Engineering on driving behaviour inter-dependencies for the purpose of safe autonomous vehicles

Analyse von Abhängigkeiten im Fahrverhalten im Sinne eines sicheren autonomen Fahrzeuges

Master-Thesis von Galin Bobev aus Burgas, Bulgarien

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Vorgelegte Master-Thesis von Galin Bobev aus Burgas, Bulgarien

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Darmstadt, den 30. Januar 2015

(G. Bobev)

Contents

Notations

Abbreviations

2d	two dimensional
3d	three dimensional
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
AOI	Area-of-Interest
API	Application Programming Interface
AIM	Autonomous Intersection Management
C2C	Car-to-Car
ECU	Electronic Control Unit
XP	Extreme Programing
FZD	Institute of Automotive Engineering at Technische Universität Darmstadt
GUI	Graphical User Interface
IDE	Integrated Development Environment
ISP	The Interface-Segregation Principle
ITS	Intelligent Transportation System
LIDAR	Light Detection and Ranging
MVC	Model-View-Controller
RADAR	Radio Detection and Ranging
SDK	Software Development Kit
TTC	Time-to-Collision
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle

Terminology of driving assistant systems

Autonomous vehicle	An autonomous vehicle is capable of fully controlling the vehicles dynamics without the supervision of a driver [1].
Ego vehicle	The vehicle from whose perspective a given situation is observed or developed.
Target vehicle(s)	The vehicle or the vehicles which are relevant in the interpretation of a driving situation.

1 Introduction

1.1 Motivation

The progress of computer science and the increasing hardware performance give the basis for the engineering of new complex and advanced algorithms in resource limited environment such as the automobile. As there are still challenging driving situations, that lead to dramatic casualties in the daily traffic, this gives the basis for new research areas. The development of Advanced Driver Assistance Systems (ADASs) are still on topic and transfer to the domain of autonomous vehicles.

Such systems attempt to support the driver in a particular driving situation. The main ideas are to make driving more comfortable and more safe. The research and development of an autonomous vehicle goes one step further. Such a vehicle is capable of carrying out fully autonomously an entire driving maneuver and to take the driver out of the loop. That kind of vehicles should make the traffic not safer but more predictable. Although there are first attempts in this area, for the development of a fully autonomous vehicle have to managed a whole sequence of complex challenges from perception performance to legal issues.

In order an Advanced Driver Assistance System (ADAS) to be developed or a driving situation to be automated an engineer has to solve various problems. Figure 1 illustrates a simplified diagram of the process. Starting point is the data that are available at time t_i. There are many sources that could provide a stream of data in various formats and at various rates. A vehicle could be equipped with on-board sensors giving feedback about the dynamics and the state of the vehicle. Another data source are sensors that capture the surrounding environment as an image or light, ultrasonic or radio waves reflection. Along with this there is the navigation data as digital maps in on- and offline format and live positioning and orientation of the vehicle. The connectivity possibilities allow a vehicle to be online and to use live services. This results in plenty other data sources.

The next step of such a system is to predict the driver intention in order to support him/her. There is the need to know what the driver is attempting to do next so the available data could be appropriate interpreted in the situation analysis step. In the development of autonomous vehicle this step could appropriately be skipped as the driver intention is the vehicle's intention.

The situation analysis attempts to understand the driving situation in details. In this step all relevant parameters and objects are analyzed so that the situation (e.g. intersection crossing) feasibility is computed.

The next step in this process is the motion prediction of the own vehicle. After analyzing the situation and making a decision (e.g. stop before intersection) one should predict the motion of the own vehicle in the future so that the decision could be performed in the last step as planned. The entire system is time dependent. The calculation should be performed on real time as the surrounding world is changing in real time. Considering this and the complexity of each process step explains the engineering effort that should be spent into the development of real world system of that type.

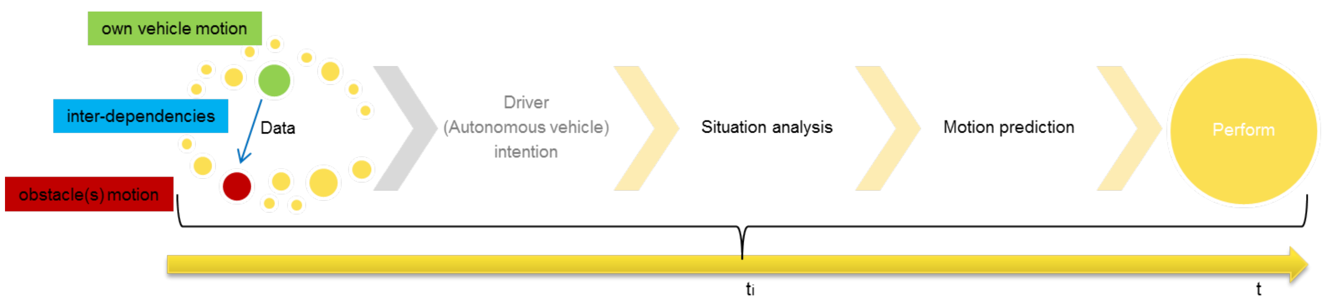


Figure 1: Driving behaviour inter-dependencies in the realization process of an Advanced Driver Assist Systems.

(a) Data **(b)** Intention **(c)** Analysis **(d)** Prediction

Figure 2: An example diagram for a possible outcome (d) in a traffic situations, where a system analyses (c) the traffic situation with the given data (a) and driver intention (b).

Figure 1 illustrates another challenge - the driving behaviour inter-dependencies. Each participant in a driving situation is part of this situation and influence the outcome of it through its behaviour. Changing direction, crossing intersection, overtaking and other driving situations with more than one participant are complex situations where the behaviour of each object affects the progress as well the outcome of the situation. If the vehicle ahead breaks suddenly or if at an intersection the vehicle with rights of way turns unexpected to the right, the other participants should react in order to prevent a collision or to cross the intersection quicker. This driving behaviour inter-dependencies bias the entire process of an ADAS or an autonomous vehicle. It is assumed, that exact in complex situation of that kind, where such novel systems attempt to make the traffic safer, the driving behaviour inter-dependencies are hindering the process severely. Engineering on this topic and finding a potential for a system for assisting the driver with the goal of a safer traffic is the motivation of this work. It can be seen as a first step towards safe autonomous vehicles in complex traffic situations.

1.2 Problem Statement

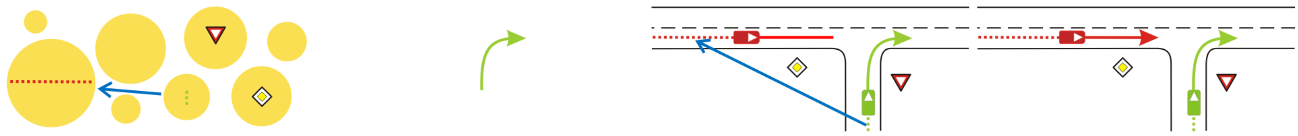
Crossing intersection is a complex task where the behaviour of the participants at the situation influence each other directly. Although there are strict rules for each role (e.g. traffic on main street has the rights of way) there is room for mistakes that may lead to fatal casualties. Some of the factors that may change a situation outcome are bad vision, overestimation of own vehicle or driving potential or underestimation of the situation complexity.

Figure 2 illustrates the influence of the analysis of driving behaviour inter-dependencies in the development of an autonomous vehicle according to the process diagram in Figure 1. In the visualization two different colors are used representing the role of the participants. Green is the color of the own vehicle (in this context an autonomous vehicle) that has the intention to turn to the right at the intersection. The red color is used for the traffic on the main street which has the rights of way.

The starting point is the available data that consists of the recording of the own vehicle motion an the obstacle motion at the time of analysis of the situation. The second step, where the intention of the driver should be predicted, could be skipped as this is the known intention of the own autonomous vehicle. The third step is the analysis of all the available data and making a decision if turning to the right is possible considering some marginal conditions. At this point there is no a-priori knowledge available about the inter-dependencies between the two participants so that the decision is to plan the trajectory of the own vehicle as illustrated in Figure 3d where the own vehicle should wait at the intersection until the traffic on the main street clears.

Figure 3 shows the same situation with the one difference that there is a-priori knowledge about the inter-dependencies of the two vehicles computed from the motion of the both. This knowledge influence the analysis step so the predicted motion of the own vehicle is to make the right turn before the traffic on the main street reaches the intersection.

In this thesis it is assumed that there are inter-dependencies at urban intersections and their analysis could help in the future development of autonomous vehicle. The problem that this work faces is how to gather realistic information for the analysis of driving behaviour inter-dependencies for the purpose of autonomous vehicles. The two main questions that have to be considered is how to obtain a realistic data and process it to extract the real world information.



(a) Data **(b)** Intention **(c)** Analysis **(d)** Prediction

Figure 3: An example diagram for a possible outcome (d) in a traffic situations, where a system analyses (c) the traffic situation with the given data (a), driver intention (b). and a-priori knowledge about driving behaviour inter-dependencies.

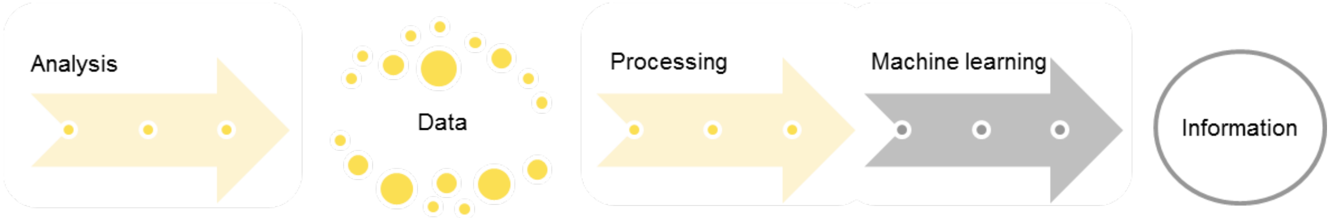


Figure 4: The goal of the master thesis is to analyze the blind spots in the process of gathering a realistic information for the purpose of safe autonomous vehicles.

1.3 Goals of the Thesis

Figure 4 illustrates the direction of the analysis of the problem chosen in this thesis. Starting point is the analysis of the driving situation at urban intersections in detail and identifying the necessary data. The next step is to define a minimal processing pipeline for the data in order to be used in a machine learning matter. The focus is set only on these issues and therefor the information extraction part of the diagram in Figure 4 (gray) is not treated in the master thesis, because it involves another issue that will exceed the scope of the work.

The goal of the thesis is to engineer on the blind spots of the *Analysis* and *Processing* steps and as a result to provide a reasonable framework for analyzing realistic driving behaviour inter-dependencies with a machine learning techniques. The chosen strategy consists of 3 steps:

1. Analysis of the topic *driving behaviour inter-dependencies at urban intersections*
2. Definition of a realistic data set for further analysis of the driving behaviour inter-dependencies
3. Pipeline definition for the processing of the data

The approach on the problem uses a *Theory vs. Praxis* working model so the work attempts to give proof of all theoretical assumptions in a real world conditions. This strategy allows a realistic observation of the given problem.

1.4 Structure of the Thesis

The thesis starts with the research of the literature in chapter 2. The related scientific works are discussed and an overview of the used techniques and approaches in similar topics is given. Then the reader is introduced to some basic knowledge, that is required to understand the applied methods and techniques.

In chapter 4 a theoretical observation of the problem statement is given in order to generate a world model instance. The theoretical definitions are verified in chapter 5. A realistic instance of the theoretical model and the established deviations between the theory and the praxis are taken into account.

This is the basis for the definition of the data processing pipeline in chapter 6. It is initially defined as a black box in section 6.1 and then realized in praxis as a software program. The details about implementation of each pipeline process and the associated challenges are described in section 6.2. The developed software program and its main features are specified in chapter 7.

The thesis is completed with a summary and conclusion. The possible further work on the same topic is discussed.

2 Related Work

The research of the literature shows to the time of writing the thesis that there are no other scientific works covering precisely the problem in the focus of this work.

While discussing the topic of the work one can identify four main key terms for the research of the literature - driving behaviour, vehicle inter-dependencies, autonomous vehicle and urban intersection from the view point of automotive engineering. This terms represent problem domains that deliver a large range of papers. Therefor the research was based on two reference papers, that was provided by the supervisors [2], [3]. This circumstances lead to the review of state of the art scientific works.

2.1 Driving Behaviour and Inter-dependencies

The terms *driving behaviour* and *inter-dependencies* belong together as long as they are more than one vehicles or objects in a traffic situation that are analyzed. Their use in the matter of automotive engineering can be traced back to year 1938. One of the first studies in this field could be found in the work of Gibson and Crooks [4]. In 1938 they discovered the need of research for safe travel at intersection and defined the *The Field of Safe Travel*. Figure 5 illustrates their idea and rises the problem of inter-dependencies in a driving situation. Despite the fact that the technology and the vehicles of 21th century are much more advanced this work is a pioneer covering a problem in theory which after more than 70 years is still on topic.

The works of Lefèvre [5], [6], [7] and [3] are a series of a modern consideration and treatment of this topic. Lefèvre and et al. extendedly developed in their works [5], [6] and [7] a method for estimating the intentions of drivers and detecting conflicts at intersections. They validated the approach with field trials using passenger vehicles equiped with Car-to-Car (C2C) wireless communication units and in simulation. The problematic is that the field trials were realized under controlled conditions. The driver of the test vehicle had to performed a predefined *dangerous* situation. As the outcome and the motion of the vehicles is strictly defined there are no inter-dependencies between the vehicles such as in a realistic driving situation.

The last work from 2014 Lefèvre is a survey on motion prediction and risk assessment for intelligent vehicles. The paper categorizes and overviews the theoretical approaches in the challenge of detecting dangerous situations and techniques for avoiding or mitigating accidents [3]. The prediction of the evolution of the current traffic situation and its analysis in terms of the risk are central. Lefèvre defines the analysis of traffic situation as a complex collection of interdependent objects and recognizes the need for the analysis and understanding of driving behaviour inter-dependencies in order to design and develop a ADAS.

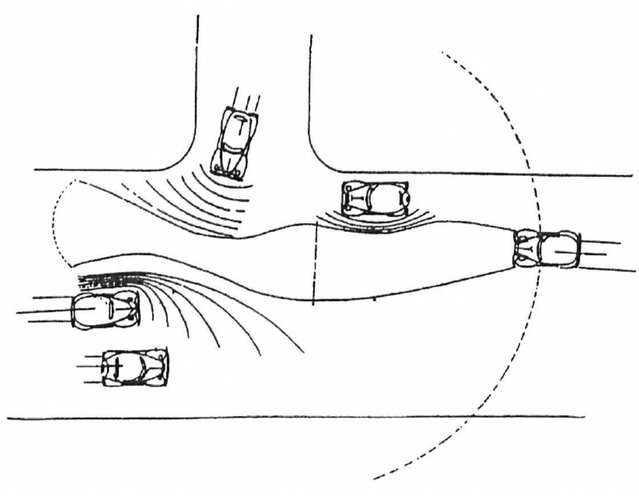


Figure 5: The concept of field of safe travel [4]

In the book [8] is given a summary about the driver behaviour in automotive environments with aspects of critical issues in driver interactions. The published works cover the topic in a theoretical matter and give various ways of modeling the driver behaviour. On the one hand the authors treat the task of driving as a mental process, driven by the driver's condition, internal risk management and others mental parameters. On the other hand they describe it as a complex task of many interdependent objects and circumstances. Although the discussed driver models are theoretically correct, in the book are not given any observations how they score in a real world and inter-dependencies at urban intersections are not analyzed.

Another example that attempts to model the driver behaviour is found in the work of Sadish and et al. [9]. They base their achievements on an experimentally-collected data in driving simulation software. The work of Gindele [10] researches in the same field and goes one step further in the analysis of the driving behaviour. The presented filter that is able to estimate the behaviour of traffic participants and anticipate their future trajectories takes into account the influence of the motion of other vehicles on the own motion. Their domain of application is highway traffic situations and not urban intersections. As the most works in this area this theoretic approach is validated on a data generated with a simulation software.

The work of Schreier [2] proposes an approach for long-term trajectory prediction and criticality assessment for driver assistance systems. They define a novel criticality measure that allows to reason about imminent collisions of vehicle several seconds in advance. Although they consider driving behaviour inter-dependencies their approach is a collection of theoretical procedures that is tested under a laboratory condition with the use of a simulation software. This is one of the many examples that tries to solve a real world problem based on a theoretical representation of driving data.

2.2 Urban Intersection from the View Point of Automotive Engineering

This paragraph attempt to give on overview about the interpretation of an urban intersection from the view of automotive engineering. Two direction of research could be identified while searching papers in this field. On the one hand there are scientific works about Intelligent Transportation System (ITS) and Autonomous Intersection Management (AIM) that attempt to optimize the task of intersection traffic management while considering preconditions about safety and comfort. On the other hand there are scientific works about the research of advanced driver assistance systems (ADASs) with the main purpose of supporting the driver at urban intersection in order to minimize collisions and casualties.

An example of the first type of scientific works can be found in [11]. The researchers at the department of mechatronics of the university of Paderborn define a structure of a system capable of planning a safe trajectory for autonomous intersection crossing. They analyze the problem of two vehicle nearing an intersection from different entries and attempting to cross it at the same time. In order to prevent collision and automate the process the authors introduce a intelligent traffic manager which computes a discretized version of the intersection, calculates non-colliding motion trajectories for each participant and combine them in a node reservation matrix. This matrix represents the position of each vehicle over the time. For this purpose the vehicles exchange information with the traffic manager via Vehicle-to-Infrastructure (V2I) communication technique. The problem with the proposed approach is the fact that it takes into consideration a perfect world. This means that each vehicle moves as planned. They do not consider any uncertainties or realistic real world traffic conditions.

Bouraoui demonstrates in [12] a similar approach for safe intersection crossing. The realization of the project is in comparison to [11] more realistic as the research is based and validated on real cybercars. They use a traffic manager and V2I communication. The data sources are extended by the ability of the cybercars [1] to communicate with each other via Vehicle-to-Vehicle (V2V) modules. Despite this facts the experiments take place under labor condition. The field trials assume a very simplified real world

[1] A cybercar is a fully automated road vehicle that can transport people or goods. It requires the infrastructure to be under the control of a management system.

representation. The authors recognize the need that the algorithm should be tested under a more realistic conditions in order to verify their results.

The most practical work and different interpretation of the urban intersection comes from the German national research institute for road construction and road safety. Maier analyzes in [13] the driver behaviour for the purpose of continuous traffic flow and for the outline of comfort urban intersections. The researchers tried to identify the driver behaviour at urban intersection in order to optimize the construction and to help by the decision making for a new intersection. They set up two video cameras to record the traffic at intersection. Than they manually extracted the parameters they needed from the video data records. Although the design of their experiment is capable of capturing the driving situation, the data format (video records) is not suitable for the analysis of the vehicle motion. A reconstruction of a traffic scene from a video sequence is more time consuming that collecting the data with sensor that are developed for this purpose e.g. Radio Detection and Ranging (RADAR).

The analysis of an inter-section situations with the purpose of designing a ADAS have more in common with the topic of this thesis. The research of the literature returns two doctor dissertations that partly discuss the problematic of driving behaviour inter-dependencies at urban intersections.

Williams performed experiments at urban intersection with the goal to analyze the driver behaviour [14]. In focus were two intersection - one with traffic lights and an intersection of a major and a minor street. The task was to identify parameters describing the driver behaviour while crossing the intersection. The identified parameters gave the basis of future research of driver assistant system for urban intersection. In her work she used a test vehicle equipped with sensors to collect the vehicle velocity and the longitudinal acceleration. she used a video based system to observe the driver during the tests. The age of the driver and some aspects of his/her overall driving experience were the parameters that distinguish the driver behaviour the most. Although this findings could help to describe a driver behaviour at urban intersection they do not give any outcome about the inter-dependencies between and especially about the influence of the other objects on the whole experiment.

Mages researches in his dissertation [15] the driving behaviour at urban intersection in terms of identifying the structure of a safety system that should help prevent collision. He analyzed the accident statistics and defined a set of a representative intersection that are potentially demanding and therefor dangerous. After that he used a test vehicle and test subjects to drive along the course and collect data. The design of the experiments and the test equipment conduce for the analysis of the driving behaviour of the test subjects at an urban intersection. This gave the basis of a series of hypothesis how a system that should support the driver in such traffic situations must be outlined. Subsequently he implemented and validated the proposed system in a driving simulator.

The contact point of his work to this thesis is the fact that Mages used environment detection sensors at some of the intersections to collect additional data about the motion of the other participants. This data was primary used for the validation of his hypothesis about the driving behaviour of the test subjects. There is no further information on how the data was processed and if it could be used for the purposes of this problem. At the same time his initial idea for the collection of this data variates to the needs of this thesis.

2.3 Autonomous Driving

The development of autonomous vehicles is one of the current reasons for the research of driving behaviour inter-dependencies. One of the modern driver in the area of autonomous vehicle is the DARPA Grand Challenge [2]. The main objective is to compare vehicle capable of handling autonomous driving in the desert. In the version DARPA Urban challenge[3] the objective shifts to the problem of autonomous urban driving where various of vehicle compete in a urban likely environment. The DARPA challenges are strictly ruled witch leads to an overfitting of the autonomous systems to the given challenge scenario along with it the given tasks are proved to be not that much realistic *Stadtpilot*. The participants from

2 http://archive.darpa.mil/grandchallenge05/
3 http://archive.darpa.mil/grandchallenge/

university of Braunschweig Germany continued developing their autonomous vehicle after the challenge as the project named *Stadtpilot*. They describe in [16] the challenges in the development of an autonomous vehicle in the real world. Some of them are the crossing of an intersection and the negotiation with other vehicles which are discussed in their further work [17].

Another example of autonomous vehicle challenging the task of inter-dependencies at urban intersections is the self driving vehicle from Google. Andrew Chatham presents at the Embedded Linux Conference 2013 in his keynotes [18] that the understanding of the situation at intersection is crucial for an autonomous vehicle. He defines the crossing of an intersection as a social problem. An autonomous vehicle has to handle a driving situation in a realistic matter in order to proceed in an environment of vehicles driven by human beings. One of the example for this inter-dependencies is the crossing of a four-way-stop intersection. With the implemented logic to handle this kind of situations the self driving car from Google influence the motion of the other participants and succeeds in this task.

2.4 Summary

The research of the papers and literature highlights the tendency in the understanding of the driving behaviour inter-dependencies. There are various works about making the traffic safer and controlling it. Most of them attempt to solve a portion of a real world problem in a theoretical matter. In most of the cases the researchers do not use real world data for testing or to validate the achieved results. The few which take a more practical approach to a given problem restrict them to the data of a predefined traffic situations. The data is collected under a controlled environment where the drivers and the participants are aware of the problem in research or are sensitized due to the conditions e.g. test vehicle, restricted testing ground etc..

This thesis may lead to benefits for a large spectrum of works as one of the goals is to collect realistic data of a traffic situations at urban intersections.

3 Basics

In this chapter the reader will be shortly introduced to a few topics that should be understood to a certain degree before following with the next chapters of the thesis.

The intent of this work is to engineer on driving behaviour inter-dependencies for the purpose of safe autonomous vehicles. It sets the first steps in a pipeline for the processing of realistic automotive data . The pipeline should process the data in such a way that they can be used in machine learning techniques. The focus is set on the data and the processing and the machine learning part is out of the scope of this thesis. If one want to read further information about this topics, the following books can be proposed [19], [20].

The implemented software program is discussed in a separate chapter. The specifics related to the computer science are described along with the description of the program. The main problem domain, that inducts special terms, is the domain of automotive engineering. The required knowledge is described in the following sections.

3.1 General Knowledge

A Cartesian coordinate system is used continuously through the sections of this work. In the steps, where the problem statement is analyzed, the Cartesian coordinate system is chosen to be used in the definition of world model. All relevant objects are oriented and can be located with their Cartesian coordinates. The two dimensional (2d) representation is used as depicted in figure 6. The x-axle is pointing to the right in its positive direction and the y-axle is rising up on the plane in its positive direction.

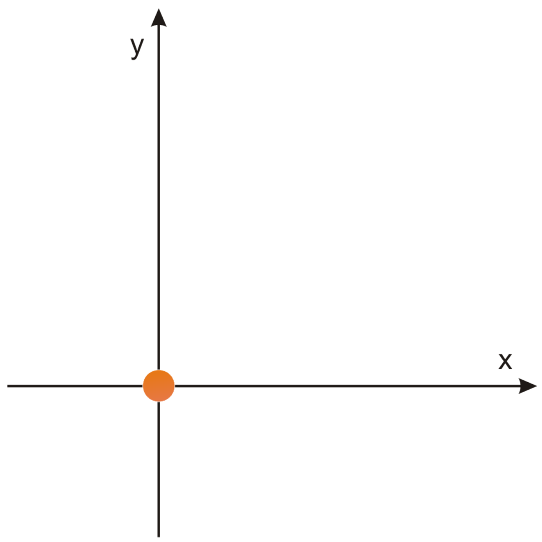


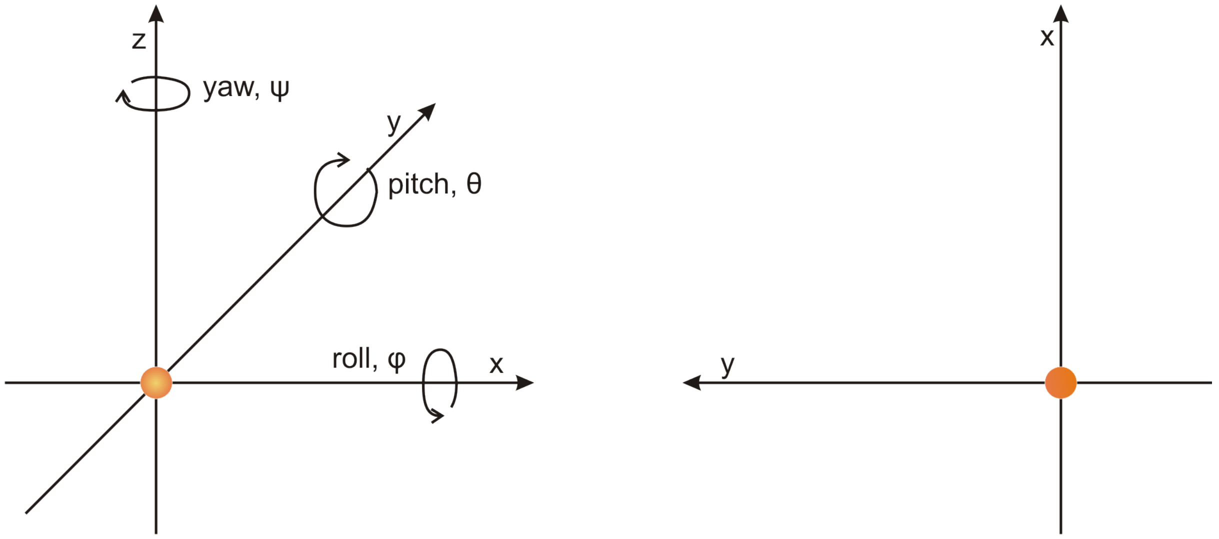
Figure 6: Cartesian coordinate system in two dimensional (2d) space

3.2 Automotive Engineering

This thesis is a combination of information technologies and automotive engineering. A practical issue from the domain of automotive engineering is analyzed from the view point of the computer science. Therefor the reader is given a short introduction of the related topics.

3.3 Vehicle Coordinate System

The vehicle coordinate system is fixed to an origin point of the vehicle. Most of the cases the origin lies on the middle point of the front or real axle of the vehicle [21]. Figure 6 illustrates the coordinates of the system in a three dimensional (3d) and a 2d world. The positive end of the x-axis is pointing into the direction of the vehicle and the positive end of the y-axis is pointing to the left. The z-axis rises in its positive direction.



(a) Vehicle coordinate system in three dimensional (3d) space

(b) Vehicle coordinate system in two dimensional (2d) space

Figure 7: Vehicle coordinate system in three dimensional (3d) and in two dimensional (2d) space.

All parts and data relevant to the vehicle refers to the vehicle coordinate system.

3.4 Environment Detection

Nowadays most of the vehicles are equipped with a hardware for sensing the environment in order to generate a data scream of the surroundings for an ADAS in the vehicle. Although there are various sensors and manufacturers, the following sections will introduce the reader into the hardware used in this work.

3.4.1 Light Detection and Ranging (LIDAR)

For the purpose of the thesis a basic understanding of the working logic of a laser scanner is required. In general such a sensor detects objects and their distance by means of laser beans. In simplified terms, such a sensor sends a laser bean, receives the echo with a photo diode receiver and processes the data by means of a time to flight calculation [22].

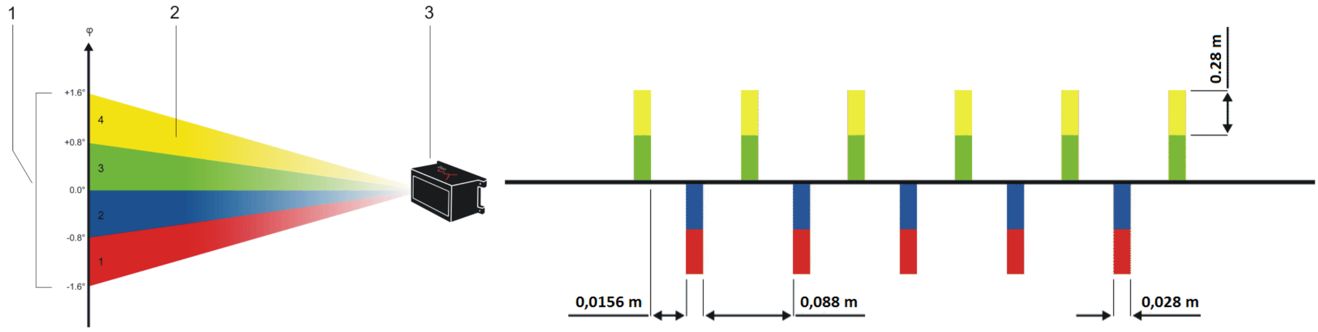
The sensors, that are applied in this work, are of the type ibeo LUX 2010 [4]. They use several rotating laser beams to scan the surrounding. Figure 8 illustrates the beans emission in vertical and horizontal orientation that are spread with an angular resolution of 0.25° into four layer. Each of the layer has a vertical resolution of 0.8° allowing to discretize an object in height. The scan data consists of the distance, the angle and the echo pulse width. Additional properties are a multi-target capability. This allows the recognition of multiple objects in a single measurement.

3.4.2 Fusion

The meaning of the word fusion is used in this work as common for the automotive and data processing domain. By fusion one should understand the procedure that merges a multiple data sources into a single one.

An example for application of this technique is often found in the domain of automotive engineering. A vehicle could be equipped with multiple sensors detecting the surrounding environment. As each sensor

[4] http://www.ibeo-as.com/ibeo_lux.html



(a) Vertical resolution of an ibeo LUX 2010 sensor. Source: ibeo documentation **(b)** Beam size at 20m with an angular resolution of 0.25°. Source: ibeo documentation

Figure 8: ibeo LUX 2010 multi-layer technology and detection of the surrounding.

has its own position and orientation on the vehicle, thus on the world, the generated data stream could be merge by the use of a fusion software to a single representation of the world.

The usage of multiple sensors, whose detection range overlaps, serves for better precision, increasing the range and robustness. How the fusion works in detail and can be applied in an application depends on the manufacturer of the sensors.

4 Inter-dependencies Problem Definition

The problem of the thesis about engineering on driving behaviour inter-dependencies for the purpose of safe autonomous vehicles at urban intersection is discussed in this chapter. The problem definition is too general and a theoretical analysis is required in order to specify the problem to a certain focus. Some constraints about the exact environment, situation and the location should be defined. This approach to the problem will give on overview of its complexity and the corresponding challenges to it. At the end of the chapter the world model is observed with the aim for identification of data sources for its further analysis.

4.1 Theoretical World Model

A world model that represents the thesis problem is build progressively the following sections . How an urban intersection is defined and a theoretical intersection model could be defined is the first step. The possible traffic situations are analyzed and one of them is selected to be added to the model. Roles to the participants in the traffic situation are assigned in the next step of the observation and a view point to the occurrence is chosen. In order the traffic model to be completed motion models for the participants are defined. The results are combined and the model of the problem is built.

4.1.1 Urban Road Definition

The first step of the theoretical observation of the problem is to define what an urban area is and more particularly which type of streets are at interest for the problem.

The definition and specification of the urban area are related to the German traffic laws. There will be no consideration about the consistency to other European countries or world wide. Although similarities could be found in the road construction all over the world, the analysis and the definition of an urban area is restricted in this thesis to Germany as defined in [23].

As depicted in Table 1 all streets can be categorized in five different categories. The streets are classified by the traffic density and are further more specialized with the use of 6 different levels of spatial conditions.

Only street of the type *HS IV* and *ES IV* are considered in this thesis. This categories specify the common known urban type of streets. This type of streets handles the urban traffic until it gets to the the streets with higher capacities *HS III, VS III* and so on. The category *ES V* is discarded, because it defines streets within a living area, that have strict regulations. Their main purpose is for parking and connecting the living area to a street of higher level.

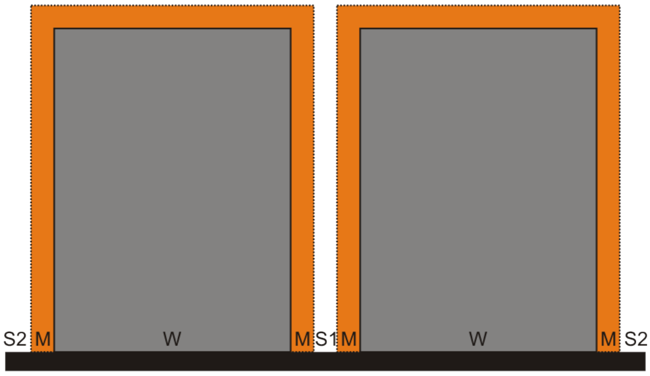
The starting point for the definition of the urban area and in particularly the geometrical constraints of the streets in focus is given by the categories *HS IV* and *ES IV*. The streets of type *HS IV* have higher priority in comparison to the streets of type *ES IV*. All observations that have to be taken to construct such a streets are described in [23]. There are no hard conditions, but a large range of factors has to be considered e.g. type of vehicles that use the street, traffic density, pedestrian lane, bicycle lane, shops,

Link function	**Motorway**	**Highway**	**Streets without buildings**	**Streets with buildings**	**Service street**
continental	AS 0	-	-	-	-
large area	AS I	LS I	-	-	-
trans-regional	AS II	LS II	VS II	-	-
regional	-	LS III	VS III	HS III	-
close area	-	LS IV	-	**HS IV**	**ES IV**
small area	-	LS V	-	-	ES V

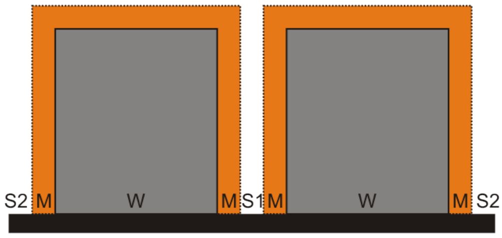
Table 1: Different roads according to their function and category. The notation is taken from [23].

Parameter	Unit	Description	Car	Delivery truck	Truck	Bicyclist	Bus	Tram
w_o	[m]	Width of the object	1.75m	2.55m	2.55m	1.00m	2.65m	2.65m
s_0	[m]	Margin of movement	0.15m - 0.25m	0.20m - 0.25	0.20m - 0.25m	0.00m	0.20m - 0.25m	0.30m
s_1	[m]	Safety gap between moving objects	0.25m	0.25m	0.25m	0.75m	0.40m	0.40m
s_2	[m]	Safety gap to roadside	0.50m	0.50m	0.50m	0.50m	0.50m	0.50m

Table 2: Theoretical vehicle widths and safety gaps that can be used for the calculation of the total roadway width [23].



(a) Theoretical road width for street of type *HS* (major street in this work)



(b) Theoretical road width for street of type *ES* (minor street in this work)

Figure 9: Visualization of the calculation of the road width considering safety gaps and vehicle length. Annotations: w - vehicle length, m - vehicle movement disturbtion, s1 - safety gap between moving objects, s2 - safety gap sidewise

trees, intersections and much more. This work restricts itself only to the analysis of the geometrical condition for the purpose of a more precise definition of the streets. On page 25 and 27 a definition of the vehicles widths and safety gaps depending on the different traffic conditions can be found. This values are depicted in Table 2 and used to define the equation 1 for the calculation of the width of a two-lane roadway of type *HS* and *ES*.

This equation does not take into account any specific properties such as parked vehicles, shops, trees, bicycle lane and so on. It is simplified to return the minimum width of street with a given number of lanes i. The used parameters conform to Table 2.

$$w_{roadway}(i) = i * (w_o + 2 * s_0) + s_1 * (i - 1) + 2 * s_2 \tag{1}$$

The total width is a sum of the width of two vehicles and their movement deviation gap, safety gap between them, and the safety gap to the road side. Calling the equation 1 with the different parameters from Table 2 returns a theoretical width for a two-lane street of type *HS* between 5.50m and 7.50m and for a street of type *ES* between 4.50m and 6.50m. The mean value of 6.50m for *HS* and 5.50m for *ES* are used in the further steps of the theoretical model definition. Figure 9 illustrates the results.

4.1.2 Intersection Definition

Two types of intersections could be identified while concerning the crossing of two streets. The crossing may build an intersection in *T-form* or *X-form*. At this point a restriction is made in order to work on a single problem and the focus is set to the definition of a T-intersection. The traffic regulation at the intersection should be defined in the next steps of the observation. A traffic regulation at a T-intersection can be implemented in tree ways:

- with the base rule - the object to the right is priority
- with traffic signs
- or with traffic lights

The first type defines the object to the right as a priority vehicle that has the rights to cross the intersection first. It is the most intrinsic regulation and is the basis for all others. It is used on streets with low traffic and harder speed limits that not conform the the urban area definition from section 4.1.1 and therefore overruled.

The regulation of an intersection through a traffic signs is applied on a crossing of streets with different priorities and traffic densities [23]. It suits the discussed problem the most, because it lets the driver to make the decision an plan its movement in comparison to the third type of regulation. Traffic lights automatically control the flow of vehicles and are mainly installed at intersection with multiple lanes and high traffic, which also does not conform to the defined urban area streets in section 4.1.1.

The chosen method for intersection regulation is by the use of traffic signs. This regulation should be further specialized, because there are several signs that may come into use.

An intersection of a street with *rights of way* with a street with *give way* regulation in *T-form* is proposed in this work. The give way regulation is privileged and allows a flowing traffic to be achieved. A stop condition is rejected, because it automatically terminates the condition of moving traffic.

At this point the street with *rights of way* is defined as the *major street* and the street with *give way* regulation as the *minor street*. The crossing of this two streets is the intersection in interest. The intersection type that is used into the following chapters and for the analysis of the problem is graphically illustrated in Figure 10.

In order to base the rest of the world model on the chosen intersection a fixed coordinate system should be found. This allows each objects to be located relating to the world model. A Cartesian coordinate system is defined corresponding to the definition in section 3.1. The origin is set on the edge at the starting point of an intersection. The coordinate system is illustrated in the intersection model Figure 10.

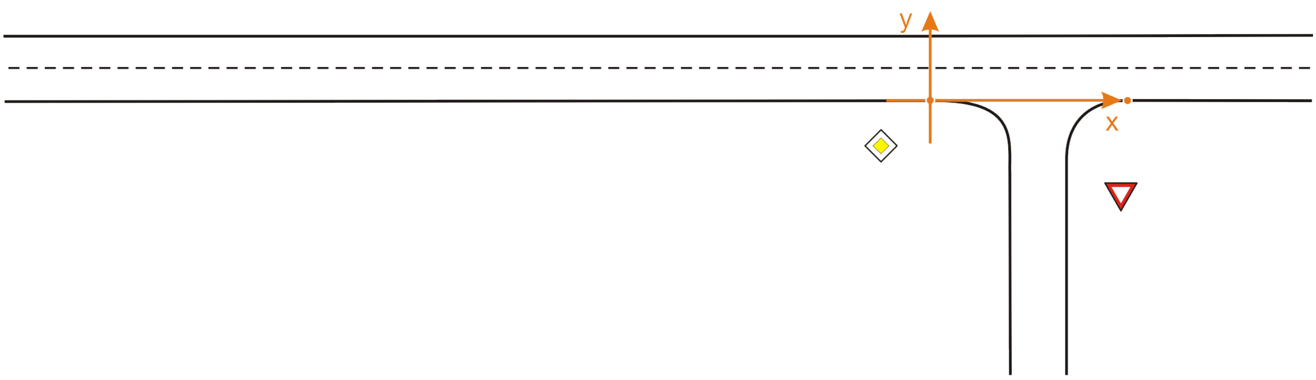
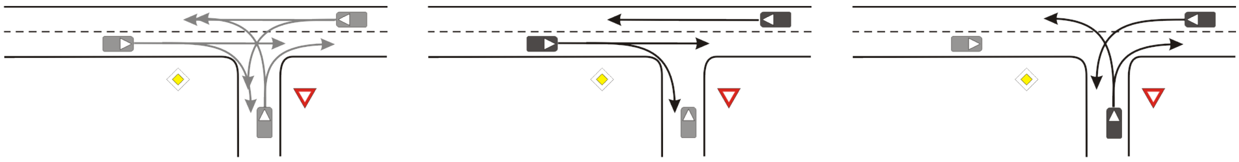
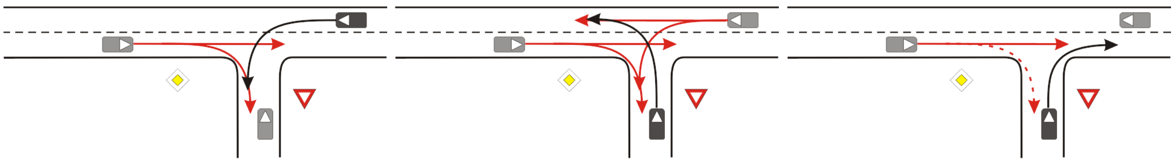


Figure 10: Theoretical model of the intersection in interest for the analysis of driving behaviuor interdependencies. A T-form crossing of a street with rights of way (called major street in this work) with a street with give way regulation (called minor street in this work).



(a) The set of all possible situations at the defined intersection with vehicles approaching at each end
=
(b) All situations where the vehicle has rights of way and theoretically there is no need for advanced support
+
(c) All situations where the vehicle has no priority and has to give way in order to proceed with its maneuver

Figure 11: Categorization of the driving situations at the defined intersection with respect to the priority hierarchy.



(a) Approaching the intersection from the major street and turning to the left into the minor street

(b) Approaching the intersection from the minor street and turning to the left into the major street

(c) Approaching the intersection from the minor street and turning to the right into the major street

Figure 12: Possible situation at the defined intersection, where the vehicle does not have the rights of way and conflicts with other vehicles.

4.1.3 Situation Definition

As the problem is to engineer on driving behaviour inter-dependencies the possible traffic situations should be observed. So far the urban area, the road specifics and the intersection in interest was modeled. In the next step the actual driving situation, that will be analyzed, will be defined.

The set of all possible situations at the defined intersection with vehicles approaching at each end is illustrated in Figure 11a. They can be categorized with respect to the priority hierarchy. The first category contains a theoretically trivial driving situations. Those are the ones where a vehicle, that has rights of way, crosses or turns at the intersection. It is a priority vehicle and can proceed with its intention without considering the motion of the other participants. This theoretical observation leads to their rejection for further analysis, because in theory there are not interacting with other objects. The rest of the situations are illustrated in Figure 11c and represent the set of traffic situations with conflict of interest. They are described in detail in Figure 12.

A vehicle on the major street with the intention to turn in to the minor street is depicted in Figure 12a. It conflicts with the upcoming traffic on the major street. The rest of the Figures 12b and 12c depict the possible situations with an vehicle on the minor street. It always conflicts with at least one vehicle on the major street.

Not all of the depicted traffic situations can not be analyzed in the scope of this thesis. One further restriction is made to the definition of the world model and only one situations is selected. The situation illustrated in Figure 12c, where a vehicle on the minor street attempt to turn to the right at the intersection, is added to the world mode. The vehicle is conflicting with the traffic on the major street coming from the left side. The rest of the objects will be not treated. This extends the world model and illustrated in Figure 13.

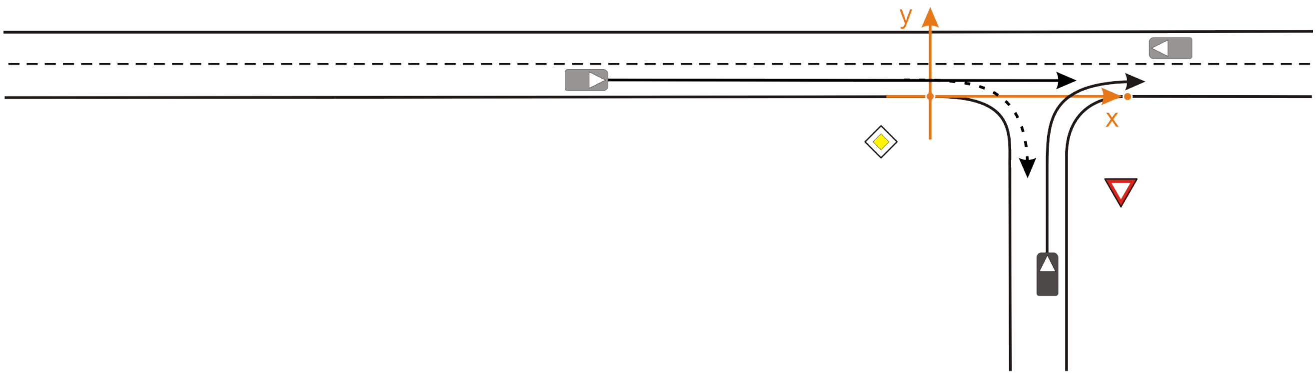


Figure 13: The intersection model is extended by the defined traffic situation.

4.1.4 Participants definition

The final step in the definition of the world model is the assignment of roles to the participants in the defined traffic situation and the calculation of the boundaries of the Area-of-Interest (AOI).

The chosen traffic situation represents a vehicle on the minor street that attempts to turn to the right and merge into the traffic on the major street. It is the one that has to plan and adapt its motion to the current traffic situation. The assumption is made that this vehicle can influence the traffic on the major street with its motion. The analysis of this assumption, about the inter-dependencies between the objects, could be used into the development of an autonomous vehicle. Therefor this vehicle is assigned to be an ego object. It is the main object of a scene and the further analysis of the traffic situation is based on it.

The traffic on the major street, that conflicts with the motion of the ego object, becomes the role called target(s). This vehicles are participating in the scene, while the ego object attempts to turn to the right at the intersection. The assigned roles in the defined traffic situation are illustrated in Figure 14.

A traffic situation is a temporal event. In order to analyze it in detail, its progression over the time and the complete course of an object has to be existing. This is still missing in the current definition of the world model. In order to complete the world model the motion model of the ego and the corresponding targets should be defined. They will be used to calculate the temporal parameters of the world model.

There is an extensive range of papers how a driver can be model. An example how complex and advanced a driver model can be designed is found in [8]. The situations (driver model) are examined in this thesis from the view point of an autonomous vehicle, therefor the ego model should correspond to such a vehicle. On the other hand finding and designing a complex model, that suits to the problem, is

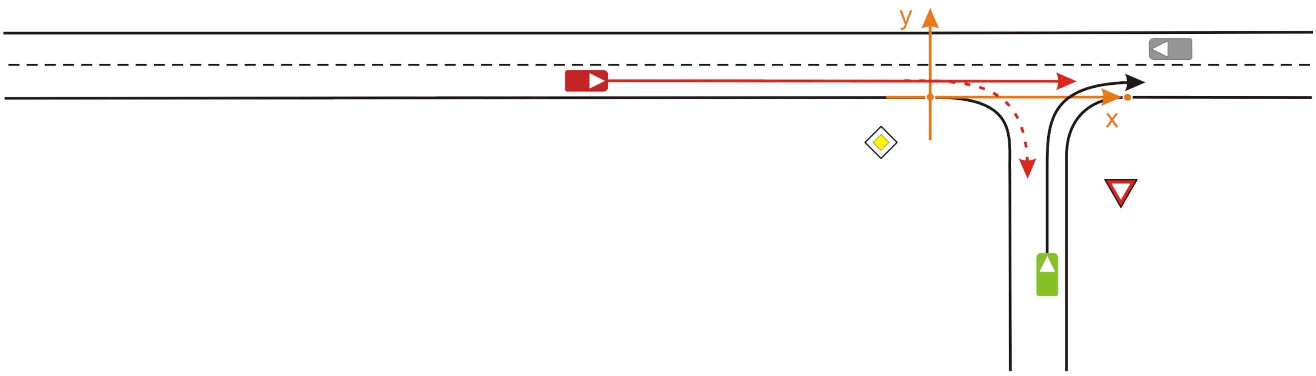


Figure 14: Roles assignment for the participants in the defined traffic situation. The vehicle on the minor street is colored in green and has the role of an ego object. All objects on the major street that are relevant to the scene are colored in red and called targets.

Parameter	Unit	Description	Value
Intersection parameters			
r_{corner}	[m]	The radius of the corner at the intersection of the major and minor street at the right side.	10.00m
$w_{intersection}$	[m]	The width of the intersection measured on the x axes.	25.50m
Major street parameters			
$v_{max,major}$	[m/s]	The maximum allowed speed on the major street.	13.89m/s
w_{major}	[m]	The width of the major street.	6.50m
Minor street parameters			
$v_{max,minor}$	[m/s]	The maximum allowed speed on the minor street.	13.89m/s
w_{minor}	[m]	The width of the minor street.	5.50m
Ego vehicle parameters			
$a_{a,ego}$	[m/s^2]	Maximum acceleration while increasing the velocity of the vehicle.	4.67m/s^2
$a_{b,ego}$	[m/s^2]	Maximum acceleration while decreasing the velocity of the vehicle.	-5.50m/s ^{2}
$a_{lateral,ego}$	[m/s^2]	Lateral acceleration.	2.30m/s^2
$r_{turning,ego}$	[m]	Radius of turning.	11.375m
w_{ego}	[m]	Width of the ego vehicle.	1.75m
l_{ego}	[m]	Length of the ego vehicle.	4.00m
Target vehicle parameters			
w_{target}	[m]	Width of the target vehicle.	1.75m
TTC	[s]	Temporal safety gap to the object in front of the vehicle.	1.50s

Table 3: Assumptions extracted from the literature about the intersection geometry and regulation specifics, ego and target dynamics dynamics.

too elaborative for the purpose of this work. The the required motion models in defined in this work in a cost-effective way. For the definition of the model the dynamics constraints of an ADAS - Adaptive Cruise Control (ACC) - are used [22]. As the ACC system is realized in serial vehicles, it should obey and follow real world constraints. There are predefined limits concerning the dynamics of a vehicle in longitudinal and lateral direction. This work proposes a motion models bases on the values of an ACC in the version Stop and Go [22], because lower velocities are expected.

All parameters and their values, that are used to model the motion of the ego and the targets, are listed in Table 3. The intersection model is extended by the definition of the radius of the intersection turning curve $r_{cornering}$ and the width of the intersection $w_{intersection}$. The intersection width can be calculated with the equation 2. The maximum allowed speed on the major and minor street is set to be 13.89m/s (=50km/h). Further the dynamic values of the ego and a target are populated according to the constraints for an ACC with Stop and Go. A target vehicle is defined to keep a safety gap (Time-to-Collision (TTC)) of 1.5 to the object in front. This value represent a common driver reaction time [22]. The last new parameter is the radius of turning for the ego object, that is defined in equation 3. It defines how the ego object will turn at the intersection. The equation defines a constant following of the street edge, while keeping a safety gap as defined in Table 2.

$$w_{intersection} = 2 * r_{intersection} + w_{minor} \tag{2}$$

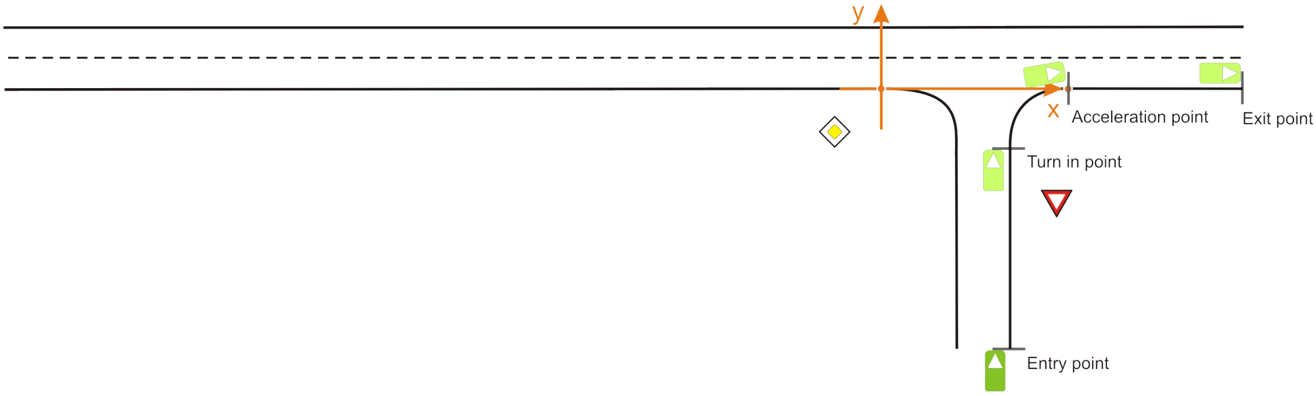


Figure 15: Theoretical ego motion while performing a right turn at the defined intersection. Motion model is specialized by the four points - Entry, Turn In, Acceleration and Exit.

Parameter	Unit	Entry point	Turn in point	Acceleration point	Exit point
t	[s]	0.0s	1.60s	5.09s	6.97s
dt	[s]	0.0s	1.60s	3.49s	1.88s
a(t)	[m/s^2]	-5.50m/s^2	0.0m/s^2	4.67m/s^2	0.0m/s^2
v(t)	[m/s^2]	13.89 m/s^2	5.11m/s^2	5.11m/s^2	13.89m/s^2
s(t)	[m]	0.0m	15.16m	33.03m	50.88m
ds(t)	[m]	0.0m	15.16m	17.87m	17.85m
x	[m]	15.00m	15.00m	26.50m	44.36m
y	[m]	-25.16m	-10.00m	1.50m	1.50m

Table 4: The location in the world model and the dynamics of the ego vehicle thought each phase of the defined motion model.

$$r_{turning} = r_{intersection} + s_2 + w_{ego}/2 \tag{3}$$

The proposed models are defined in the following paragraphs. First the ego motion model is introduced and it is used to define the motion model of the target(s).

Ego motion model

The *right turn*, that an ego object attempts to perform at the defined intersection, is theoretically defined in this thesis as a 5 phases process that are defined as it follows:

1. Phase: Driving with a constant speed on the minor street
2. Phase: Reaching the intersection and preparation for the maneuver (braking, look around, etc.)
3. Phase: Turning in and going around the corner
4. Phase: Starting to accelerate to merge into the traffic on the major street and reach the maximum allowed speed
5. Phase: Driving with a constant speed on the major street

The first and last phase are not part of the actual occurrence at the intersection. The entry and exit speed of the vehicle is defined from the constraints set to be valid at this phases. The maximum allowed on the major and minor speed is used. The motion of the ego object at the intersection is described in the phases from 2 to 4 and it is defined in listing 1 with the use of the parameters in Table 3. The listed function calculates the dynamics of the vehicle thought the phases and defines the location of the starting point of each phase. The results are illustrated in Figure 15 and listed in Table 4.

```
function [ego] = EgoMovementParameters(intersection, v_entry, v_exit, phi_turning, a_accelerating, a_breaking, a_turning, r_turning)
    parameters = struct('t', 0.0, 'dt', 0.0, 'a', 0.0, 'v', 0.0, 's', 0.0, 'ds', 0.0, 'x', 0.0, 'y', 0.0);
    ego = struct('entryPoint', parameters, 'turnInPoint', parameters, 'accelerationPoint', parameters, 'exitPoint', parameters);

    % Define the ego dynamics on "Entry_Point"
    ego.entryPoint.t = 0.0;
    ego.entryPoint.dt = 0.0;
    ego.entryPoint.a = a_breaking;
    ego.entryPoint.v = v_entry;
    ego.entryPoint.s = 0.0;
    ego.entryPoint.ds = 0.0;

    % Define the ego dynamics on "Turn_in_Point"
    ego.turnInPoint.a = 0.0;
    ego.turnInPoint.v = sqrt(a_turning * r_turning);
    ego.turnInPoint.dt = (ego.turnInPoint.v - ego.entryPoint.v) / ego.entryPoint.a;
    ego.turnInPoint.t = ego.entryPoint.t + ego.turnInPoint.dt;
    ego.turnInPoint.ds = ego.entryPoint.a / 2.0 * ego.turnInPoint.dt * ego.turnInPoint.dt + ego.entryPoint.v * ego.turnInPoint.dt;
    ego.turnInPoint.s = ego.entryPoint.ds + ego.turnInPoint.ds;

    % Define the ego dynamics on "Acceleration_point"
    ego.accelerationPoint.a = a_accelerating;
    ego.accelerationPoint.v = ego.turnInPoint.v;
    ego.accelerationPoint.ds = phi_turning * r_turning;
    ego.accelerationPoint.s = ego.turnInPoint.s + ego.accelerationPoint.ds;
    ego.accelerationPoint.dt = ego.accelerationPoint.ds / ego.accelerationPoint.v;
    ego.accelerationPoint.t = ego.turnInPoint.t + ego.accelerationPoint.dt;

    % Define the ego dynamics on "Exit_point"
    ego.exitPoint.a = 0.0;
    ego.exitPoint.v = v_exit;
    ego.exitPoint.dt = (v_exit - ego.accelerationPoint.v) / a_accelerating;
    ego.exitPoint.t = ego.accelerationPoint.t + ego.exitPoint.dt;
    ego.exitPoint.ds = a_accelerating / 2.0 * ego.exitPoint.dt * ego.exitPoint.dt + ego.accelerationPoint.v * ego.exitPoint.dt;
    ego.exitPoint.s = ego.accelerationPoint.s + ego.exitPoint.ds;

    %
    % Define the position of "Entry_Point"
    ego.entryPoint.x = intersection.width - intersection.radius - intersection.lane.width / 2;
    ego.entryPoint.y = 0.0 - intersection.radius - ego.turnInPoint.ds;

    % Define the position of "Turn_in_Point"
    ego.turnInPoint.x = ego.entryPoint.x;
    ego.turnInPoint.y = 0.0 - intersection.radius;

    % Define the position of "Acceleration_point"
    ego.accelerationPoint.x = intersection.width;
    ego.accelerationPoint.y = 0.0 + intersection.lane.width / 2.0;

    % Define the position of "Exit_point"
    ego.exitPoint.x = ego.accelerationPoint.x + ego.exitPoint.ds;
    ego.exitPoint.y = 0.0 + intersection.lane.width / 2.0;
end
```

Listing 1: Function for the calculation of the theoretical ego motion model. It computes the dynamics of the ego vehicle at each phase and the position in the world model of the transition points between the phases.

The *entry point* represents the location in the world model, where the ego is awake of the intersection and starts reducing its velocity until it reaches the *turn in point* and goes around the corner. The next step is the merging into the traffic on the major street. It is indicated in phase 3 of the motion model, where the ego starts increasing its velocity from the *acceleration point* until it reaches the maximal allowed speed. This is defined as the *exit point* and denotes the transition of phase 4 into phase 5. The temporal and spatial boundaries of a scene are calculated by the model and the start and end of an observation can be defined.

Target motion model

The motion of a target vehicle is defined as a drive with a constant velocity. An assumption is made that such a vehicle drives along the major street with the maximum allowed speed (= 50km/h see Table 3) and keeps a constant safety gap of 1.5s (see Table 3) to the objects in front. When the ego object performs it maneuver, this safety measure should be not violated. Therefor the worst case is observed. When the ego object is exiting the scene, the target should be 1.5s behind it. In order to calculate the theoretical entry point of the target into the scene a motion model was defined as a function. With the use of a backwards calculation and the motion model of the ego object the location of the target according to the ego motion in the world model can be computed. The method is defined in listing 2 and the computed results are listed in Table 5. A graphical illustration of the target motion model is given in Figure 16.

```
function [ target ] = TargetParameter(egoParameters, v_target, ttl, ego_length, intersection)
    parameters = struct('x', 0.0, 'y', 0.0);
    target = struct('entryPoint', parameters, 'turnInPoint', parameters, 'accelerationPoint', parameters, 'exitPoint', parameters);

    % Define the position of a target, when the ego object is at the "Exit␣Point"
    target.exitPoint.x = egoParameters.exitPoint.x - ego_length - ttl * v_target;
    target.exitPoint.y = intersection.lane.width / 2.0;

    % Define the position of a target, when the ego object is at the "Acceleration␣Point"
    target.accelerationPoint.x = target.exitPoint.x - egoParameters.exitPoint.t * v_target;
    target.accelerationPoint.y = intersection.lane.width / 2.0;

    % Define the position of a target, when the ego object is at the "Turn␣in␣Point"
    target.turnInPoint.x = target.accelerationPoint.x - egoParameters.accelerationPoint.t * v_target;
    target.turnInPoint.y = intersection.lane.width / 2.0;

    % Define the position of a target, when the ego object is at the "Start␣Point"
    target.entryPoint.x = target.turnInPoint.x - egoParameters.turnInPoint.t * v_target;
    target.entryPoint.y = intersection.lane.width / 2.0;
end
```

Listing 2: Function for the calculation of the target motion model. It computes the position of an target vehicle in the world model according to the ego motion and a safety distance measure TTC.

The entry point of a target object is in the chosen parameter configuration $P_{target,entry} = (-170.11m, 1.5m)$. This means that, when the ego object entries the scene at $P_{ego,entry}$, all objects that have passed the point $P_{target,entry}$ are influenced by the motion of the ego and called targets.

Parameter	Unit	Entry point	Turn in point	Acceleration point	Exit point
x	[m]	-170.11m	-147.94m	-77.26m	19.52m
y	[m]	1.5m	1.5m	1.5m	1.5m

Table 5: The location in the world model of the target object considering a worst case scenario. Through backwards calculation the entry point of a target into the scene is located.

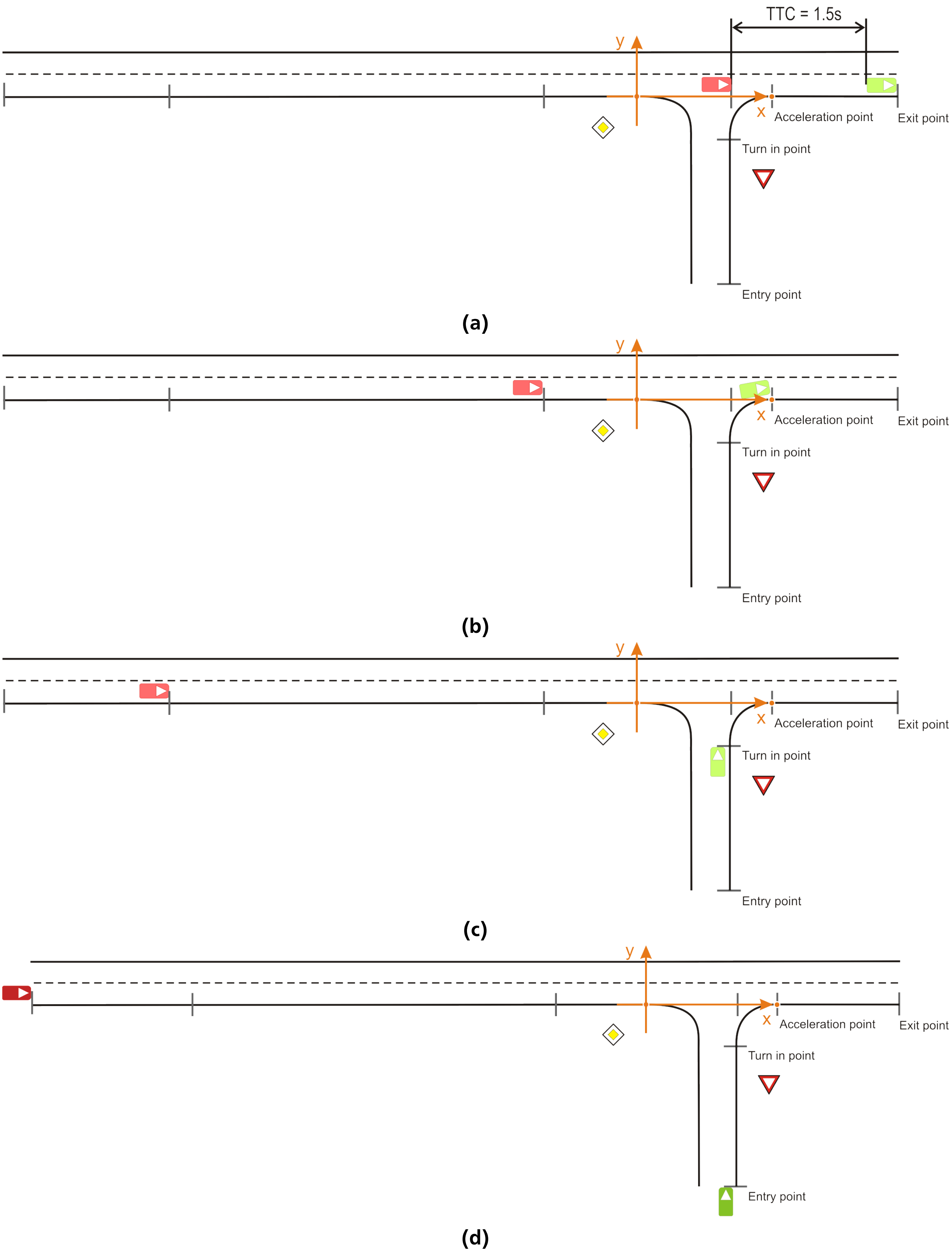


Figure 16: The location and an target vehicle in the world model according to the motion of the ego vehicle.

4.1.5 The Theoretical World Model

This section summaries the theoretical deliberations and definition in the complete theoretical world model. At first the urban area was specified and the type of urban intersection in interest was defined. Then a regulation for the traffic was selected with respect to allow the implementation of a flowing traffic. The possible situations at the defined intersection were observed and a sample situation, that embody driving behaviour inter-dependencies, was ruled for the goal of the thesis. The model was extended by the roles of the participants in the traffic situation and their theoretical motion was modeled in detail. Thus the boundaries of the Area-of-Interest (AOI) could be computed. The theoretical model for the problem analysis in this thesis was completed and is illustrated in Figure 17. It is the reference point for the further engineering on the driving behaviour inter-dependencies for the purpose of safe autonomous vehicle.

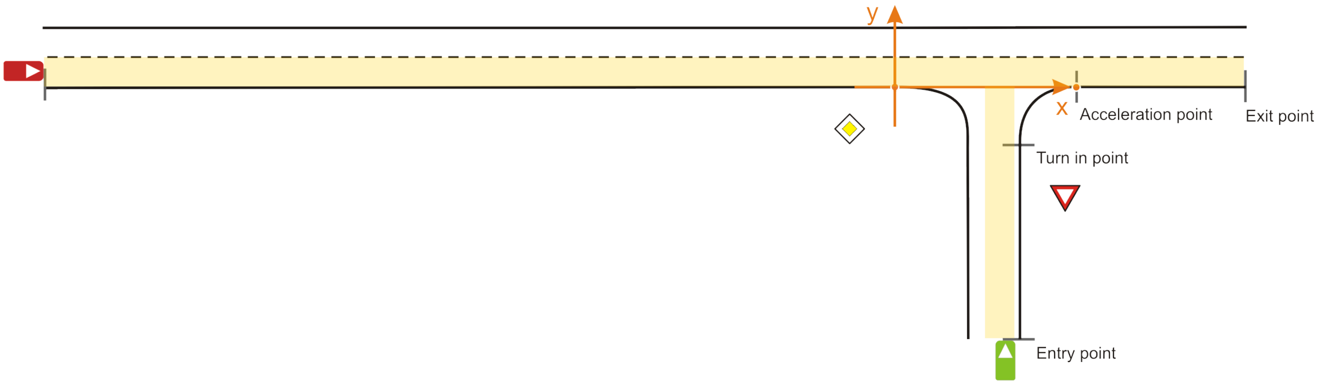


Figure 17: Theoretical model of the intersection.

Parameter	Unit	min	max
x	[m]	-170.11m	44.36m
y	[m]	-22.16m	1.5m

Table 6: Boundaries of the world model AOI.

4.2 Data Sources

One of the goals of the thesis is to identify the required data sources in order to analyze the traffic situation and gather information about the driving behaviour inter-dependencies. The research of the related works in section 2 shows that there is no other systems handling particularly this problem and for that reason no finite set of data source can be defined.

Still this work attempts to identify possible direction in the search of data sources and could identify three main categories as illustrated in Figure 18. They are based on the conclusions of the related topics from the literature research.

As the goal is to engineer on driving behaviour inter-dependencies one need the data about the motion of the ego object and the target(s). Williams used in her experiments [14] data about the driver itself. She could analyze the driver behaviour tracking its eyes movement, control of the vehicle and personal profile. In [8] a description is given about the possibility to analyze the driver or model it by the use of driver related data sources.

Section 4.1.3 defines the traffic situation in interest and section 4.1.4 simplifies the world model to two types of traffic objects - ego and target(s). In order to expand the analysis one should consider to observe the environment. Therefor a data source for detection of other objects and participants should be obtained.

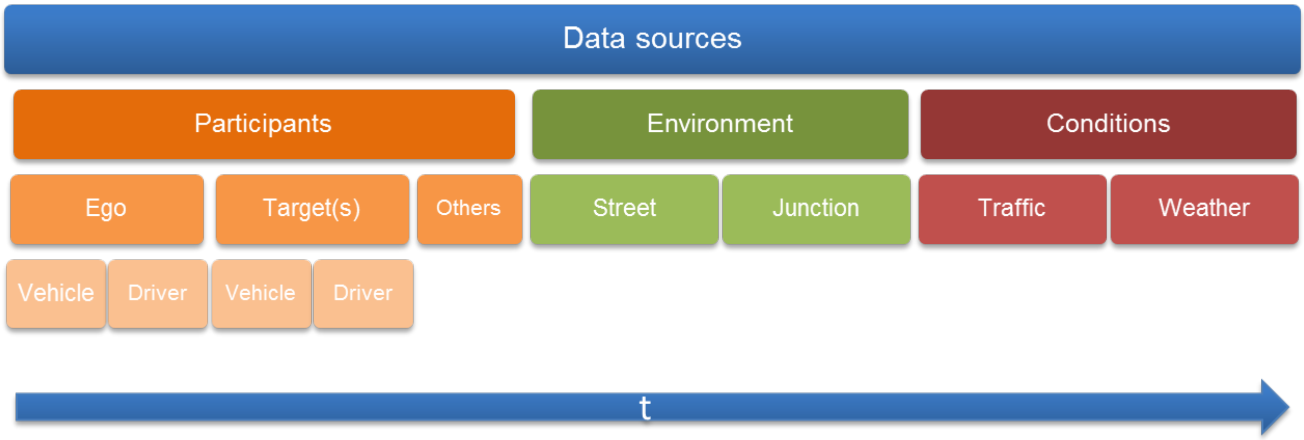


Figure 18: Theoretical data sources.

Maier performed experiments at 19 different urban intersection [13]. The characteristic of the intersection did not show any significant effect over the traffic situation, but the regulation of the traffic at the intersection did. They suppose that pedestrians and non-motirized participants such as cyclists may influence the driver behaviour, but could not give an observation of this thesis.

The further observation of the data sources leads to the category with the conditions for the time of the occurrences. In order to rule out other variables, that may or may not influence the driving behaviour, one need to observe data about the weather and traffic condition, and a time dependent information such as time of day, holidays etc..

5 Inter-dependencies Problem Instance

The focus on the problem about driving behaviour inter-dependencies is set on the analysis of the problem in a realistic way. In the previous chapter the characteristics of the issue was defined and the topic was described in theory. This is the reference point for the further steps in this work. In this chapter the problem analysis is shifted to the real world. Based on the theoretical definitions an instance of the theoretical world model is found and a novel concept for data collection in correspondence to the issues is realized. This leads to a series of challenges and a comparison between the theory and the praxis.

In the following section a real world model for the problem is successively constructed in correspondence to the theoretical preconditions and additional practical limitations. The data collection concept is then applied on the found instance and a set of realistic data is recorded for the further analysis of the problem.

5.1 Real World Model

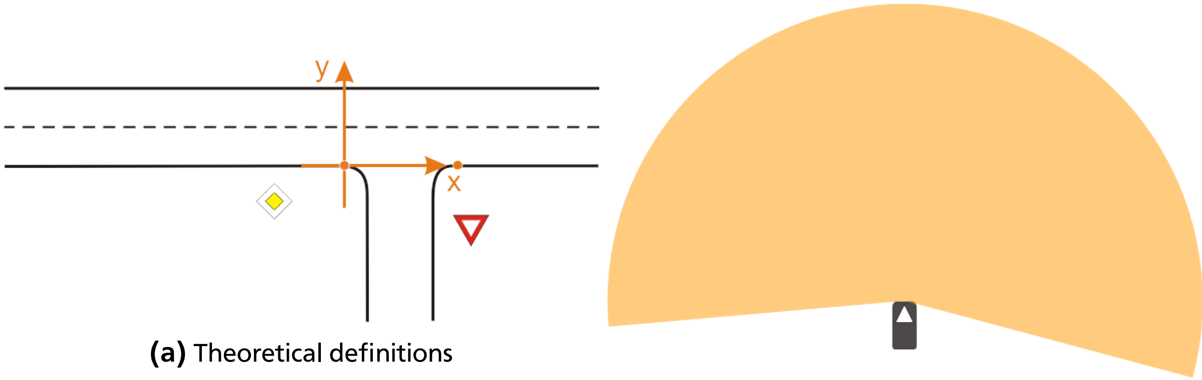
The real world mode should suit the theoretical definitions from section 4.1. This is the main requirement and therefor a realistic instance of an urban intersection with the specified traffic regulations should be found. It is required for the collection of realistic data needed for the analysis of the driving behaviour inter-dependencies. The following sub sections will review the challenges in this task and the accomplished results.

5.1.1 Theoretical Definitions and Practical Limitations

The theoretical definitions are the reference point for the search of an intersection, but there are additional limitations and constants in order to handle the problem in a realistic matter as well due to the chosen concept for the data collection. An instance of the defined intersection can be found in the real world traffic or under laboratory conditions e.g. testing ground. At the beginning of the work an initial tests were organized and performed on the test track of the Institute of Automotive Engineering at Technische Universität Darmstadt (FZD) in Griesheim, Germany (A description of the experiments can be found in section 8.3).

The collected data showed that the traffic situation can be analyzed with the chosen concept, but the conditions for the drivers was not realistic due to the fact that the density of the traffic and the demand of the situation can not be variated - additional test drivers and test vehicles, safety regulations. Therefor the use of an replica of an intersection was out ruled. An intersection in a real world urban area should be found.

Considering the participants of a traffic situation and the collection of the data additional limitations are defined. A sample group of drivers can be used in order to reproduce a traffic situation. They become a task sheet and drive along at an intersection while their data is collected. The problematic with the sample group is the fact that there is a certain learning effect, when a driver repeats the same task multiple times. This could be prevented or minimized, if one uses a large group of drivers. In combination with this consideration one should define how the data of a traffic scene is collected. This could be done in two ways - on-line or off-line. On-line means in this context, that the data are recorded directly on the vehicles. Therefor a test vehicle or each participant's vehicle should be equipped with the needed hardware and it should provide the data collection interface. This method is on the one hand too costly and time consuming and on the other hand has the significant disadvantage that the driver of the vehicle is aware that she/he is observed and its driving data is collected. This could lead to changes of her/his driving habits and deliver unrealistic data. Therefor an off-line method is chosen. Off-line means that the occurrence is taken from the perspective of an observer. The actual data collection remains undetected and the participants of the traffic situation are unaware of the fact that their data are part of the research. This facts rule out the need of sample group and define one of the major limitations and challenges for the search of an realistic real world instance.



(a) Theoretical definitions

(b) Practical limitations.

Figure 19: The theoretical definitions and practical limitations for the real world model.

The final consideration is what kind of data could be collected. This is predefined as the concept for the data collection is given. A test vehicle is placed by the FZD at the disposal. It is equipped with tree laser scanner sensors, that can detect the surroundings in front of the vehicle. It is described in detail in section 5.2.1 and for the purpose of this section only a simplified illustration is shown in Figure 19b. This sets the final precondition and the search for an instance can be initiated. Considering the theoretical definitions and the practical limitations converts the search of an instance to the challenge to find a replica of the theoretical intersection under real world urban conditions and observe the traffic situation with the use of the given data collection concept.

5.1.2 Intersection Selection

A set of criteria is defined considering the theoretical definitions and practical limitations that an intersection should fulfill in oder to be selected as suitable.

The identified criteria are listed in Table 7. The criteria about the intersection could be found in the first section. They are based on the theoretical definitions and require that there is no other intersection with traffic lights directly before or after the intersection in interest. If there is such an intersection, then on the one hand it has higher priority [23] and on the other hand it controls the traffic and makes it deterministic. The additional requirements generated by the data collection concept are depicted in the second section and the criteria describing the defined traffic situation in focus are listed in the last one two sections about the major and minor street. The acceptable answer for a given criterion are marked in bold. If there is no answer marked in bold than the criteria has not hard conditions and each of the answer could be valid in combination with other criterion.

The search of an intersection was performed in the area of Darmstadt, Germany. At first a digital map of the region was observed to identify possible instances. The results were visually validated and the most suitable were identified. In the last step of the selection a test measurement was performed at the intersection in order to check all of the criteria.

The results are listed in Table 8. The protocols of the test of the criteria at each intersection are attached in appendix 8.3. Only one intersection could be found that fulfills all the defined criteria. The rest of the intersection was matched to be unsuitable mostly, because there was no possibility to stay as observer, the detection range was to low or the detection was influenced by the parking position of the vehicle.

Only intersection, that could pass all of the criteria and was selected for the further analysis in this work, is illustrated in Figure 20.

ID	Intersection	Value
J1	Are there traffic lights near the intersection?	yes / **no**
J2	Is there a "Right of way" sign on the major street? (No. 301 or 306)	**yes** / no
J3	Is there a "Give way" sign on the minor street? (No. 205)?	**yes** / no
ID	**Parking**	**Value**
P1	Is it possible to park without breaking any rules?	**yes** / no
P2	Is the orientation of vehicle valid for the sensors?	**yes** / no
P3	Would the vehicle disturb the traffic?	yes / **no**
P4	It is possible to stay with working motor or is there a possibility to connect to a power supply?	**yes** / no
ID	**Major street with right of way**	**Value**
R1	Is the view to the street free of obstacles?	**yes** / no
R2	Is the detected range satisfactory?	**yes** / no
R3	Is the maximum allowed speed 50 km/h?	**yes** / no
R4	Is there a bicycle lane?	yes / no
ID	**Minor street with give way regulation**	**Value**
G1	Is the view to the street free of obstacles?	**yes** / no
G2	Is the detection range satisfactory?	**yes** / no
G3	Is the maximum allowed speed 50 km/h?	**yes** / no
G4	Is there a crosswalk for pedestrians?	yes / no
Conclusion		
1 - SUITABLE	2- SUITABLE TO A LIMITED EXTENT	3 - UNSUITABLE

Table 7: All criteria an real world intersection should fulfill in order to be chosen for the analysis.

(a) View at the intersection **(b)** View from the major street **(c)** View from the minor street

Figure 20: Real world instance of an intersection. Nordring and Bunsenstraše in Griesheim, Germany.

No.	Location		Intersection			Parking				Major street				Minor street				Conclusion
	1st St.	2nd St.	J1	J2	J3	P1	P2	P3	P4	R1	R2	R3	R4	G1	G2	G3	G4	
1	Nieder-Ramstädter Str.	Kiesstr.	~~yes~~	yes	yes	yes	~~no~~	no	yes	~~no~~	~~no~~	yes	no	~~no~~	~~no~~	yes	no	3
2	Nieder-Ramstädter Str.	Hoffmann Str.	no	yes	yes	yes	~~no~~	no	yes	yes	~~no~~	yes	no	~~no~~	~~no~~	yes	no	3
3	Pützerstr.	Lindenhofstr.	~~yes~~	yes	yes	~~no~~	yes	no	yes	yes	~~no~~	yes	yes	yes	yes	yes	no	3
4	Heinrichstr.	Gervinusstr.	~~yes~~	yes	yes	yes	yes	no	yes	~~no~~	~~no~~	yes	no	yes	~~no~~	yes	no	3
5	Pützerstr.	Lindenhofstr.	~~yes~~	yes	yes	~~no~~	yes	~~yes~~	yes	yes	yes	yes	yes	yes	~~no~~	yes	no	3
6	Frankfurterstr.	Büdingerstr.	no	yes	yes	yes	yes	no	yes	yes	~~no~~	yes	yes	yes	yes	yes	no	3
7	Holzhofallee	Schöfferstr.	~~yes~~	yes	yes	yes	~~no~~	no	yes	yes	~~no~~	yes	no	~~no~~	~~no~~	yes	no	3
8	Karlstr.	Hölgestr.	~~yes~~	yes	yes	yes	yes	no	yes	yes	~~no~~	yes	no	~~no~~	~~no~~	yes	no	3
9	Pallaswiesenstr.	Schloßgartenplatz	no	yes	yes	yes	~~no~~	no	yes	~~no~~	~~no~~	~~no~~	no	~~no~~	~~no~~	yes	no	3
10	Darmstädter Str.	Karl-Marx-Str.	~~yes~~	yes	yes	yes	~~no~~	no	no	~~no~~	~~no~~	yes	no	~~no~~	~~no~~	yes	no	3
11	Nordring	Bunsenstr.	no	yes	yes	yes	yes	no	yes	yes	yes	yes	no	yes	yes	yes	no	1
12	Aschaffenburger Str.	Max-Planck-Str.	no	yes	yes	~~no~~	yes	~~yes~~	yes	~~no~~	~~no~~	yes	no	yes	yes	yes	no	3
13	Groß-Umstädter Str.	Max-Planck-Str.	no	yes	yes	yes	yes	no	yes	yes	~~no~~	yes	no	yes	~~no~~	yes	no	3
14	Groß-Umstädter Str.	Ringstr.	no	yes	yes	~~no~~	yes	no	yes	yes	~~no~~	yes	no	~~no~~	~~no~~	~~no~~	no	3

Table 8: List of examined intersections in the search of a suitable real world instance.

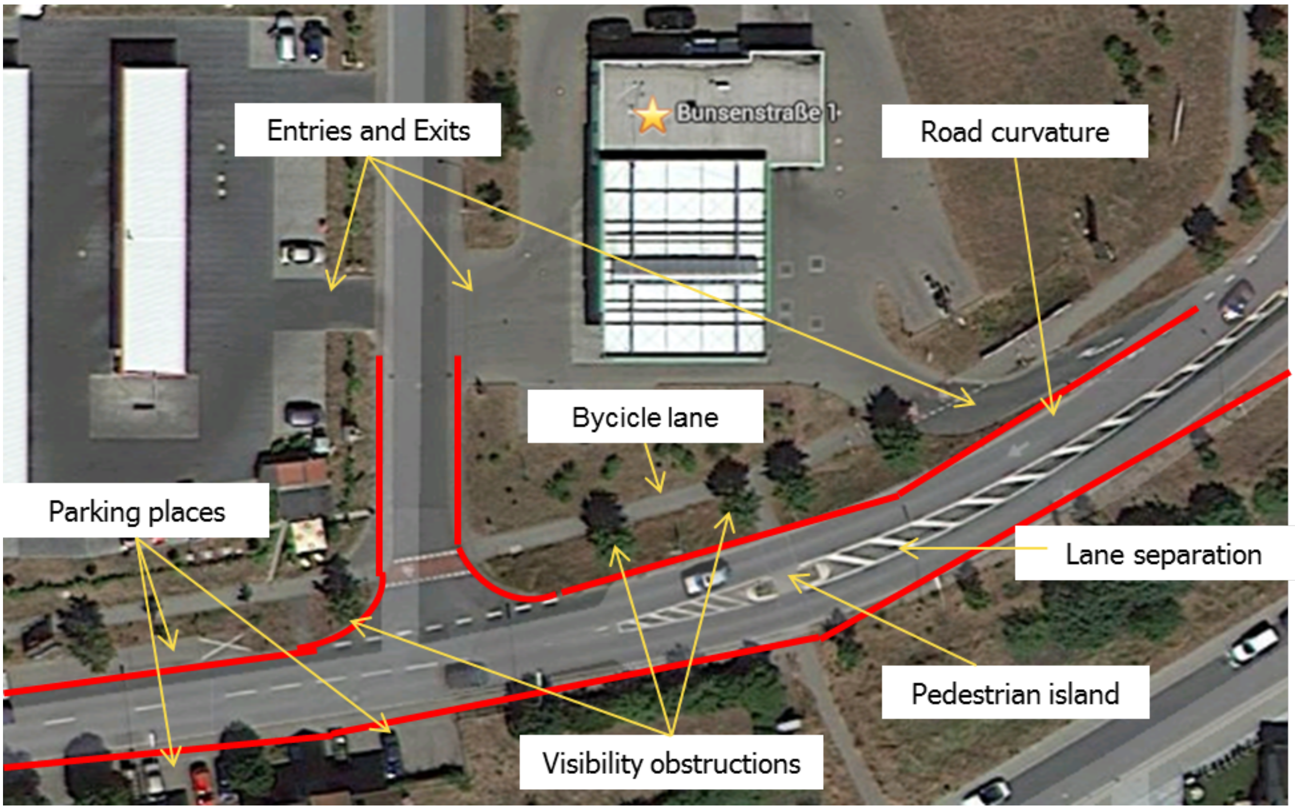


Figure 21: Deviation of the real world intersection instance to the theoretical representation of an urban intersection. Source: GeoBasis-DE/BKG Google , 2015-01-10

Parameter	Unit	Description	Value
Intersection parameters			
r_{corner}	[m]	The radius of the corner at the intersection of the major and minor street at the right side.	13.00m
$w_{intersection}$	[m]	The width of the intersection measured on the x axes.	28.00m
Minor street parameters			
$v_{max,minor}$	[m/s]	The maximum allowed speed on the minor street.	9.90m/s
w_{minor}	[m]	The width of the minor street.	5.00m
Ego vehicle parameters			
$r_{turning,ego}$	[m]	Radius of turning.	12.875m

Table 9: Changes in the parameters used for the modeling of the intersection geometry and regulation specifics, ego and target dynamics dynamics

5.1.3 Deviations to Theoretical Model

In this section a comparison between the selected intersection and the theoretical model is made. This impresses the challenges of the praxis.

The intersection model defined in section 4.1.3 is complete and serves for the theoretical observation and definition of the problem in focus. Although the model is defined in detail, it has to be much more complex to represent an intersection entirely. Some of the deviations of the real world instance to the theoretical observation of the world are depicted in Figure 21. If the theoretical definitions are used for the further analysis, then the representation of the problem will be falsified.

Parameter	Unit	Entry point	Turn in point	Acceleration point	Exit point
t	[s]	0.0s	0.81s	4.53s	6.34s
dt	[s]	0.0s	0.81s	3.72s	1.81s
a(t)	[m/s^2]	-5.50m/s^2	0.0m/s^2	4.67m/s^2	0.0m/s^2
v(t)	[m/s^2]	9.90 m/s^2	5.44m/s^2	5.44m/s^2	13.89m/s^2
s(t)	[m]	0.0m	6.22m	26.44m	43.93m
ds(t)	[m]	0.0m	6.22m	20.22m	17.49m
x	[m]	15.00m	15.00m	28.00m	45.49m
y	[m]	-17.72m	-11.50m	1.50m	1.50m

Table 10: The corrected location in the world model and the dynamics of the ego vehicle thought each phase of the defined motion model.

Parameter	Unit	Entry point	Turn in point	Acceleration point	Exit point
x	[m]	-141.50m	-130.23m	-67.36m	20.65m
y	[m]	1.5m	1.5m	1.5m	1.5m

Table 11: The corrected location in the world model of the target object considering a worst case scenario. Through backwards calculation the entry point of a target into the scene is located.

In order to correct the assumptions a test measurement was performed at the intersection. The main purpose was to calculate the exact deviation in the geometry of the intersection and to adapt the world model (the curvature of the road was not taken into account). The analysis of the dynamics of the vehicles was limited only to the validation of the entry velocities. It reviewed that the vehicles driving on the minor street are not approaching the intersection with the expected velocity. The measured maximal ego velocity was 9.90m/s (=35.5 km/h). The assumptions about the world model was corrected and are listed in Table 9.

The motion of the ego and target object was calculated with the values of the real world instance and can be seen in Table 10 and 11.

5.1.4 The Real World Model

The verification of the theoretical definition from section 4.1 on a real world instance shows, that they can hold only to certain extent. The model has to be adapted to the real world conditions. The real world model was defined performing the calculations for the ego and target motion with the new parameters . It will be used in the next steps of this thesis and the further observation will be based on it.

Figure 22 illustrated the word model after the adaptation to the real conditions. The Area-of-Interest (AOI) is changed. Table 12 depicts the boundaries of the defined situation. In comparison to the theoretical model the region on x direction is 27.48m smaller and in y direction by 4.44m. This reduces the AOI by 29.17 %.

5.2 Data Sources

This section is the practical equivalent for the theoretical observation of the possible data sources to analyze the driving behaviour inter-dependencies at the defined intersection. In section 4.2 the reader was introduced to the categories of data sources that could be identified from the related work. No other work could be found that tries to solve the problem. As there are no reference this work attempt to solve the problem in a novel way. The following sections will expose the used concept for the detection of the environment and describe the collected data.

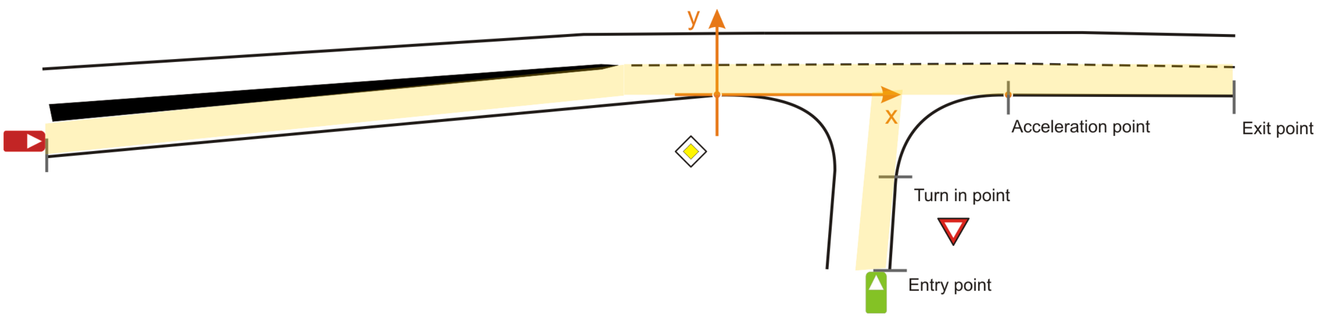


Figure 22: The real world intersection model.

Parameter	Unit	min	max
x	[m]	-141.50m	45.49m
y	[m]	-17.72m	1.5m

Table 12: Boundaries of the world model AOI.

5.2.1 Environment Detection Concept

A test vehicle was placed at the disposal by the Institute of Automotive Engineering at Technische Universität Darmstadt (FZD). It is equipped with 3 laser scanner sensors that are integrated into the front of the vehicle (see Figure 23). They allow to detect moving and static objects in front of the vehicle with a radial range from about 50m and 200°. The interface provides a data stream of scan points and objects at a frequency of 25Hz. Their format is described in section 8.3.

In general the scan points are low level information of the surroundings. A special software analyses this data. It segments the scan points and generates segments as a group of associate points. It then tracks the data and builds an object list. Each of the objects has a position, size, outline and velocity. It transforms the data into the vehicle coordinate system so the detected objects can be located in relation of the vehicle position. The sensors are developed to work in an automotive environment and therefor their main features is the ability to detect multiple objects, track and classify them. This gives the opportunity to use them for the environment detection in this work. As their are implemented in a vehicle the idea of the concept is to set the test vehicle as an observer at the intersection and use the hardware to detect the surroundings and collect data.

This is a novel approach and is associated with a series of challenges. The first influence of the concept on the project appears in section 5.1.2, where the selection of a suiTable real world intersection was adapted in such a way that the test vehicle can be used for the data collection (see Table 7 with the criteria). The chosen intersection was primary selected, because it was the only one that fulfilled the requirements set by idea to use the test vehicle as observer. The main problem is to find a parking spot

(a) (b) (c)

Figure 23: Test vehicle with three laser scanner integrated in the front of the car.

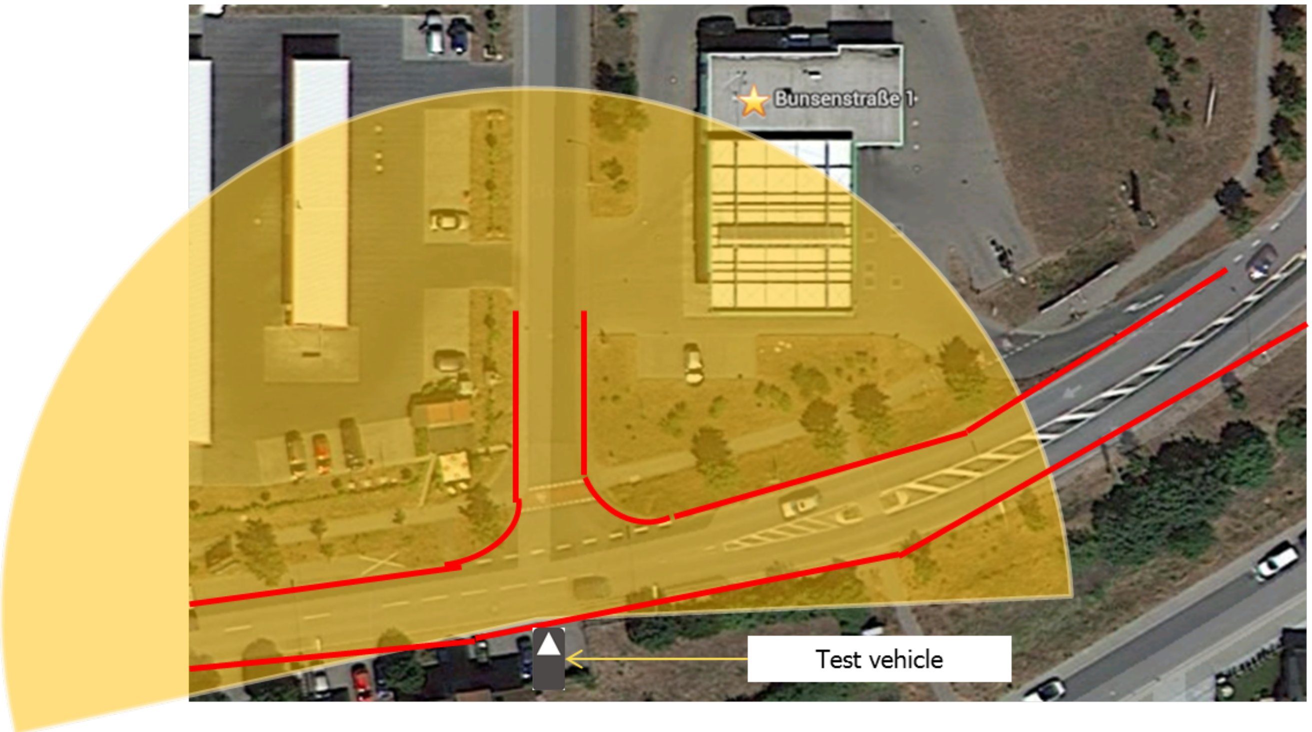


Figure 24: Deviation of the real world intersection instance to the theoretical representation of an urban intersection. Source: GeoBasis-DE/BKG Google , 2015-01-10

that has clear view (free of obstacles blocking the view) on the occurrence at the intersection and to accomplish the detection of a a significant percent of the Area-of-Interest (AOI).

Figure 24 illustrates how the test vehicle was used on the actual intersection. It could by parked on the opposite side of the intersection. The sensor range is sufficient on the minor street, but did not cover the complete AOI on the major street. Nevertheless this is the most realistic collocation that could be found within the scope of this work.

5.2.2 Sensor Calibration

The state and condition of the sensors was at the beginning of the thesis unknown. There was a documentation of the mounting points and the orientation of the three laser scanner and this values were entered into the data recording software. The results of the object recognition and object reflection was unsatisfactory. The visualization shows artifacts in the data. One of the obvious problem was that some of the objects was detected as multiple objects. This was the reason to perform a precise calibration of the sensors and validate the mounting points and the orientation angles of the three sensors.

The calibration procedure was organizes according to the documentation of the sensor manufacturer. The adjustment is performed in 3 steps that must be repeated for each sensors.

1. Determine the exact mounting position
2. Adjust the pitch angle
3. Adjust the yaw angle

This procedure was performed in the workshop at FZD. For this purpose the front bumper of the test vehicle was dismantled. This gave the opportunity to measure the exact distance from each sensor to the origin of the vehicle's coordinate system.

(a) Test vehicle dimension marked on the ground

(b) Test vehicle positioned on the marked area

(c) Visual validation of the front point with the marker

(d) Visual validation of the front axes with the markers

(e) Visual validation of the rear axes with the markers

Figure 25: Test vehicle with three laser scanner integrated in the front of the car.

As the ground of the workshop is level the adjustment of the pitch angle were performed there. Due to a space limitations the yaw angle adjustment had to be done outside the workshop. This led to a field test on the testing ground of FZD in Griesheim. The next paragraphs describes it.

Positioning of the test vehicle

The adjustment of a vehicle requires perfect environment conditions so that the level of the ground do not influence the adjustment parameters. a reference point is required which exact position should be known. Hence the location and the positioning of the test vehicle on the testing ground are one of the important factors to determine an exact adjustment parameters. For this purpose was defined a model for positioning of the test vehicle in respect of the field conditions.

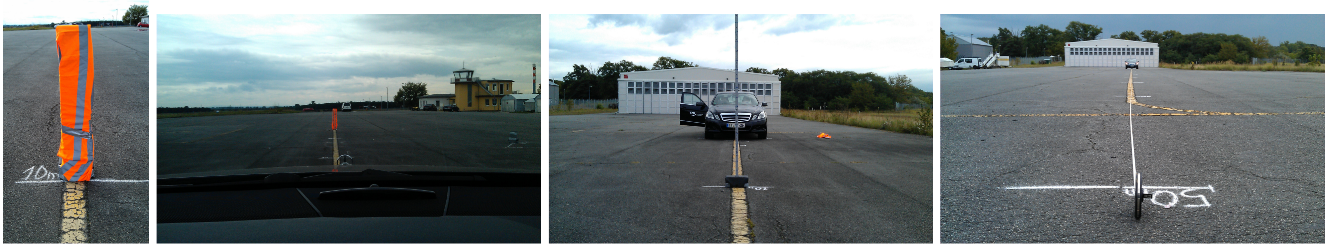
As the vehicle dimensions are known (see appendix 8.3) the ground was marked according to them so while positioning the vehicle the driver has 5 reference points to validate the orientation of the vehicle to the reference line. Figure 25 shows the model in praxis. The expected position of each wheel and of the middle point of the front are marked in respect to a reference point with coordinates (0, 0). This allows an easy way to define a measuring area on the field while making advantage of a given field features such as the road marking that could be seen in Figure 25a.

Yaw angle calibration

The calibration of the yaw angle was performed with a reference object that was set in front of the test vehicle and moved from 10m up to 50m in 10m steps on the reference line. The described procedure is demonstrated in Figure 26.

Longitudinal and lateral accuracy

After all adjustment was met the values was validated in a test of the sensor's accuracy in longitudinal and lateral direction. How the test was performed is demonstrated in Figure 26. For the purpose of exact measurement was used an reference object with a width of about 4cm. This parameter of the objects



(a) (b) (c) (d)

Figure 26: Using a reflection object (a) for the adjustment of the yaw angle (b) and testing the longitudinal an lateral accuracy of the sensors with a reference object (c) that is moved along the reference line.

Sensor	10m	20m	30m	40m	50m
left	43.80	43.70	43.60	-	-
middle	0.20*	0.20	0.20	-	-
right	unknown	-44.80	-44.80	-	-

Table 13: Test result of the nominal sensor yaw angle setting.

Sensor	10m	20m	30m	40m	50m
left	43.60	43.60	43.50	43.50	43.4
middle	0.1	-0.1	-0.1	-0.1	-0.1*
right	-44.70*	-45.00	-45.0	-49.9	-49.9*

Table 14: Test result of the actual sensor yaw angle setting.

gives the opportunity to gave just one or a few reflection points, so measured value in longitudinal and lateral direction could be accurately detected.

The testing of the nominal sensor accuracy show that the sensors return corrupt lateral measurements. The entered rotation angles of the sensors were wrong. After performing an additional calibration and testing the angles were set to new more precise values that is recognizable by the achieved accuracy values in longitudinal and lateral direction.

Results

The calibration shows that due to wrong yaw and roll angle the sensors returned corrupt lateral values. The fusion was not capable to handle the wrong settings of the sensors and produced multiple instances of same objects on different locations. The test for recognizing the reason of the fault behaviour were repeated with the new values for the mounting position and the orientation angles of the three sensors. The measured values present a total improvement in regard to lateral accuracy. While observing the visualization no displacement of the reflection could be detected.

5.2.3 Data Collection

The next step of this work is to collect a set of data records. Therefor a field experiences were organized. The test vehicle was used to collect the occurrences at the selected intersection on three different days. In order to collect as much as possible different situation, the measurements were performed at different times (see Table 17). The time from 6am to 18pm could be covered. It appeared that before or after that time, due to the dimming conditions and the fact that the vehicles were driving with lights on, the test vehicle was disturbing the traffic. As it is equipped with additional hardware (see image 27) and has

Reference point		Nominal sensor accuracy		Actual sensor accuracy	
x [m]	y [m]	x [m]	y [m]	x [m]	y [m]
5.00	0.00	4.98	0.01	5.00	0.00
10.00	0.00	9.98	0.01	10.00	0.00
15.00	0.00	15.00	-0.02	15.00	0.00
20.00	0.00	19.99	-0.03	19.99	0.00
25.00	0.00	24.99	+0.06	24.99	0.00
30.00	0.00	29.99	0.00	29.99	0.00
35.00	0.00	35.02	0.22	34.99	0.00
40.00	0.00	40.03	0.16	39.99	0.00
45.00	0.00	45.00	-0.15	44.99	0.00
50.00	0.00	49.99	-0.17	49.99	0.00
55.00	0.00				
60.00	0.00				

Table 15: Longitudinal and lateral accuracy

Sensor	Mounting position			Orientation		
	x [m]	y [m]	z [m]	roll	pitch	yaw
left	3.445	0.674	0.364	0.00	0.00	43.6
middle	3.625	0.025	0.339	0.00	0.00	-0.1
right	3.487	-0.638	0.359	0.00	0.00	-45.0

Table 16: Laser scanner adjustment settings.

logos on it, it was easily discovered at that time. The few data records, that was collected before 6am or after 18pm was removed from the total data set in order to keep the data realistic. This observation was made by the person that took the measurements. Each of the measurements day is recorded in writing. The protocols could be found in section 8.3.

A statistic about the weather was taken and could be used in the further analysis of the data. As the data set of this work covers only three days where it was mostly sunny and cloudy, this information is not used. It could be helpful, when the data set is extended and there are more records.

Data Classification

During the measurement was identified that the situation in interest is to general. Even that this work focuses on a single situation analysis (see section 4.1.3) multiple variation could be perceived.

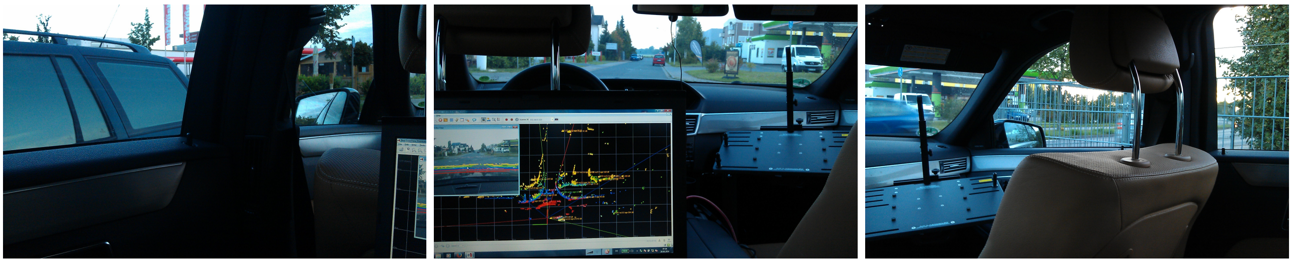
The situation of turning right at an intersection can be discretized in a two ways - by ego and targets. For the ego there are four different considerations - alone, vehicle in front, ego in the middle, vehicle behind. The targets can be discretized by their number. This defines a 4 by x matrix of different categories. The used categorization is the following:

1. Discretization by targets: 0, 1, 2, x

2. Discretization by obstacles on the minor street: none, single, multiple

3. Discretization by obstacles location on the minor street: ahead, in front, behind, nearing, in front and behind

4. Discretization by direction of the obstacles in the minor street: turn left, turn right



(a) (b) (c)

Figure 27: Inside of the test vehicle. Researcher view to the intersection.

Time of day	Day 1 Wednesday	Day 2 Thursday	Day 3 Friday
00:00			
01:00			
02:00			
03:00			
04:00			
05:00			
06:00			9
07:00		15	13
08:00	8	16	1
09:00	19	21	
10:00	16		26
11:00		18	28
12:00		34	26
13:00		17	9
14:00	37	12	
15:00	31		22
16:00		10	41
17:00		38	4
18:00		50	
19:00			
20:00			
21:00			
22:00			
23:00			
Sum	**111**	**231**	**179**
Total	521		

Table 17: Description of the collected data by time. In the time spots where no measurement was taken are let empty in the Table.

This generates a set of 14 x 4 = 56 categories as illustrated in Figure 28. After each data collection session the data was manually categorized and summarized. The resulting data is illustrated in Figure 29.

Weather	Day 1	Day 2	Day 3
sunny		x	x
cloudy	x	x	x
rainy			

Table 18: List of checked intersections for data collection

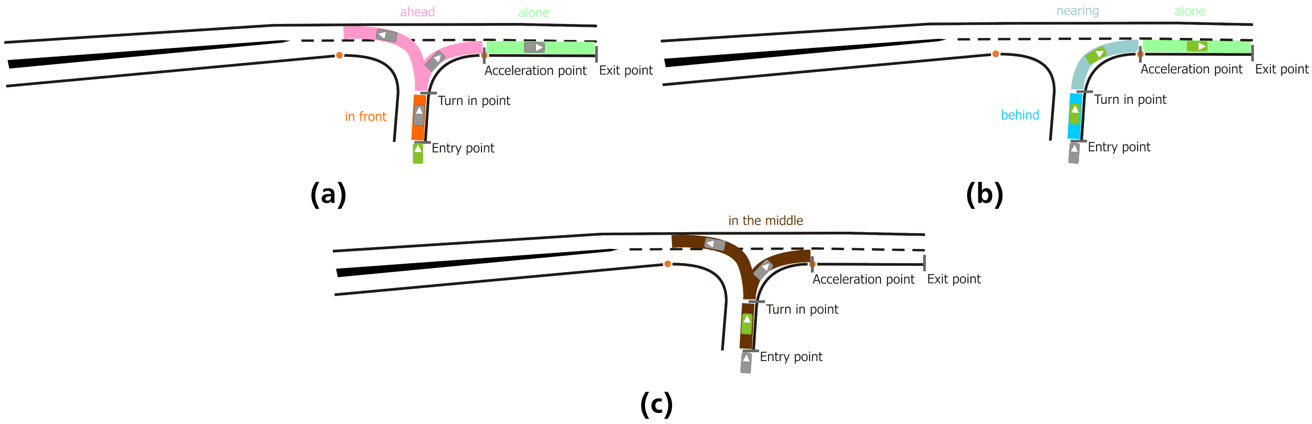
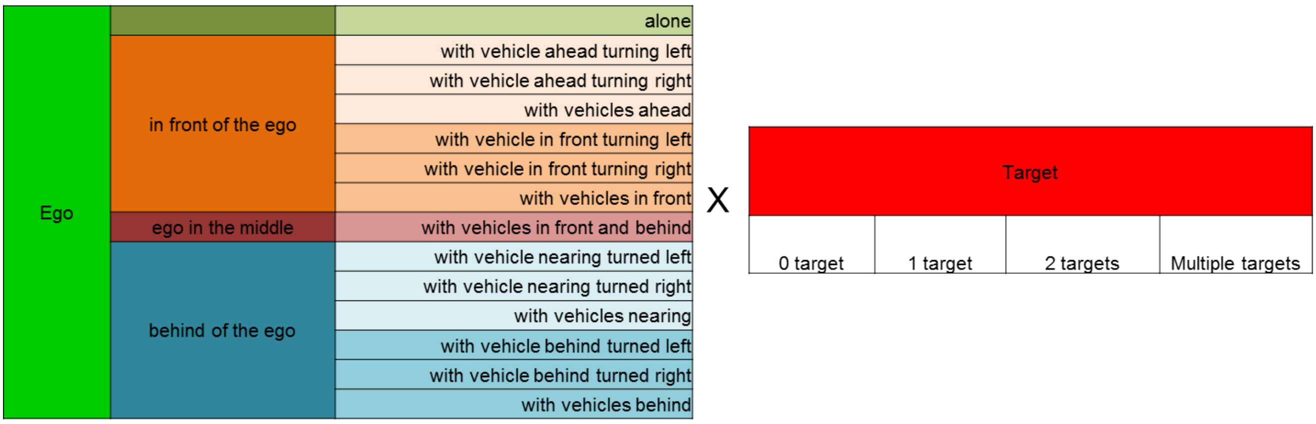


Figure 28: Categorization of the driving maneuver - turn right - regarding to the obstacles on the ego trajectory and their position in respect to the ego. In front and ahead (a), behind and nearing (b) and ego in the middle (c).

5.3 Summary

This concept represents one of the main challenges in this work. It combines the computer science and information technologies with the automotive engineering. On the one hand one should analyze the problem from the view point of an Advanced Driver Assistance System (ADAS) or an autonomous vehicle and on the other hand should analyze the problem with the application of computer science.

An real world instance of the problem could be sound the over 500 situations could be recorded with the novel environment detection concept. Nevertheless additional limitations of the world model had to made in order to proceed with the work. Even that only one situations was chosen in the theoretical observation of the problem, it is still challenging to analyze and detect all possible occurrences. The realistic data sources provide only the information about the motion of the vehicle as illustrated in Figure 30.



(a) Types of combination of participants for a right turn.

			Target			
			0 target	1 target	2 targets	Multiple targets
Ego	59,05%	59,05%	17,09%	14,89%	11,84%	15,23%
	19,12%	6,43%	0,34%	0,85%	0,00%	0,68%
			2,37%	1,35%	0,34%	0,51%
			0,00%	0,00%	0,00%	0,00%
		12,69%	0,85%	0,68%	1,52%	3,05%
			1,02%	0,68%	1,18%	2,37%
			0,34%	0,17%	0,17%	0,68%
	5,75%	5,75%	1,18%	1,02%	1,18%	2,37%
	16,07%	9,48%	1,18%	1,35%	0,34%	0,85%
			1,69%	1,86%	1,02%	0,68%
			0,17%	0,00%	0,34%	0,00%
		6,60%	0,51%	0,51%	0,51%	1,35%
			0,51%	1,02%	0,51%	1,52%
			0,00%	0,00%	0,00%	0,17%

(b) Types of combination of participants for a right turn.

Figure 29: Types of combination of participants for a right turn.

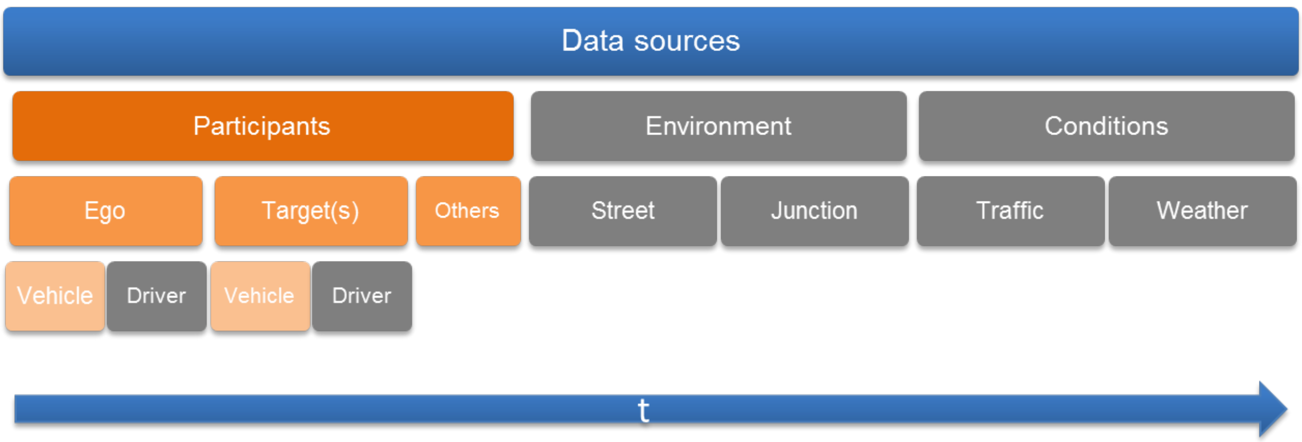


Figure 30: Realistic data sources.

6 Data processing

This section handles the problem about processing the data in such a way that it can be used in machine learning techniques. To accomplish this task a data processing pipeline has to be defined. The problem is described in the next section 6.1 as a black box, allowing to stay independent of its implementation. The following section 6.2 proposes a realistic implementation of the black box.

6.1 Theoretical black box

The pipeline is illustrated in Figure 31. It defines a data processing routine that treats the problem in a theoretical matter. This means that the pipeline is defined as a black box. It describes the logic of the single processes, but does not go any further into the realization of the pipeline. This allow an abstract view to the data processing problem that remains independent to the realization techniques.

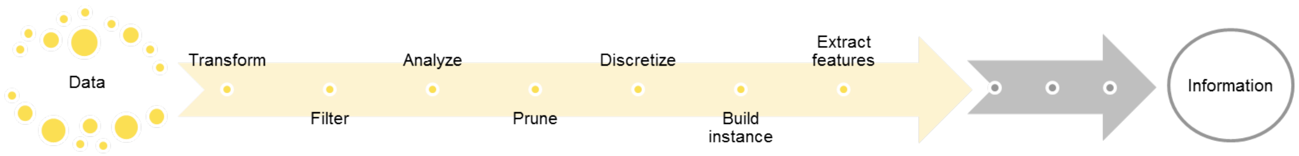


Figure 31: Structure of the data processing pipeline in theory.

6.1.1 Transform

The data in particular about the motion of the ego, targets and other participants, should be transformed into the fixed intersection coordinate system as it is collected in different coordinates. This makes the further interpretation and analysis of the data independent from the data sources.

6.1.2 Filter

A traffic scene is complex set of objects. Having a large set of data sources could lead to an large set of data that also could contain noise. At this step a filter could be helpful to reduce the quantity.

6.1.3 Analyze

This process has the main functionally to analyze the scene and find the objects in interest according to the definition of the world and problem model. The analysis step should identify the ego and the targets and mark them so they are recognizable between the rest of the objects in the data.

6.1.4 Prune

In theory the data is considered to be a continues stream. One has to prune each single situation in order to extract a single instance of the defined problem, therefore there is the need of this process. The output is the pruned data from the data stream containing just the traffic situation from the time point, where the ego passes the entry point, to the moment, where the ego exits the scene at the exit point.

6.1.5 The rest of the pipeline

The processes *Discretize*, *Build instance* and *Extract features* are define as abstract methods. This work does not cover them, because the internal logic of this processes is depending on the used machine learning techniques through the next steps. As at that point is not known how exactly the information will be extracted from the data, there is no reason to discuss possible definitions of this processes.

6.2 Practical Implementation

The structure of the realized pipeline is illustrated in Figure 32. One can recognize three additional processes in contrast to the theoretical definition (see Figure 31). They are resulting due to a practical problems linked with data quality and the laser scanner fusion software characteristics.

The following sections describe the realization of each single pipeline process in detail and give an overview about the problems related to working with real world data. Some of them are significant to the goal of this thesis and therefore listed at the end of each section.

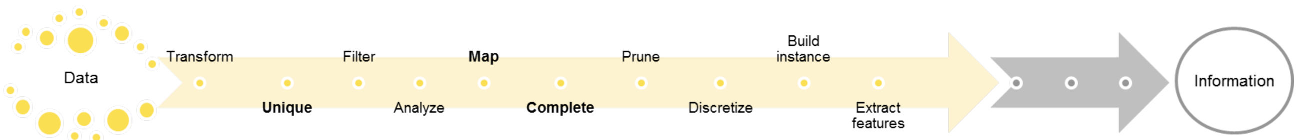


Figure 32: Structure of the realized data processing pipeline.

6.2.1 Transform

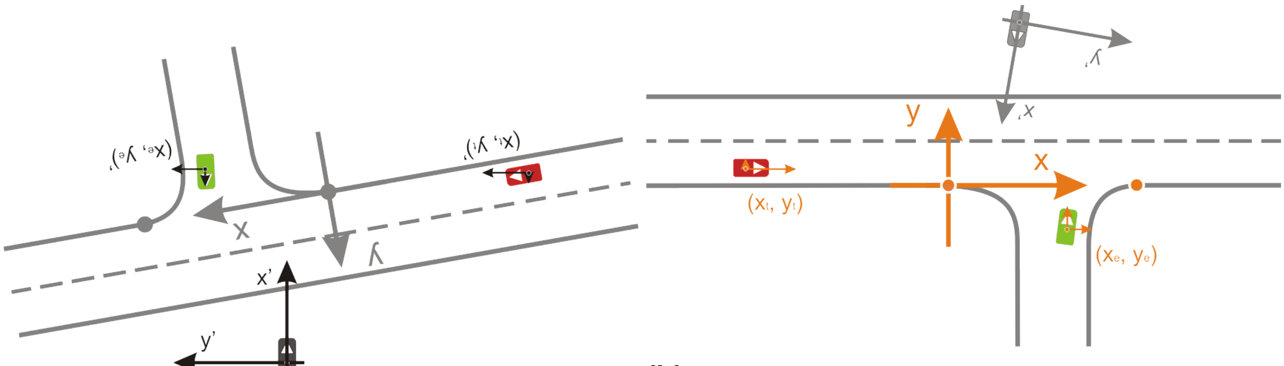
As the sensors are installed into a test vehicle, they are configured to work in the specified vehicle coordinate system. This means that all objects and scan points refer to the middle point of the rear axes of the test vehicle and their orientation is based to the x and y orientation of the vehicle coordinate system.

The world model has as origin the start point of the intersection. In order to transform the data into the world model one should first translate the test vehicle coordinate origin to the intersection origin and then rotate the objects according to the rotation of the test vehicle to the intersection. The final step is to adapt the coordinate axes as the intersection coordinate systems is in Cartesian format. This actions will result into a full transformation of the recorded data as illustrated in Figure 33.

$$x_t = x_v - x_{offset} \tag{4}$$

$$y_t = y_v + y_{offset} \tag{5}$$

$$x = x_t * cos(\psi) + y_t * sin(\psi) \tag{6}$$



(a) Coordinates of the data in row format

(b) Coordinates of the data after the transformation in Cartesian coordinate system

Figure 33: Data coordinates before and after the transformation.

$$y = -y_t * sin(\psi) + y_t * cos(\psi) \tag{7}$$

In order to successfully perform the transformation (translation and rotation), as defined in equations 4, 5, 6 and 7, one needs the values of three parameters - x_{offset}, y_{offset} and ψ. The first two parameters define the offset in x and y direction of the test vehicle origin point to the intersection origin point and ψ is the rotation angle of the test vehicle to the intersection.

$$x = -y_v \tag{8}$$

$$y = x_v \tag{9}$$

After the transformation the x and y values should be adapted according to equations 8 and 9. The transformation and adaptation of the coordinate axes should be performed for all properties of an objects that are used such as the object box center, object bounding box, and the absolute object velocity.

Problem - Reference points

One of the first challenges, while implementing the pipeline, is to find the values of the parameters - x_{offset}, y_{offset} and ψ. Therefor one need to know the position of the test vehicle to at least two points $P_1(x_1, y_1)$ and $P_2(x_2, y_2)$ with known coordinates in the world model. This work proposes to choose P_1 and P_2 to be the entry and exit point of an intersection on the major street. The entry point of the intersection is the origin of the intersection based coordinate system so it has the coordinates $P_1 = P_{origin,intersection} = (0, 0)$. The second reference point lies on the x axes and so has the coordinates $P_2 = P_{exit,intersection} = (x_2, 0)$. The x_2 value can be calculated using the Protagoras equation and building the distance between the measured reference points (see equations 10, 11, 12).

$$x_{delta} = x_{2,measured} - x_{1,measured} \tag{10}$$

$$y_{delta} = y_{2,measured} - y_{1,measured} \tag{11}$$

$$x_2 = sqrt(x_{delta} * x_{delta} + y_{delta} * y_{delta}) \tag{12}$$

This gives the basis for the calculation of the argument ψ. The rotation angle can be calculated with the following equation 13

$$\psi = asin-(x_{delta}/x_2) + \pi \tag{13}$$

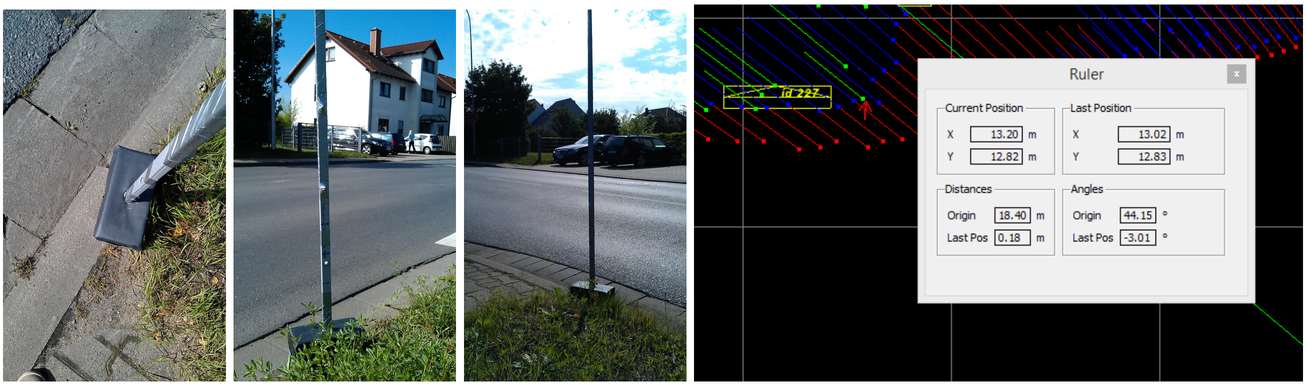
The rest of the arguments are calculated with the equations 14, 15, 16.

$$d_{entry} = sqrt(x_{1,measured} * x_{1,measured} + y_{1,measured} * y_{1,measured}) \tag{14}$$

$$x_{offset} = sin(\psi) * d_{entry} \tag{15}$$

$$y_{offset} = cos(\psi) * d_{entry} \tag{16}$$

The problem in this task is to measure the reference points on the intersection. For this purpose a special reference object, that is illustrated in Figure 35b, was constructed. It was positioned on the entry



(a) The reference object **(b)** Measuring the entry point **(c)** Measuring the exit point **(d)** Inaccuracy in the detection of the reference point in a measurement

Figure 34: Using a reference object (a) to measure the coordinates of the intersection entry (b) and exit (c) point. The sensor resolution leads to inaccuracy in the detection of the reference point in a measurement (d).

and on the exit point (see Figure 34b and 34c) and a test measurement was performed to capture its x and y coordinate with the sensors.

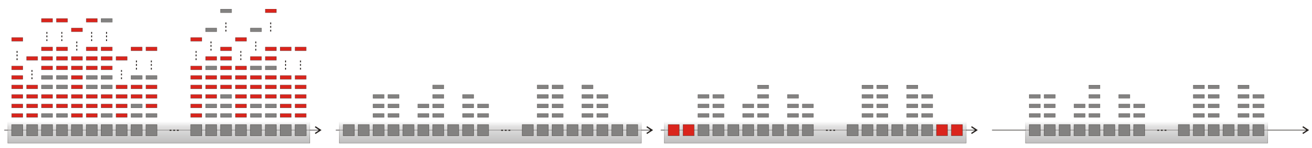
The reflection object was design with the requirement to stand still while traffic is passing by, returns just one reflection point, could be positioned exactly on the intersection's reference points and could be carried from one person. The construction of the object as a plastic bar fixed in a small concrete block fulfilled all of the requirements. Nevertheless the chosen method shows some disadvantages. As the ground is not alway even, the object rolls. Considering the length of the object of just over 2 meters, the small angle leads to a large variations to the real value in the reflextion point measured with the upper two layers of the sensors. The effect is shown in Figure 34d, where the reflection of the object bar from the first upper layer (green) (compare green point) has a deviation of about 0.18m to the reflection of the lower layer (red). In order to minimize the error the reflection of the lower two sensor layers was used to identify the reference object in a measurement. This was not that successfull as the sensor resolution did not allow the clear separation of the reference object from the kerb. The problem was solved using a MATLAB[5] script to find the measured average distance between P_1 and P_2 and correct the coordinate values in order the transformation to deliver the same result for each data set. Although this can remove an error in the translation of the world and prevent the world to be scaled, this not guaranty a small deviations of the rotation of the world.

6.2.2 Unique

As the used data is realistic there is no perfect representation of the traffic situation. This means that the collected data is not complete, because on object get lost due to traffic that blocks the sensors view or deficiency in the sensor's detection range. This leads to constantly changing ids of the object in the data.

In a late step of the pipeline implementation was discovered that the ids of the objects are not unique. It appears that an object's id is released, after the object get lost, and assigned to to other object. This characteristic of the sensor software makes the analysis of a data record impossible. This was the reason to add the *Unique* process to the pipeline. It reinterprets the ids of the objects. The routine assigns an unique id to each object and tracks it until it get lost and than it blocks its ids to be used for other objects. The *Unique* process uses a four-digit id format starting by 1000 in comparison to the original ids.

5 http://de.mathworks.com/



(a) 1st step of the filter

(b) 2nd step of the filter

Figure 35: The filter reduces the data by checking if of an objects passes the threshold values (a) and removing the empty data records at the top and bottom of the data stack (b).

	Unclassified	Unknown small	Unknown big	Pedestrian	Bike	Car	Truck
class distribution	0.0%	55.80%	40.75%	0.32%	0.0%	2.97%	0.16%
average confidence	0.0%	63.86%	49.87%	55.84%	0.0%	70.30%	62.40%

Table 19: Distribution of the object classes and the average certainty of the classification.

6.2.3 Filter

The main purpose of the filter process in the pipeline is to reduce the data quantity without decreasing the quality of the data. On the one side there is a noise in the recording generating an unusable data (noise = phantom objects than come and go because they are build on grass, gravel or dynamic light reflection). On the other hand there are the attributes of the objects, that are listed in appendix 8.3. One can consider to set a threshold for the value to reduce the noise and sample out the objects.

This work implements a 2-step filter. Figure 35 illustrates the functionality of the filter process. It reduces the data by checking if of an objects passes the threshold values in the 1st step and removes the empty data records at the top and bottom of the data stack in the second step.

Problem - Filter

The realization of the filter function is not challenging, but finding a good threshold for the object attributes is. In appendix 8.3 all attributes, that an object can have, are listed. One can recognize several categories of attribute types. A threshold can be set to filter an object in correspondence to its velocity, position, orientation, classification, or description. The velocity, position and orientation should be removed, because an ego or an target can have any velocity and orientation (due to the position of the test vehicle while recording a target could be nearing or clearing). To consider the position of an object as a filter can be applied just to some areas as at this state there is no information how the analysis should handle the object position e.g. tracking, the position of the vehicle is not suiTable as a filter. The only attributes in question are the ones about the classification and object description.

Table 19 contains statistic data about the object classification certainty. None of the classes is recognized with a high certainty. The highest value in average achieves the car class. There is no ground true data so the classification can be evaluated. While taking the recordings a car was identified as car, unknown small, unknown big and truck so the chosen filter allows a car, truck and unknown big to pass it.

As an object can get lost, filtering by the age of an object is not that suiTable too. When the object appears again, it has an age of 0. If the threshold is set high this will increase the gap between object lost and object appears again. If the threshold is set low than the noisy object will not be filtered. Figure 36 illustrates the age distribution of the objects over the data samples. One can recognize that the noisy data is located in the sector of objects with age <0.2s. This data will still contain a new appearing relevant objects, but setting an threshold on the age attribute of an object will reduce the data quantity by about 22.04%. Analyzing the data shows that a filter can only reduce the data quality, but can not help increase the data quality by reducing interference objects

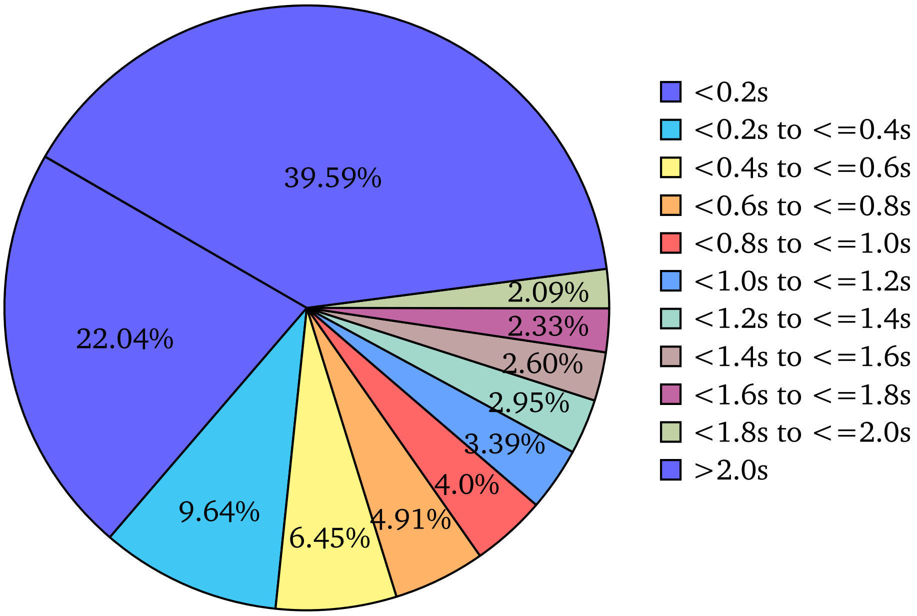


Figure 36: Age distribution.

The filter is set to remove all object with an age smaller or equal than 0.2s and the class type of - Unclassified, Unknown small, Pedestrian and Bike. The overall reduction of the data quantity is in average 63.62%.

6.2.4 Analyze

The main function of the *Analyze* process is to find the ego and the corresponding targets in the stream of data. Although the filter reduces the data quantity by over 63%, as described in section 6.2.3, this is still a challenging task. The *Analyze* process attempts to solve the task by the definition a theoretical movement trajectories for the ego and targets.

Figure 37 illustrates the implemented trajectories. The method uses a 4-point model to define them. The first and the last point correspond to the entry and exit point of an object, as depicted in section 4.1.4. The other two points are used to represent the curvature of the major road (target trajectory) respectively the bending of the intersection (ego trajectory). All of the points are extracted manually from a test measurement. The delivered software for the sensor allows to visualize the reflection of each sensor layer. Thereby one can find in the measurement the pavement along the road and can recognize the boundaries of the road. The software offers a scale function that can be used to calculate the distance to a reflection point.

The four points are selected to lie on the edge of the road and suit the road structure. Then they are transformed in the world model with the functions from the *Transform* process (see section 6.2.1). The

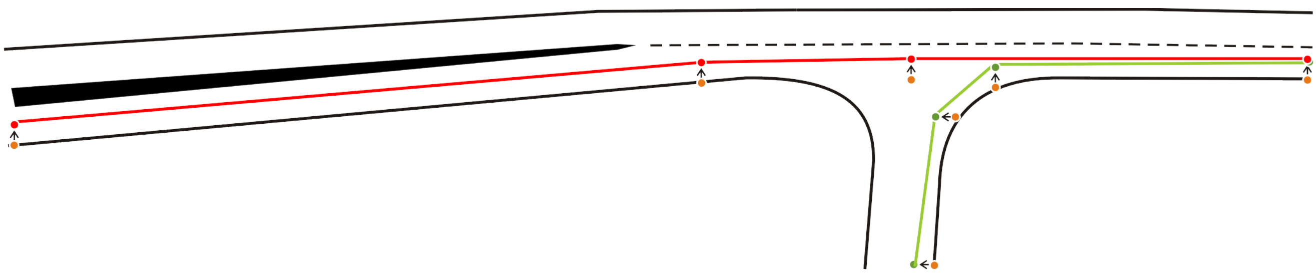


Figure 37: Definition of the expected object trajectories as a four-point line.

points, that lie on the major street are shifted by an offset in positive y-direction and the points that lie on the minor street are shifted on the x-axle in negative direction. The offset is the theoretical middle point of the driving lane. It can be calculated using equation 17 with the theoretical street parameters described in Table 2. After that a line is built to go through them and so the trajectories, that represent the ego and target trajectories, are generated as illustrated in Figure 37.

$$trajectory_{offset} = w_o/2 + s_0 + s_2 \tag{17}$$

Each object in the data record is analyzed by the *Analyze* process, if it can be matched to one of the given trajectories. The full method of finding the ego and the target(s) is implemented in 3 steps.

The first step is to check, if on object lies on one of the trajectories, and to calculate its position on in. If it can be matched to an trajectory, then it is tracked until it disappears or the data record reaches its end. The trail that a vehicle covers on the trajectory is computed by the *Analyze* method and used in the next processing step. If the object can be matched to both trajectories (ego and target), then its motion is tracked on both. In this step the direction of driving of an object is recognized while determining the trail. If the object follows a trajectory in a opposite way, then it is considered to be an oncoming traffic and is removed from the object list.

The computed trail values for each object are used in the second step of the process. The trail value represents the distance that an object covers on a particular trajectory. This value is compared to the total length of the given theoretical trajectory and a certainty measure is calculated. This is the percentage of the covered distance on a trajectory and is used to remove noise in the data. On the one hand the noise can be generated by objects that are near the driving lane and matched to an trajectory too, but on the other hand a source of error could be phantom objects. Those are objects that actually does not exist in the real world, but the sensors identify them due to a multiple reflection or deficiency in the detection resolution. They appear for a short time in the measurement near an actual object and then suddenly disappear.

In the third step the process the roles are assigned. If an object was matched to only one of the two trajectories than it belongs to a single role (ego or target). If an object was matched to both of the trajectories, then the highest value indicates its relationship to a certain role.

This *Analyze* process was implemented on an ugly stage of the project. The defined logic is based on findings that was achieved in the initial tests (see appendix 8.3) of the concept. The data of the test records reviewed the problem that an object can get lost, but its impact on the situation interpretation could be handled with the proposed logic. One of the reason this logic to fail on the real data is the fact that only two vehicle was used to reproduce the situation and the conditions were advantageous for the detection of the scene. This shows how challenging real world conditions for the goals of the thesis are. Although the initial test were performed in a realistic environment, in comparison to simulation data, the extracted findings, about the problem, could not hold with the conditions of a real world traffic situation. The extent of the analysis problem is described in the next paragraph.

Problem - Sensing concept

The concept chosen to detect the surroundings does not deliver robust data. The motion of the objects is not detected complete due to several factors. Figure 38 illustrates the complexity of a real world traffic situation and the detection problem for the sensors. On the one hand the sensor does not cover the entire Area-of-Interest (AOI) and on the other hand the high density of vehicles at the intersection leads to their overlap.

Figure 39 shows the distribution of the ego and target object(s) certainties along the ego and target trajectory. The values reveal how often an object get lost. The distribution of the data is skewed to the right. The median certainty for an ego object is 3.18% and 5.17% for an target object. The certainties are so low that the objects with a higher certainty value are outliers.

The low certainties are caused by two factors - phantom objects appearing just for a short period of time, and continuously disappearing objects due to high traffic driving near the test vehicle. The problem

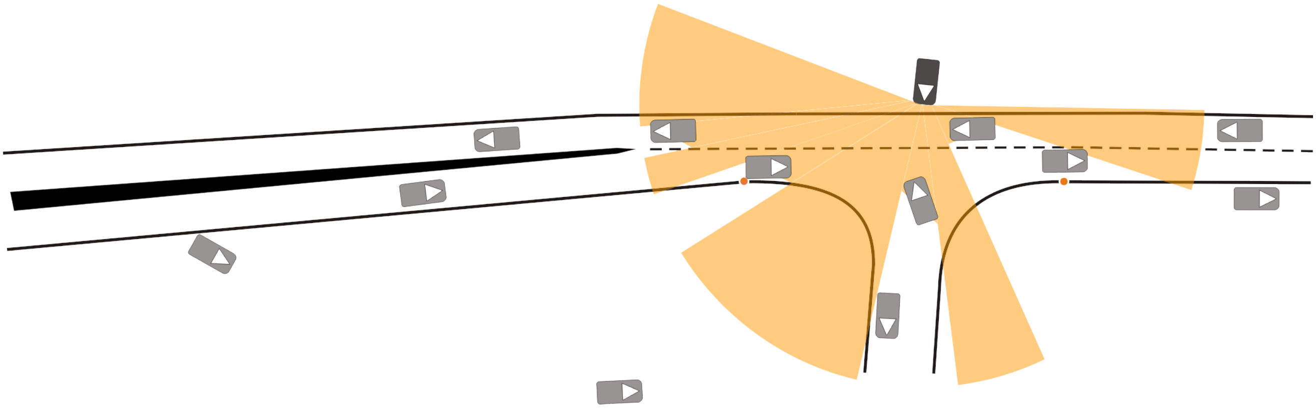


Figure 38: Complexity of the situation analysis.

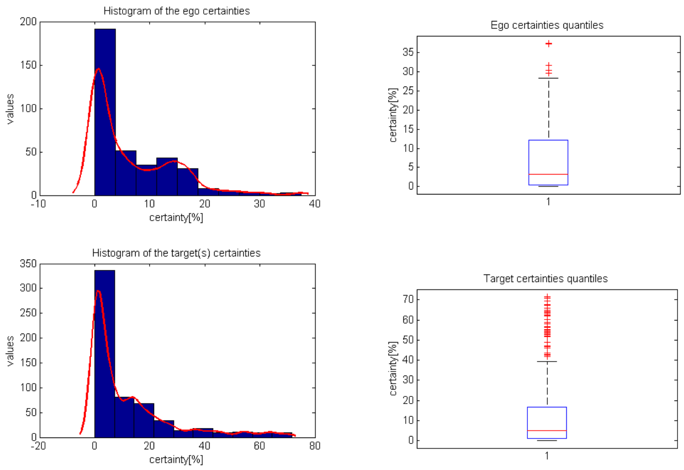


Figure 39: Histograms of the ego and target object(s) certainties.

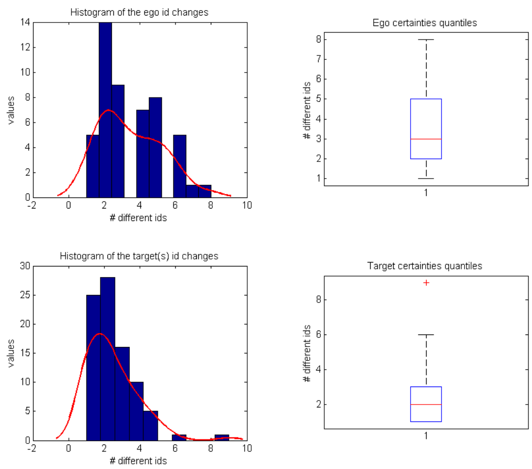


Figure 40: Statistics about the ego and target id changes.

could not be handled by the the proposed 4-point trajectory model. The trajectories of the ego and target objects overlap at the end of the intersection. When an object get lost at this time and appears again, it will be assigned to the both trajectories. This makes the role assignment to fail.

To proceed with the realization of the pipeline an additional process has to be implemented that can solve this problem. The proposed solution will be described in the next section 6.2.5.

6.2.5 Map

The pipeline is supplemented with the *Map* process. The chosen method in the *Analyze* step is not capable to fully interpret the driving scene and to find the ego object nor the target(s). Figure 40 gives an overview of the characteristics of an id to change. The histograms and the box plots shows that the id of an ego object is more likely to change in comparison to a target and that changes in the ids of an target object are more normal distributed, but can contain outliers.

In order to proceed with the processing of the real world data, the *Map* method is introduced at this step of the progress. It defines a manual interpretation of the data record with the use of an map file. This file contains an enumeration of the relevant objects (see sample file in listing 3). It is divided in two sector - *TARGETS* and *EGO* - used to establish witch object ids belong to the ego and witch to the targets.

```
TARGETS
1814
3481 4612 4898
4248 4927 5248 5803
5938 6620 6899 7104 7399
EGO
2774 3980 4287 4710 5299 5620 6404
```

Listing 3: Sample map file.

As a traffic scene can involve just an ego without any targets, the map file should define at least the ids of the ego. If there are targets, their ids should be listed successively in the *TARGETS* section. The conditions concerning the syntax and semantics of the map file are:

- the *TARGETS* section should not be deleted, if there is no target
- each object is defined as a list of ids, separated by a free space
- each object should be defined on a new line into the corresponding section
- the expected order of the ids of an object as well as the target's order has to be chronological

The functionality of the *Map* process completes the analysis of a traffic scene and the remaining objects in the data record match the problem definition. In order to simplify the analysis the *Map* process replaces the multiple ids of an object by just a one. The objects that build the ego has a new id equal 0 and the targets get the ids=1,2,3... according to order of definition in the map file.

Problem - Map file generation

A map file is generated manually. The designed program (see section 7) allows a data record to be played back and can visualize the laser scanner objects as abstract shapes (circles). The id of each object is plotted along the object movement. This features can be used to visually observe a traffic situation and create a map file for a data record. Despite all the fact, this task take in average about 7 minutes per data record. Another issue is the fact that sometime an object can change its id up to 9 times (see Figure 40). This may lead to increasing the working time on a data record and to wrong id entries as the id changes appear in a short period of time.

Comparing the data from Figure 39 to the data in Figure 40 allows to calculate the noise in the data. The *Analyze* process finds in data set, used for the calculation of the statistics on each pipeline process, 963 different object which are located in the area of the defined driving trajectories. This test data set contains a manually generated map files, that define only a 382 different objects as ego or target(s). It follows from the foregoing that 60.33% of the data is noise as depicted in Table 20.

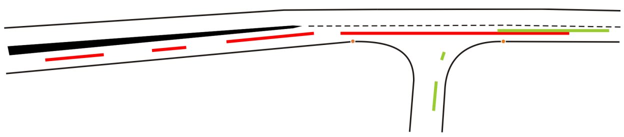
Found objects	Mapped objects	Noise
963	382	60.33%

Table 20: Noise in the data.

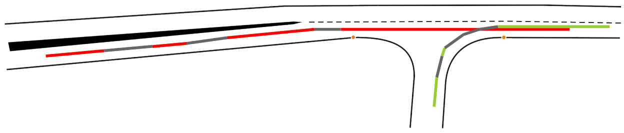
6.2.6 Complete

To this step the problematic with the object lost was discussed. This results in another challenge in the pipeline. The motion of an object is not complete as depicted in Figure 41a. It is a collection of single segments that may vary in the time (see Table 21).

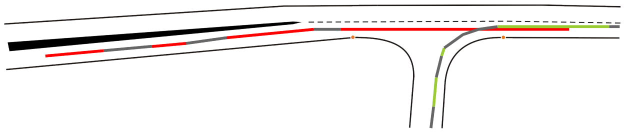
The blind spots between two segments can easily be found. The search for the boundaries of an empty segment at the beginning or at the end of a traffic scene is more challenging. This points depend on the defined problem model and have only one motion point to reference (at the beginning this is the first occurrence of an object and at the end is the last instance in the data record, before it gets lost). Trying to



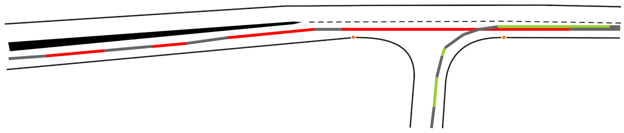
(a) Segments of the object motion in the real world data



(b) Filling of the blind spot in the segments of an object's motion



(c) Filling of the blind spot in the segments of an object's motion



(d) Filling of the blind spot in the segments of an object's motion

Figure 41: The processing steps in the *Complete* process.

Description	min	mean	max
Ego blind spot between two motion segments	0.08s	0.67s	6.60s
Missing section of the ego motion to the entry point	0.04s	1.00s	7.60s
Missing section of the ego motion to the exit point	0.04s	0.10s	1.12s
Target blind spot between two motion segments	0.08s	0.48s	3.24s
Missing section of the target motion to the entry point	2.84s	3.85s	8.12s
Missing section of the target motion to the exit point	0.04s	0.24s	2.16s
Overall completion of the ego motion	0.45%	8.94%	49.62%
Overall completion of the motion of a target	0.48%	24.28%	71.96%

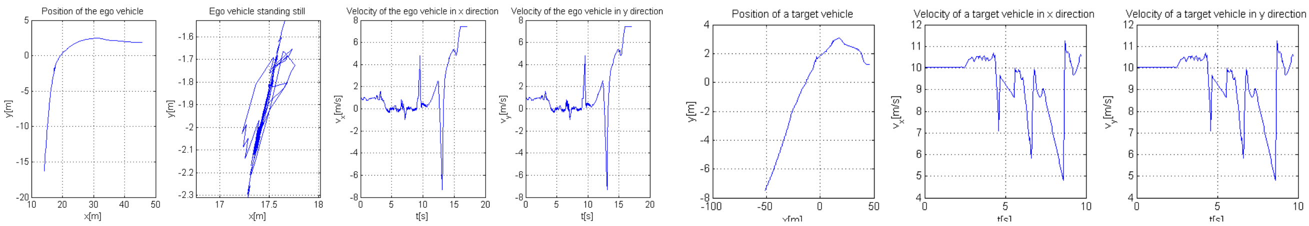
Table 21: Statistics about the object motion blind spots.

complete those segments may lead to a buffer overflow in the data record, as it may not be large enough to store the predicted data.

```
// Complete method
DO for ego
        CALL findBlindSpots with ego data
        CALL completeBlindSpots with ego data and list of the blind spots
END DO

FOR each target
        CALL findBlindSpots with target data
        CALL completeBlindSpots with target data and list of the blind spots
END FOR

DO for ego
        CALL completeEgoMotionEntry with intersection model
        CALL completeEgoMotionEntry with intersection model
END DO

FOR each target
        CALL completeTargetMotionEntry with intersection model and ego motion
        CALL completeTargetMotionExit with intersection model and ego motion
END FOR
```

Listing 4: Complete method.

Figure 41 illustrates the logic behind the *Complete* process. Listing 4 describes the method in detail. First the blind spots in the motion of the ego object are located and completed, then the same procedure is repeated for each target object. In the next step the process amplifies the empty section of the ego motion to the entry and exit point as defined in the problem model. In this matter the time constrains relevant to a scene are computed and the motion of the target objects can be completed.



(a) A complete ego motion data. **(b)** A complete motion of a target object.

Figure 42: The processing steps in the *Complete* process.

To compute the missing data entries with the dynamics of an vehicle for the blind spots demands a object motion model. The *Complete* process assumes that an object does not rapidly changes its velocity and orientation. The proposed model defines the motion of a vehicle to follow a constant strategy.

Problem - Motion model

This model does not suit well to the real world data. There two factors interrupting the motion prediction. After an object appears and is detected by the sensors, there is a certain delay until the dynamic data such as the velocity is correctly captured. This leads to error peaks in the prediction of the vehicle motion. The effect can be seen in Figure 42a and 42a. The second factor refers only to the ego motion. As an ego vehicle may stop at the intersection and get covered from the passing vehicles not its velocity but its position is noisy when it get detected again.

6.2.7 Prune

The prune process of the pipeline does not require a detail description. Its implementation is conform to the theoretical definition of the process in section 6.1.4. The process searches the data records an finds the first data entry of the ego object, where the ego is passed by the entry point, and the last entry, where the ego passes the exit point of the defined world model. Than the data record is pruned to this constraints and the rest of the redundant data is deleted.

6.2.8 The Rest of the Pipeline

The processes *Discretize*, *Build instance* and *Extract features* implements a dummy functionality. The driving scene is discretized in an equal time segments. Some dummy features are extracted from each segment and a sample learning instance is generated. This data is than forwarded to the export routine and saved as an .arff file [6].

This processes depend on the method that will be used to gather an information from the given data. They should be adapted for the further use and therefor does not stay in focus in this work. The dummy implementation is realized to complete the data processing pipeline and fulfill the goal of the thesis.

[6] http://www.cs.waikato.ac.nz/ml/weka/arff.html

7 The Software

The laser scanner data are taken in a proprietary format. The manufacture does not offer a software capable of realize the pipeline, but provides an Application Programming Interface (API) to work with off-line records. In order to implement the pipeline an own program had to be developed.

The emerged program is implemented in the programing language C++ within the Integrated Development Environment (IDE) Microsoft Visual Studio Premium 2012 [7]. Extreme Programing (XP) was used as methodology for the development of the software product, because not all of the requirements was unknown in the early stages. The Graphical User Interface (GUI) was implemented conforming to the architectural pattern Model-View-Controller (MVC). Another characteristic of the software is the fact that the pipeline is programmed with the agile design technique The Interface-Segregation Principle (ISP) as described by Robert Martin in his book [24]. This allows an agile way to add, remove or edit a process from the pipeline in future releases. This is an advantage to the last methods of the pipeline - Discretize, Build Instance and Extract features - as they should be additionally extended.

The program was developed using the following software configuration of the sensors:

- ECU, Firmware 5.0.8
  - 4-SensorFusionSystem v4.2.8
- Software
  - IbeoSDK 2.4.2
  - IbeoLaser View Premium
    - LaserView v3.6.3
    - IbeoApi v4.5.1
    - Elia v1.8.1

The required additional SDK and libraries are:

- Ibeo-SDK
  - ibeosdk_VS2012.lib
- boost_1_52_0 [8]
  - libboost_thread-vc110-mt-1_52.lib
  - libboost_system-vc110-mt-1_52.lib
  - libboost_date_time-vc110-mt-1_52.lib
- Microsoft DirectX SDK 28June2010 [9]
  - d3d9.lib
  - d3dx9.lib
  - d3dx9d.lib
  - dxguid.lib
  - version.lib

The program offers two working modes - GUI and console - and full configuration of the implemented processes and elements. In the next sections a description how to use the program could be found.

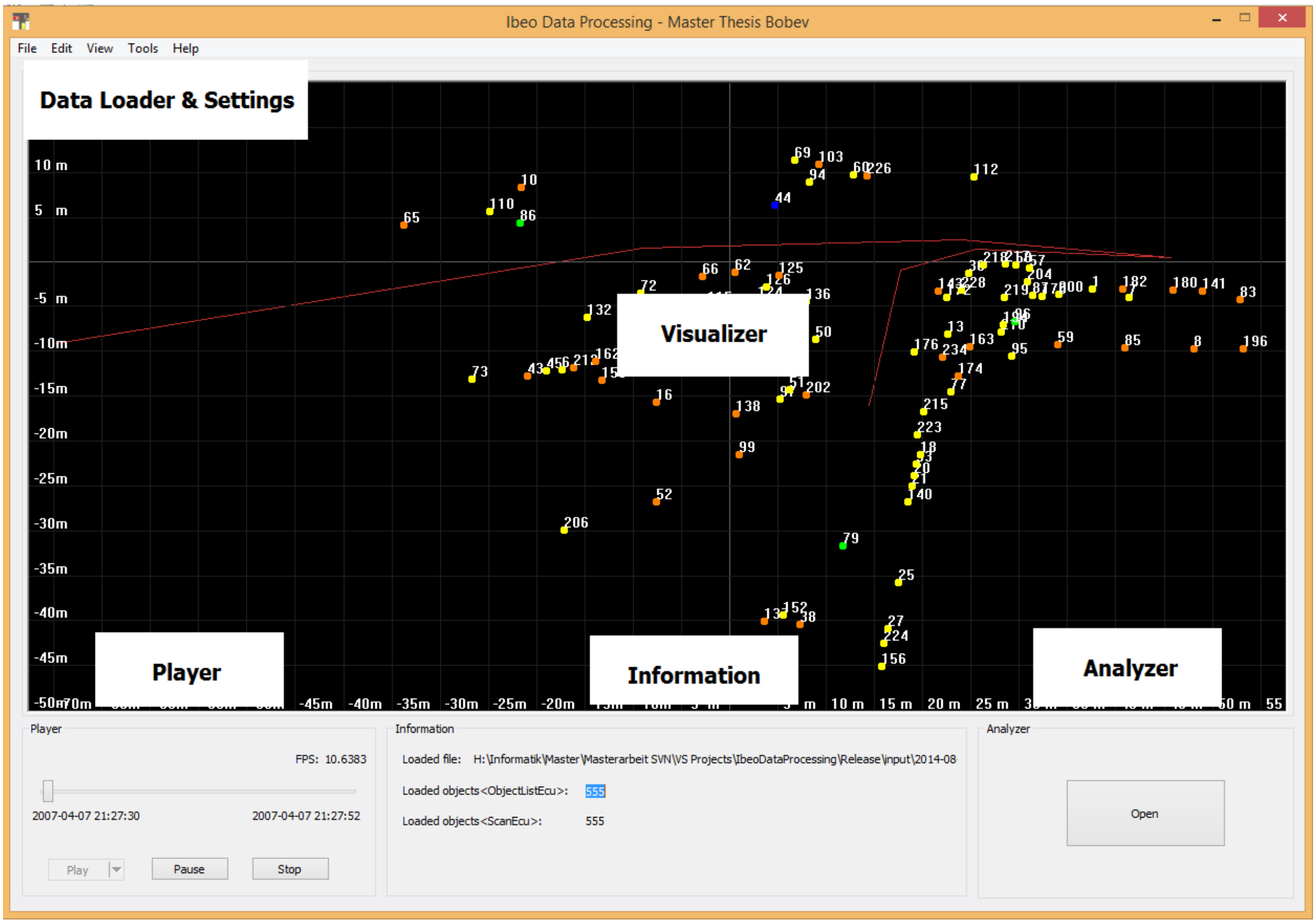
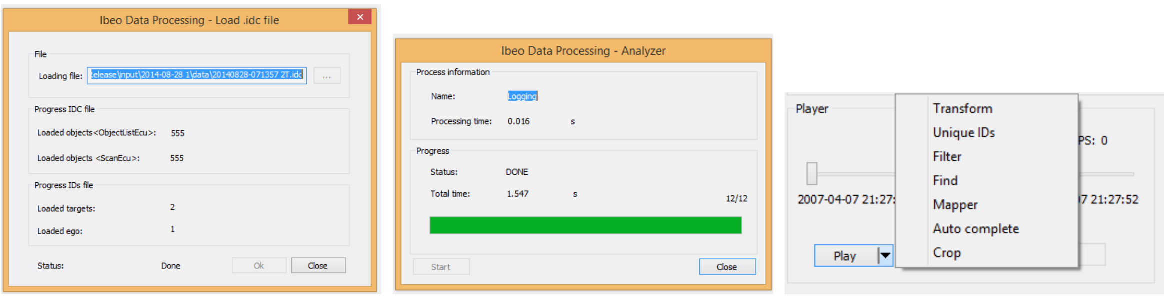


Figure 43: The GUI view of the data processing software developed in this thesis.



(a) Data Loader **(b)** Analyzer **(c)** Player

Figure 44: The controls of the GUI elements.

7.1 GUI modus

The GUI modus of the program offers a manual way to work with the data and analyze it. The settings of the pipeline processes can be changed directly in the program. One can test the results with the use of the player and the visualizer, and tune the analyzer parameters. An overview of the main controls and elements of the view is given in Figure 43.

The *Settings* an the *Data Loader* can found and opened in the menu of the program. In the central area of the GUI is positioned the *Visualizer*. In the bottom part of the GUI are located the controls of the

7 http://www.microsoft.com/de-de/download/details.aspx?id=30654
8 http://www.boost.org/
9 http://www.microsoft.com/en-us/download/details.aspx?id=6812

Player, information about the loaded data and the controls of the pipeline process named *Analyzer* (from left to the right). This core of the program is built by this elements and they will be described in the next subsections.

7.1.1 Data Loader

The *Data Loader* can be opened through clicking on *File->Open*. Performing this action makes a new window pop up (see Figure 44a) and the user is given the opportunity to browse for a laser scanner data file in the proprietary *.idc* format. After choosing a file the intention should be verified with a click on the *Ok* button. The loading of the file into the program is triggered by this action. The corresponding map file is found and loaded automatically parallel to the data record. An information about the progress and the status of the loading is displayed. If an exception occurs or the map file was missing, then an error message will appear.

7.1.2 Analyzer

The program's main functionality is encapsulated in the module called *Analyzer*. The pipeline is implemented inside the *Analyzer* as four independent controllers:

- preprocessing
- discretize
- feature extraction
- export

The first 7 processes of the pipeline are carried out by the *preprocessing* controller. As this processes handle the data in a similar matter and do not change it structure, there are combined to an independent logical unit in the program. The result of it is a model containing a single situation, which is handled over to the *discretize* controller and in order *features to be extracted* and *exported* in the last step.

Each of the four controllers is programmed with the software design technique ISP. This means that the *preprocessing* step could be extended or new discretization, feature extraction or export routine can be implemented in an agile way. Changes to this controllers will not lead to accommodations in other parts of the software.

The controls of the *Analyzer* could be opened with the click on the *Open* button in the bottom right corner of the GUI (see Figure 44b). A new window will be popped up and the analyzer process could be started. When the analyzer is done the window could be closed. The name of the current process in progress and its processing time is displayed in it.

7.1.3 Player

An advanced data model is used in the program. The raw laser scanner data can be stored by the *Data Loader* into it a space for each process of the pipeline will be allocated into the data model. This helps into the process of analyzing the data and helps debugging a pipeline process.

The *Player* is designed to handle this feature and an intuitive control element (see Figure 44c) for the playback of the data model is implemented. One can chose using the split play button [10] which process data to be visualized.

7.1.4 Visualizer

The laser scanner data is displayed with the *Visualizer*. A a grid for a better distance orientation is plotted as well the x and y axes of the world model coordinate system and the ego and target trajectories are highlighted (see Figure 43). The used colors can be fully customized.

[10] https://msdn.microsoft.com/en-us/library/windows/desktop/dd940505%28v=vs.85%29.aspx

7.2 Console Modus

The program can be used as a console application. If it is started from a command line, the console mode of the program will be triggered within the main method. In order to start the program successfully two initial parameters, as defined in listing 5, have to be provided.

```
IbeoDataProcessing.exe /i:INPUT_FOLDER /o:OUTPUT_FILE
```

Listing 5: Template batch file for starting the program in console mode.

The path to the folder containing the data sets, that has to analyzed, must be set instead of the wildcard *INPUT_FOLDER*. Each data set should be in a separate folder under the input folder. It has to contain two folders - *data* and *iini*. The configuration file for the *Analyzer* is searched in the *ini* folder. The *data* folder should include only the laser scanner .idc files ant the text map files.

The wildcard *OUTPUT_FILE* is used to define the relative location and the name of the output file. It should correspond to the implemented export data type by the *Analyzer*.

The software program can be used in console modus as a machine learning data generation tool. The pipeline processes are carried out fully autonomous for each file of the given data sets. The program logic is illustrated in Listing 6 as a pseudo code.

```
Set input folder
Set output file

        FOR each folder in input
                CALL FindIniFile(folder path concatenated with \\ini)
                Set configuration from ini file

                CALL FindDataFolder(folder path concatenated with \\data)
                Set data folder

                FOR each file in data folder
                        Set file name

                        CALL LoadDataRecordFile(file name with extension idc)
                        CALL LoadMapFile(file name with extension txt)

                        Set data model

                        CALL startAnalyzer(data model)

                END FOR
        END FOR
```

Listing 6: Data processing in the console modus.

7.3 Settings

There are two types of settings. The first one is for configuring the program and the world model, the second type are the settings about the pipeline process. This functionality is implemented with the help of *.ini* [11] files.

7.3.1 GUI modus

The settings are loaded at the start of the program from the files and saved back into them at the end of the program. The parameters of the the analyzed intersection can be set under *Edit->Junction* and the visualizer can be adapted under *Edit-Visualizer*, if needed. The settings about the pipeline process could be found under *Tools->Properties Analyzer->Preprocessing*. Each process can be separately configured.

7.3.2 Console modus

The program considers only the settings of the *Analyzer* that are in the provided ini folder, when it is started in console modus.

[11] An *.ini* file is a simple text file with a basic structure composed of sections, properties and values. Every property has a *name* and a *value* that a delimited by an equal sing. The key-value properties can be grouped into sections.

8 Conclusion and Outlook

8.1 Summary

This work engineered on the topic of driving behaviour inter-dependencies for the purpose of safe autonomous vehicles at urban intersections. The problem was defined to general therefor the first approach step to the problem was to identify a theoretic representation of the real world model application. This let to the definition of an urban area in the terms of the German traffic regulation and the specification of an urban intersection in theory. The intersection represents a crossing of a major street with rights of way with a minor street with the regulation *give-way*. Further more the possible traffic situations were identified and an instance that may lead to conflicts between the participants was chosen as a reference for the rest of the work. The traffic situation represented vehicles driving on the major street with rights of way and a vehicle on the minor street with the intention to turn to the right at the intersection and to introduce a theoretical conflict. Into the next step a literature research was performed to identify data sources for the analysis of the inter-dependencies between the vehicles.

The main intention of the work was to process the problem in a realistic matter. Hence a real world instance of the defined urban intersection was found to verify the theoretical model and find possible variations and adapt the world model. The data sources was matched to a realistic set because of the limitations of the given surroundings detection hardware. This circumstances established a novel way for the detection and analysis of the driving behaviour at urban intersections. A test vehicle, that was equipped with three laser scanner in the front, was used for the observation of a real-word traffic situations. More than 500 single right turning events could be recorded and used for the further investigation of the problem.

This gave the basis for the definition of a pipeline for preprocessing the data in such a way that it could be used in a machine learning techniques. The pipeline was firstly designed as a theoretical black box and then realized as a software program. Once again the theoretical considerations about this part of the problem were verified in praxis. The theoretical pipeline was unable to handle the data entirely, therefore three additional processes had to be added to it.

At this state the blind spots from the definition of the problem over the collection of a realistic real world data to the processing for the use in machine learning techniques was filled.

8.2 Conclusion

Even in a theoretical matter there is no unique definition of an urban intersection model. There are guidelines for the road design and construction, but no strict regulations. Hence the definition of generally valid theoretical model of an intersection have to be very complex. The verification of the model used in this work showed that even a simple model highly varies to a real-word instance of it.

The same conclusion is valid for the definition of the traffic situation. Although the chosen scenario, where a vehicle on a minor streets attempts to turn to the right at and intersection, is trivial to define in a theory, the verification on observations of a real world traffic situations generates a large set of categories for this single event. With the increasing of the complexity of the situations e.g. more traffic, pedestrians, bad weather,it increases the effort to analysis and interpret the situations. While in theory all this could be simulated, finding a real world representation could be a challenge.

The driving is a complex task and the handling a demanding situations such as crossing an intersection is discerning. This fact could be observed as well in the road accident statistics as in the lack of scientific works on similar topics based on real world data.

The information about the driving behaviour inter-dependencies lies in the data of the situation. To be able to extract it and separate it from the other information one should have a full representation of the happening. If the analysis is limited just to the pure vehicle motion, than there is a theoretical possibility to be able to recognize inter-dependencies, if a reference model is available. At this circumstances the used concept for date collection is too minimalistic. On the one hand it fails to detect a representative range of the traffic situation and on the other hand the data quality is not sufficient.

The research of the problem identifies the challenges that have to be vanquished in order to work with a real world data for the analysis of driving behaviour inter-dependencies. The insufficient quality of the data leads to its manual correction in order to proceed with its preprocessing. The realized pipeline is design to handle the output of a laser scanner sensors. For further data sources it should be extended.

8.3 Outlook

The use of digital maps will eliminate the need of a theoretical representation of an intersection. The defined characteristics could be extracted from the map and the process could be automated in the software program.

The concept for the collection of the data proof to be not that suitable for the recording of the happening at an urban intersection. A mobile sensor units that are hidden in common objects e.g. dustbins allows more degrees of freedom, when it comes to positioning and orientation. Recording the traffic from different view points will increase the redundancy and give the opportunity to expand the range of observed situation. If the collected data has a better quality this may reduce the computational and analysis effort.

Another consideration is to collect data at multiple intersection and in this way to eliminate the effects of the intersection on the driving behaviour and validate the achieved results.

9 Appendix

The appendix is dedicated to the additional information about the initial tests of the environment detection concept, the description of the data parameter, the test vehicle, the description of the examined intersections and the protocols of the recordings.

9.1 Initial Tests

Initial tests were performed on 23. May 2014 under controlled condition. Four potential driving situations at an intersection were reproduced on the testing ground of FZD in Griesheim.

9.1.1 Test: Wait before turning to the left

Participants position

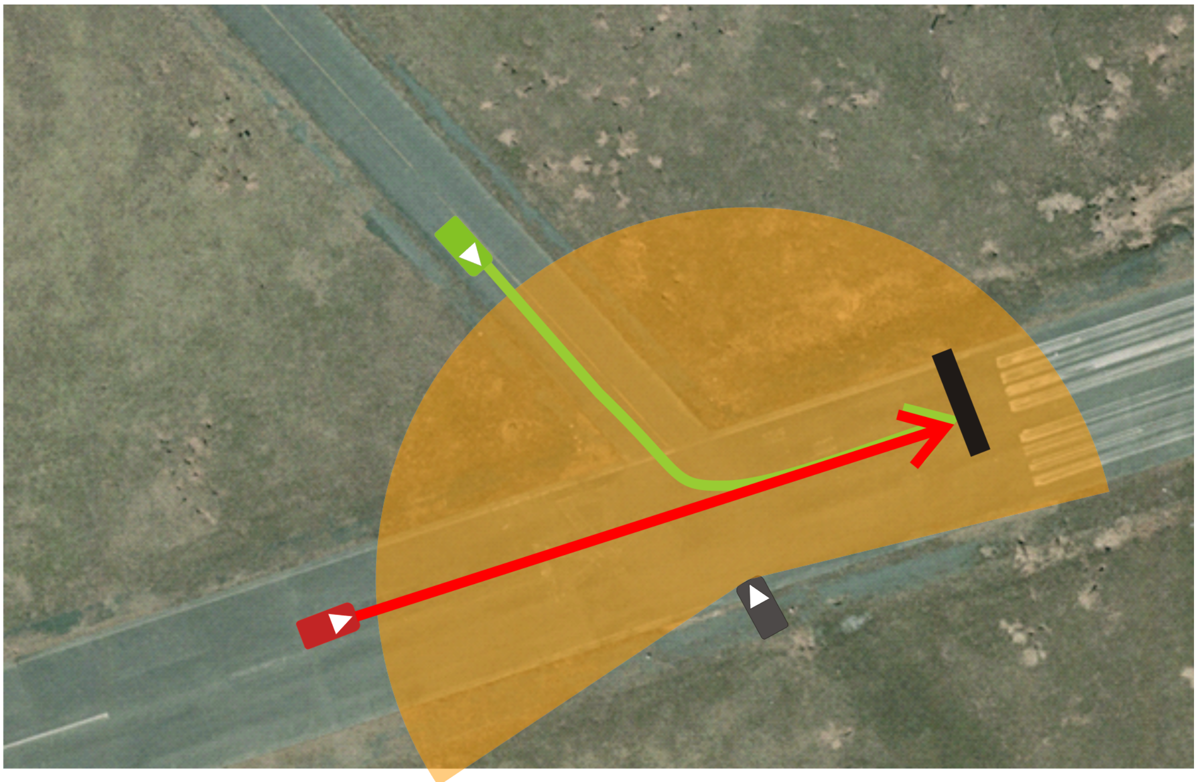


Figure 45: Test under controlled conditions: Give way and turn to the left. Source: Google Maps

Test description

Role	Color coding	Task description
Test vehicle	black	Gives the start signal.
Target	red	Starts moving after the signal, accelerates to 30 km/h and keeps a constant velocity of 30 km/h until it passes the end point.
Ego	green	Starts moving after the signal, accelerates to 30 km/h, stops at the intersection and wait for the target to pass by. Then it makes the turn and drives until it passes the end point.

Table 22: Test under controlled conditions: Give way and turn to the left.

9.1.2 Test: Turn to the left as first

Participants position

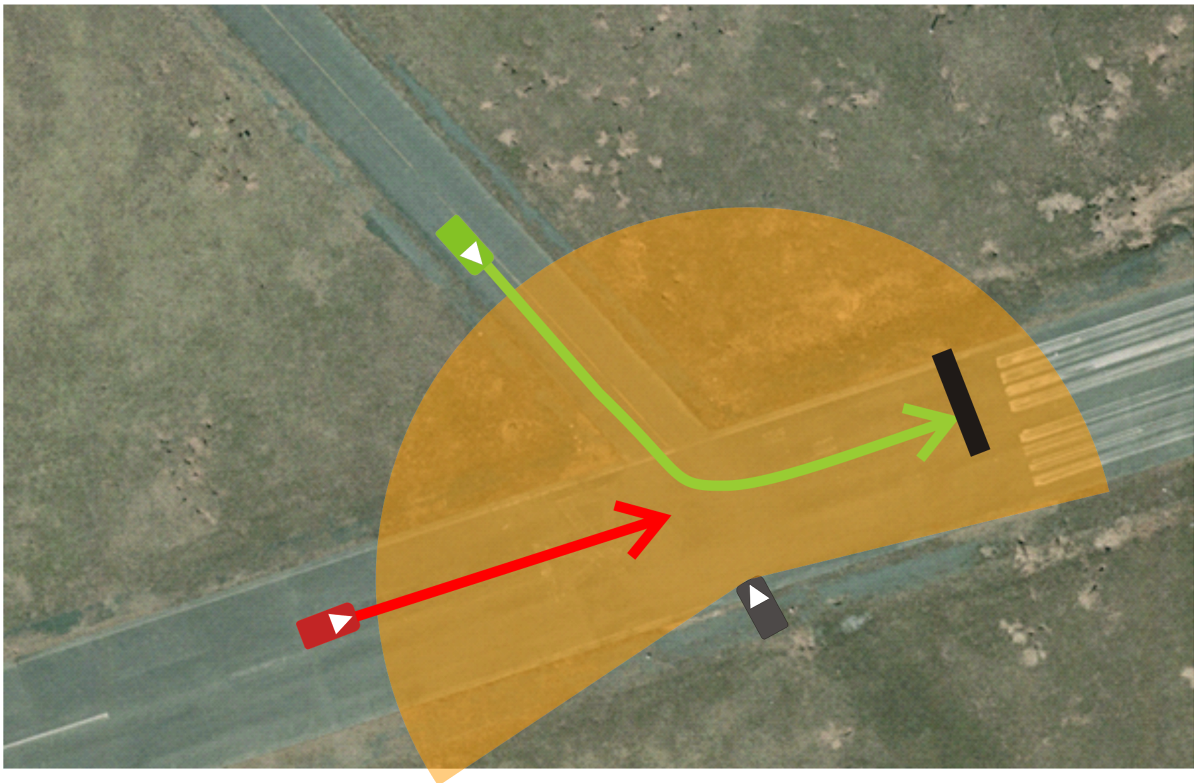


Figure 46: Test under controlled conditions: Turn to the left. Source: Google Maps

Test description

Role	Color coding	Task description
Test vehicle	black	Gives the start signal.
Target	red	Starts moving after the start signal and accelerates to 30 km/h. Then it tries to keep a constant velocity of 30 km/h until it passes the end point.
Ego	green	Starts moving after the start signal and accelerates to 30 km/h. Then it makes the turn before the target could reach him and drives until it passes the end point.

Table 23: Test under controlled conditions: Turn to the left.

9.1.3 Test: Wait before turning to the right

Participants position

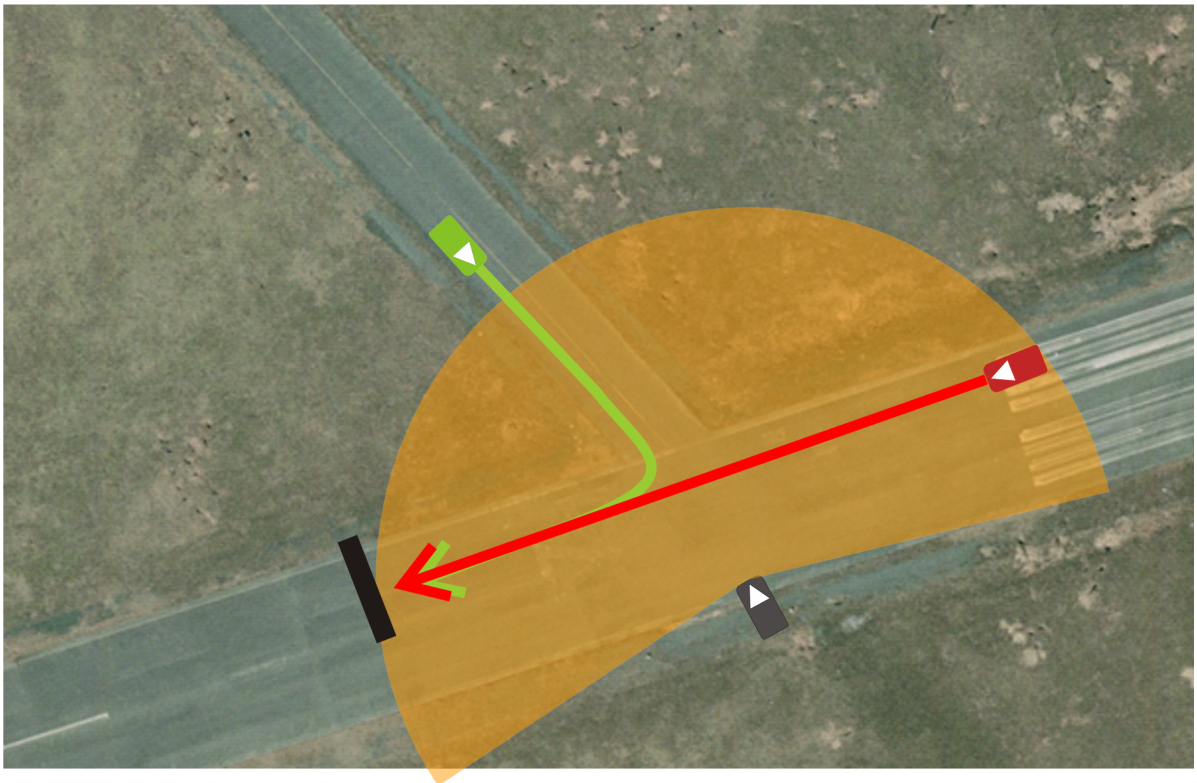


Figure 47: Test under controlled conditions: Give way and turn to the right. Source: Google Maps

Test description

Role	Color coding	Task description
Test vehicle	black	Gives the start signal.
Target	red	Starts moving after the start signal and accelerates to 30 km/h. Then it tries to keep a constant velocity of 30 km/h until it passes the end point.
Ego	green	Starts moving after the start signal and accelerates to 30 km/h. Then it stops at the intersection and wait for the target to pass by. Then it makes the turn and drives until it passes the end point.

Table 24: Test under controlled conditions: Give way and turn to the right.

9.1.4 Test: Turn to the right as first

Participants position

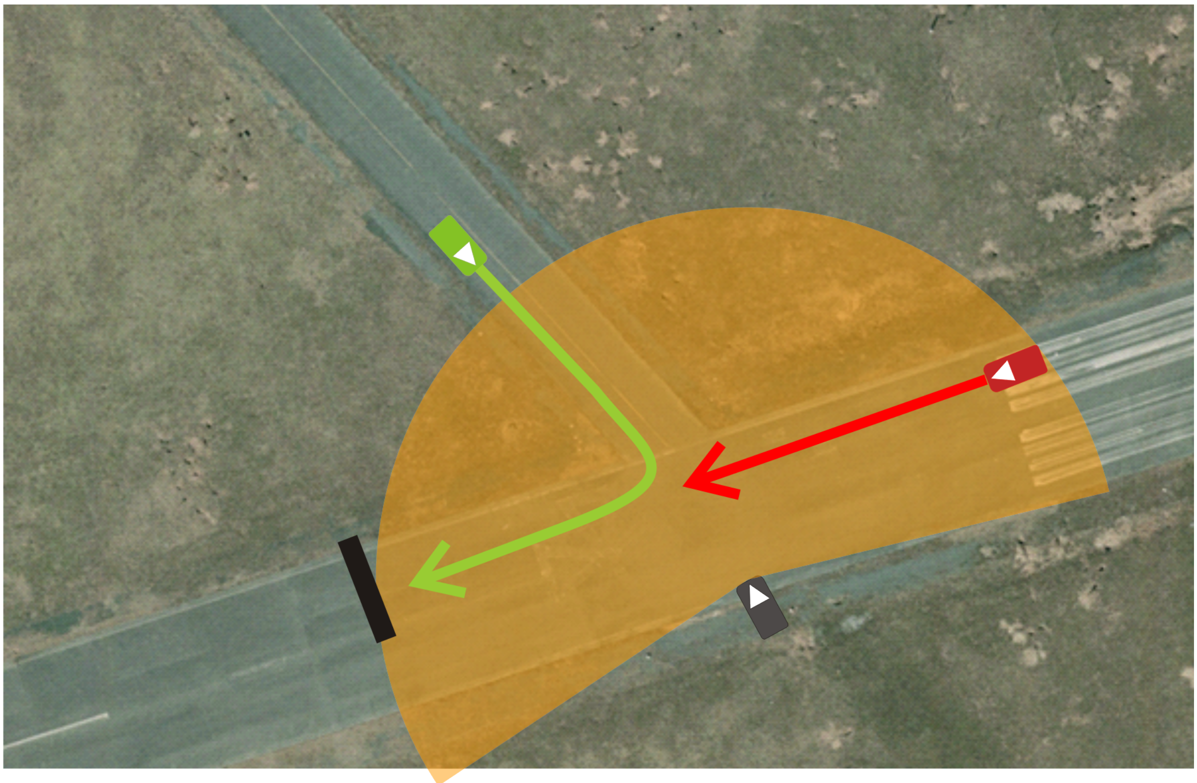


Figure 48: Test under controlled conditions: Turn to the right. Source: Google Maps

Test description

Role	Color coding	Task description
Test vehicle	black	Gives the start signal.
Target	red	Starts moving after the start signal and accelerates to 30 km/h. Then it tries to keep a constant velocity of 30 km/h until it passes the end point.
Ego	green	Starts moving after the start signal and accelerates to 30 km/h. Then it makes the turn before the target could reach him and drives until it passes the end point.

Table 25: Test under controlled conditions: Turn to the right.

9.2 Data Sources

This section of the appendix is dedicated to the data interface of the ibeo laser scanner software. It contains the definition and the description of the provided objects and their parameter by the API.

9.2.1 ibeo::ObjectECU Parameters Description

Absolute velocity

unit	[m/s]
description	Absolute velocity of this object with ego motion taken into account. Inform about the object velocity in the real world.
method	Point2dFloat getAbsoluteVelocity();

Absolute velocity sigma

unit	[m/s]
description	Standard deviation of the absolute velocity.
method	Point2dFloat getAbsoluteVelocitySigma();

Bounding box center

unit	[m]
description	Center point of the bounding box of this object.
method	Point2dFloat getBoundingBoxCenter();

Bounding box size

unit	[m]
description	Size of the bounding box (a rectangle parallel to vehicle coordinate system)
method	Point2dFloat getBoundingBoxSize();

Classification

unit	[-]
description	Object class. Classes are: 0 - unclassified 1 - unknown small 2 - unknown big 3 - pedestrian 4 - bike 5 - car 6 - truck
method	enum ObjectClass getClassification();

Classification age

unit	[-]
description	Number of scans this object has been classified as current class.
method	UINT32 getClassificationAge();

Classification certainty

unit	[%]
description	Certainty of the classification of this object. The higher this value is the more reliable is the assigned object class.
method	UINT8 getClassificationCertainty();

Counter points

unit	[-]
description	Point over the object
method	vector<Point2dFloat> getCounterPoints();

Hidden status age

unit	[-]
description	Number of scans this object has only been predicted without measurement updates.
method	UINT 16 getHiddenStatusAge();

Closest point

unit	[-]
description	Closest contour point of this object as index of the contour point list.
method	UINT8 getIndexOfClosestPoint();

Number of the contour points

unit	[-]
description	Number of contour points transmitted fro this object.
method	UINT8 getNumberOfCounterPoints();

Object age

unit	[-]
description	Number of scans this object has been tracked for.
method	UINT 32 getObjectAge();

Object box box center

unit	[m]
description	Center point (tracked) of this object.
method	Point2dFloat getObjectBoxCenter();

Object box sigma

unit	[-]
description	Standard deviation of the object box center point
method	Point2dFloat getObjectBoxSigma();

Object box size

unit	[m]
description	Size of the object box in the object coordinate system (vehicle coordinate system rotated arround z axis by object course angle).
method	Point2dFloat getObjectBoxSize();

Object id

unit	[-]
description	Unique number of the object from tracking.
method	UINT 16 getObjectId();

Orientation

unit [°]
description Orientation/rotation of the object in reference to the ego vehicle
method float getOrientation();

Relative velocity

unit [m/s]
description Velocity of this object relative to the ego vehicle. Ego motion is not taken into account here.
method Point2dFloat getRelativeVelocity();

Relative velocity sigma

unit [m/s]
description Standard deviation of the relative velocity.
method Point2dFloat getRelativeVelocitySigma();

Timestamp

unit [-]
description Time when this object was observed. More precisely: the reference point of this object.
method NTPTime getTimestamp();

Yaw angle

unit [rad]
description Orientation or heading of the object.
method Point2dFloat getYawAngle();

Yaw angle sigma

unit [-]
description Standard deviation of the yaw angle of the object.
method Point2dFloat getYawAngleSigma();

9.2.2 ibeo::ScanECU Parameters Description

Device id

unit [-]
description ID of the device measuring this point.
method UINT8 getDeviceId();

Echo

unit [-]
description Number of this point
method UINT8 getEcho();

Echo pulse width

unit [m]
description Echo width of this scan point (zero-based).
method float getEchoPulseWidth();

Flags

unit	[-]
description	Flags: 0x0001 - ground 0x0002 - dirt 0x0004 - rain/snow/spray/fog/... 0x1000 - transparent 0xXXXX - reserved
method	UINT16 getFlags();

Layer

unit	[-]
description	Scan layer of this point (zero-based).
method	UINT8 getLayer();

Position X

unit	[m]
description	X position of this scan point.
method	float getPositionX();

Position Y

unit	[m]
description	Y position of this scan point.
method	float getPositionY();

Position Z

unit	[m]
description	Z position of this scan point.
method	float getPositionZ();

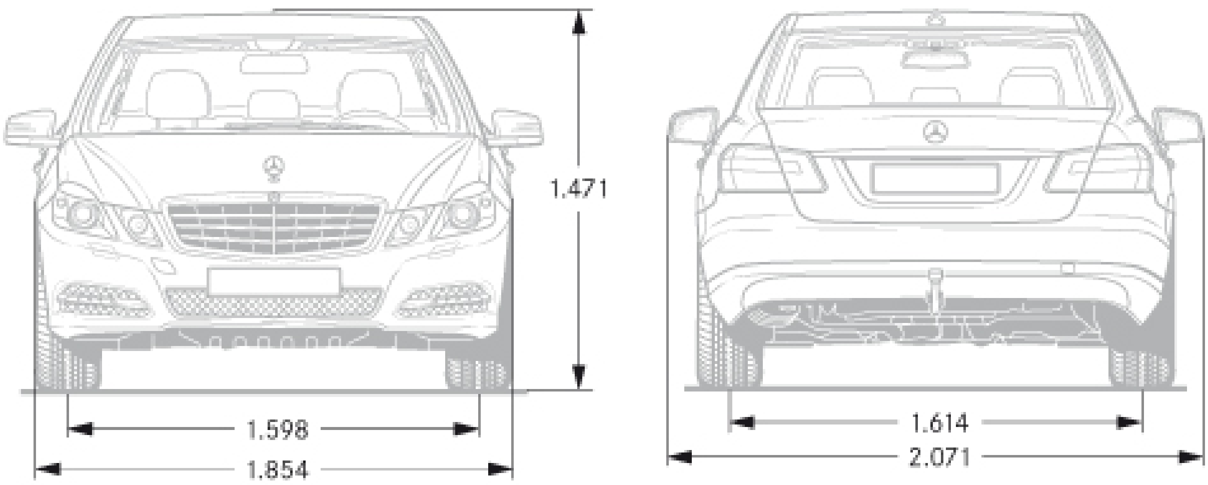
Timestamp

unit	[ms]
description	Time offset when this scan point was measured based in the scan start time.
method	UINT32 getTimeOffset();

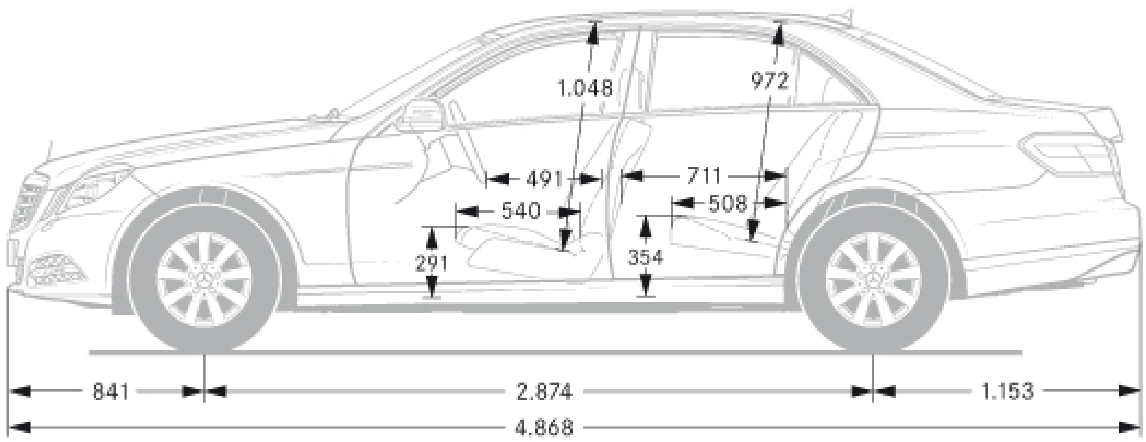
9.3 Test Vehicle

This section of the appendix includes information about the test vehicle. It was kindly placed at the disposal by the Institute of Automotive Engineering at Technische Universität Darmstadt (FZD). It is a Mercedes-Benz E-Class 350 CGI W212 equipped with additional hardware and software for the purpose of research and development in the domain of advanced driver assistance systems.

9.4 Test Vehicle Dimension



(a)



(b)

Figure 49: Dimension of the test vehicle. Source: Daimler AG.

9.5 Intersections Description

9.5.1 Intersection No. 1

Information

Location:	Darmstadt
Intersection name:	Nieder-Ramstädter Straße x Kiesstraße
Date:	2014-08-14, 15:25

Criteria [1]

ID	Intersection	Value
J1	Are there traffic lights near the intersection?	(yes) / **no**
J2	Is there a "Right of way" sign on the major street? (No. 301 or 306)	**(yes)** / no
J3	Is there a "Give way" sign on the minor street? (No. 205)?	**(yes)** / no
ID	**Parking**	**Value**
P1	Is it possible to park without breaking any rules?	**(yes)** / no
P2	Is the orientation of vehicle acceptable for the sensors?	**yes** / (no)
P3	Would the vehicle disturb the traffic?	yes / **(no)**
P4	It is possible to stay with working motor or is there a possibility to connect to a power supply?	**(yes)** / no
ID	**Major street with right of way**	**Value**
R1	Is the view to the street free of obstacles?	**yes** / (no)
R2	Is the detected range satisfactory?	**yes** / (no)
R3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
R4	Is there a bicycle lane?	yes / (no)
ID	**Minor street with give way regulation**	**Value**
G1	Is the view to the street free of obstacles?	**yes** / (no)
G2	Is the detection range satisfactory?	**yes** / (no)
G3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
G4	Is there a crosswalk for pedestrians?	yes / (no)
Conclusion		
1 - SUITABLE	2- SUITABLE TO A LIMITED EXTENT	3 - (UNSUITABLE)

Remarks

- the intersection is too far away; the ground is uneven and the sensors detect too much ground
- there is a bus and tram station in the middle of the major street
- the major street is too width so the intersection is to far away and the sensor can not detect enough of the minor street;could not park so we can get a good view to the major street
- another negative point is the lack of ego objects (objects driving on the minor street)

Table 26: Description of an intersection - No. 1

[1] The acceptable answer for a given criterion are marked in **bold**. If there is no answer marked in **bold** than the criteria has not hard conditions and each of the answer could be acceptable in combination with other criterion. The real answer is marked in brackets.

9.5.2 Intersection No. 2

Information

Location: Darmstadt
Intersection name: Nieder-Ramstädter Straße x Hoffmannstraße
Date: 2014-08-14, 15:45

Criteria [1]

ID	Intersection	Value
J1	Are there traffic lights near the intersection?	yes / **(no)**
J2	Is there a "Right of way" sign on the major street? (No. 301 or 306)	**(yes)** / no
J3	Is there a "Give way" sign on the minor street? (No. 205)?	**(yes)** / no
ID	**Parking**	**Value**
P1	Is it possible to park without breaking any rules?	**(yes)** / no
P2	Is the orientation of vehicle acceptable for the sensors?	**yes** / (no)
P3	Would the vehicle disturb the traffic?	yes / **(no)**
P4	It is possible to stay with working motor or is there a possibility to connect to a power supply?	**(yes)** / no
ID	**Major street with right of way**	**Value**
R1	Is the view to the street free of obstacles?	**(yes)** / no
R2	Is the detected range satisfactory?	**yes** / (no)
R3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
R4	Is there a bicycle lane?	yes / (no)
ID	**Minor street with give way regulation**	**Value**
G1	Is the view to the street free of obstacles?	**yes** / (no)
G2	Is the detection range satisfactory?	**yes** / (no)
G3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
G4	Is there a crosswalk for pedestrians?	yes / (no)
Conclusion		
1 - SUITABLE	2- SUITABLE TO A LIMITED EXTENT	3 - (UNSUITABLE)

Remarks

- the parking position is uneven; test vehicle has a large roll angle so layer 1-3 of the left sensor reflect only the road surface
- the minor street has an inclination; the sensors can not detect any object on that street
- the parking position allows a detection range of only 5 to 10 meters after the intersection

Table 27: Description of an intersection - No. 2

[1] The acceptable answer for a given criterion are marked in **bold**. If there is no answer marked in **bold** than the criteria has not hard conditions and each of the answer could be acceptable in combination with other criterion. The real answer is marked in brackets.

9.5.3 Intersection No. 3

Information

Location:	Darmstadt
Intersection name:	Pützerstraße x Lindenhofstraße (orientation Judenstilbad)
Date:	2014-08-25, 09:45

Criteria [1]

ID	Intersection	Value
J1	Are there traffic lights near the intersection?	(yes) / **no**
J2	Is there a "Right of way" sign on the major street? (No. 301 or 306)	**(yes)** / no
J3	Is there a "Give way" sign on the minor street? (No. 205)?	**(yes)** / no
ID	**Parking**	**Value**
P1	Is it possible to park without breaking any rules?	**yes** / (no)
P2	Is the orientation of vehicle acceptable for the sensors?	**(yes)** / no
P3	Would the vehicle disturb the traffic?	yes / **(no)**
P4	It is possible to stay with working motor or is there a possibility to connect to a power supply?	**(yes)** / no
ID	**Major street with right of way**	**Value**
R1	Is the view to the street free of obstacles?	**(yes)** / no
R2	Is the detected range satisfactory?	**yes** / (no)
R3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
R4	Is there a bicycle lane?	(yes) / no
ID	**Minor street with give way regulation**	**Value**
G1	Is the view to the street free of obstacles?	**(yes)** / no
G2	Is the detection range satisfactory?	**(yes)** / no
G3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
G4	Is there a crosswalk for pedestrians?	yes / (no)
Conclusion		
1 - SUITABLE	2- SUITABLE TO A LIMITED EXTENT	3 - (UNSUITABLE)

Remarks

- no parking possibilities; only one parking slot with view to the intersection is for handicapped persons
- the next intersection is not far away and also has a traffic light
- the major street is to large
- cross traffic blocks highly the view to the intersection

Table 28: Description of an intersection - No. 3

[1] The acceptable answer for a given criterion are marked in **bold**. If there is no answer marked in **bold** than the criteria has not hard conditions and each of the answer could be acceptable in combination with other criterion. The real answer is marked in brackets.

9.5.4 Intersection No. 4

Information

Location:	Darmstadt
Intersection name:	Heinrichstraße x Gervinusstraße
Date:	2014-07-10, 13:40

Criteria [1]

ID	Intersection	Value
J1	Are there traffic lights near the intersection?	(yes) / **no**
J2	Is there a "Right of way" sign on the major street? (No. 301 or 306)	**(yes)** / no
J3	Is there a "Give way" sign on the minor street? (No. 205)?	**(yes)** / no
ID	**Parking**	**Value**
P1	Is it possible to park without breaking any rules?	**(yes)** / no
P2	Is the orientation of vehicle acceptable for the sensors?	**(yes)** / no
P3	Would the vehicle disturb the traffic?	yes / **(no)**
P4	It is possible to stay with working motor or is there a possibility to connect to a power supply?	**(yes)** / no
ID	**Major street with right of way**	**Value**
R1	Is the view to the street free of obstacles?	**yes** / (no)
R2	Is the detected range satisfactory?	**yes** / (no)
R3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
R4	Is there a bicycle lane?	yes / (no)
ID	**Minor street with give way regulation**	**Value**
G1	Is the view to the street free of obstacles?	**(yes)** / no
G2	Is the detection range satisfactory?	**yes** / (no)
G3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
G4	Is there a crosswalk for pedestrians?	yes / (no)
Conclusion		
1 - SUITABLE	2- SUITABLE TO A LIMITED EXTENT	3 - (UNSUITABLE)

Remarks

- the cross traffic is to intense and it is synchronous to the traffic on the major street
- no vehicle on the minor street in more than 10 minutes

Table 29: Description of an intersection - No. 4

[1] The acceptable answer for a given criterion are marked in **bold**. If there is no answer marked in **bold** than the criteria has not hard conditions and each of the answer could be acceptable in combination with other criterion. The real answer is marked in brackets.

9.5.5 Intersection No. 5

Information

Location: Darmstadt
Intersection name: Pützerstraße x Lindenhofstraße (orientation - public parking space)
Date: 2014-07-10, 13:20

Criteria [1]

ID	Intersection	Value
J1	Are there traffic lights near the intersection?	(yes) / **no**
J2	Is there a "Right of way" sign on the major street? (No. 301 or 306)	**(yes)** / no
J3	Is there a "Give way" sign on the minor street? (No. 205)?	**(yes)** / no
ID	**Parking**	**Value**
P1	Is it possible to park without breaking any rules?	**yes** / (no)
P2	Is the orientation of vehicle acceptable for the sensors?	**(yes)** / no
P3	Would the vehicle disturb the traffic?	(yes) / **no**
P4	It is possible to stay with working motor or is there a possibility to connect to a power supply?	**(yes)** / no
ID	**Major street with right of way**	**Value**
R1	Is the view to the street free of obstacles?	**(yes)** / no
R2	Is the detected range satisfactory?	**(yes)** / no
R3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
R4	Is there a bicycle lane?	(yes) / no
ID	**Minor street with give way regulation**	**Value**
G1	Is the view to the street free of obstacles?	**(yes)** / no
G2	Is the detection range satisfactory?	**yes** / (no)
G3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
G4	Is there a crosswalk for pedestrians?	yes / (no)
Conclusion		
1 - SUITABLE	2- SUITABLE TO A LIMITED EXTENT	3 - (UNSUITABLE)

Remarks

- no legal parking possibilities
- the vehicle on the major street adapt their speed according to the traffic lights at the next intersection
- almost no traffic on the minor street
- cross traffic is intense

Table 30: Description of an intersection - No. 5

[1] The acceptable answer for a given criterion are marked in **bold**. If there is no answer marked in **bold** than the criteria has not hard conditions and each of the answer could be acceptable in combination with other criterion. The real answer is marked in brackets.

9.5.6 Intersection No. 6

Information

Location:	Darmstadt
Intersection name:	Frankfurterstraße x Büdingerstraße
Date:	2014-07-10, 13:00

Criteria [1]

ID	Intersection	Value
J1	Are there traffic lights near the intersection?	yes / **(no)**
J2	Is there a ”Right of way” sign on the major street? (No. 301 or 306)	**(yes)** / no
J3	Is there a ”Give way” sign on the minor street? (No. 205)?	**(yes)** / no
ID	**Parking**	**Value**
P1	Is it possible to park without breaking any rules?	**(yes)** / no
P2	Is the orientation of vehicle acceptable for the sensors?	**(yes)** / no
P3	Would the vehicle disturb the traffic?	yes / **(no)**
P4	It is possible to stay with working motor or is there a possibility to connect to a power supply?	**(yes)** / no
ID	**Major street with right of way**	**Value**
R1	Is the view to the street free of obstacles?	**(yes)** / no
R2	Is the detected range satisfactory?	**yes** / (no)
R3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
R4	Is there a bicycle lane?	(yes) / no
ID	**Minor street with give way regulation**	**Value**
G1	Is the view to the street free of obstacles?	**(yes)** / no
G2	Is the detection range satisfactory?	**(yes)** / no
G3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
G4	Is there a crosswalk for pedestrians?	yes / (no)
Conclusion		
1 - SUITABLE	2- SUITABLE TO A LIMITED EXTENT	3 - (UNSUITABLE)

Remarks

- the vehicles on the minor street cover the traffic on the major street
- only a few meters after the intersection could be detected with the sensors
- parking slot does not allow free positioning of the test vehicle

Table 31: Description of an intersection - No. 6

[1] The acceptable answer for a given criterion are marked in **bold**. If there is no answer marked in **bold** than the criteria has not hard conditions and each of the answer could be acceptable in combination with other criterion. The real answer is marked in brackets.

9.5.7 Intersection No. 7

Information

Location: Darmstadt
Intersection name: Holzhofallee x Schöfferstraße
Date: 2014-07-10, 12:50

Criteria [1]

ID	Intersection	Value
J1	Are there traffic lights near the intersection?	(yes) / **no**
J2	Is there a "Right of way" sign on the major street? (No. 301 or 306)	**(yes)** / no
J3	Is there a "Give way" sign on the minor street? (No. 205)?	**(yes)** / no
ID	**Parking**	**Value**
P1	Is it possible to park without breaking any rules?	**(yes)** / no
P2	Is the orientation of vehicle acceptable for the sensors?	**yes** / (no)
P3	Would the vehicle disturb the traffic?	yes / **(no)**
P4	It is possible to stay with working motor or is there a possibility to connect to a power supply?	**(yes)** / no
ID	**Major street with right of way**	**Value**
R1	Is the view to the street free of obstacles?	**(yes)** / no
R2	Is the detected range satisfactory?	**yes** / (no)
R3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
R4	Is there a bicycle lane?	yes / (no)
ID	**Minor street with give way regulation**	**Value**
G1	Is the view to the street free of obstacles?	**yes** / (no)
G2	Is the detection range satisfactory?	**yes** / (no)
G3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
G4	Is there a crosswalk for pedestrians?	yes / (no)
Conclusion		
1 - SUITABLE	2- SUITABLE TO A LIMITED EXTENT	3 - (UNSUITABLE)

Remarks

- only a few meters after the intersection could be detected with the sensors
- the parking position is uneven; test vehicle has a large roll angle so layer 1-3 of the left sensor reflect only the road surface

Table 32: Description of an intersection - No. 7

[1] The acceptable answer for a given criterion are marked in **bold**. If there is no answer marked in **bold** than the criteria has not hard conditions and each of the answer could be acceptable in combination with other criterion. The real answer is marked in brackets.

9.5.8 Intersection No. 8

Information

Location:	Darmstadt
Intersection name:	Karlstraße x Hölgestraße
Date:	2014-07-10, 12:30

Criteria [1]

ID	Intersection	Value
J1	Are there traffic lights near the intersection?	(yes) / **no**
J2	Is there a "Right of way" sign on the major street? (No. 301 or 306)	**(yes)** / no
J3	Is there a "Give way" sign on the minor street? (No. 205)?	**(yes)** / no
ID	**Parking**	**Value**
P1	Is it possible to park without breaking any rules?	**(yes)** / no
P2	Is the orientation of vehicle acceptable for the sensors?	**(yes)** / no
P3	Would the vehicle disturb the traffic?	yes / **(no)**
P4	It is possible to stay with working motor or is there a possibility to connect to a power supply?	**(yes)** / no
ID	**Major street with right of way**	**Value**
R1	Is the view to the street free of obstacles?	**(yes)** / no
R2	Is the detected range satisfactory?	**yes** / (no)
R3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
R4	Is there a bicycle lane?	yes / (no)
ID	**Minor street with give way regulation**	**Value**
G1	Is the view to the street free of obstacles?	**yes** / (no)
G2	Is the detection range satisfactory?	**yes** / (no)
G3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
G4	Is there a crosswalk for pedestrians?	yes / (no)
Conclusion		
1 - SUITABLE	2- SUITABLE TO A LIMITED EXTENT	3 - (UNSUITABLE)

Remarks

- only a few meters after the intersection could be detected with the sensors
- the road has a slope and a turning; the sensors range is not satisfactory
- the major street has a tram lane

Table 33: Description of an intersection - No. 8

[1] The acceptable answer for a given criterion are marked in **bold**. If there is no answer marked in **bold** than the criteria has not hard conditions and each of the answer could be acceptable in combination with other criterion. The real answer is marked in brackets.

9.5.9 Intersection No. 9

Information

Location:	Darmstadt
Intersection name:	Pallaswiesenstraße x Schloßgartenplatz
Date:	2014-07-10, 13:15

Criteria [1]

ID	Intersection	Value
J1	Are there traffic lights near the intersection?	yes / **(no)**
J2	Is there a "Right of way" sign on the major street? (No. 301 or 306)	**(yes)** / no
J3	Is there a "Give way" sign on the minor street? (No. 205)?	**(yes)** / no
ID	**Parking**	**Value**
P1	Is it possible to park without breaking any rules?	**(yes)** / no
P2	Is the orientation of vehicle acceptable for the sensors?	**yes** / (no)
P3	Would the vehicle disturb the traffic?	yes / **(no)**
P4	It is possible to stay with working motor or is there a possibility to connect to a power supply?	**(yes)** / no
ID	**Major street with right of way**	**Value**
R1	Is the view to the street free of obstacles?	**yes** / (no)
R2	Is the detected range satisfactory?	**yes** / (no)
R3	Is the maximum allowed speed 50 km/h?	**yes** / (no)
R4	Is there a bicycle lane?	yes / (no)
ID	**Minor street with give way regulation**	**Value**
G1	Is the view to the street free of obstacles?	**yes** / (no)
G2	Is the detection range satisfactory?	**yes** / (no)
G3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
G4	Is there a crosswalk for pedestrians?	yes / (no)
Conclusion		
1 - SUITABLE	2- SUITABLE TO A LIMITED EXTENT	3 - (UNSUITABLE)

Remarks

- the intersection area requires low speed and most of the vehicle on the minor street stop before crossing the intersection
- almost no parking possibilities
- the area around the intersection is full of obstacles such as big stones, bushes etc.; only few meters detection range

Table 34: Description of an intersection - No. 9

[1] The acceptable answer for a given criterion are marked in **bold**. If there is no answer marked in **bold** than the criteria has not hard conditions and each of the answer could be acceptable in combination with other criterion. The real answer is marked in brackets.

9.5.10 Intersection No. 10

Information

Location:	Roßdorf
Intersection name:	Darmstädter Straße x Karl-Marx-Straße
Date:	2014-07-10, 14:00

Criteria [1]

ID	Intersection	Value
J1	Are there traffic lights near the intersection?	(yes) / **no**
J2	Is there a "Right of way" sign on the major street? (No. 301 or 306)	**(yes)** / no
J3	Is there a "Give way" sign on the minor street? (No. 205)?	**(yes)** / no
ID	**Parking**	**Value**
P1	Is it possible to park without breaking any rules?	**(yes)** / no
P2	Is the orientation of vehicle acceptable for the sensors?	**yes** / (no)
P3	Would the vehicle disturb the traffic?	yes / **(no)**
P4	It is possible to stay with working motor or is there a possibility to connect to a power supply?	**yes** / (no)
ID	**Major street with right of way**	**Value**
R1	Is the view to the street free of obstacles?	**yes** / (no)
R2	Is the detected range satisfactory?	**yes** / (no)
R3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
R4	Is there a bicycle lane?	yes / (no)
ID	**Minor street with give way regulation**	**Value**
G1	Is the view to the street free of obstacles?	**yes** / (no)
G2	Is the detection range satisfactory?	**yes** / (no)
G3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
G4	Is there a crosswalk for pedestrians?	yes / (no)
Conclusion		
1 - SUITABLE	2- SUITABLE TO A LIMITED EXTENT	3 - (UNSUITABLE)

Remarks

- no parking slot that allows the positioning of the test vehicle in a free orientation
- the minor street is narrowed by parked vehicles
- parking slot does not allow the detection of the area after the intersection

Table 35: Description of an intersection - No. 10

[1] The acceptable answer for a given criterion are marked in **bold**. If there is no answer marked in **bold** than the criteria has not hard conditions and each of the answer could be acceptable in combination with other criterion. The real answer is marked in brackets.

9.5.11 Intersection No. 11

Information

Location: Griesheim
Intersection name: Nordring x Bunsenstraße
Date: 2014-07-10, 16:30

Criteria [1]

ID	Intersection	Value
J1	Are there traffic lights near the intersection?	yes / **(no)**
J2	Is there a "Right of way" sign on the major street? (No. 301 or 306)	**(yes)** / no
J3	Is there a "Give way" sign on the minor street? (No. 205)?	**(yes)** / no
ID	**Parking**	**Value**
P1	Is it possible to park without breaking any rules?	**(yes)** / no
P2	Is the orientation of vehicle acceptable for the sensors?	**(yes)** / no
P3	Would the vehicle disturb the traffic?	yes / **(no)**
P4	It is possible to stay with working motor or is there a possibility to connect to a power supply?	**(yes)** / no
ID	**Major street with right of way**	**Value**
R1	Is the view to the street free of obstacles?	**(yes)** / no
R2	Is the detected range satisfactory?	**(yes)** / no
R3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
R4	Is there a bicycle lane?	yes / (no)
ID	**Minor street with give way regulation**	**Value**
G1	Is the view to the street free of obstacles?	**(yes)** / no
G2	Is the detection range satisfactory?	**(yes)** / no
G3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
G4	Is there a crosswalk for pedestrians?	yes / (no)
Conclusion		
1 - (SUITABLE)	2- SUITABLE TO A LIMITED EXTENT	3 - UNSUITABLE

Remarks

- gas filling station and car wash station generate a high flow of traffic on the minor street
- the major street is carrying out a high traffic flow
- parking slot belongs to the residents of the apartment building

Table 36: Description of an intersection - No. 11

[1] The acceptable answer for a given criterion are marked in **bold**. If there is no answer marked in **bold** than the criteria has not hard conditions and each of the answer could be acceptable in combination with other criterion. The real answer is marked in brackets.

9.5.12 Intersection No. 12

Information

Location:	Dieburg
Intersection name:	Aschaffenburger Straße x Max-Planck-Straße
Date:	2014-07-10, 15:30

Criteria [1]

ID	Intersection	Value
J1	Are there traffic lights near the intersection?	yes / **(no)**
J2	Is there a "Right of way" sign on the major street? (No. 301 or 306)	**(yes)** / no
J3	Is there a "Give way" sign on the minor street? (No. 205)?	**(yes)** / no
ID	**Parking**	**Value**
P1	Is it possible to park without breaking any rules?	**yes** / (no)
P2	Is the orientation of vehicle acceptable for the sensors?	**(yes)** / no
P3	Would the vehicle disturb the traffic?	(yes) / **no**
P4	It is possible to stay with working motor or is there a possibility to connect to a power supply?	**(yes)** / no
ID	**Major street with right of way**	**Value**
R1	Is the view to the street free of obstacles?	**yes** / (no)
R2	Is the detected range satisfactory?	**yes** / (no)
R3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
R4	Is there a bicycle lane?	yes / (no)
ID	**Minor street with give way regulation**	**Value**
G1	Is the view to the street free of obstacles?	**(yes)** / no
G2	Is the detection range satisfactory?	**(yes)** / no
G3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
G4	Is there a crosswalk for pedestrians?	yes / (no)
Conclusion		
1 - SUITABLE	2- SUITABLE TO A LIMITED EXTENT	3 - (UNSUITABLE)

Remarks

- there is a no parking spot around the intersection
- the only way to collect data is to park on the opposite side at the intersection but than the test vehicle would disturb the traffic

Table 37: Description of an intersection - No. 12

[1] The acceptable answer for a given criterion are marked in **bold**. If there is no answer marked in **bold** than the criteria has not hard conditions and each of the answer could be acceptable in combination with other criterion. The real answer is marked in brackets.

9.5.13 Intersection No. 13

Information

Location:	Dieburg
Intersection name:	Groß-Umstädter Straße x Max-Planck-Straße
Date:	2014-07-10, 15:40

Criteria [1]

ID	Intersection	Value
J1	Are there traffic lights near the intersection?	yes / **(no)**
J2	Is there a "Right of way" sign on the major street? (No. 301 or 306)	**(yes)** / no
J3	Is there a "Give way" sign on the minor street? (No. 205)?	**(yes)** / no
ID	**Parking**	**Value**
P1	Is it possible to park without breaking any rules?	**(yes)** / no
P2	Is the orientation of vehicle acceptable for the sensors?	**(yes)** / no
P3	Would the vehicle disturb the traffic?	yes / **(no)**
P4	It is possible to stay with working motor or is there a possibility to connect to a power supply?	**(yes)** / no
ID	**Major street with right of way**	**Value**
R1	Is the view to the street free of obstacles?	**(yes)** / no
R2	Is the detected range satisfactory?	**yes** / (no)
R3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
R4	Is there a bicycle lane?	yes / (no)
ID	**Minor street with give way regulation**	**Value**
G1	Is the view to the street free of obstacles?	**(yes)** / no
G2	Is the detection range satisfactory?	**yes** / (no)
G3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
G4	Is there a crosswalk for pedestrians?	yes / (no)
Conclusion		
1 - SUITABLE	2- SUITABLE TO A LIMITED EXTENT	3 - (UNSUITABLE)

Remarks

- only one parking spot that is at the level of the intersection
- the test vehicle should be parked parallel to the major street - no data can be collected after the intersection
- minor street is turning and this minimizes the range of the data collection to few meters

Table 38: Description of an intersection - No. 13

[1] The acceptable answer for a given criterion are marked in **bold**. If there is no answer marked in **bold** than the criteria has not hard conditions and each of the answer could be acceptable in combination with other criterion. The real answer is marked in brackets.

9.5.14 Intersection No. 14

Information

Location: Dieburg
Intersection name: Groß-Umstädter Straße x Ringstraße
Date: 2014-07-10, 15:50

Criteria [1]

ID	Intersection	Value
J1	Are there traffic lights near the intersection?	yes / **(no)**
J2	Is there a "Right of way" sign on the major street? (No. 301 or 306)	**(yes)** / no
J3	Is there a "Give way" sign on the minor street? (No. 205)?	**(yes)** / no
ID	**Parking**	**Value**
P1	Is it possible to park without breaking any rules?	**yes** / (no)
P2	Is the orientation of vehicle acceptable for the sensors?	**(yes)** / no
P3	Would the vehicle disturb the traffic?	yes / **(no)**
P4	It is possible to stay with working motor or is there a possibility to connect to a power supply?	**(yes)** / no
ID	**Major street with right of way**	**Value**
R1	Is the view to the street free of obstacles?	**(yes)** / no
R2	Is the detected range satisfactory?	**yes** / (no)
R3	Is the maximum allowed speed 50 km/h?	**(yes)** / no
R4	Is there a bicycle lane?	yes / (no)
ID	**Minor street with give way regulation**	**Value**
G1	Is the view to the street free of obstacles?	**yes** / (no)
G2	Is the detection range satisfactory?	**yes** / (no)
G3	Is the maximum allowed speed 50 km/h?	**yes** / (no)
G4	Is there a crosswalk for pedestrians?	yes / (no)
Conclusion		
1 - SUITABLE	2- SUITABLE TO A LIMITED EXTENT	3 - (UNSUITABLE)

Remarks

- no legal parking slot
- the detection is not robust - cross traffic and guardrails
- minor street is not of the wanted type

Table 39: Description of an intersection - No. 14

[1] The acceptable answer for a given criterion are marked in **bold**. If there is no answer marked in **bold** than the criteria has not hard conditions and each of the answer could be acceptable in combination with other criterion. The real answer is marked in brackets.

9.6 Recordings Protocols

This section of the appendix includes all protocols about the recordings. Each protocol contains the date and the location of the measurement, the distances to the reference points and the remarks, that was written during the recording.

9.6.1 Recording at an Intersection - 25.08.2014

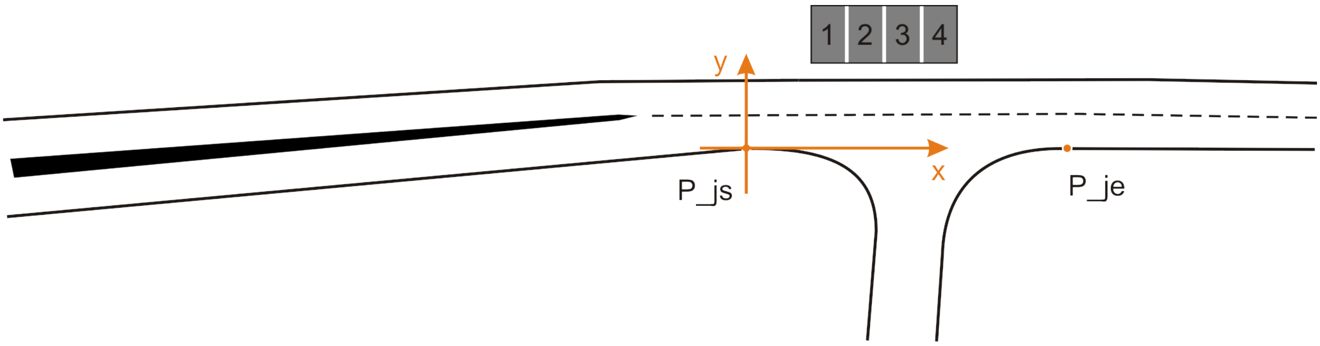
Information

Location: Griesheim, Germany
Name: Bunsenstr. x Nordring
Date: 26.08.2014, 15:00

Parking position

Reference point	Value	Unit	Description
P_js	(13.15, -15.97)	[Point2D]	Measured distance to the start point of the intersection
P_je	(13.88, 13.45)	[Point2D]	Measured distance to the end point of the intersection
P_js_corrected	(,)	[Point2D]	Corrected distance to the start point of the intersection
P_je_corrected	(,)	[Point2D]	Corrected distance to the end point of the intersection

Parking slot: 2



Remarks

- after measuring the reference points one should wait until vehicles at the gas station change
- this parking position is advantageous if there are more than one vehicle at the intersection and the first one wants to turn right
- sensor range to the right not sufficient
- one can see further than the sensor can detect any objects
- 16:20 high traffic in direction Darmstadt

9.6.2 Recording at an Intersection - 27.08.2014 1st recording

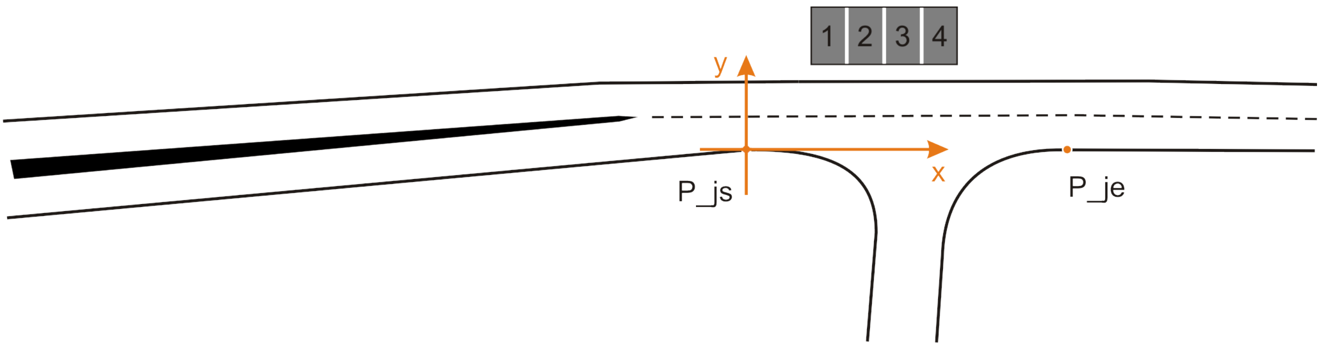
Information

Location: Griesheim, Germany
Name: Bunsenstr. x Nordring
Date: 27.08.2014, 08:00

Parking position

Reference point	Value	Unit	Description
P_js	(14.45, -14.99)	[Point2D]	Measured distance to the start point of the intersection
P_je	(12.27, 12.93)	[Point2D]	Measured distance to the end point of the intersection
P_js_corrected	(14.4500, -14.9900)	[Point2D]	Corrected distance to the start point of the intersection
P_je_corrected	(12.2702, 12.9271)	[Point2D]	Corrected distance to the end point of the intersection

Parking slot: 1



Remarks

- 8:30 low traffic in both directions
- 9:15 no one at the gas station
- 10:15 almost no one at the gas station. If the gas station is empty than in the next 15 minutes will be no target
- at the morning is the car wash empty

9.6.3 Recording at an Intersection - 27.08.2014 2nd recording

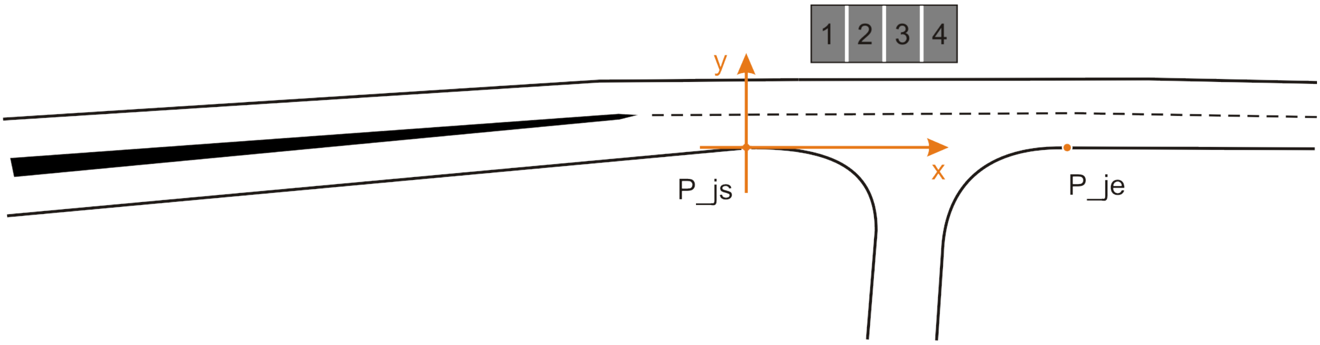
Information

Location:	Griesheim, Germany
Name:	Bunsenstr. x Nordring
Date:	27.08.2014, 14:00

Parking position

Reference point	Value	Unit	Description
P_js	(13.68, -16.22)	[Point2D]	Measured distance to the start point of the intersection
P_je	(12.84, 11.77)	[Point2D]	Measured distance to the end point of the intersection
P_js_corrected	(13.6800, -16.2200)	[Point2D]	Corrected distance to the start point of the intersection
P_je_corrected	(12.8400, 11.7694)	[Point2D]	Corrected distance to the end point of the intersection

Parking slot: 1



Remarks

- 14:07 start
- 16:45 end

9.6.4 Recording at an Intersection - 28.08.2014 1st recording

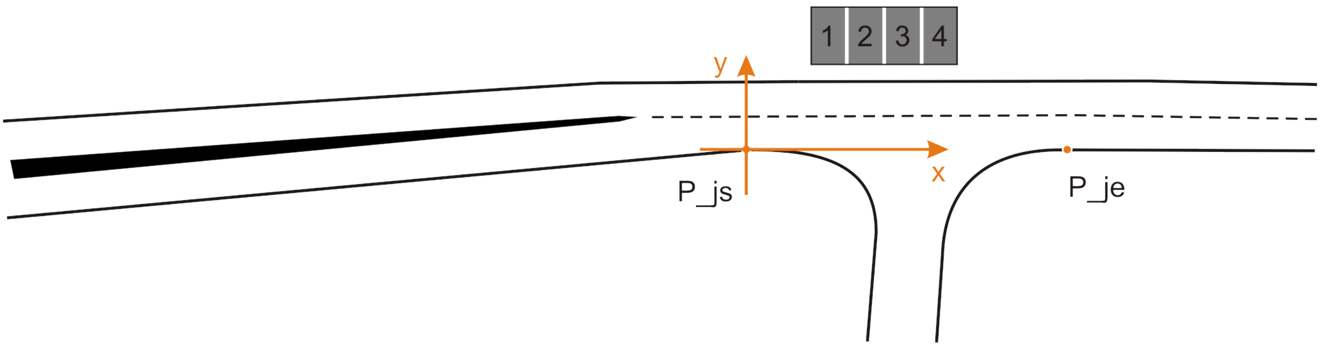
Information

Location:	Griesheim, Germany
Name:	Bunsenstr. x Nordring
Date:	28.08.2014, 07:00

Parking position

Reference point	Value	Unit	Description
P_js	(14.10, -15.69)	[Point2D]	Measured distance to the start point of the intersection
P_je	(12.77, 12.28)	[Point2D]	Measured distance to the end point of the intersection
P_js_corrected	(14.1000, 15.6900)	[Point2D]	Corrected distance to the start point of the intersection
P_je_corrected	(12.7700, 12.2804)	[Point2D]	Corrected distance to the end point of the intersection

Parking slot: 1



Remarks

- 07:10 start
- 07:10 - 07:30 no one at the gas station
- most of the traffic goes in direction Darmstadt
- 07:30 - 08:00 no one at the gas station but the traffic is continual in both directions
- 08:00 - 09:00 almost no one at the gas station and low traffic in both directions
- 10:00 end

9.6.5 Recording at an Intersection - 28.08.2014 2nd recording

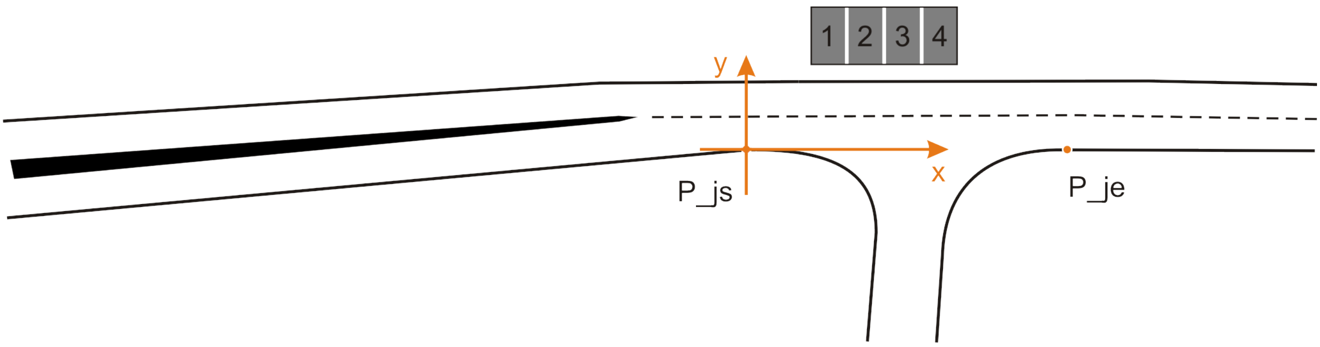
Information

Location:	Griesheim, Germany
Name:	Bunsenstr. x Nordring
Date:	28.08.2014, 11:00

Parking position

Reference point	Value	Unit	Description
P_js	(13.58, -16.12)	[Point2D]	Measured distance to the start point of the intersection
P_je	(13.11, 11.88)	[Point2D]	Measured distance to the end point of the intersection
P_js_corrected	13.5800, -16.1200)	[Point2D]	Corrected distance to the start point of the intersection
P_je_corrected	(13.1100, 11.8781)	[Point2D]	Corrected distance to the end point of the intersection

Parking slot: 1



Remarks

- 11:00 start
- every once in a while high density traffic
- sunny, the car wash is occupied

9.6.6 Recording at an Intersection - 28.08.2014 3rd recording

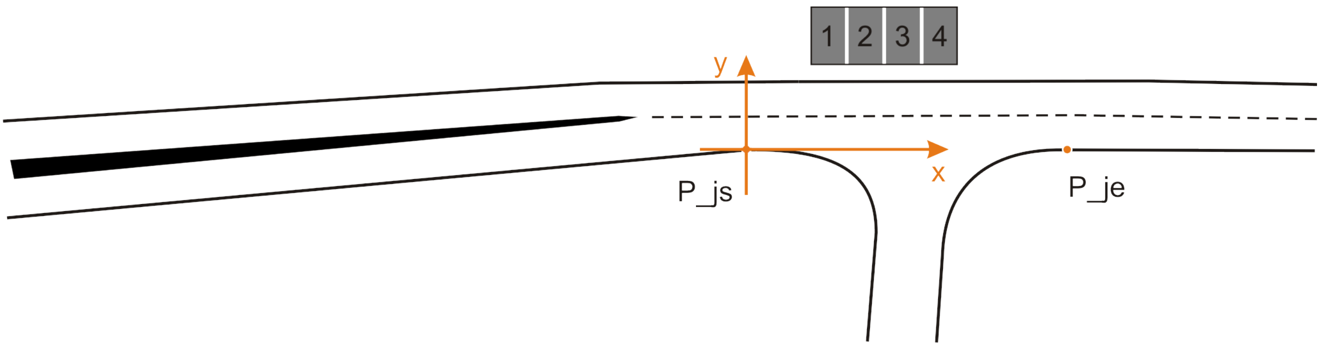
Information

Location: Griesheim, Germany
Name: Bunsenstr. x Nordring
Date: 28.08.2014, 16:30

Parking position

Reference point	Value	Unit	Description
P_js	(14.10, -15.33)	[Point2D]	Measured distance to the start point of the intersection
P_je	(12.71, 12.64)	[Point2D]	Measured distance to the end point of the intersection
P_js_corrected	(14.1000, -15.3300)	[Point2D]	Corrected distance to the start point of the intersection
P_je_corrected	(12.7101, 12.6375)	[Point2D]	Corrected distance to the end point of the intersection

Parking slot: 1



Remarks

- 16:46 start
- high traffic density
- 18:00 it's getting dark and 2 of 3 drivers discover the test vehicle. Possible reason: laptop display is too bright, most of the vehicles are with turned on headlights and can see into the car

9.6.7 Recording at an Intersection - 29.08.2014 1st recording

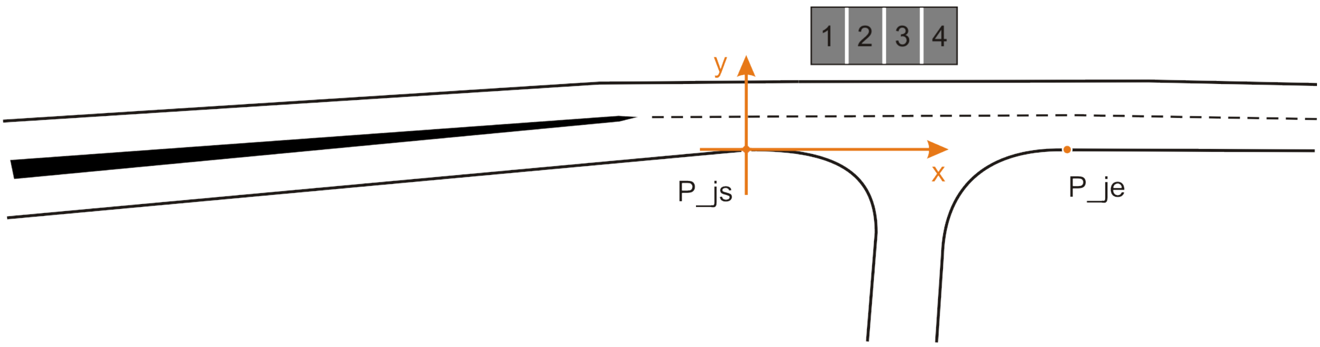
Information

Location: Griesheim, Germany
Name: Bunsenstr. x Nordring
Date: 29.08.2014, 06:30

Parking position

Reference point	Value	Unit	Description
P_js	(13.61, -15.82)	[Point2D]	Measured distance to the start point of the intersection
P_je	(12.67, 12.16)	[Point2D]	Measured distance to the end point of the intersection
P_js_corrected	(13.6100, -15.8200)	[Point2D]	Corrected distance to the start point of the intersection
P_je_corrected	(12.6698, 12.1663)	[Point2D]	Corrected distance to the end point of the intersection

Parking slot: 1



Remarks

- start 06:40
- almost no traffic
- 06:40 - 07:30 it's still dark and 2 of 3 drivers discover the test vehicle. Possible reason: laptop display is too bright, most of the vehicles are with turned on headlights and can see into the car
- end 08:30

9.6.8 Recording at an Intersection - 29.08.2014 2nd recording

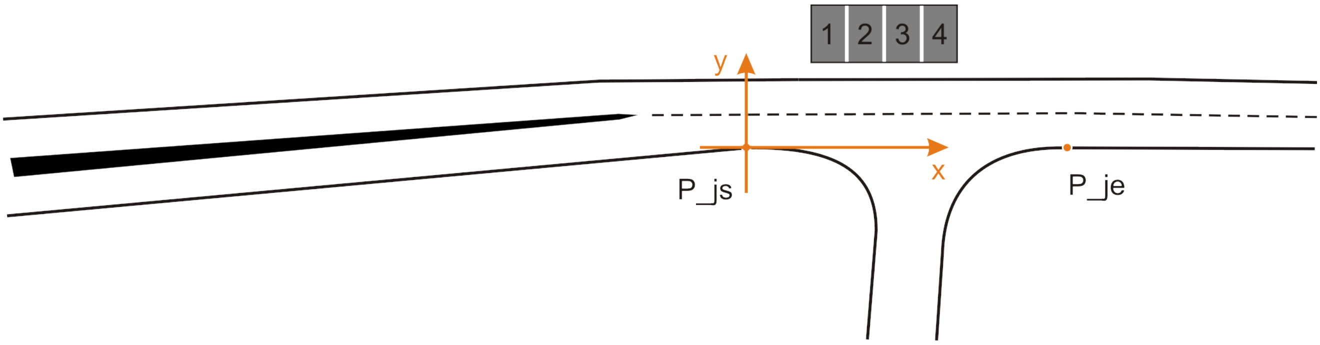
Information

Location: Griesheim, Germany
Name: Bunsenstr. x Nordring
Date: 29.08.2014, 10:15

Parking position

Reference point	Value	Unit	Description
P_js	(14.57, -15.15)	[Point2D]	Measured distance to the start point of the intersection
P_je	(12.31, 12.76)	[Point2D]	Measured distance to the end point of the intersection
P_js_corrected	(14.5700, -15.1500)	[Point2D]	Corrected distance to the start point of the intersection
P_je_corrected	(12.3099, 12.7607)	[Point2D]	Corrected distance to the end point of the intersection

Parking slot: 1



Remarks

- start 10:30
- between 12:00 and 13:00 to much traffic
- drivers are tense
- cross traffic intense
- 06:40 - 07:30 it's still dark and 2 of 3 drivers discover the test vehicle. Possible reason: laptop display is too bright, most of the vehicles are with turned on headlights and can see into the car
- end 13:30

9.6.9 Recording at an Intersection - 29.08.2014 3rd recording

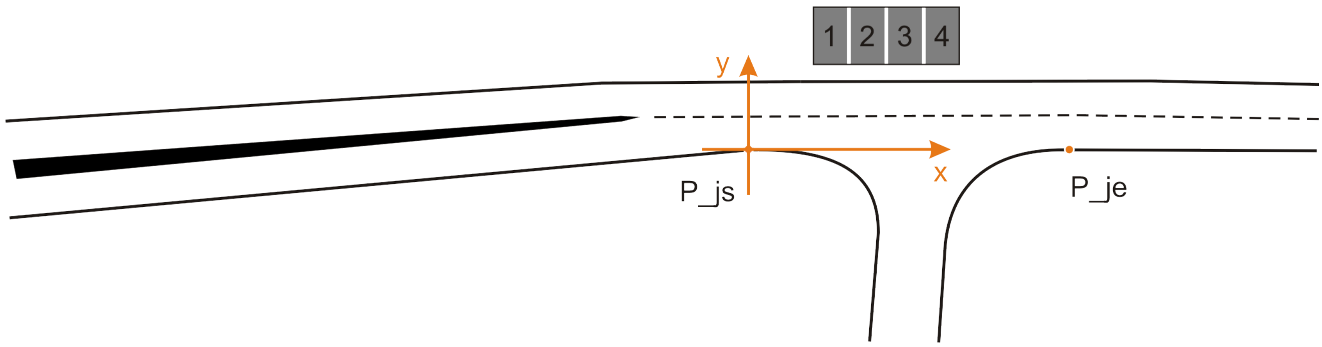
Information

Location: Griesheim, Germany
Name: Bunsenstr. x Nordring
Date: 29.08.2014, 14:50

Parking position

Reference point	Value	Unit	Description
P_js	(14.11, -15.67)	[Point2D]	Measured distance to the start point of the intersection
P_je	(12.78, 12.30)	[Point2D]	Measured distance to the end point of the intersection
P_js_corrected	(14.1100, -15.6700)	[Point2D]	Corrected distance to the start point of the intersection
P_je_corrected	(12.7800, 12.3004)	[Point2D]	Corrected distance to the end point of the intersection

Parking slot: 1



Remarks

- start 15:00
- nice weather - intense traffic
- most of the vehicles on the minor street come from the car wash
- 16:40 the traffic drops
- end 17:00

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