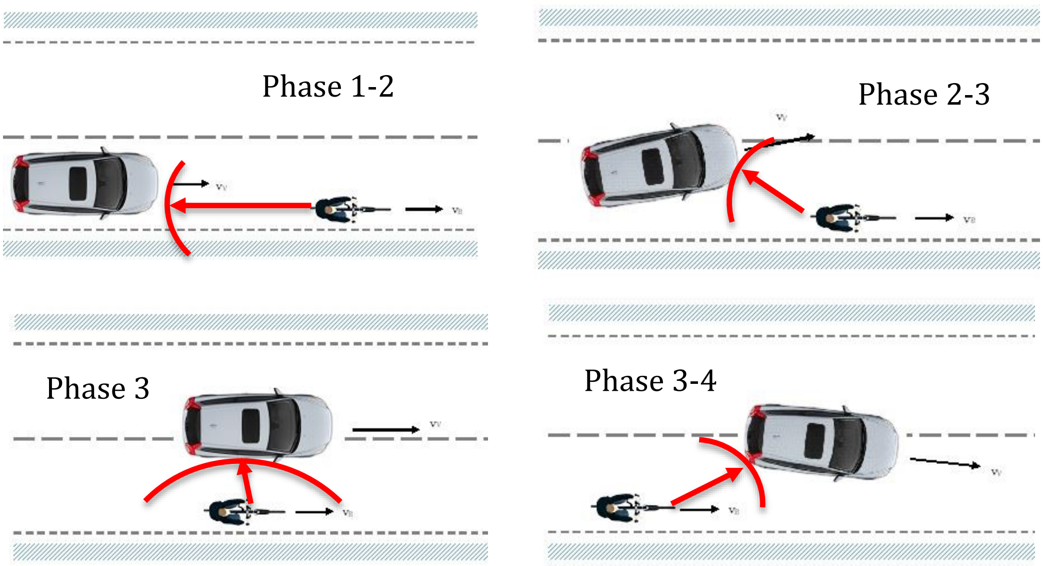

Figure 29: Comfort zone boundaries for each phase [1], [2]

With regards to the data recorded by the car, it is almost impossible to distinguish the phases, as this would need distance measurements around the car. There are patterns that allow to identify an overtaking maneuver as such, but there is no possibility to see the phase change from two to three and three to four. The situation would have been different if the car had had a LIDAR, because this may enable this measurement, but in the set-up on hand, only the bicycle was equipped with a distance measure equipment and therefore the car data cannot be used to distinguish between the phases. A short summary table can be found in the Appendix D.

Although the main objective of this thesis was methodological, a small sample of data was also analyzed. The preliminary results of those analyses are presented below.

To give a first and rough estimation of the CZB, five randomly chosen flying overtaking maneuvers were analyzed. From those maneuvers, the change from phase one to phase two happened on average at 15 m distance behind the cyclist or 1.5 s before the center of the car was next to the center of the bike.

The change from phase two to phase three started when the vehicle entered the "virtually extended passing zone". On average, this happened at a minimum distance to the bicycle of 3 m or 0.4 s before the center of the car was next to the center of the bike. This distance is mainly determined by the length of the "virtually extended passing zone" (which was set to 2 m) and the lateral distance the vehicle will have in phase three.

On average, the change from phase three to four happened when the vehicle left the "virtually extended passing zone" at a distance of 2.8 m to the cyclist or 0.3 s after the center of the vehicle and bicycle had passed.

To get more detailed and reliable values, all data sets should be analyzed for all phases. Due to time restrictions, the focus of this thesis was put on evaluating the methodology and only the comfort zone boundary in phase three could undergo a more detailed analysis, as those values were not only easy to obtain, but are also mainly used in research.

In phase three, the cyclist was passed at an average distance of 1.8 m, which is equivalent to the lateral clearance and leeway during the maneuver, and a standard deviation of 0.5. However, the closest maneuver recorded was at 0.6 m distance, also flagged by the cyclist as very uncomfortable and unsafe. This and other maneuvers similar close usually occurred on road strips with wide lanes and good visibility conditions. The reason for this close maneuvers seem not to be the road infrastructure, but more the presence of oncoming traffic, as the closer a vehicle was in phase three, the higher was the probability for the presence of oncoming traffic.

The meaning of those values and which conclusions might be drawn from analyzing the data as well as the performance of the sensors are discussed in the next chapter.

5 Discussion

This chapter presents the discussion of the results and will focus on the comfort zone boundaries, sensor performance and phase identification. It concludes by giving recommendations and prospectives for future experiments.

5.1 Preliminary CZB Analysis

The analysis of the comfort zone boundaries of drivers in phase three, which is the lateral clearance chosen to overtake a cyclist, has shown that the leeway for the cyclist is strongly depending on the presence of oncoming traffic. If there is oncoming traffic, drivers still overtake the cyclist, but they drive closer to him due to the “obstacle” in the other lane. This might suggest that drivers feel comfortable to prioritize reaching their destination in time rather than the safety of the cyclist (as waiting for a gap in the oncoming traffic would make them slowing down and wait behind the cyclist for some time). Often, drivers would just have needed to release the accelerator to avoid oncoming traffic in phase 3, but only few drivers did that. This implies that during accelerative maneuvers, the cyclist is generally given more leeway than during flying overtaking maneuvers, as those drivers waited until they could assure a safe and comfortable overtaking maneuver.

As a further result, overall, about 30% of the drivers violated the recommendation to keep at least 1.5 m lateral clearance to the cyclist during the overtaking maneuver, most of which happened when drivers decided to overtake at the presence of oncoming traffic or under inadequate sight conditions.

This is also supported when analyzing the difference between accelerative and flying overtaking maneuvers. During accelerative maneuvers, the cyclist is generally given more leeway than during flying overtaking maneuvers.

5.2 Sensor Performance

In Chapter 4, the recorded data from all the sensors has been shown and explained. The pressure sensors used in the experiment were unable to measure the desired variables and can therefore not be used for further experiments. The other sensors used in the experiment provided measurements that will be discussed within this section.

The LIDAR is a very convenient device to capture distances around the bicycle. Compared to other sensors such as ultrasonic sensors, it has a wider field of view and higher range. However, in addition to the high cost, some other issues have been identified that need to be taken into account for future experiments.

The LIDAR specifications state a maximum detecting distance of 120 m, but this theoretic value has never been reached during the experiment. The maximum detecting distance during the experiments was 100 m. Overall, the mean distance when the LIDAR first detected a vehicle was at 70.7 m behind the bicycle with a standard deviation of 21.5. On the other hand, the shortest distance at which a vehicle was detected behind the bicycle was roughly 22 m. This huge variation comes not only from to the LIDAR as a sensor itself, but also from reflectivity problems that did not enable an earlier detection, and to three other factors:

- Road geometry: The LIDAR detection is very sensitive to the relative position of the car. Slight changes in height (e.g. hilltops or depressions), drastically decrease detection range. In addition, especially right curves reduced the first contact distance, as the vehicles were close to the border of the covered area (whereas left curves increased detection range), due to the installation of the LIDAR on the left side of the bike. This influence can be seen in Figure 30 (blue bars), where there are significant differences between the different sections.
- Wobbling: For vehicles close to the cyclist, the wobbling has little to no impact on the measured distances. However, the roll movement of the LIDAR highly affected the detection of vehicles at a 100 m distance. This problem sometimes made vehicles appear at a 100 m distance, but then suddenly disappear and reappear at a distance of just 40 m and continuous tracking from there on. Furthermore, as mentioned earlier, although driving on a straight road, this effect caused detected vehicles to move in a sine wave behind the cyclist, with the amplitude becoming smaller the closer they came to the cyclist.
- Type of overtaking maneuver: This factor cannot be changed, but needs to be kept in mind. During piggy backing maneuvers (more than one car overtaking the cyclist in a row), the vehicles behind the following vehicle can usually not be detected as they are covered. Usually, they can only be seen when the following vehicle starts deviating from the lane (start of phase two). At that moment, the vehicles behind the following vehicle are already quite close to the bicycle as well, resulting in a comparatively short detection distance.

With regard to the last contact distance (how far in front of the bike a vehicle is still detected), the situation is worse. The before described influences make the distances to the front even smaller, leading to a last detection of a vehicle at a mean of just 38 m with a standard deviation of 14. Although minimum and maximum values are roughly the same as for the first contact, the mean is about half of what it is to the back of the bike. This problem is intensified by the position of the LIDAR (see Section 4.1.1), located in the back of the bike. Improving visibility to the front could be achieved by moving the LIDAR further away from the bike, but this would be very conspicuous and very likely influence the driver behavior (which has to be avoided by any means), or by mounting a second LIDAR in the front of the bicycle. The individual performance per section as well as a comparison between first and last contact can be obtained from Figure 30.

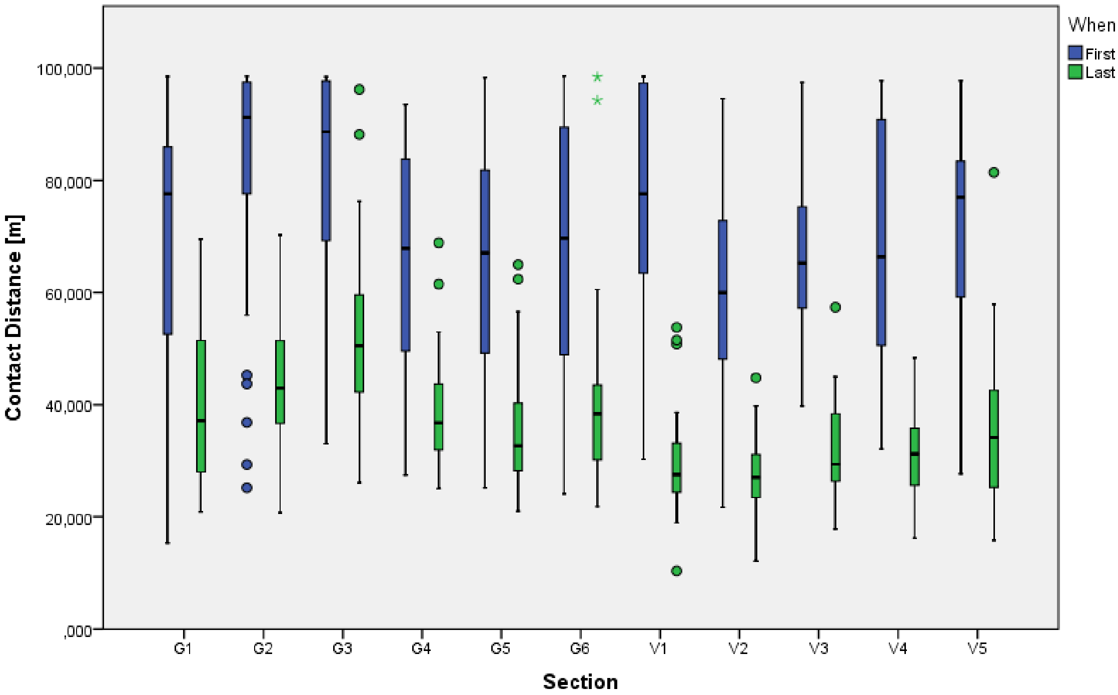

Figure 30: First and last contact distances of vehicles from the LIDAR

Despite initial expectations, derived measures from the LIDAR distances are hard to obtain due to the difficulties in tracking of objects. The measurement of distances has been done manually, but could be improved in the future by writing an algorithm for tracking the vehicles. The automated tracking might calculate the distance of the vehicle over time and allow a better estimation of the speed of the car. However, performing this procedure manually is time consuming and might produce unreliable results. Although the LIDAR records distances at a frequency of 20 Hz, at relative speeds of up to 19.5 m/s there is still a lot of "uncertainty" left about how fast the vehicle actually was. The further derivation process to obtain accelerations will most probably produce even more unreliable results.

The eye tracking system has proven to work, although with some restrictions. In order to ensure good quality of the measurements, calibration should be done as often as possible, but at least every ten minutes. Besides, the plotting of the gaze direction onto a forward looking video of the car will facilitate the analysis for future experiments. Although looking at gaze heading and pitch in a plot over time allows for good estimations, certainty would get better with an overlay of the gaze direction onto a video.

The CAN logger as well as the GPS system worked as expected and provided the data needed for analysis. However, it is recommended to additionally equip the car with a lane tracking system, as the measurement of the position in the lane of the car was missing and could be obtained by such a system.

5.3 Phase Identification

Based on the used sensors, it was possible to identify the four phases as described in Section 3.1. Using the LIDAR not only enables to measure the comfort zone boundaries, but also to obtain the timestamps for when a phase change happens.

Due to time restrictions, this complete analysis could only be done for a small number of overtaking maneuvers that were randomly chosen. In all those maneuvers, the phase changes can be seen and the described comfort zone boundaries measured. However, three issues need to be kept in mind:

- The start of the overtaking maneuver is not necessarily the point in time when the LIDAR first makes contact with an approaching vehicle. This point in time can sometimes be too late (e.g. when the vehicle is covered by a leading vehicle), or too early (e.g. the LIDAR makes contact at the highest possible distance, but the driver is not yet aware of the cyclist). Based on those considerations, it seems therefore not reasonable to measure how long phase one lasts, but it would be valuable to identify for how long a car follows the cyclist during an accelerative maneuver.
- The analysis has also shown that the “virtually extended passing zone” is a good choice as no significant changes in CZB happen (e.g. lateral clearance to cyclist is constant within this zone). It is however rarely possible to exactly detect when the vehicle enters the zone, as the capturing moments are usually slightly before or after the moment when the vehicle really enters the zone. At a speed of 25 m/s (90 km/h), which was the maximum speed allowed at the chosen test routes, the vehicle moves 1.25 m from one scan to another. In the worst case, this leads to an error of 0.625 m of when the vehicle enters the augmented passing zone of the cyclist. This is of course just a matter of milliseconds, but might still influence decisions made on this analysis.
- The end of phase four cannot always be measured with precision due to the wobbling and the early loss of contact of the vehicle in the front. As a consequence, it cannot be clearly identified when a vehicle has finally ended the maneuver and therefore the duration of phase four seems unreasonable to be measured.

Regarding the definition of the phases, a substantial limitation has become evident. The identification of comfort zone boundaries as well as the phase changes requires a sensor similar to the LIDAR, independently of the installation on the bicycle or on the car. The substitution of the LIDAR by other sensors such as a RADAR or ultrasonic sensors might be possible, but will take more effort and work and is therefore not recommended. As a matter of fact, the only phase change that could be identified without the LIDAR is the change from phase one to two, when the car starts moving away from the curb. This change could be measured by a lane tracking system and should ideally give the same point in time as the LIDAR. Apart from the phase change, the “virtually extended passing zone” can only be defined and measured by the LIDAR.

Especially for the chosen conditions and boundaries, the LIDAR has proven to be the best sensor of choice. It may occur that some datasets need to be discarded, but generally the LIDAR has worked well. Limitations have been explained in preceding chapters, but they can be controlled to some extent and do not hinder data collection inherently.

In phase three, an average passing distance (which equals the lateral CZB) of 1.8 m has been measured. This is a very good value, as it is above the recommended distance of 1.5 m that should be kept to a cyclist during overtaking maneuvers.

Furthermore, the change from phase one to two usually happened at a distance of 15 m. Since the bike was riding at an average speed of 6 m/s (roughly 22 km/h), a safe TH of 2 s for the vehicle would result in a minimum distance of 12 m. This in fact is only true for accelerative maneuvers where the cars slowed down to the speed of the bike. Assuming an average speed of vehicles passing the cyclist of 79 km/h (calculated from the number of overtaking maneuvers per section and the speed limit in each section) during the overtaking maneuvers, a safe TH of 2 s would result in a distance of roughly 44 m. For flying maneuvers, this in fact is more than three times the distance recorded during the experiments. However, since the vehicles were not following the cyclist at a distance of 15 m, but more initiated their lateral movement to overtake the cyclist at that distance, the conclusion that all of those maneuvers are critically unsafe may not be drawn. These results should be compared to values from overtaking maneuvers between vehicles to identify possible differences (or similarities).

5.4 Future Prospects and Research

This section provides possible solutions to some problems and difficulties encountered during the tests and provides also possible complementary input in order to get more realistic data.

The biggest issue that should be addressed is the wobbling of the bike. One approach imaginable is a fully electrical bicycle with an accelerator mounted at the bikes' handlebar that eliminates the necessity to pedal. In addition, every device necessary to be operated by the cyclist should be allocated within finger-reach so that the cyclist is not required to remove his hands from the handlebar while cycling. Especially the push button in the current set-up requires to release the right hand from the handlebar, resulting in an unstable movement of the bicycle. With the data already available, an algorithm could be developed that filters the angular deviation of the bicycle and therefore the LIDAR data, facilitating the data for future analysis. In simplified terms, the IMU's angular values could be subtracted from the LIDAR's angular values, simulating a wobbling-free ride. To avoid the workaround with the IMU-data, a system similar to a Steadycam-rig (Steadicam, 2015) for motion picture cameras can be taken into consideration and reviewed for feasibility. Another possibility would be to add support wheels to the bicycle (as known from children bikes), so that wobbling of the whole bike is not possible. Additionally, a laser pointer similar to the one Llorca et al. (2014) attached to their bike for the experiment can be used to help the cyclist keep his lateral distance to the curb constant.

For determination of the beginning of the second phase and end of the fourth phase (see Section 3.1) the distance to the curb is the best indicator. The set-up described in Section 3.6 is inconvenient to detect this distance. The steering angle might be a valid indicator, but would need a discussion on which thresholds have to be used. The state-of-the-art method would be a car equipped with a lane tracking system, from which the information about the position in the lane could be acquired. A lane tracking system measures the lateral distance of the ego-vehicle within the lane, using lane markings as reference points (Romdhane, 2011). This lateral position detection can then be used to distinguish the transition from phase to phase.

Since the work on hand was also a pilot study, only a relatively small sample of overtaking maneuvers was recorded, which becomes even smaller when subtracting those maneuvers conducted by the authors. After improving and extending the experimental set-up, more data can be collected. When the cars' set-up has been potentially updated (Lane Tracking System included), it is recommended to perform more overtaking maneuvers with one driver in order to make profound propositions about the CZBs from the drivers' perspective and then extend the experiment to a larger group of test persons. These should cover a good cross-section through demographic groups, such as gender, age, size, profession and much more.

Furthermore, future experiments should also be performed in a variety of weather conditions, since this is also an influential factor. Another influence is traffic: cycling during commuting hours will have different results than cycling in the afternoon or late evening for example.

Last but not least, the cyclist should always be the same person, using the same bike and equipment as well as wearing the same clothes. This comes from the possible influence a change in those may have, as explained in Section 2.1.3.

It is also recommended to use both, an equipped bicycle and an equipped car. This will provide the best data quality and all measurements necessary to evaluate driver behavior and comfort zone boundaries. Using only an equipped bike would enable to record the comfort zone boundaries, but no data about the driver behavior (e.g. pedal use, gaze direction, steering) can be obtained. In fact, the distances can be recorded, but it cannot be reported if they are representing the drivers comfort zone (as some drivers may also choose to perform "uncomfortable" overtaking maneuvers).

This issue of only using an equipped car might be solved by mounting a LIDAR to the car, but this would lead to less data recorded and the data analysis would get a lot harder (as identifying a bicycle in the LIDAR data is more difficult than identifying a car or truck, see Figure 31).

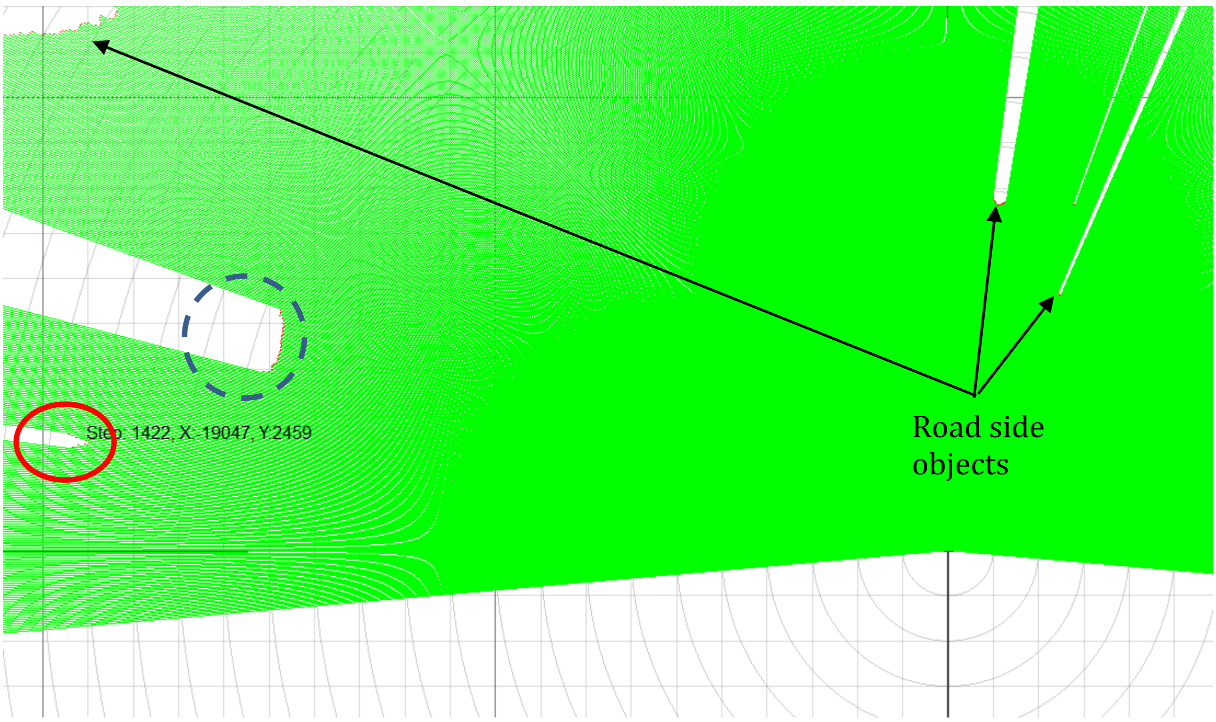

Figure 31: Bicycle and car in LIDAR data set (bicycle: red solid circle, car: blue broken circle)

All of the obtained data can then be used as a basis for designing autonomous driving systems. Drivers' comfort zone boundaries are usually the input needed to design those systems, as they should work and "behave" like humans. The data from those experiments is therefore an essential input needed to progress the state of the art systems.

6 Conclusion

Researchers are drawing more and more attention to the safety of cyclists due to the increased usage of bicycles worldwide. Despite the increased interest, some fields still lack insights, as it is the case of the overtaking of cyclists. The main focus so far has been on the lateral clearance between cyclist and vehicle when the vehicle is next to the bike. However, other phases of overtaking maneuvers also require attention and have been the focus of this methodological work.

The main result of this thesis is the new classification of the overtaking maneuver between a motorized vehicle and a bicycle into four phases. Considering the respective overtaking strategy (flying or accelerative), the classification has proven its usability for analyzing overtaking maneuvers. Regarding the instrumentation, the LIDAR installed on the bike has proven suitable to recognize the four defined phases of an overtaking maneuver as well as their corresponding distance measurements for the drivers' comfort zone boundaries. It is able to measure the drivers' comfort zone boundaries during an overtaking maneuver not only to the side of the cyclist, but also partly to the back and front. However, only using an equipped car would provide behavioral data of the driver, but would rarely allow the recording of phase changes and comfort zone boundaries, even if a LIDAR is mounted in a useful place on the car (e.g. on the front bumper on the right, enabling vision to the front and side of the car). As a final recommendation, in order to provide the best results, the combination of an instrumented bike and an instrumented car seems to be the ideal experimental solution, although hard to implement in a naturalistic study.

This methodology was applied for collection and analysis of 373 overtaking maneuvers, which were used to verify the extent to which data from an instrumented bicycle and an instrument car can be used to assess overtake phases and the related drivers' comfort zone boundaries. From the recorded data, only the detailed analysis of the lateral clearance (as done in all studies before) was possible due to time restrictions and the simplicity of this measurement (other than the remaining CZB, this measurement is always at the same relative position to the cyclist and can therefore easily be obtained compared to the others). With an average passing distance of 1.8 m, vehicles generally gave the cyclist enough leeway. However, violations of the 1.5-m–distance-recommendation were periodically recorded, especially when vehicle drivers decided to overtake the bike although there was oncoming traffic. Those decisions always resulted in a dangerously close passing distance of less than 1 m, with the closest maneuver of 0.6 m lateral clearance between vehicle and bicycle.

This is however only one moment in a sequence of events happening. In other phases, there may be other dangers that are equally as risky, but have not been researched so far. One of those might be the distance at which vehicles follow the cyclist when they need to perform an accelerative maneuver. The next steps shall therefore be to extend the analysis to all phases, and further divide the chosen comfort zone boundaries by other confounding factors such as road properties or oncoming traffic. It seems also necessary to identify more complex indicators (e.g. time and acceleration based) and analyze those as well. Last but not least, a minimum set of requirements for an instrumented car and bicycle that is able to identify the phases and measure the comfort zone boundaries should be validated for each of the four phases, allowing for future economical experiment set-ups.

From what has been analyzed within this thesis, cyclists seem to be generally safe. However, generally does not mean always, as there have been situations with cars coming very close to the cyclist. This reflects the huge variety of comfort zones and objectives (e.g. reaching destination in time, safety, obey rules) out on the street, related to different drivers and personalities.

7 References

Basford, L., Reid, S., & Lester, T. (2002). Drivers' perceptions of cyclists. *Transport Research Laboratory*

Bicyclist image (2015). URL http://art.ngfiles.com/images/35000/35778_slim-bean_top-down-cyclist.jpg (2015-02-13)

Buehler, R. (2011). Determinants of transport mode choice: a comparison of Germany and the USA. *Journal of Transport Geography, 19(4)*, 644-657.

Cambridge dictionaries online (2014). URL http://dictionary.cambridge.org/dictionary/british/overtake (2015-02-02)

Chapman, J.R., & Noyce, D.A. (2012). Observations of driver behavior during overtaking of bicycles on rural roads. *Transportation Research Record: Journal of the Transportation Research Board*, *2321*(1), 38-45.

Chuang, K.H., Hsu, C.C., Lai, C.H., Doong, J.L., & Jeng, M.C. (2013). The use of a quasi-naturalistic riding method to investigate bicyclists' behaviors when motorists pass. *Accident Analysis & Prevention*, *56*, 32-41.

Collins dictionaries (2014). URL http://www.collinsdictionary.com/dictionary/english/overtaking (2015-02-02)

Colbourn, C. J., Brown, I. D., & Copeman, A. K. (1978). Drivers' judgments of safe distances in vehicle following. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *20*(1), 1-11.

Corin, R.J., He, L., & Dominy, R.G. (2008). A CFD investigation into the transient aerodynamic forces on overtaking road vehicle models. *Journal of Wind Engineering and Industrial Aerodynamics*, *96*(8), 1390-1411.

da Silva, M. G. (2002). Measurements of comfort in vehicles. *Measurement Science and Technology*, *13*(6), R41.

Dozza, M., & Fernandez, A. (2012). Understanding bicycle dynamics and cyclist behavior from naturalistic field data. *Intelligent Transportation Systems, IEEE Transactions on*, *15*(1), 376-384.

Dozza, M., Werneke, J., & Mackenzie, M. (2013). e-BikeSAFE: A Naturalistic Cycling Study to Understand how Electrical Bicycles Change Cycling Behaviour and Influence Safety. In *International Cycling Safety Conference* (pp. 1-10).

Dragutinovic, N., Brookhuis, K. A., Hagenzieker, M. P., & Marchau, V. A. (2005). Behavioural effects of advanced cruise control use: A meta-analytic approach. *European journal of transport and infrastructure research EJTIR*, *5 (4)*.

Engström, J., & Hollnagel, E. (2007). A general conceptual framework for modelling behavioural effects of driver support functions. In *Modelling Driver Behaviour in Automotive Environments* (pp. 61-84). Springer London.

Frings, D., Parkin, J., & Ridley, A.M. (2014). The effects of cycle lanes, vehicle to kerb distance and vehicle type on cyclists' attention allocation during junction negotiation. *Accident Analysis & Prevention*, *72,* 411-421.

Gonçalves, J. P., & Ambrósio, J. A. (2003). Optimization of vehicle suspension systems for improved comfort of road vehicles using flexible multibody dynamics. *Nonlinear Dynamics*, *34*(1-2), 113-131.

Hegeman, G., Brookhuis, K., & Hoogendoorn, S. (2005). Opportunities of advanced driver assistance systems towards overtaking. *European journal of transport and infrastructure research EJTIR, 5 (4).*

Heißing, B., & Ersoy, M., (2011). Fahrwerkhandbuch – Grundlagen, Fahrdynamik, Komponenten, Systeme, Mechatronik und Perspektiven. Hrsg von Stefan Gies Springer

Kato, Y., Iwasa, T., Matsuda, M., & Miyai, Y. (1981). *Aerodynamic Effects to a Bicycle Caused by a Passing Vehicle* (No. 811425). SAE Technical Paper.

Ljung Aust, M., & Dombrovskis, S. (2013). Understanding and improving driver compliance with safety system feedback. *National Highway Traffic Safety Administration.*

Ljung Aust, M., & Engström, J. (2011). A conceptual framework for requirement specification and evaluation of active safety functions. *Theoretical Issues in Ergonomics Science*, *12*(1), 44-65.

Llorca, C., Angel-Domenech, A., Agustin-Gomez, F., Ferrer, V., & Garcia, A. (2014). Motor vehicles overtaking cyclists on two-lane rural roads: analysis on speed and lateral clearance, *International Cycling Safety Conference 2014.*

Mehta, K., Mehran, B., & Hellinga, B. (2014). An analysis of the lateral distance between motorized vehicles and bicyclists during overtaking maneuvers, *Bicycling Perspective on Roadway Design and Operations.*

Michon, J. A. (1985). *A critical view of driver behavior models: what do we know, what should we do?* (pp. 485-524). Springer US.

Niska, A., Blomqvist, G., & Hjort, M. (2014). Skid Resistance - Important for Cycling Safety*, International Cycling Safety Conference 2014.*

Ohlin, M., Strandroth, J., & Tingvall, C. (2014). The Combined Effect of Speed Reduction, Vehicle Frontal Design, Autonomous Emergency Braking and Helmet Use in Reducing Real Life Bicycle Injuries*, International Cycling Safety Conference 2014.*

Oxford dictionaries (2014a). URL http://www.oxforddictionaries.com/definition/english/overtake (2015-02-02)

Oxford dictionaries (2014b). URL http://www.oxforddictionaries.com/definition/english/comfort (2015-02-02)

Petrov, P., & Nashashibi, F. (2011). Planning and nonlinear adaptive control for an automated overtaking maneuver. In *Intelligent Transportation Systems (ITSC), 2011 14th International IEEE Conference on* (pp. 662-667). IEEE.

Petzoldt, T., Schleinitz, K., Krems, J. F., & Gehlert, T. (2014, November). Drivers' gap acceptance in front of approaching bicycles: effects of bicycle speed and bicycle type. In *International Cycling Safety Conference (ICSC2014), 3rd, 2014, Gothenburg, Sweden*.

Piccinini, G. F. B., Rodrigues, C. M., Leitão, M., & Simões, A. (2014). Driver's behavioral adaptation to Adaptive Cruise Control (ACC): the case of speed and time headway. *Journal of safety research*, *49*, 77-e1.

Porter, J.M. and Gyi, D.E. (1998) 'Exploring the optimum posture for driver comfort', Int. J. of Vehicle Design , Vol. 19, No. 3, pp.255-266.

Pucher, J., Buehler, R., & Seinen, M. (2011). Bicycling renaissance in North America? An update and re-appraisal of cycling trends and policies. *Transportation research part A: policy and practice, 45(6),* 451-475.

Richter, T., & Ruhl, S. (2014). Untersuchung von Maßnahmen zur Prävention von Überholunfällen auf einbahnigen Landstraßen. *Gesamtverband der Deutschen Versicherungswirtschaft e.V.: Forschungsbericht Nr. 24*.

Romdhane, N. B., Hammami, M., & Ben-Abdallah, H. (2011). A lane detection and tracking method for driver assistance system. In *Knowledge-Based and Intelligent Information and Engineering Systems* (pp. 407-417). Springer Berlin Heidelberg.

Schramm, A., & Haworth, N. (2014). Roundabout design and cycling safety, *International Cycling Safety Conference 2014.*

Shamir, T. (2004). How should an autonomous vehicle overtake a slower moving vehicle: Design and analysis of an optimal trajectory. *Automatic Control, IEEE Transactions on*, *49*(4), 607-610.

Silvano, A.P., Ma, X., & Koutsopoulos, H.N. (2014). Vehicle-bicycle interaction at roundabouts, *International Cycling Safety Conference 2014.*

Simon, H. A. (1990). Invariants of human behavior. *Annual review of psychology*, *41*(1), 1-20.

Steadicam (2015). URL http://tiffen.com/steadicam/ (2015-05-28)

Stone, M., & Broughton, J. (2003). Getting off your bike: cycling accidents in Great Britain in 1990–1999. *Accident Analysis & Prevention, 35(4),* 549-556.

Summala, H. (2007). Towards understanding motivational and emotional factors in driver behaviour: Comfort through satisficing. In *Modelling driver behaviour in automotive environments* (pp. 189-207). Springer London.

Vogel, K. (2003). A comparison of headway and time to collision as safety indicators. *Accident analysis & prevention*, *35*(3), 427-433.

Walker, I. (2007). Drivers overtaking bicyclists: Objective data on the effects of riding position, helmet use, vehicle type and apparent gender. *Accident Analysis & Prevention, 39(2),* 417-425.

Walker, I., Garrard, I., & Jowitt, F. (2014). The influence of a bicycle commuter's appearance on drivers' overtaking proximities: An on-road test of bicyclist stereotypes, high-visibility clothing and safety aids in the United Kingdom. *Accident Analysis & Prevention*, *64*, 69-77.

Wegman, F., Zhang, F., Dijkstra, A. (2012). How to make more cycling good for road safety? *Accident Analysis & Prevention*, 44(1), 19-29.

Williams, M. (1991). The protective performance of bicyclists' helmets in accidents. *Accident Analysis & Prevention*, *23(2),* 119-131.

Wilson, T., & Best, W. (1982). Driving strategies in overtaking. *Accident Analysis & Prevention*, *14*(3), 179-185.

Zibung, E., Riddez, L., & Nordenvall, C. (2014). Helmet use in bicycle trauma patients: a population-based study. *European Journal of Trauma and Emergency Surgery*, 1-5.

[1] Century Volvo (2015). Image of car in top view. URL: http://www.century-volvo.com/new/Volvo/2013-Volvo-C30-af74572b0a0a00de46d99725a651ff62.htm (2015-06-12)

[2] NewGrounds (2015). Image of bicyclist. URL: http://www.newgrounds.com/art/view/slim-bean/top-down-cyclist (2015-06-12)

8 Appendix

A – Variables during the overtaking maneuver

	Variable	Measurement	Sensor bike	Sensor car
Phase 1	Approx. Time headway TH_v between car and bike	Distance car-bike, speed car	LIDAR	RADAR
Preparation phase	Speed car	Speed of the car	LIDAR deriv.	GPS, CAN data
	Speed bike	Speed of the bike	GPS (deriv.) (const)	RADAR
	Acceleration car	Change in speed over time	LIDAR deriv.	GPS, CAN data
	Lateral distance to curb for the car	Lateral distance from car to curb	LIDAR	Lane tracking
	Lateral distance to curb for the bike	Lateral distance from bike to curb	Tape measure, Laser (const.)	camera
	Longitudinal distance to oncoming traffic	Distance to next oncoming vehicle in opposing lane	LIDAR	RADAR
	Driver gaze location	Driver gaze		Smart eye
	Head motion	Driver head motion		Smart eye
	Steering	Steering angle δ		CAN data
	Pedal use (car) brake	Pedal position		CAN data
	Pedal use (car) acc	Pedal position		CAN data
	Activation of indicator	Indicator use	Back camera	CAN data
	Waiting time (see phase definitions for start end endpoint)	Time T_1	Timestamp Lidar	
Phase 2	Acceleration car	Accelerator position, speed deriv.	LIDAR deriv.	GPS, CAN data
Pull out phase	Pedal use acc	Pedal position		CAN data
	Speed car	Speed of the car	LIDAR (deriv.)	GPS, CAN data
	Speed bike	Speed of the bike	GPS (deriv.)	RADAR
	Duration (see phase definitions for	Time T_2	Timestamp lidar	

	start end endpoint)			
	Time headway TH between car and bike at beginning of phase	Distance car-bike, speed car	LIDAR	CAN data, RADAR
	Steering	Steering angle δ		CAN data
	Yaw angle	Yaw angle		CAN data
	Driver gaze location	Driver gaze		Smart eye
	Head motion	Driver head position		Smart eye
	Lateral distance to curb for the car	Lateral distance from car to curb	LIDAR	Lane tracking
	Lateral distance to curb for the bike	Lateral distance from bike to curb	Tape measure, Laser	camera
	Oncoming traffic (Yes/No)	Presence of oncoming vehicle	Camera, LIIDAR	RADAR
	Longitudinal distance to oncoming traffic	Distance to next oncoming vehicle in opposing lane	LIDAR	RADAR
Phase 3	Acceleration car	Accelerator position, speed deriv.	LIDAR deriv.	GPS, CAN data
Passing phase	Speed car	Speed of the car	LIDAR deriv.	GPS, CAN data
	Speed bike	Speed of the bike	GPS deriv.	RADAR
	Duration (see phase definitions for start end endpoint)	Time T_3	Timestamp Lidar	
	Driver gaze location	Driver gaze		Smart eye
	Head motion	Driver head position		Smart eye
	Lateral clearance car bike	Distance car-bike	LIDAR, Ultrasonic sensor	
	Longitudinal distance to oncoming traffic	Distance to next oncoming vehicle in opposing lane	LIDAR	RADAR
	Acceleration car	Accelerator position, speed deriv.	LIDAR deriv.	GPS, CAN data

	Pedal use acc	Pedal position		CAN data
	Pedal use brake	Brake pedal position		CAN data
	TTC to oncoming traffic	Distance to oncoming traffic, speed of car	LIDAR deriv.	RADAR
	Force on cyclist by air	Air pressure	Pressure Sensor	
	Steering	Steering angle δ		CAN data
Phase 4	Time headway TH_b between car and bike	Distance car-bike, speed car	LIDAR	RADAR
Returning phase	Speed car	Speed of the car	LIDAR deriv.	GPS, CAN data
	Speed bike	Speed of the car	GPS deriv.	RADAR
	Acceleration car	Speed deriv.	LIDAR deriv.	GPS, CAN data
	Lateral distance to curb for the car	Lateral distance from car to curb	LIDAR	Lane tracking
	Lateral distance to curb for the bike	Lateral distance from bike to curb	Tape measure, Laser (const)	
	Force on cyclist by air	Air pressure	Pressure Sensor	
	Longitudinal distance to oncoming traffic	Distance to next oncoming vehicle in opposing lane	LIDAR	RADAR
	Driver gaze location	Driver gaze		Smart eye
	Head motion	Driver head position		Smart eye
	Activation of indicator	Indicator use	Back camera	CAN data
	Duration (see phase definitions for start end endpoint)	Time T_4	Timestamp LIDAR	
	Steering	Steering angle δ		CAN data
	Yaw angle	Yaw angle		CAN data
	Pedal use brake	Pedal position		CAN data
	Pedal use acc	Pedal position		CAN data

B - Road choices

Section	Length [km]	Lane width [m]	Shoulder width [m]	Speed limit [km/h]	Road condition	Visibility condition	
Göteborg 1 (G1)	0.7	3.8	0.7	70	3	5	
Göteborg 2 (G2)	1.4	3.4	0.7	90	4	5	1)
Göteborg 3 (G3)	1.2	3.4	1	90	4	4	
Göteborg 4 (G4)	1.3	2.8	0.4	70	5	3	
Göteborg 5 (G5)	1.8	3.2	0.4	70	5	4	2)
Göteborg 6 (G6)	2.1	2.8	0.4	70 (50)	5	2	3)
Vårgårda 1 (V1)	1.9	2.7	0.3	80	4	5	
Vårgårda 2 (V2)	1.8	2.8	0.2	80	4	3	
Vårgårda 3 (V3)	1.0	3.0	0.2	80	4	5	
Vårgårda 4 (V4)	2.3	3.0	0.25	80	4	3	
Vårgårda 5 (V5)	1.4	3.7	0.3	90	4	4	

Table I: Detailed information on chosen routes (1=very bad, 5=very good)

1) Big holes
2) Speed camera
3) Overtaking prohibited section

Sight conditions: Range from clear view for a far distance (5) to heavily obstructed view even on short distances (1)

Road condition: Surface conditions without damage (5) to surface conditions with lots of damages such as holes or cracks (1)

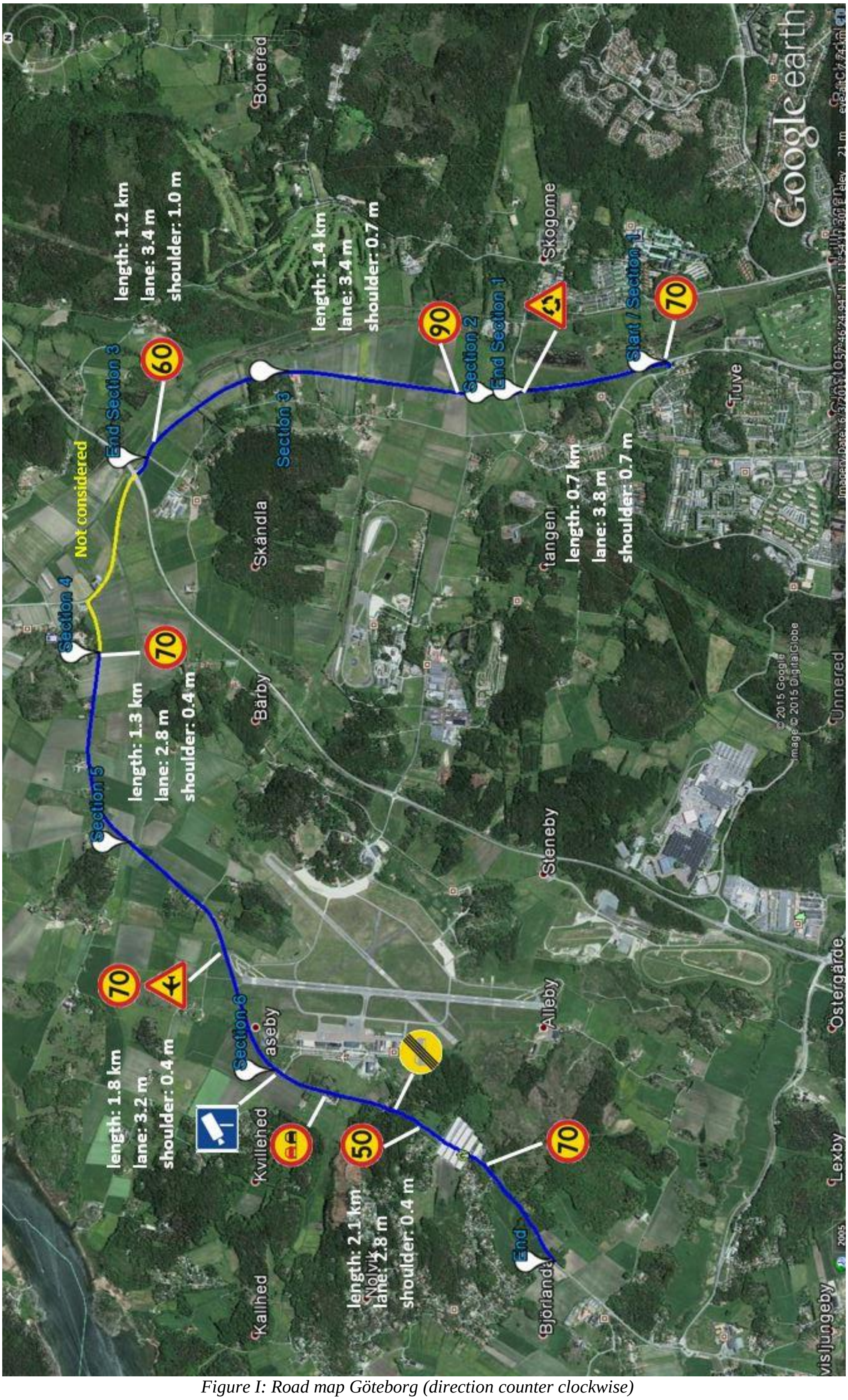

Figure I: Road map Göteborg (direction counter clockwise)

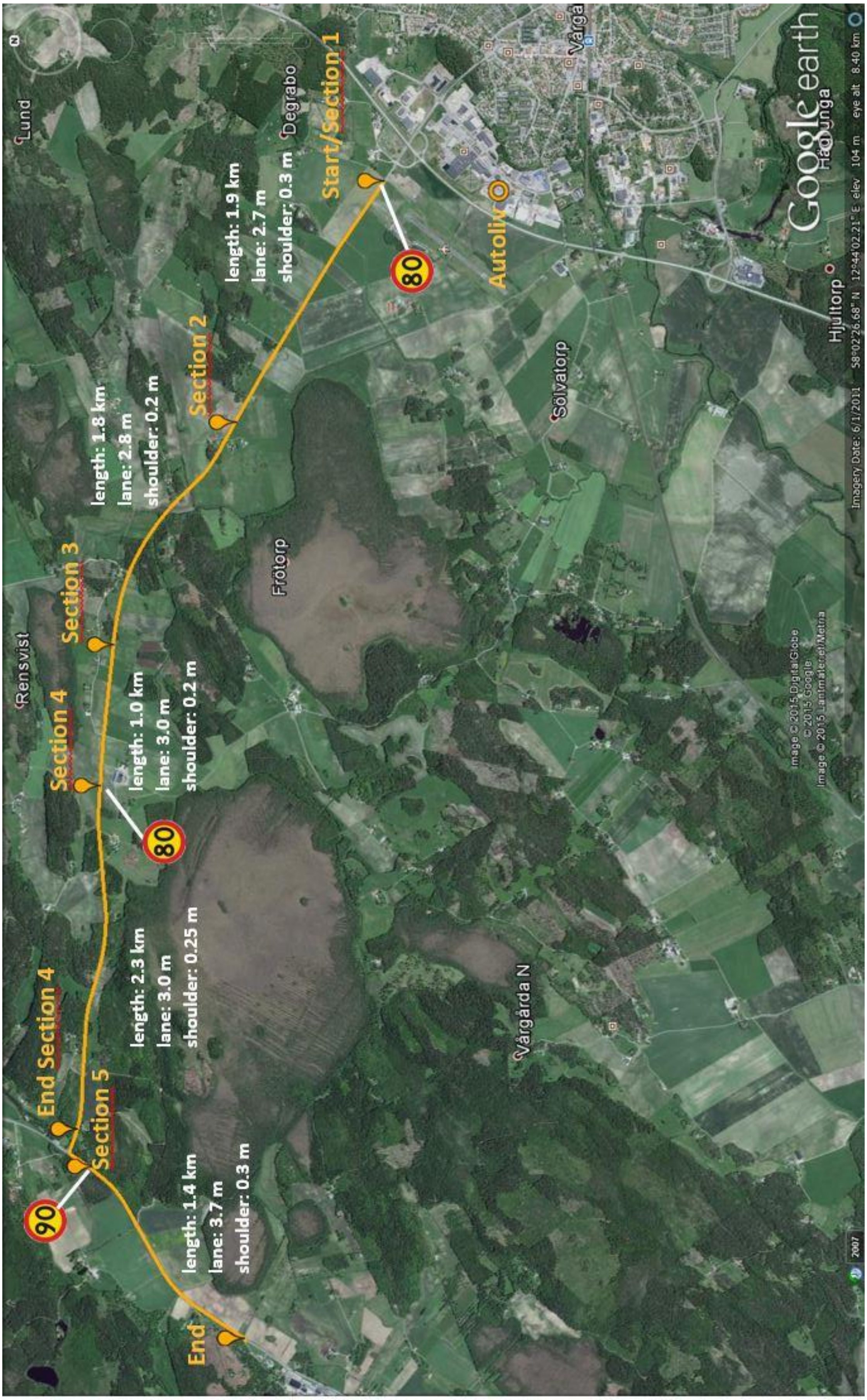

Figure II: Road map Vårgårda (direction counter clockwise)

C - Final Set-up Bike – Sensor Properties

Sensor Type	Sensor Name	Data Provided	Resolution	Sample Frequency
Camera	GoPro Hero	video frames	1920x1080 pixel	30 fps
Accelerometer	Phidgets IMU 1044	3D acceleration	76.3 µg	100 Hz
Compass		3D directional vector	3 mG	100 Hz
Gyroscope		3D angular rate	0.02 °/s	100 Hz
Pressure Sensor	Phidgets 1140	absolute air pressure	0.413 kPa	100 Hz
Pressure Sensor	Phidgets 1141	absolute air pressure	0.111 kPa	100 Hz
GPS	Phidgets GPS 1040	latitude and longitude	minimum circular error 2.5 m	10 Hz
		Heading	depending on above	10 Hz
		Velocity	100 mm/s	10 Hz
Brake Force Sensor	Flexiforce resistive force sensor	Force	0.01 N	100 Hz
LIDAR	Hokuyo UXM-30LXH-EWA	distances	1 mm and 0.125 degree	20 Hz

D – Phase identification possibilities

	Start 1	1 → 2	2 → 3	3 → 4	End 4
Logic	Cyclist has been detected as “obstacle” by driver	Car starts deviating from its position in the lane	Vehicle enters virtually augmented passing zone	Vehicle leaves virtually augmented passing zone	Vehicle ended maneuver (back in lane, back to speed)
Bike	LIDAR makes contact with vehicle	Side of the car is seen in the LIDAR	LIDAR measurement	LIDAR measurement	LIDAR loses contact to vehicle
Car	Cyclist is seen/noticed by driver	Increasing distance to curb (e.g. from lane tracking system, steering angle)	LIDAR or RADAR on car	LIDAR or RADAR on car	Speed reached (e.g. from CAN), position reacquired (e.g. lane tracking system, steering angle)