Vehicle Safety Institute

Schubert Florian, BSc

Evaluation of Autonomous Accident Avoidance Strategies on Motorways in Rear-end Crashes

MASTER THESIS

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Supervisors: Dipl.-Ing. Dr.techn. Ernst Tomasch

Dipl.-Ing. Harld Kolk, BSc

Evaluator: Univ.-Prof. Dipl.-Ing. Dr.techn. Hermann Steffan

Graz, May 2016

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ABSTRACT

More than 90% of the road accidents with casualties, especially those on highways are caused by human drivers. This fact is one of the driving forces behind the development of new technologies like autonomous driving to avoid accidents. Other reasons are comfort improvement or to show the technical possibilities nowadays.

The goal of this master thesis is to develop an autonomous driving assistant in a simulation environment which is able to manage standard situations, like a traffic jam, on a highway autonomously. For the implementation the accident reconstruction programme "PC Crash" and the mathematics programme "Matlab" is used.

The autonomous driving assistant is based on a decision making algorithm which is able to handle various situations that might occur on the highway. To do so the assistant is based on the road traffic regulations of Austria and is designed for a high comfort standard and driving in a fluent way. Furthermore visual and kinematic coherences are taken into account into the decision making algorithm. First the lanes are checked visually if they are empty and within a parallel process the time to collision is calculated in order to decide if there is enough time left to execute an overtaking process without any collision with other cars. Moreover acceleration, deceleration and lane changing manoeuvers are implemented. To plan and execute those manoeuvers the traffic in the closer environment of the autonomous car is observed by sensors in each time step. The environment consists of vehicles or objects ahead or behind the Ego-car, respectively the right or the left side. Furthermore the lanes are observed and taken into account diagonal to the front and to the back. To avoid critical situations lane changes based on the decision making algorithm are set. If there is no possibility to evade an obstacle because of an occupied environment of the autonomous car, a full brake manoeuver is started.

The decision making algorithm is evaluated on a generic overtaking manoeuver. The developed decision making algorithm was able to perform a passing manoeuver with different traffic density without any collisions. Furthermore, unexpected emergency situations, like a stopped vehicle on the driven lane, can be handled.

Based on a real road accident the autonomous driving assistant was evaluated. In the accident reconstruction there is no information about traffic density, amount of vehicles on the other lanes, time-distance interval, etc. Thus three different scenarios were simulated to evaluate the behaviour of the autonomous car in an accident situation. The autonomous car could handle each of the three different scenarios.

KURZFASSUNG

Über 90% der Verkehrsunfälle mit Personenschaden auf Autobahnen werden durch menschliches Fehlverhalten verursacht. Dieser Umstand ist einer der treibenden Kräfte hinter der Automatisierung des Fahrzeugverkehrs. Des Weiteren spielen sowohl ein möglicher Komfortgewinn als auch die technische Machbarkeit eine Rolle.

Das Ziel dieser Masterarbeit ist es einen vollautomatischen autonomen Fahrassistenten zu programmieren, dem es möglich ist alle relevanten Fahrmanöver, wie zum Beispiel ein Verkehrsstau, auf einer Autobahn selbstständig durchzuführen. Für die Umsetzung wurde das Verkehrsunfallrekonstruktionsprogramm „PC Crash“ und das Mathematikprogramm „Matlab“ verwendet.

Der Fahrassistent für autonomes Fahren basiert auf einem Entscheidungsalgorithmus, welcher es ermöglicht Situationen auf Autobahnen zu erfassen und Unfälle zu vermeiden. Grundlage für den Entscheidungsalgorithmus ist die österreichische Straßenverkehrsordnung und die Voraussetzung sich möglichst komfortabel und flüssig im Straßenverkehr zu bewegen. Berücksichtigt sind im Entscheidungsalgorithmus visuelle und kinematische Zusammenhänge. Visuell wird zunächst geprüft ob die Fahrspur frei von Objekten oder Fahrzeugen ist und parallel dazu, wird auf Grund einer Time-To-Collision berechnet, ob eine ausreichend lange Zeit für einen Überholvorgang besteht, ohne eine Kollision mit anderen Fahrzeugen zu bewirken. Dahingehend sind sowohl Beschleunigungs- und Bremsmanöver als auch Fahrspurwechselvorgänge implementiert. Um diese Fahrmanöver planen und ausführen zu können wird das Verkehrsgeschehen im näheren Umfeld rund um das Fahrzeug mit Hilfe von Sensoren, in jedem Zeitschritt überwacht. Als Umfeld gelten hierbei Objekte oder Fahrzeuge vor und hinter dem Ego- Fahrzeug beziehungsweise links oder rechts von diesem. Ebenfalls werden die Fahrspuren diagonal nach vorne und nach hinten überwacht und berücksichtigt.

Um kritische Fahrsituationen zu vermeiden, wird auf Grund des Entscheidungsalgorithmus die Fahrspur gewechselt. Besteht keine Ausweichmöglichkeit, wenn zum Beispiel das Umfeld durch andere Fahrzeuge besetzt ist, so wird ein Vollbremsmanöver eingeleitet.

Der Entscheidungsalgorithmus wurde an Hand eines generischen Überholmanövers überprüft.

Mit dem entwickelten autonomen Fahrassistenten war es möglich einen Überholvorgang mit unterschiedlicher Verkehrsdichte auszuführen, ohne einen Verkehrsunfall auszulösen. Ebenfalls konnten unvorhergesehene Notsituationen, wie ein stehendes Fahrzeug auf der Fahrspur, gelöst werden.

Auf Grund des Realunfalls wurde der autonome Fahrassistent ebenfalls überprüft. In der Unfallrekonstruktion sind allerdings keine Informationen zur Verkehrsdichte, Anzahl an Fahrzeugen auf den einzelnen Fahrspuren, Zeit-Weg-Abstände, etc. vorliegend. Daher wurden drei unterschiedliche Szenarien simuliert, um das Verhalten eines autonom entscheidenden Fahrzeugs in einer Unfallsituation zu überprüfen. In jedem der drei unterschiedlichen Szenarien konnte das autonome Fahrzeug den Unfall verhindern.

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LIST OF ABBREVIATION

AHDAS	Autonomous Highway Driving ASsistant
CEDATU	Central Database for In-Depth Accident Study
COG	Centre of Gravity
DARPA	Defense Advanced Research Projects Agency (US authority)
Ego-car	Car on which all decisions are made for; equipped with sensors and is manoeuvred autonomously
ESC	Electronic Stability Control
GHz	Giga Hertz
GPS	Global Positioning System
KHz	Kilo Hertz
Lidar	Light Detection and Ranging
LRR	Long Range Radar
MHz	Mega Hertz
MRR	Mid Range Radar
n.a.	Not applicable
SRR	Short Range Radar
TROCS	Tartan Racing Operator Control System
TTC	Time to collision
X-RATE	Extended Effectiveness Rating of Advanced Driver Assistance Systems

1 INTRODUCTION

1.2 Motivation

Today some vehicles drive already semi-autonomous for example the Tesla Model S (2015) or the new Mercedes E-Class (2016). The automatization and networking in the automotive sector will increase in the near future. Thus, it makes sense to handle the challenges of increasing traffic rates and to reduce the number of traffic accidents using this technology. As opposed to the industry sector where "Industry 4.0" is pushed the automotive sector deals with "Mobility 4.0" which stands for cross-linked and autonomous driving. An essential prerequisite are intelligent cars, which are able to scan their environment and to communicate with each other, as well as with the road traffic relevant environment. The aim is to increase safety and comfort or enable an environment friendly transport of people and goods also by implementing the "intelligent" infrastructure. [1]

A main reason mentioned by Berg A. [1] is to promote a high level of automation is its aim to decrease accidents. Whereas the implementation of driving assistant systems like ESC in the past improved the safety in road traffic. This will lead to an increasing number of assistant systems and a decreasing number of accidents caused by humans. In Germany, as seen in Figure 1-1, 91.3% of all road accidents in 2014 with injuries were caused by humans. Furthermore, the accident related causes (7.8% of all road accidents in Germany with injuries in 2014) are depending on the human behaviour because the driver has to adapt his driving behaviour to the road and visibility conditions. Based on the statistics for casualties in road accidents and the correlation to already implemented safety measures like ESC, it is to be expected that the total number of casualties or injured road users will decrease as a result of implementing more autonomous systems. However, the great number of electronic parts and complexity in this field unavoidably leads to an increase of technical problems and failures. Thus the accidents caused by technical problems might increase. As long as there is no prohibition that a human is allowed to steer a car as long the human element has to be considered and will have an influence on the statistics of injured and killed road users. [1]
The accident causes are often the driver's fatigue, carelessness or mistakenly manoeuvers in emergency situations. [2]

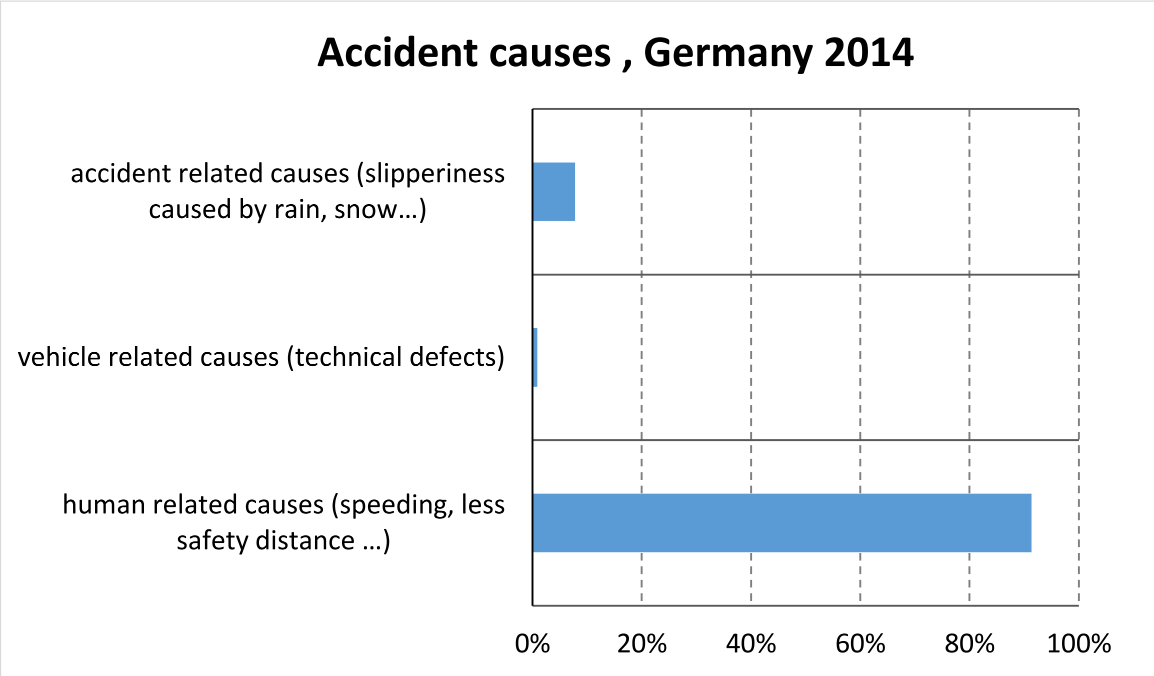


Figure 1-1: Accident causes in Germany 2014 related to all road accidents with injuries [1, p. 136]

1.3 Objectives

The objective of this master thesis is to develop a programme module that is able to handle a simulated car driving autonomously on the highway. First a literature study concerning requirements and existing strategies should be done.

Relevant requirements for the driving assistant are:

a) The assistant should react, based on the road traffic regulations of Austria. For example, there should be a defined safety distance or no overtaking options on the right lane. Furthermore, the assistant is programed to provide a high comfort level for the car passengers.

b) The assistant should be able to manage all relevant situations that occur on a highway such as adaption of speed to a preceding vehicle. To decelerate or to accelerate to the target speed of the preceding car or a given speed limit. Furthermore, overtaking processes or lane keeping manoeuvers are required.

c) An option to handle critical situations with an emergency procedure to react properly to stopped vehicles or obstacles on the road.

d) The number of vehicles involved in the programme should be variable and is only limited to the maximum of only 32, which can be handled by “PC Crash”.

e) The number of lanes has to be variable. There should be more than one lane

f) The driving assistant should be proofed on generic road traffic accident-scenarios in "PC Crash". First simple situations with only rear end crashes without further vehicles should be tested. Afterwards complex situations with further vehicles around the Ego-car should be evaluated.

At the end an Evaluation of the results should be done.

There should be the possibility to implement the driving assistant at a later point into the module X-RATE (Extended Effectiveness Rating of Advanced Driver Assistance Systems) that is developed on the Vehicle Safety Institute.
X-RATE is a programme primarily designed as a tool to investigate the effectivity of Advanced Driver Assistance Systems. For that purpose, it can be seen as an extended control software that is able to automatically set up simulations in a driving dynamics simulation software and interact with the simulation software on a time-step basis, thus providing the possibility to simulate sensor detection including sight obstruction and different active safety strategies. [3]

1.4 Requirements for Autonomous Driving

First of all, the basic technical requirements for autonomous driving have to be mentioned. To make a vehicle capable of driving itself, it is necessary that the car is able to recognise its environment. Firstly, the vehicle's own position has to be clear. Therefore, many OEMs use highly precise maps to be able to orientate on the road. Secondly, the environment detection has to be realised and the third point is the required driving strategy. [4]

1.4.1 Exact Position

The basis of all decisions of an autonomous car is its own position, which has to be as clear as possible. To gain an exact positon GPS- Data is not precise enough because the accuracy is in the range of meters. To be able to handle complex situations an accuracy in centimeters is required. Hence, highly precise maps are created, which include often right of way regulations or traffic lights. Daimler, for example, uses image processing methods to detect the own position based on generic image characteristics especially in cities, or based on lane markings and curbs on country roads. [5]

Figure 1-2: Mercedes map on left side; Matched camera picture and map in the middle; Data fusion of reality and map on the right side [5]

BMW generates its maps by driving the relevant route manually and collect information as long as it is necessary to create a high precise map. The map consists of so-called information graphs, which contains knots and tilts. The knots represent the landmarks (lane markings or roadside structure) and are connected by the tilts (Figure 1-3). Those information are connected and implemented in the high precise map (Figure 1-4) [4]

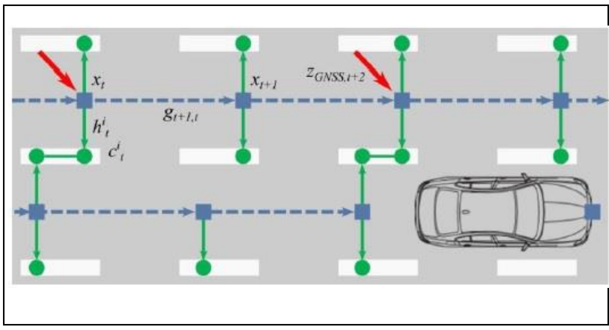


Figure 1-3: Measured data: Knots (green points), tilts (green lines) and driven trajectory (blue line) [4]

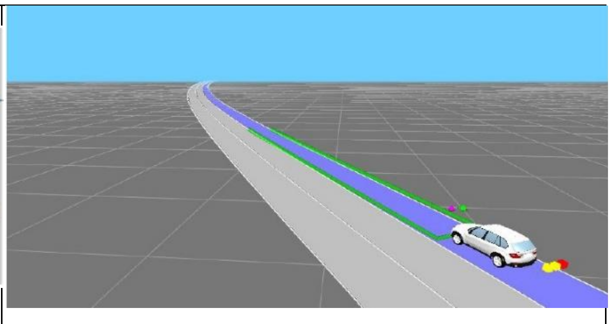


Figure 1-4: High precise map [4]

1.4.2 Environment Observation

A consistent observation of the environment is crucial to detect all other road users or other obstacles and therefore to be able to drive autonomously. To gain an exact environment perception sensors are required to cover all directions and different distances. To fulfil these qualifications, in series cars already implemented sensor types are used. [4]

Standard sensor types, which are available to the market, are shown in Figure 1-5.

The correctness of sensor information has a high influence on the operation of driver assistance systems. The performance of sensors depends on the sensor principle and can be very different. Depending on the used sensor there is an influence on the characteristics according to function depending where they are installed. [6]

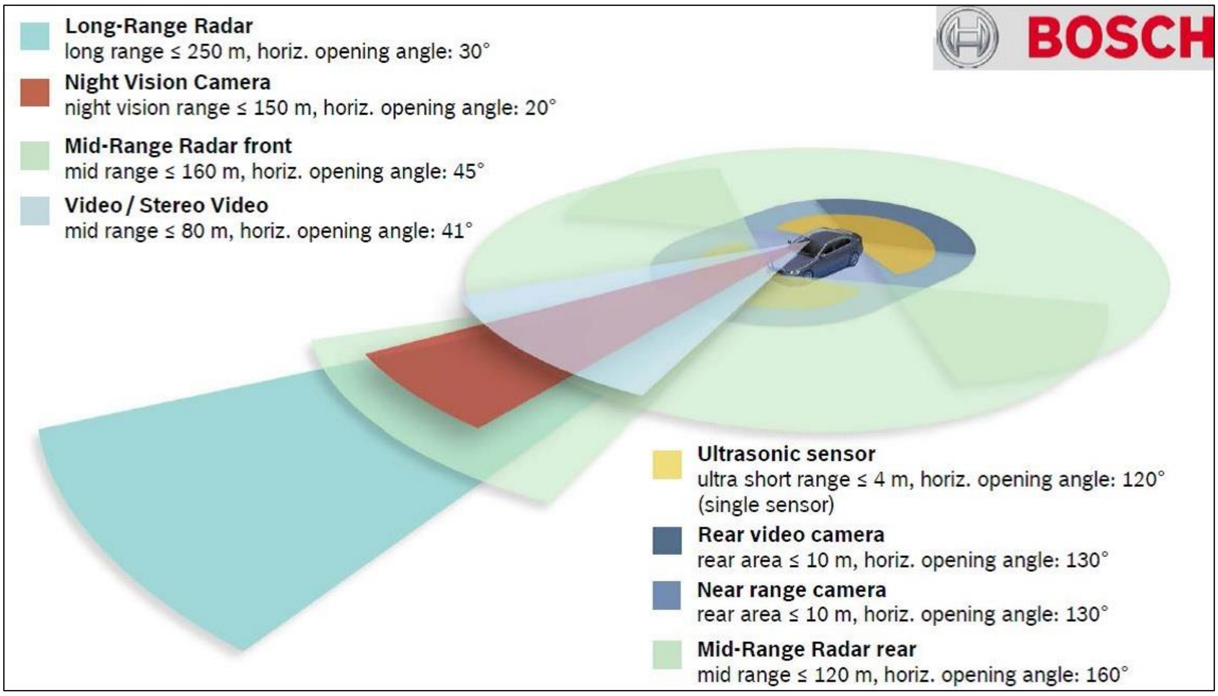


Figure 1-5: Different sensor types, which are used in modern series passenger cars [7]

In general there are many different types and combinations of sensors implemented, to use the strengths of each sensor and to conceal the weaknesses of others they are oriented in an overlapping range. [6] In Figure 1-6 the implemented sensors in a today's passenger car can be seen. The majority of the implemented sensors in a modern passenger car are placed in the front and the back side of the car. That is relevant because a large distance range has to be handled. The quality of the different sensors are related to its range, thus an overlapping observation for the total range is necessary. Radar sensors are either installed behind the plastic bumper or in an open construction. Ultrasonic sensors are implemented in the bumper and are also situated on the sides of the car. Different camera systems are installed behind the windscreen in general but can be installed at the front, back or underneath the rear-view mirrors in an open construction too.

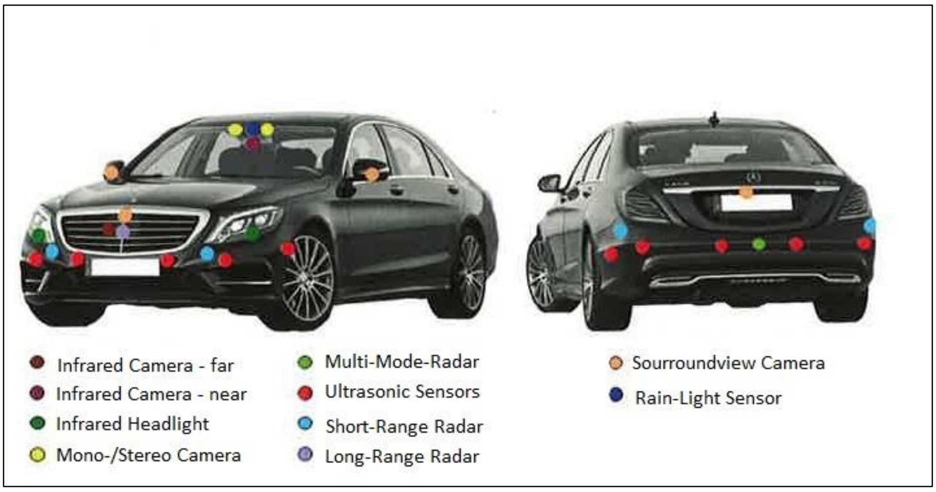


Figure 1-6: Location of environment monitoring sensors at an actual passenger car [6]

- Radar sensors

Radar (Radio Detection and Ranging) sensors are used to detect objects, measure the differential velocity and the position in relation to the own vehicle. Electromagnetic waves, which are reflected by the obstacle, are emitted. The reflected waves are detected and evaluated. Based on the Doppler Effect the frequency shift between the signal transmitted and the one received, in correlation to the time delay, the relative velocity and distance to objects is calculated. [6]

Radar sensors offer in their range a high and constant detection accuracy in radial direction. There are weaknesses concerning the detection of pedestrians or the roadside. The first radar sensors in series passenger cars were implemented in 1999 by Mercedes-Benz in the S-Class. [8]

Radar sensors can cover different ranges and opening angles and they can be divided into different frequency bands. Depending on the requirements of the car manufacturer, such as costs, accuracy, range or installation space different sensors with different frequencies in the range of 24.0- 24.25GHz, 76- 77GHz and 21.65- 26.65GHz are used. Radar sensors can be divided into Long Range Radar (LRR), Mid Range Radar (MRR) and Short Range Radar (SRR) depending on their range of detection. [6]

The parts of a Long Range Radar can be seen in Figure 1-7.

Table 1-1: Specifications of selected Radar sensors [9, p. 300 ff]

	Long Range Radar e.g. Continental ARS 300	**Mid Range Radar** e.g. Bosch MRR 4^{th} gen.	**Short Range Radar** e.g. Continental SRR 200
Frequency	76-77 GHz	76-77 GHz	24.05-24.25 GHz
Range	1-200 m	0.36-160 m	0.3-35m
Horizontal opening angle	17°	12°-90° (dependent on range)	90°
Other	mostly used in the front	cheaper than LRR	

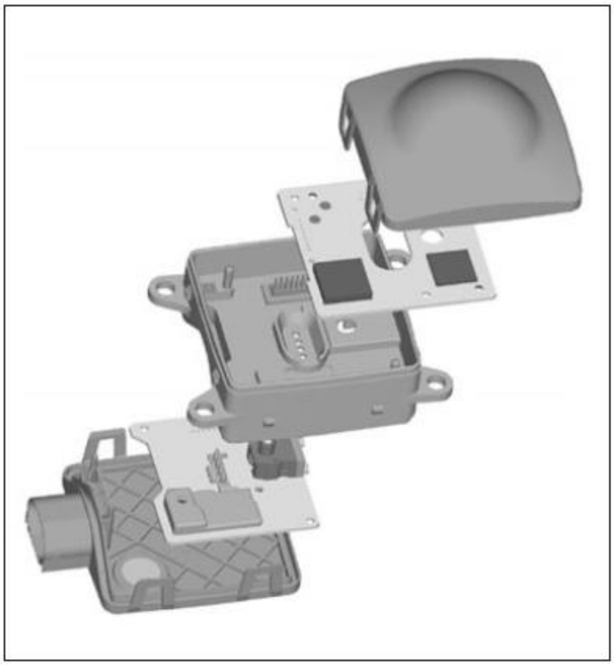


Figure 1-7: Long Range Radar LRR2 of Bosch [10]

Radar beams can penetrate non electric conductive objects. Thus they can be installed behind covers. There are some limitations as far as colours of the car is concerned. For a car for example colours with many metal particles (silver metallic) can disturb the emitted beams. Furthermore the thickness of the cover has to be adjusted to the wave length of the used radar sensor. Thus, the sensors are implemented into the vehicle front in an open construction as seen in Figure 1-8 or behind special covers as seen on picture Figure 1-9. and Figure 1-10.

Figure 1-8: Front Radar sensor in open construction [11]

Figure 1-9: Front Radar sensor covered [12]

Figure 1-10: Front Radar sensor [13]

Furthermore, 24GHz radar sensors are implemented on the rear side of the car. They are used for lane change alerter among other functions, and can be implemented covered as shown in Figure 1-11.

Figure 1-11: Radar sensors implemented on the rear side of a car [6]

- Ultrasonic Sensors

Ultrasonic sensors are often used as parking distance control. They cover the closer area around the car with an average range of less than 10m. They can also be used for driving assistants to cover the closer area around the car but are limited to a low differential speed ratio. Another advantage is the low price which is about one quarter down to one tenth of a radar sensor. A standard ultrasonic sensor is shown in Figure 1-12. [6]

Ultrasonic sensors emit acoustic waves with a frequency of 40 to 50 kHz and as a result, the interpretation of the sensor data is done by measuring the time period between emitting and receiving the acoustic waves. [14]

The horizontal opening angle ranges from 120° to 140° and the vertical opening angle from 60° to 70°. The vertical angle is limited to prevent wrong signals from an uneven ground. As observed by other waves too there is the possibility of different affects like material based reflexion, absorption, transmission, refraction, diffraction and interference. Thus, acoustic waves can be interrupted by rain, snow, wind and similar acoustic noises or be influenced by the air temperature because of the behaviour of sound in the air. [15, pp. 243-258]

Figure 1-12: Ultrasonic sensor (Bosch) [6]

- Lidar Sensors

Lidar (Light Detection and Ranging) is an optical method for tracking and distance measurement. Lidar sensors are often installed behind the windscreen to protect it of dirt. Concerning the function of a Lidar sensor light in the ultraviolet, infrared or visible spectrum is emitted and the reflected waves are detected by photo diodes. Thus, blinding by the sun is possible and is prevented by hardware based filtering measures. A measurement frequency up to 100MHz is possible and the accuracy concerning distance measurement is in the range of centimeters. [6]

There are two kinds of Lidar sensors: Multibeam Lidar sensors and scanning Lidar sensors as seen in Figure 1-13 a) and d). Multibeam Lidar sensors employ an array of transmitting and receiving elements illuminating separate angular sections, scanning Lidar sensors usually use one transmitter and receiver with a mechanically scanned lens system.

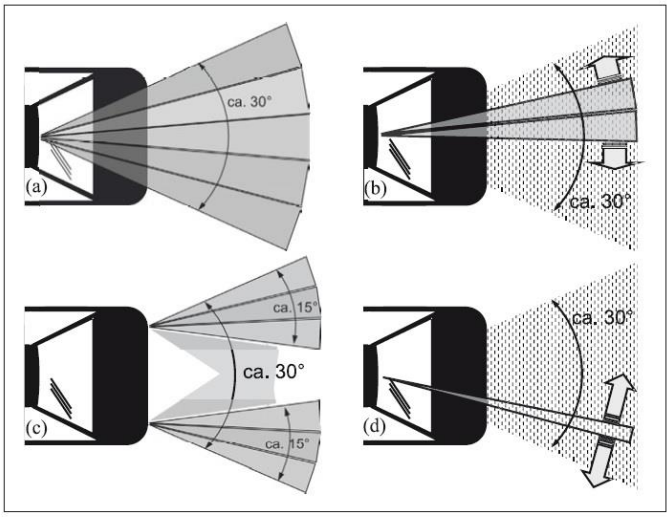


Figure 1-13: Lidar: a) Multibeam fixed; b) Multibeam sweep;

c) Multibeam allocated; d) Singlebeam scan [9, p. 182]

All Lidar sensors today operate in the near infrared and are of course limited by eye safety constrains. The sensitivity of a Lidar sensor is limited by the detection diode, which works on the physical limit today. As a result maximum sensor range is mainly influenced by lens aperture and hence by the size of the sensor. Because Lidar sensors work with laser beams which can be influenced of the environment. Thus, rain, snow and fog limit the range of a Lidar sensor. Additionally, the water spray of a preceding vehicle for front looking applications or the own water spray for backwards looking systems influence the ability of the sensor because of detecting ghost targets. Moreover dirt, dust or snow and ice coverage affect the sensor. [16]

Figure 1-14: Lidar sensor (gen3-OMRON) [9, p. 183]

- Lidar Sensor (e.g.: gen3- OMRON) shown in Figure 1-14 [9, p. 183]
    - wavelength: 905mm
    - range: 1- 150m
    - horizontal opening angle: 30°
    - speed accuracy: 1 km/h

- Camera Systems

Due to decreasing prices more cameras are implemented in passenger cars either in the visible spectrum or in the infrared spectrum as night vision systems. The gained pictures are analysed with picture processing methods and can categorise objects, such as pedestrians. The camera systems in the visible spectrum are installed behind the windscreen to guarantee a good view also supported by the windscreen wiper. Infrared cameras are installed at the vehicle front and are as a result limited, especially in winter by dust or road salt. Often stereo cameras with two lenses and image sensors are installed to generate a 3D picture to be able to calculate distances. [15, pp. 347-368]

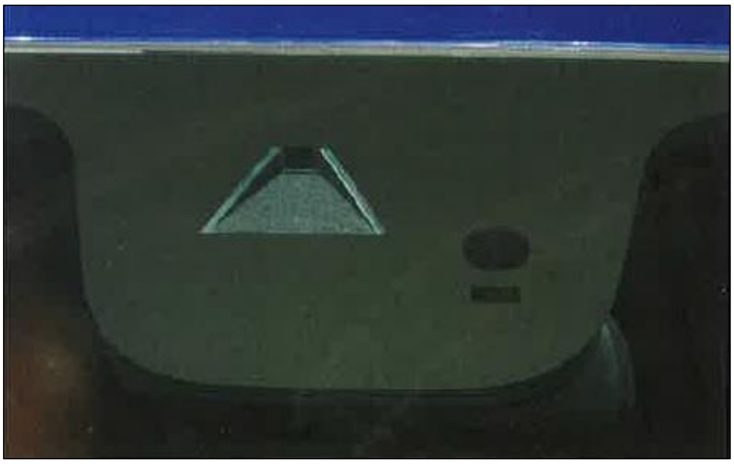


Figure 1-15: Monocamera installed behind the windscreen [6]

Table 1-2: Overview of sensor properties, their advantages and disadvantages

<table>
<tr><th></th><th>Range</th><th>opening angle</th><th>advantages</th><th>disadvantages</th></tr>
<tr><td>LRR</td><td>1-200 m</td><td>17°</td><td rowspan="3">+ indifferent to weather
+ high range
+ measures relative velocity</td><td rowspan="3">- expensive
- bad angular resolution</td></tr>
<tr><td>MRR</td><td>0.36-160 m</td><td>12°-90°</td></tr>
<tr><td>SRR</td><td>0.3-35m</td><td>90°</td></tr>
<tr><td>Ultrasonic</td><td>< 10m</td><td>120°-140°</td><td>+ cheap</td><td>- short range
- weather-sensitive</td></tr>
<tr><td>Lidar</td><td>1-150m</td><td>30°</td><td>+ protected installation
+ uncomplicated by darkness</td><td>- dirt sensitive</td></tr>
<tr><td>Camera</td><td>1-200m</td><td></td><td>+ cheap
+ high resolution</td><td>- weather sensitive
- sensitive to backlight</td></tr>
</table>

1.4.3 Driving strategy

As a third point, the driving strategy decides how the car reacts in road traffic, based on the localisation and the environment observation. This is why often algorithms are programed which are based on decision trees. [4]

1.5 Concepts realised

There are already some concepts realised by different OEMs and organisations to drive autonomously. Subsequently some concepts with different approaches which are found in the literature are described.

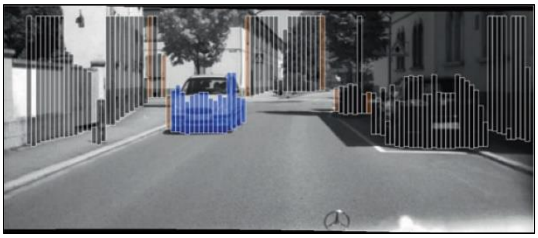
1.5.1 Mercedes Strategy: Bertha- Benz Route [5]

Mercedes [5] chose an S-class equipped with Radar sensors and cameras to observe the environment. The pictures of the stereo camera are spread up in so-called "stixel" which are a defined part of the picture. A 3D structure is described with about 300 stixel. This method is simple, compact and solid. [5]

(a) picture of the stereo camera

(b) visualisation of distance information. Red areas are closer (< 10m), green areas are distant (> 60m)

(c) implementation of stixel



(d) segmentation of stixel in static elements and moving objects.

Figure 1-16: Picture processing of Mercedes [5]

A seen in Figure 1-16 the picture processing is segmented in four steps: (a) stereo reconstruction, (b) accumulation of stereo information into stixel, (c) tracking of the stixel to calculate the velocity by comparison of the distances and (d) object segmentation. This calculation takes less one millisecond. Other road users can be recognised with the help of sample recognition processes. So pedestrians can be optically detected in about 40m and oncoming vehicles in about 200 meters. [5]

The used highly precise maps are created by driving the route manually and are processing them afterwards. As a result a map is the combination of the pictures and further information like speed limits, right of way regulations, course of the lanes and other driving related data. It is crucial to have the precise position of the car in a resolution of centimetres, not in meters, as it is standard in GPS systems for example. There is a difference to get the own position in villages and on the countryside. In cities house facades, signs or labels are used for localisation. They are also stored in the digital map. When driving autonomously all visible markings are processed and leads to an exact calculation of the car's position. Outside villages there are less landmarks which can be used for the calculation of the own position. Lane marks and curbs are used for this as result of an increased visibility of the road because of less covered space by cars due to higher safety distances. Based on the information of the digital map, the own position and the gained environment information the driving corridor has to be planned. Some requirements have to be fulfilled:

- generated behaviour has to be safe, nobody should be threatened
- road traffic regulations should be observed
- the technical boarders of vehicle dynamics
- comprehensible decisions for users and other road users
- comfortable behaviour

To meet this requirements three processing steps are generated: planning of the trajectory, behaviour generation and vehicle regulation. The most important step is the planning of the trajectory. It plans the route of the car and therefore solves a differential geometric optimization problem. The behaviour generation has to assess the traffic situation and as a result influences the boundary conditions of the differential geometric optimization problem. Furthermore, it should filter useless trajectories and plan the driving route that can be driven by the car and define the left and right end of the driving route. All possible routes of oncoming vehicles for the following 20 seconds are calculated and implemented in the general planning. [5]

The trajectory-planning tool chooses a trajectory based on the boundary conditions of the behaviour generation and the optimisation of a cost function. Furthermore, physical limitations like the maximum steering angle or possible acceleration rates have to be considered to find a driveable trajectory. To drive the calculated trajectory a vehicle regulation is necessary and is divided into lengthwise and crosswise control. [5]

In 2013 the Bertha Benz route containing villages with all its characteristics on the one and country roads with higher velocities on the other side from Mannheim to Pforzheim was driven autonomously. Velocities from 30 km/h to 100 km/h and situations with pedestrians and cyclists were managed. [5]

1.5.2 Lattice Strategy [17]

McNaughton and his team [17] developed a motion planner for autonomous highway driving based on the state lattice framework pioneered for planetary rover navigation. A trajectory planner to follow a leading vehicle, perform lane changes and merge between other vehicles is implemented in a passenger vehicle. Short-term plans for the next seconds are produced. [17]

The state lattice of Pivtoraiko et al. [18] is a method for inducing a discrete search graph on a continuous state space while respecting differential constrains on motion, which was demonstrated in the DARPA Urban Challenge in 2007 to plan motions in parking lots. This state lattice is also suitable for unstructured environments like screes. [17]

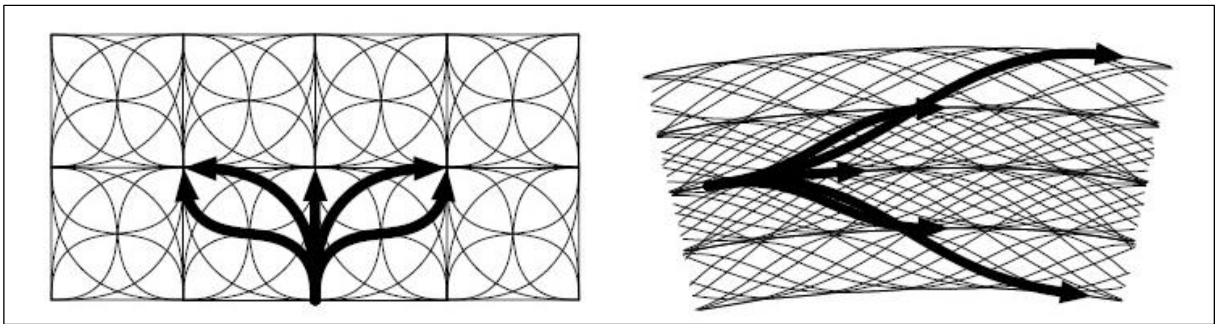


Figure 1-17: Left: regular state lattice in an unstructured environment. Right: state lattice conformed to a structured environment. [17]

The lattice is constructed around a lane centre-line defined as a sampled function. Two different types of a lattice are seen in Figure 1-17. The lattice defined a discrete grid and a linear mapping from discrete grid points to station and latitude using a simple linear multiplication, so that station is monotonic increasing starting from zero and moving right in the coordinate frame, and latitude may be positive (left) or negative (right) with respect to the centre line. A path is defined as a cubic polynomial function of arc length, for which parameters can be found to define a path connecting any pair of endpoints. Cost functions for paths and trajectories are defined. They are composed of terms that do not require the time and velocity of the states along the path to be evaluated, such as those for avoiding static obstacles. Due to the dynamic environment time and space have to be considered. When time and space are added to the state lattice, it causes an unacceptable blow-up in the size of the search space and time would last 12 million trajectory edges to evaluate at each planning cycle and is as a result too large for real time planning. To minimize the amount of options every lattice vertex that has been assigned a finite cost and a definite time and velocity, a set of outgoing trajectories representing the product of possible paths to other states on the road and a range of possible accelerations to take on the way is evaluated. [17]

Cost functions includes terms to avoid obstacles, as well as physical limitations, like rate of change of path curvature with respect to times or minimizing the lateral acceleration referring to passengers comfort. [17]

The final route is chosen based on the maximum speed depending on the range of the sensors and a controlled emergency stop. That goal is to make rapid forward progress at a reasonable cost. For optimizing the paths in combination with obstacle vehicles the space behind the obstacle car is set with high costs to manage that the own car stays outside the high cost area. [17]

1.5.3 A Robust Autonomous Freeway Driving Algorithm (Mellon University) [2]

A robust prediction and cost function based algorithm for autonomous freeway driving is described in the paper of J. Wei [2]. A prediction engine is built so that an autonomous vehicle is able to estimate human driver's intentions. In order to help generate the best strategies a cost function library is used. The algorithm is tested in a real vehicle simulation platform used by the Tartan Racing team for the DARPA Urban challenge in 2007. Firstly, the team around Mr Wei focused on an intelligent prediction engine with the ability to realize the intentions of surrounding vehicles, which provides the autonomous vehicle a look ahead ability similar to that of human drivers. Secondly, a cost function based scenario evaluation which is called by behaviour modules to evaluate the predicted scenarios and generate best strategies. Thirdly on a prediction- and cost function- based algorithm divided into three behaviour modules: distance keeping, lane selecting and merge planning. At least the focus is set on a freeway driving performance analysis that is constructed as a hybrid performance analysis tool which combines the advantages of qualitative and quantitative performance evaluation. Because of the danger of testing the algorithm on a real highway with high velocities, a real-time vehicle controller of the Tartan Racing Team called TROCS (Tartan Racing Operator Control System) is used to test and develop the algorithm. The algorithm is divided into three primary steps: candidate parameter generation, prediction and the scenario evaluation. In the candidate parameter generation step, output parameters are generated. In the distance keeper module the generator produces 20 different acceleration values ranging from -3m/s² and + 3m/s². Then the parameters set as well as the map of the current moving vehicles are sent to the prediction engine, which generates scenarios for the following seconds. The cost function-based evaluation block calculates each cost value or each scenario. Human drivers are able to communicate efficiently with each other by showing their intentions also recognizing other vehicles' intentions. Thus an experienced human driver is able to decide and start manoeuvers in advance. The look-ahead ability is implemented in the autonomous driving algorithm by using two prediction engines. [2]

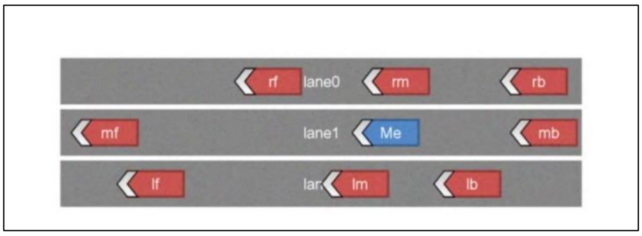


Figure 1-18: Vehicle Map [2]

For a better performance and lower computing costs, the input is summarized into a single structure, which shows the micro traffic environment as seen in Figure 1-18. In this map the distances and velocities of the 8 vehicles around the autonomous car are considered. This kind of map is chosen because of the minimum number of vehicles, which has to be considered. Furthermore it fits the autonomous vehicles' sensing range and ability. The prediction time is restricted to 5 seconds because a large prediction time increases the error. The calculation is set on the principle that the autonomous vehicle is static while other surrounding vehicles move relative with constant velocities to it. Furthermore, to handle reactions of other cars reacting on their micro traffic environment an interactive prediction kernel with basic distance-keeping ability is implemented. [2]

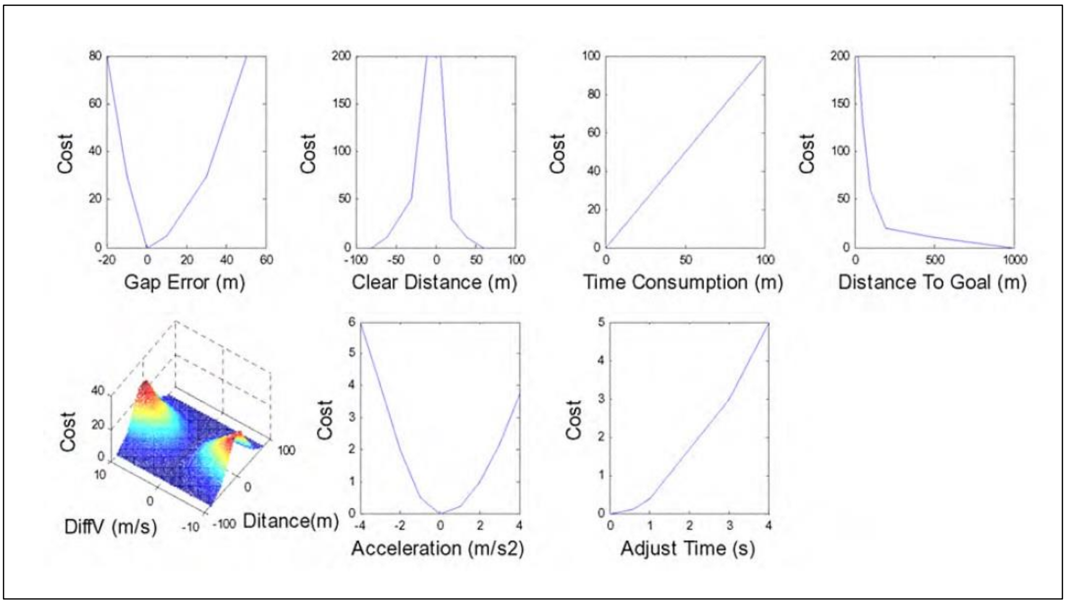


Figure 1-19: Cost Function Library of the Mellon University [2]

The system performance and robustness is based on the choice of the cost function, where 7 different base cost functions as seen in Figure 1-19 are implemented in the cost function library: [2]

1. A gap error cost is used in keeping a desired distance while following a lead vehicle. If the distance is smaller than desired the costs increase significantly
2. Clear distance costs penalizes moving too close to surrounding vehicles, which is zero when all other vehicles are above safe distances.

3. Time cost is implemented as third point.
4. The distance to goal costs are used when the car is near to the goal and is used in manoeuvers for example to merge into the right-most lane when the car is close to the exit.
5. Merge safety costs consider the velocity difference and the distance between a car merging to another lane.
6. Due to comfort reasons the acceleration costs are designed to accelerate and brake smoothly
7. In the merging process, an adjustment period is needed to get into a feasible position for merging. This non-linear cost function shows that the time below 0.8 seconds is preferred.

The cost functions are spread up in cost weights to clarify how important the cost factors are in the scenario evaluation. The three modules for freeway driving are beside the distance keeper, the lane selector and the merge planner. The distance keeper keeps a reasonable distance to the lead vehicle and has two outputs, the desired acceleration and the desired velocity. The lane selector is to output the intended lane the autonomous vehicle wants to merge into. The merge planner computes the feasibility of merging and chooses the best opportunity to merge. It computes the merge commands, including desired velocity, acceleration and merge status. They can be divided into two states, adjusting and merging. The algorithm is tested and the performance is analysed. The performance evaluation shows that the algorithm increases the human driver's skills significantly. The autonomous car performs more intelligently and similarly to a human driving vehicle. The parameters in the behaviour modules only affect the preferences of the strategy, while the safety performance is strictly ensured and is as a result satisfactory. Different parameters can be adjusted to change the strategies from conservative to aggressive. Furthermore compared to the algorithm used in the DARPA challenge, 20% less time is spent driving on a freeway and the number of driving manoeuvers decreased to 70% which shows a reasonable and efficient merging and lane selection. [2]

1.5.4 BMW Strategy [4]

Rauch et al. of BMW [4] realise a prototype with implemented sensors designed for a speed range of 0-130 km/h to drive autonomously on the highway. The car is programed to drive defensively and safely. Thus the system reacts for example on a highway onramp cooperative and allows entering cars to merge into the convoy to avoid critical situations. Highly precise maps are also created by driving the route manually and collect all necessary information. For position sensing a combination of GPS navigation, lane relative land marking and a high precise digital map is used. The information about the vehicle's position is gained with the help of a camera-based lane detection and a laser scanners based lane and roadside area detection to calculate the distance to the left and right lane marking. The digital map contains all relevant lanes, roadside structure and exact bend radii. [4]

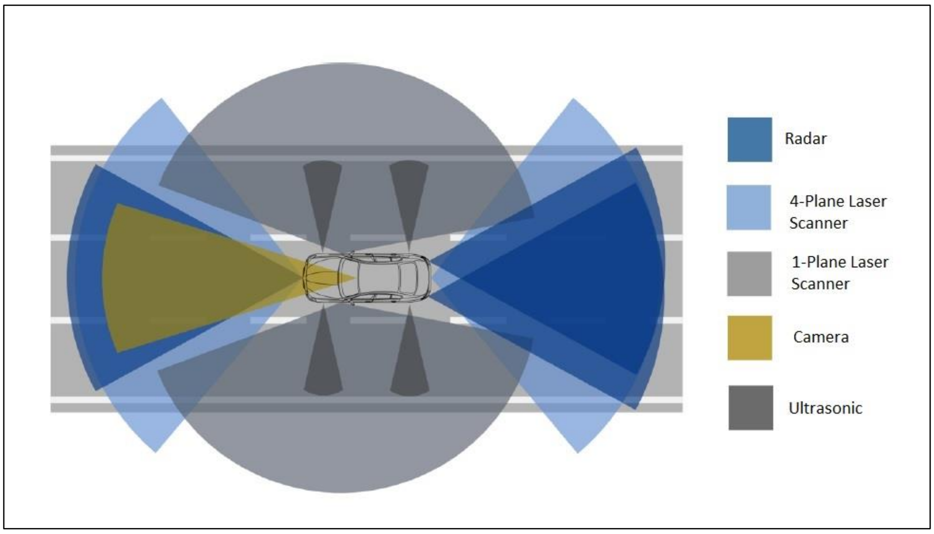


Figure 1-20: Sensors implemented in the autonomous car by BMW [4]

The car uses four laser scanners, three radar sensors, four ultrasonic sensors and one camera to detect the environment of the car in a redundant process as seen in Figure 1-20. A fusion algorithm processes this data in real time. Based on the car position, digital map and environment observation the driving strategy decides how the car should react in traffic stations and determining the nominal value for the vehicle steering. This strategy is realised by hybrid automates which react based on decision trees. One automat controls the lengthwise direction and the second one the crosswise direction. [4]

The lateral control is divided into eight different states: System off, Lane keeping, Lane change gap approach left and right, lane change left and right and lane change abort in both directions. Lane keeping describes driving on the lane without any lane changes. The lane change gap approach attempts to find a gap for overtaking when there is no possibility to do a simple lane change. A calculated lane change trajectory is interrupted in the lane change abort state and drives to the initial lane afterwards. The longitudinal control is divided into five steps: system off, dynamic cruise control, active cruise control, lane change gap approach and critical control. The programme dynamic cruise control set the pretended speed of the driver in comparison to the active cruise control, which sets the speed of the car driving in front. Critical control is necessary if another vehicle reeves to close and allows a higher acceleration in lateral control to manage this situation. [4]

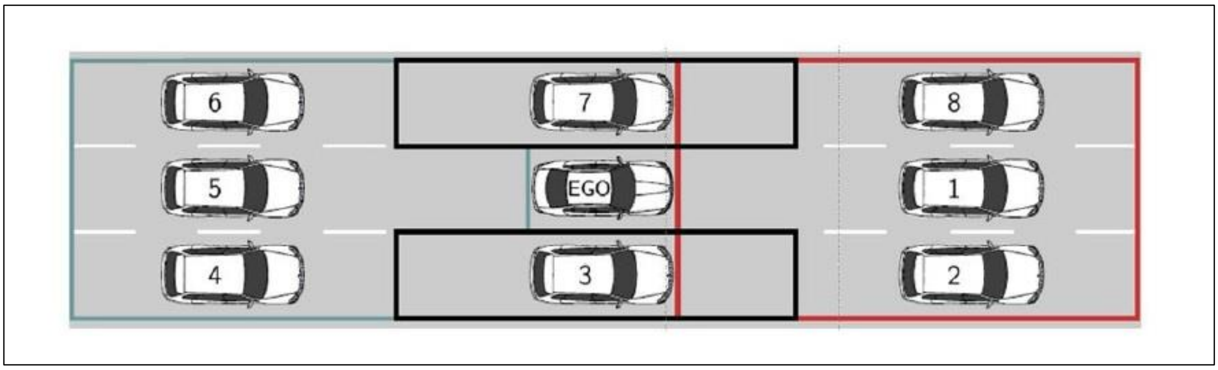


Figure 1-21: Environment description for interpretation [4]

The decision which programme is activated depends on the traffic situation. For this evaluation, the environment is spread up in 8 areas around the car, as shown in Figure 1-21, to have a feasible environment description. Either the 8 areas can be occupied or free which is based on the digital map and on the position of the Ego-car. [4]

This overall strategy was implemented in a passenger car and positively tested on the motorway from Munich to Ingolstadt in 2011. This route is about 65 kilometres long and contains two to four lanes. Construction sites, lost load or obstacles like busted truck tyres are not implemented in the described strategy. [4]

In conclusion there are different strategies chosen by the described OEMs and institutions. All strategies have in common that they need high precise maps with an accuracy in the range of centimetre to be able to drive autonomously. In those maps further information like speed limits or right of way regulations are implemented. Furthermore standard sensors like radar, lidar, ultrasonic sensors and cameras are used to observe the environment of the cars. By the classification of the environment different strategies are used. For example Daimler uses image processing and implements all other information into pictures. On the other hand BMW or the Mellon university divide their environment into 8 spaces. The advantage of the spaces are a simple and robust observation method with a low error rate. To find the shortest and most feasible path, cost functions like in the strategy of the Mellon university or by the lattice strategy are used. The decisions are made by handling decision trees where all relevant manoeuvers are described.

1.6 Steering trajectory

To be able to drive on the road also steering manoeuvers have to be calculated.

There is a division into two procedures: collision avoidance and evasion. Collision avoidance is an emergency steering manoeuvre, which tries to avoid a collision with an obstacle without any influence on the car position afterwards. It is the goal of an evasion manoeuvre to go on after the steering manoeuver. That implements that the car does not leave the road and is oriented to the initial lane. [19, p. 27]

For straight roads, W. Gratzer and M. Becke [20] describe a lane change trajectory. The steering wheel is at the beginning and at the end in neutral position and as a result, the steering angle is zero. The trajectory to the left for example is spread up into four sections. First steering to the left with a modification of the steering angle from zero to a defined maximum, increased afterwards, steered back to zero (second section). In this position, the vehicle is driving straight ahead again and the yaw angle reaches its maximum for this manoeuver. Afterwards the same procedure takes place in the same way to the right side, to steer back. [20, p. 145]

There are some different options to bring a lane change trajectory into a mathematical formula. Stringing together two circular arcs would be the simplest mathematical way and can be used to calculate the shortest way length but discontinuity of the curvature progression is a big disadvantage. [19, pp. 27-31]

In road traffic, clothoids are often used but they are very complex in the mathematical calculation. Thus another S-shape clothoid is used, the so-called sine or cosine curves. Using the sine curve the curvature radius is infinitely large at the beginning, in the middle and at the end of the curve. This means, that the steering angle is zero. The curvature radius reaches after a quarter and three quarters of the path the smallest figure and as a result the lateral acceleration is at its maximum for this manoeuver in this points. [20, p. 146]

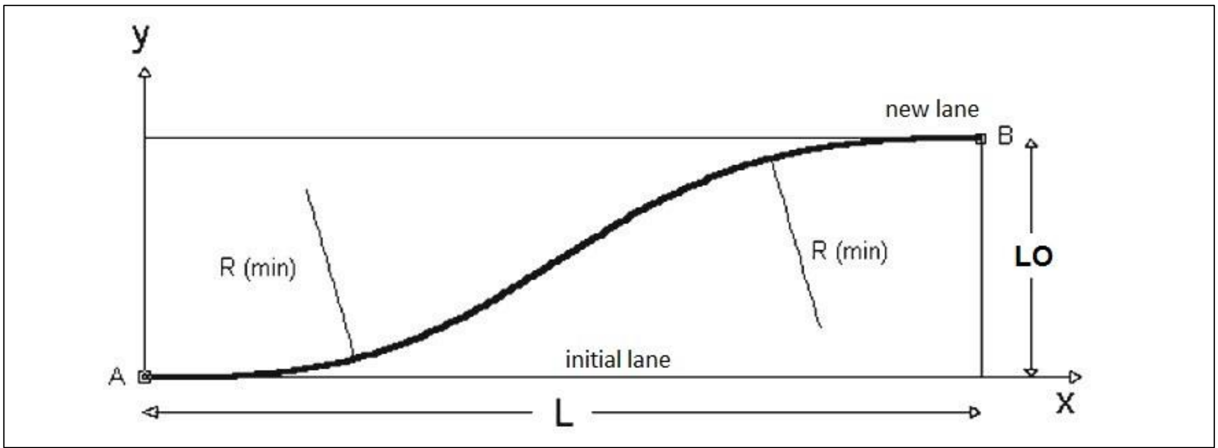


Figure 1-22: Lane change trajectory [20, p. 145]

In Figure 1-22 the sine curve with the needed *length L* of the lane change manoeuvre and the *offset LO* are shown. The equation (1-1) of the sine curve, seen in Figure 1-22, calculates the coordinate points in x and y: [20, p. 146]

$$y = LO * \left(\frac{x}{L} - \frac{1}{2\pi} * sin\frac{2\pi * x}{L}\right) \tag{1-1}$$

Calculation of the needed *length L* of the lane change manoeuvre considering the *vehicle speed v* and the set *lateral acceleration* a_L: [20, p. 147]

$$L^4 + LO * L^2 - \left(2\pi * LO * \frac{v^2}{a_L}\right)^2 = 0 \tag{1-2}$$

This equation can be solved with a standard quadratic equation and the positive solution of the square root. [20, p. 147]

Table 1-3: Needed length [m] for lateral offset of 3m [20, p. 147]

v (km/h)	**lateral acceleration (m/s²)**					
	0,5	1	1,5	2	3	4
20	34,2	24,3	19,9	17,3	14,3	12,4
30	51,3	36,3	29,7	15,8	21,1	18,3
40	68,3	48,3	39,5	34,2	28	24,3
50	85,3	60,4	49,3	42,7	34,9	30,3
70	119,4	84,5	69	59,8	48,8	42,3
100	170,6	120,6	98,5	85,3	67,7	60,4

As seen in Table 1-3 the relevant factors for the necessary lane change length are the velocity, lateral acceleration and the offset.
The *lateral acceleration* a_L depends on the *friction coefficient μ* between tyre and road and the *gravity force g.*

$$a_L = \mu * g \tag{1-3}$$

The lateral acceleration is theoretical in lateral and longitudinal direction the same and only limited by the Circle of Forces and the road friction coefficient. [21]

The figure of the lateral acceleration depends on the driven manoeuver like driving a turn or a lane change. By driving turns the lateral acceleration can reach values up to 4-5m/s², in comparison to lane change manoeuvres where values of 2m/s² are common by human drivers. On the other hand, for full braking manoeuvers a negative acceleration up to 10m/s² is possible. [22]

W. Gratzer and M. Becke [20] did an experiment with 25 to 62 years old drivers and measured about 4000 lane change manoeuvers. Therefore lateral acceleration rates of the merging process are shown in Figure 1-23. There the lateral acceleration rate of 2m/s² is described as normal and is divided into different steps until a "strong" merging manoeuver with a lateral acceleration of about 5m/s². The critical lateral acceleration rate in this paper is reached by a value above 6m/s². [20]

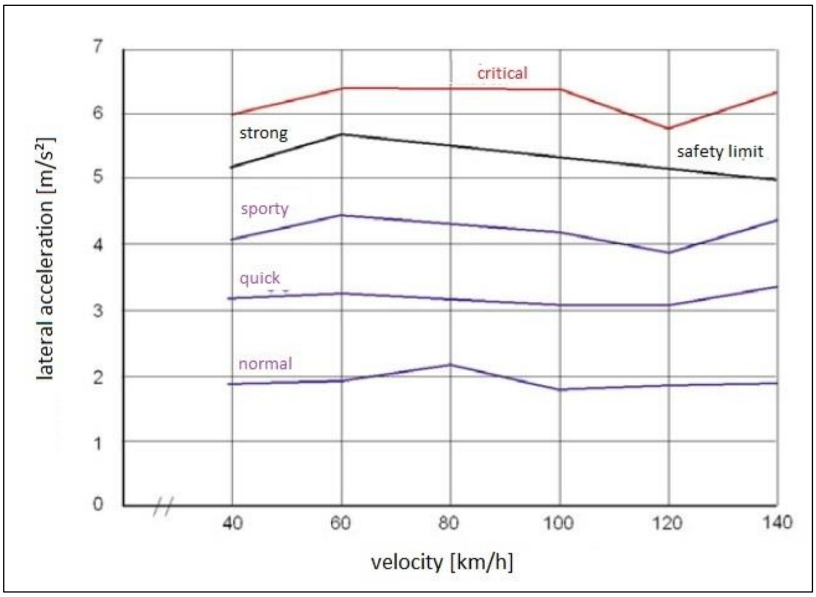


Figure 1-23: Lateral acceleration by merging manoeuver [20]

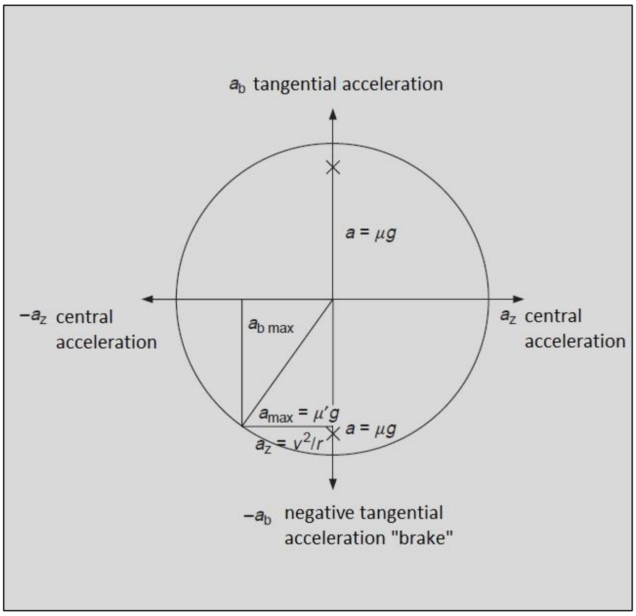


Figure 1-24: Circle of Forces [21]

For lane change manoeuvers with an acceleration rate the circle of forces (Figure 1-24) is relevant. The Circle of forces describes in equation (1-4), that a tyre which is stressed with a longitudinal force could not provide the maximal lateral force. As a result, the average maximum lateral acceleration decreases. The maximal *deceleration rate* a_{max} is the square of the *friction coefficient* μ multiplied with the *acceleration of gravity g* and subtracted by the *velocity of the vehicle v* divided by *the bend radius r*. [21]

$$a_{max} = \sqrt{(\mu * g)^2 - \left(\frac{v}{r}\right)^2} \tag{1-4}$$

1.7 Braking

1.7.1 Brake Lag Time

The brake lag time is the time that is needed to reach the half of the full braking pressure after the first pressure increase in the braking system. For passenger cars it is in the range of 0.2s to 0.4s and depends on the street conditions and how the brake pedal is pressed. [20, p. 127]

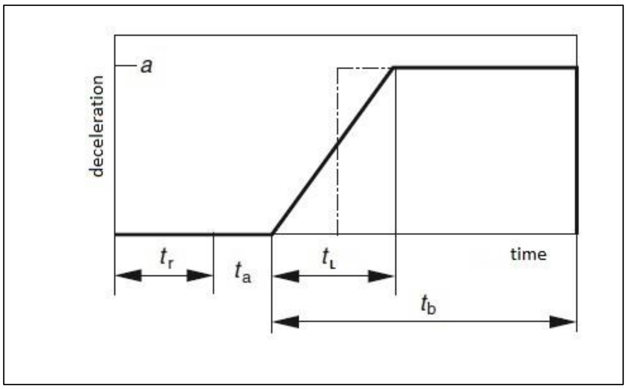


Figure 1-25: Brake Manoeuver [23, p. 17]

The whole brake manoeuvre is described by Breuer et al [23] beginning with the *reaction time* t_r the *brake response time* t_a and the time of the *total brake effect* t_b. The *maximum deceleration a* is reached after the *lag time period* t_L. Approximately half of the lag time is calculated with the full deceleration rate and the other half without any deceleration. [23]

1.7.2 Full Brake Phase

After reaching the maximum deceleration in the lag time the full brake phase follows. In this phase the deceleration remains constant at the maximum performance of the brake. [20]

The maximum deceleration during the full brake phase depends on the traction between the tyre and the subsurface. Beside the subsurface the condition of the tyres (construction, wear condition) influences the tire/road friction value and leads to different maximum deceleration values. [23, p. 15f] Thus the road surface has a big influence on the friction value as a result asphalt roads have better deceleration values than roads made out of cobblestones or gravel.

Further important factors, which influence the friction between the tyre and the road, are the road surface conditions. As shown in Table 1-4 the friction coefficient can vary from 0.05 to 0.8 under different road conditions and road surfaces.

Table 1-4: Friction coefficient in relation to road surface and weather conditions [24]cited in [25]

road surface	friction coefficient of car tyres
dry concrete	0,85
dry asphalt	0,8
wet concrete	0,7-0,8
wet asphalt	0,45-0,8
snow	0,15
ice	0,05

1.8 Ideal Strategy to avoid accidents

Generally in all driving situations a collisions can be avoided or at least the impact can be mitigated by braking manoeuvers. The stopping distance increases by the square of the relative velocity and therefore at higher velocities an evasion with a linear behaviour becomes an alternative for the driver to avoid a collision. [26]

Figure 1-26 shows the distance of the physically last point to brake and distance of the last point to steer. The red lines show the point until when a collision can be avoided by steering (LPTS- Last point to steer). The blue lines show the point until when a collision can be avoided by braking (LPTB- Last point to brake). At lower differential speed there is less distance needed for a braking manoeuvre than a steering manoeuvre.

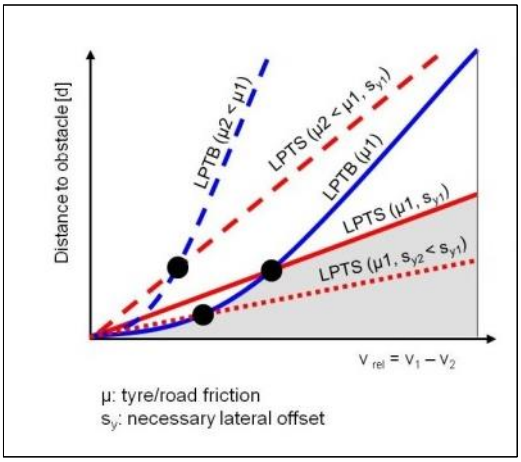


Figure 1-26: Necessary distance to avoid a collision by braking or steering [26]

The equations (1-5) and (1-6) depend on the *differential speed* v_{rel}, the necessary *lateral offset* s_y, and the average *longitudinal acceleration* a_x, respectively *lateral acceleration* a_y, which are determined by the tyre to road *friction value μ*. [26]

$$d_b = -\frac{1}{2a_x} * v^2{}_{rel} \tag{1-5}$$

$$d_e = \sqrt{\frac{2s_y}{a_y}} * v_{rel} \tag{1-6}$$

Thus if the last point of braking is missed at higher velocities there is still a possibility to avoid a collision by evading. Lower tyre road friction coefficient μ and smaller obstacle width affect the range of speed where evading becomes more effective also at lower speeds. [26]

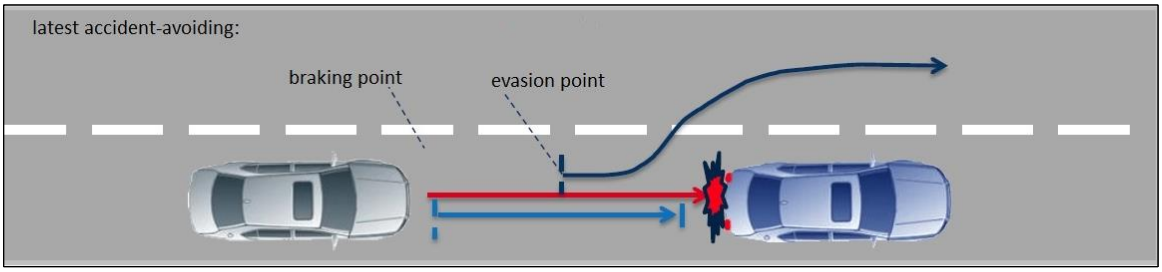


Figure 1-27: Latest Evasion- and Braking Point at higher velocities; Car at the back with 80 km/h; Car in the front 60 km/h [7]

In Figure 1-27 the last point a braking manoeuver can prevent an accident in comparison to the point an evasion manoeuver is latest possible, is visualised.

1.9 TTC

Time to Collision (TTC) notion has been applied as a safety indicator in safety analyses. [27]

A TTC value at an instant t is defined as the time that remains until a collision between two vehicles would have occurred if the collision course and speed difference are maintained. [28]

The TTC in equation (1-7) is calculated with the *distance d* between the cars divided to the *differential speed* v_{diff}. [15, p. 900]

$$TTC = \frac{d}{v_{diff}} \tag{1-7}$$

For an obstacle without any acceleration the brake distance is calculated as: [15, p. 900]

$$d_b(v_{diff}) = v_{diff} * \tau_B + \frac{v_{diff}^2}{2 * D_{max}} \tag{1-8}$$

The brake distance is the distance that is needed to eliminate the *differential speed* v_{diff} between two vehicles driving with constant speed considering the *brakes lost time* τ_B. and the *average maximum deceleration* D_{max}. The brakes lost time τ_B considers the effective time delay of the buildup phase of the brake force. Based on a linear increase of the deceleration during the lag time τ_S up to the average maximum deceleration D_{max} the brakes lost time τ_B. can be set as the half of the lag time $\left(\frac{\tau_S}{2}\right)$. [15, p. 899]

The warn distance is calculated as: [15, p. 899]

$$d_{warn}(v_{diff}) = v_{diff} * (\tau_B + \tau_R) + \frac{v_{diff}^2}{2 * D_{max}} \tag{1-9}$$

The warn distance, for an emergency brake manoeuver implements the *reaction time* τ_R of the driver. [15, p. 900]

The *time period needed for the evasion* t_{eva}. is calculated with the necessary *offset* y_{eva}, the average maximal lateral *acceleration* $a_{y,max}$, the *steering lost time* τ_S. The *steering lost time* τ_S. is set in literature with 0.1s. To calculate the *evasion distance* d_{eva} the needed time t_{eva}. of equation (1-10) and the *differential speed* v_{diff} are used. [15, p. 900]

$$t_{eva} = \sqrt{\frac{2y_{eva}}{a_{y,max}}} + \tau_s \tag{1-10}$$

$$d_{eva} = v_{diff} * t_{eva} \tag{1-11}$$

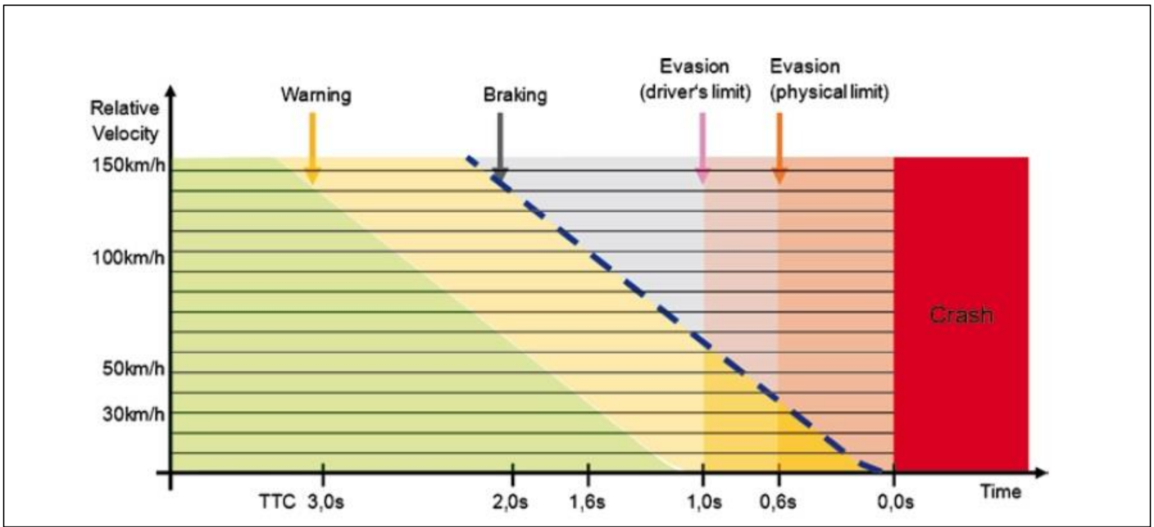


Figure 1-28: TTC / differential speed (relative velocity) [9, p. 906]

Figure 1-28 shows the ideal situation with a perfect friction coefficient for example or a vehicle with constant speed ahead. Thus the time to collision in relation to the differential speed is shown. The physical limit mentioned in literature is at 0.6s dependent on the limitation of the lateral acceleration and the brake lag time. The limit for the human driver is at 1 second. The dashed line, which shows the influence of the velocity on the brake length, marks the time when a collision can be prevented by braking. Above a differential speed of 36 km/h, an evasion manoeuver is always later possible than a deceleration manoeuver. [9, p. 906]

2 METHOD

Based on the literature research some strategies are chosen. For example the robust and simple division of the environment into 8 spaces is implemented and the environment observation is done by sensors of today's series cars. The decision making strategy is based on decision trees.

2.1 Programmes

2.1.1 OLE Interface: "PC Crash" –"Matlab"

For this master thesis the accident reconstruction programme, "PC Crash" (version "10.1") and the mathematical programme "Matlab" (version "R2015a") were used. To be able to communicate between those programmes the object system OLE (object linking embedded) is used. By means of the OLE system all relevant data is transferred from "PC Crash" to "Matlab" and after the calculation, the relevant data is sent to "PC Crash" again.

"PC Crash" is a computer programme for the calculation and reconstruction of road traffic accidents including four-wheeled vehicles, two-wheeled vehicles, trailers and pedestrians (also Multibody). Vehicle movements and collisions can be simulated in 2D or 3D. Furthermore, "PC Crash" enables to calculate forwards or backwards simulations. [29, p. 178f]

One advantage of "PC Crash" is the implementation of an impact model.

Other accident reconstruction programmes on the market are CARAT or ANALYSER PRO. [29, p. 178]

As a result X-RATE is programmed in "Matlab" in combination with "PC Crash", thus to be able to implement the autonomous driving assistant in this tool, those programmes are used.

Unfortunately, not all data calculated in "PC Crash" is transferable, which is why some parameters have to be calculated again in "Matlab". Generally, there are only parameters transferred which are with sensors determined measurement values, which are generated from the exact positioning system or vehicle related data.

All calculates simulation steps are set in time steps of 0.015 seconds in both programmes.

Parameters transferred from "PC Crash" to "Matlab":

- Cog (centre of gravity) -Position in X- and Y- coordinates of all vehicles (incl. Ego vehicle)
- velocities of all relevant vehicles
- vehicle dimensions (length, width, wheelbase and track width)
- yaw angle of the Ego vehicle

- velocity direction of the Ego vehicle

Parameters transferred from “Matlab” to “PC Crash”:

- acceleration and deceleration rates
- steering angle for each tyre
- time related information

2.1.2 AHDAS

The subprogramme AHDAS (Autonomous Highway Driving ASsistant) enables, as mentioned in the title, a car to drive autonomously on the highway.

Adjustable parameters by the user are:

- The number of lanes (greater than one)
- a breakdown lane can be activated or not
- the lane width can be adjusted
- the speed limit is adjustable

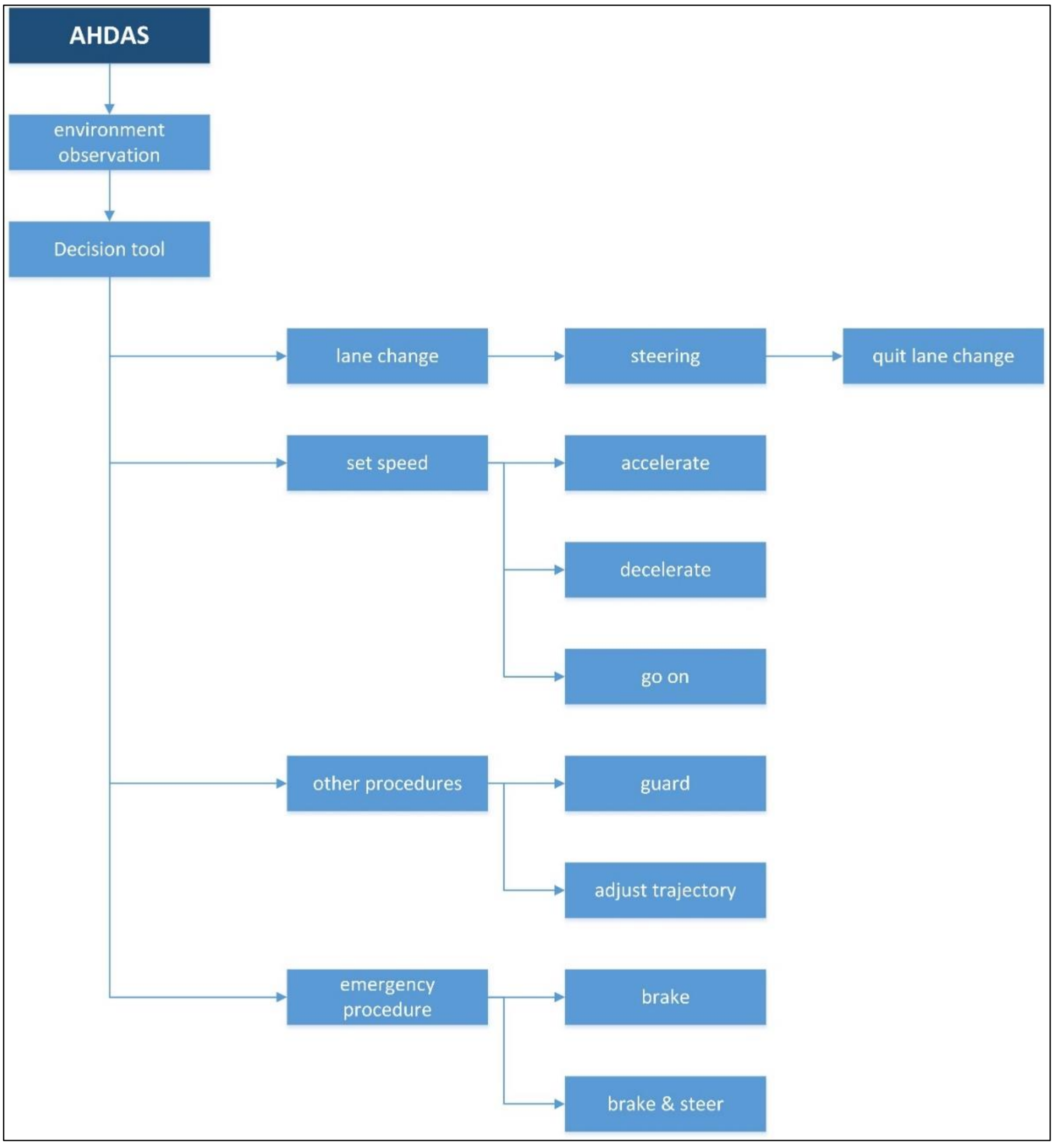


Figure 2-1: Flowchart of the overall structure of the AHDAS programme

2.2 Implementation of the basic AHDAS decisions

The basic decisions are shown in the AHDAS main procedure:

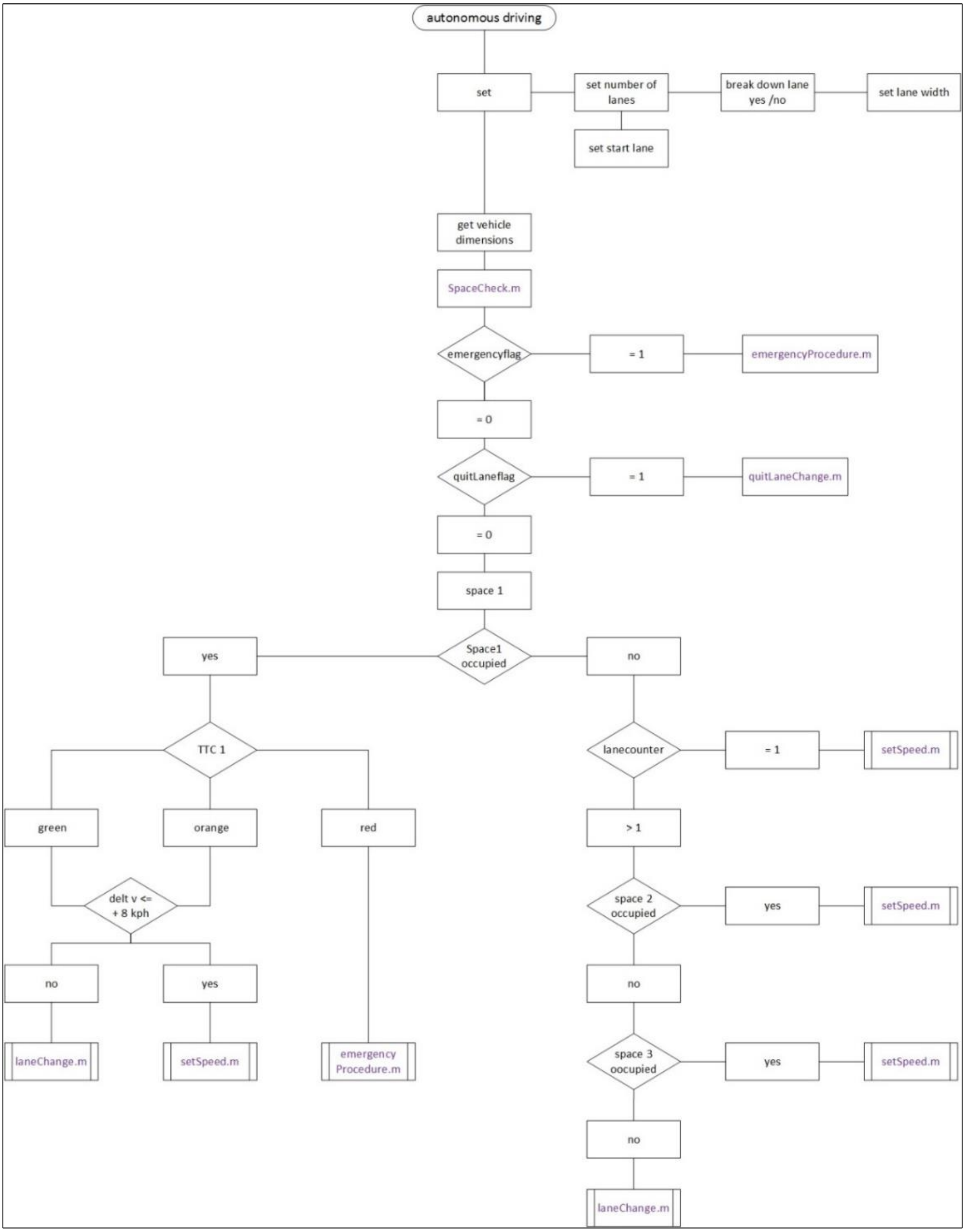


Figure 2-2: Structure of AHDAS (Autonomous Highway Driving ASsistant)

Referring to Figure 2-2 first the basic parameters have to be set according the number of lanes, if there is a breakdown lane, the lane width and the number of the initial lane the Ego-car starts. Afterwards the vehicle dimensions such as vehicle length, distances of the front axle to the centre of gravity and the vehicle width of all cars set in the “PC Crash” file. Afterwards the “Space Check” procedure starts to get all relevant information of the other cars in the simulation. The “Space Check” sub programme checks the environment of the Ego-car. For this purpose the position of each car in the file is checked and assigned to one of the predefined Spaces. If there are two or more vehicles in one space the closest car is relevant and further investigated. The next step is to check if the “Emergency flag” or the “quit Lane Flag” are activated. Those flags are used if an ongoing procedure is interrupted due to an emergency situation for example. Thus if those flags are activated the “Emergency Programme” is started. At the first time of the simulation all these figures are set to zero.

The most important space to be observed is Space 1. If this space is empty, no relevant manoeuver has to be set. Thus, the decision tree starts with the status of this space.

If Space 1 is occupied the TTC (equation (1-7)) is checked and based on the classified TTC colour a decision is chosen. For TTC “green” or “orange” it is checked if the differential speed is less than 8 km/h and the speed of the car in Space 1 is higher than 120 km/h, in this case the Ego-car stays behind the car ahead and adjusts the speed to follow the car with a safety distance of 2 seconds. This velocity is chosen to avoid long lasting overtaking manoeuvers and as a result long blocking of an overtaking lane. If the differential speed is higher than 8 km/h or the velocity of the car ahead is less than 120 km/h, the lane changing procedure is started. The third possibility is that the TTC classification resulted in “red” than the “Emergency Procedure” is started.

If Space 1 is not occupied first the driven lane is checked. If the car drives on the first lane the “Set Speed” procedure is started and if necessary the speed of the Ego-car is set to the speed limit. If the Ego-car is driving on another lane than the first one, it is checked if the right side is empty. In this case if Space 2 and 3 are not occupied there a lane change to the right is started. In the other case the” Set Speed” procedure is initiated.

After running a sub procedure the circle starts at the beginning of the “AHDAS” file until a quit condition is reached.

2.3 Space Check

2.3.1 Environment observation

The environment observation is realised by using three different sensors. A long range radar sensor with a range of 150m and a horizontal opening angle of 17° is implemented to observe the front and the rear area of the car. For the closer area a mid range radar sensor with a range of 60 m and a horizontal opening angle of 90° is installed at the front and the back side. To observe the close area around the car to the left and the right side ultrasonic sensors with a range of 10 meters are implemented and arranged that they reach the whole side of the car. In Figure 2-3 the Ego-car in a "PC Crash" file is shown with the used and visualised sensors.

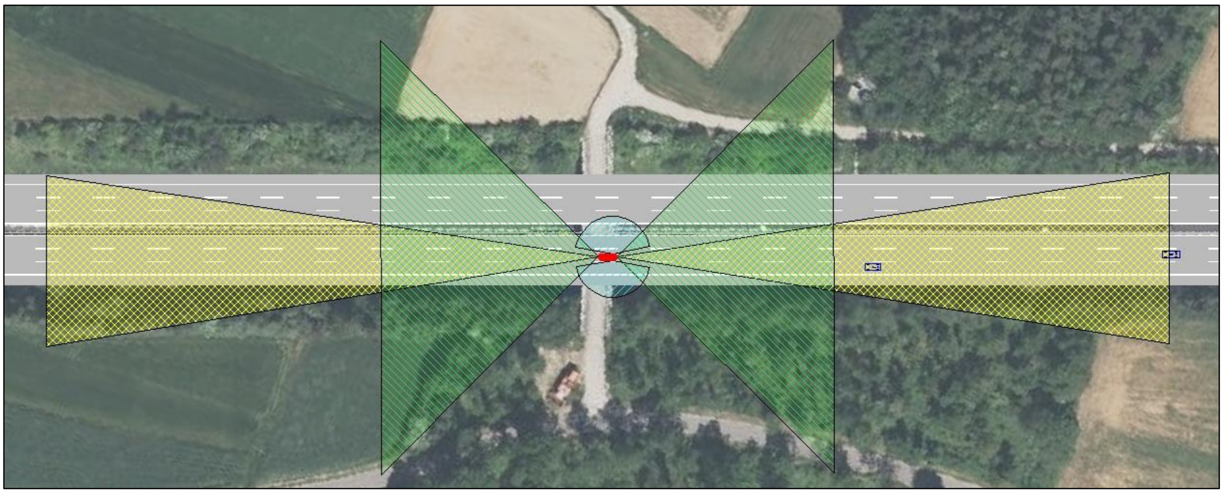


Figure 2-3: Ego-car with the visualised sensor range used to observe the environment

To observe the environment, the area around the car is spread up in 8 spaces. The next lane, if available, on the left and right side is observed. Eight spaces, seen in Figure 2-4, are chosen because this method represents the sensor observation in the best way possible.

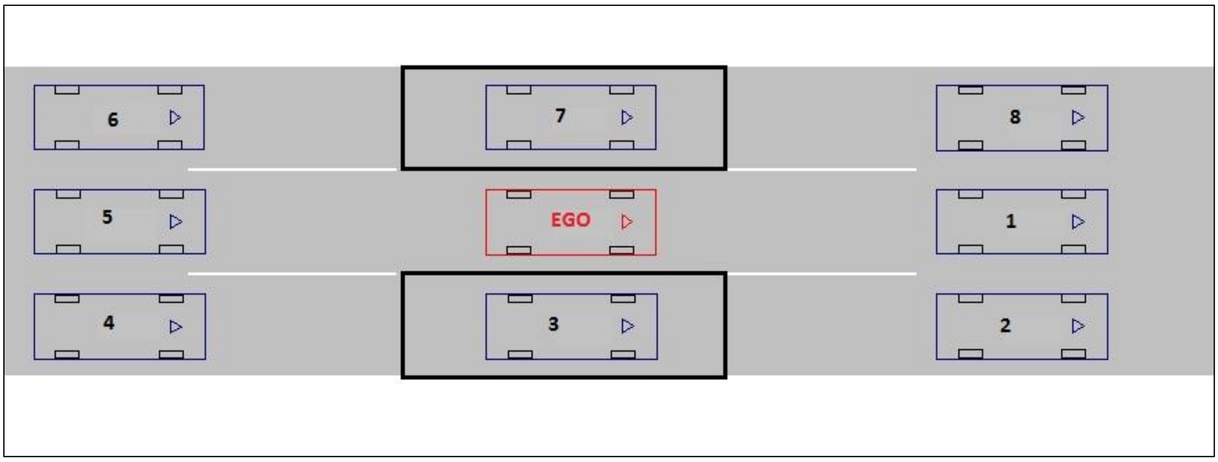


Figure 2-4: Environment observation: 8 Spaces around the autonomous vehicle (Ego-car)

The defined fields around the Ego-car (the autonomous car) are further referred to as "Space" with a digit and they represent the dimension of the lanes. The space in front of and behind the car (Space-1,2,4,5,6,and 8) are limited to 150m which is the range of the used radar sensors in the simulations.

Space 3 and 7 are limited to 6,5m to the front and to the back starting at the Cog (Center of gravity) of the Ego-car. Furthermore the observation range to the left and to the right is limited to the lane width 1.5 times.

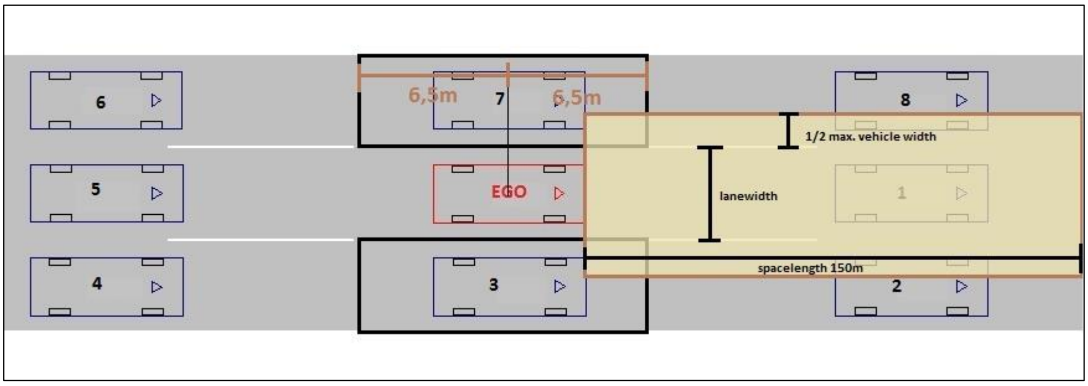


Figure 2-5: Environment observation: Dimensions of Space 1, Space 3 and 7

To be able to detect cars which do not use their lane properly or are in a lane change process the spaces are designed in an overlapping way. Thus the maximum width of all cars in the simulation is filtered and based on the maximum car width the borders of the spaces are set. For Space 1, as seen in Figure 2-5, the left border is calculated based on the Y- coordinates of the Cog of the Ego-car with half of the lanewidth added to the half of the maximum width of the car in the simulation. The spaces are calculated each simulation step and are always based on the COG coordinates of the Ego-car irrespective of the driven manoeuver. By the OLE interface the COG coordinates of the cars are handed over and as a result it is checked if the COG coordinates fit to a space. Accordingly, if a car is driving on the lane marking both neighboring spaces are set to be occupied. For this reason the width of the Space is related to the width of the lane which can be adapted by the user. If there is more than one car in a particular space the closest car to the Ego-car is filtered.

2.3.2 TTC

For decision-making processes the information if a space around the ego-car is occupied or not is too little. For this reason it is necessary to implement further information about the position of a car in the particular space. As a consequence the TTC classification is implemented, which is calculated in equation (1-7).

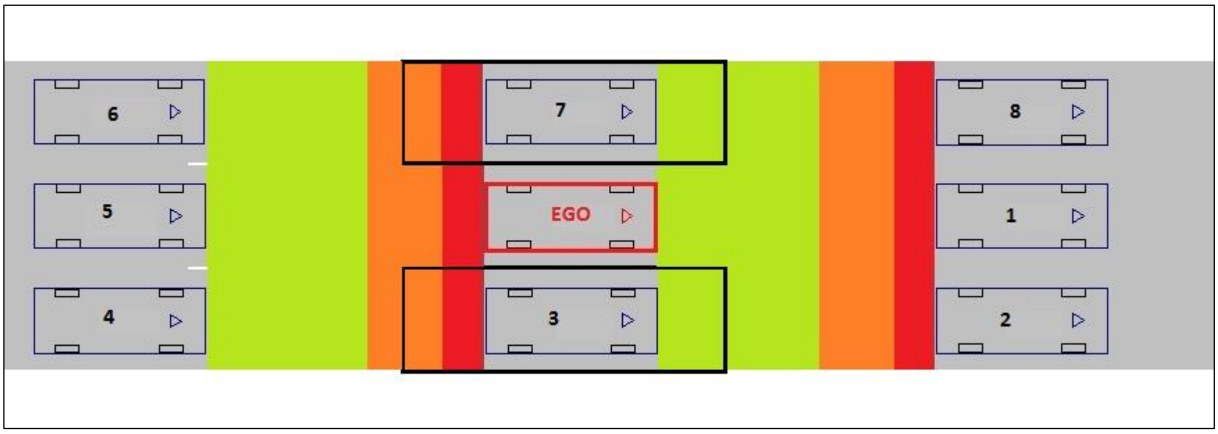


Figure 2-6: TTC classification of the Space ahead and behind the Ego-car in colours

The distance to other cars is divided into three phases visualised in. First the “green” phase, when the TTC is higher than the safety distance to the observed car. The safety distance is related to the Austrian traffic regulations defined as 2 seconds. [30] Based on this the safety distance is calculated. The “Orange” phase is limited by the safety distance on the one hand and to the *breaking distance* d_b related to equation (1-8) on the other hand. Finally all TTC distances which are smaller than the *breaking distance* d_b are classified as “red” and as a result a critical region. In Figure 1-28 the orange phase is calculated with the *warn distance* d_{warn} as upper boarder.
The autonomous car in this thesis is primary not designed to handle emergency situations but to drive as save as to never get into such a situation. Thus it is necessary to implement a longer warn distance to be able to react in a less invasive way to avoid full brake manoeuvers for example. Based on a minimum distance between cars referring to Austrians road traffic regulations the safety distance of 2 seconds is chosen. This value is an iteration referring to a defined 50m safety distance at 100km/h. [30]
The Spaces 3 and 7 are not classified with the TTC classification, those spaces are handled with the information if they are occupied or not because if these spaces are occupied any lane change manoeuver is possible because in any case the longitudinal distance is too short.

2.4 Lane change

Decision tree of the lane changing procedure:

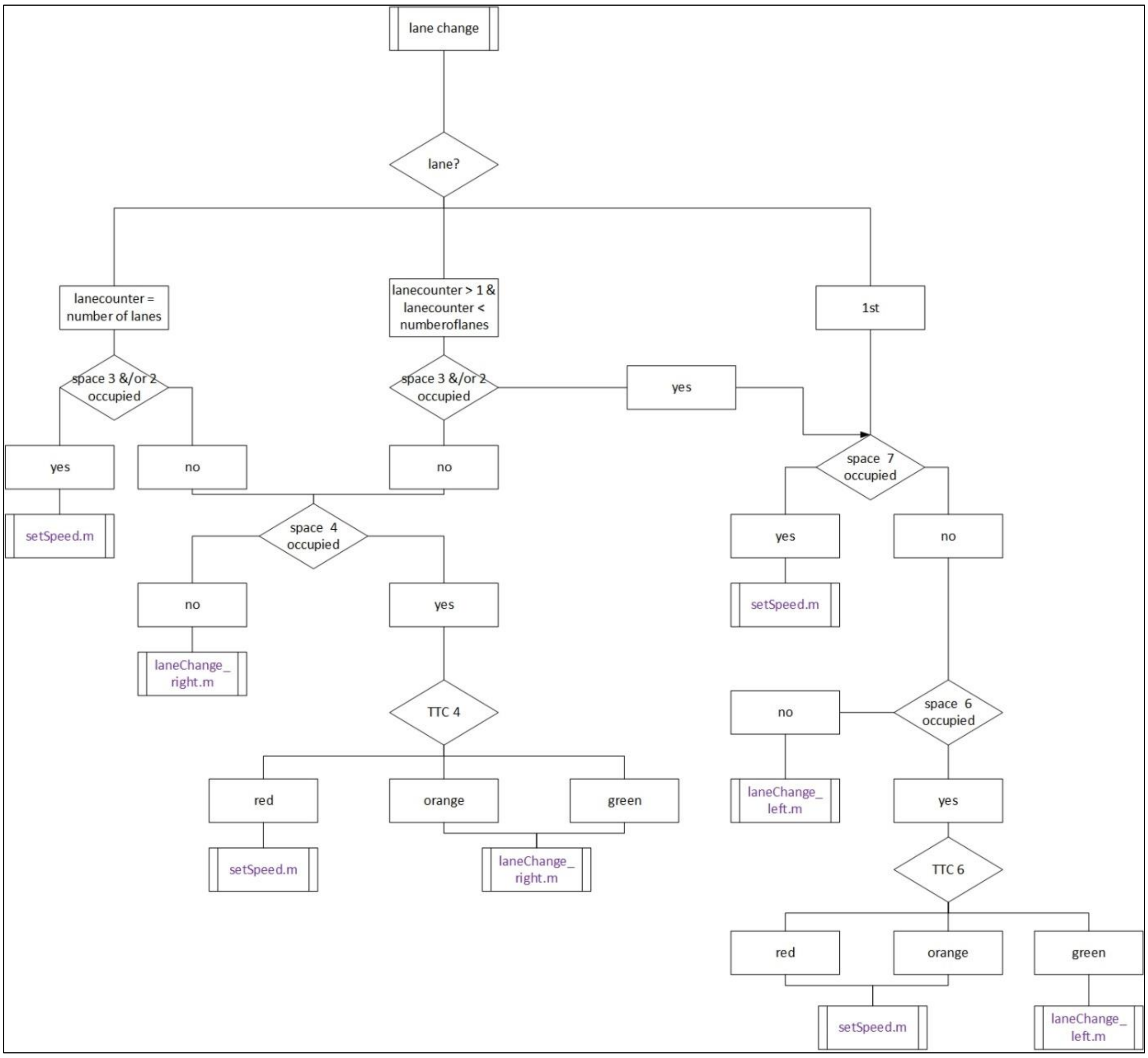


Figure 2-7: Structure of the Lane Change procedure

Based on chapter 2.2, if the AHDAS tool chooses the lane change procedure first, the driven lane is checked. Whereas it is only necessary to know if it is the first lane, a middle lane or the left lane. If the Ego-car drives on the first lane, the only option is to make a lane change to the left. For this it has to be checked if the area on the left side is empty. Consequently, Space 7 is checked and if it is occupied, there is no possibility to do a lane change and is handed over to the “Set Speed” procedure. If Space 7 is not occupied, however, the rear side of the Ego-car is checked. The first space to be checked is Space 6. If the TTC is classified as “red” or “orange”, the “lane change” procedure is quit and handed over to the “Set Speed” procedure. If the TTC is “green” a lane change to the left is started.

On a middle lane, first the possibility to do a lane change to the right is checked. Regarding the traffic regulations that request driving on the right side of a road. [31]

For this reason for a middle and the left lane, the right side of the car is checked (Space 2 and Space 3). If one space is occupied the "Set Speed" procedure is started for the left lane. For a middle lane the left side of the Ego-car is checked, especially Space 7 and as a result, the decision tree is the same than for the right lane mentioned before.

For a middle and the left lane the decision tree goes on equally if Space 2 or Space 3 are not occupied. As a result the rear side of the car has to be checked again. Space 4 is investigated and if it is not occupied or the TTC is marked "green" or "orange" a lane change to the right is started. If the TTC is "red" the speed is set again and the Ego-car stays on its initial lane. If driving on the left lane and Space 2 or Space 3 are occupied a "Set Speed" manoeuver is set. After the general direction is chosen it can be decided between a lane change to the right or to the left side.

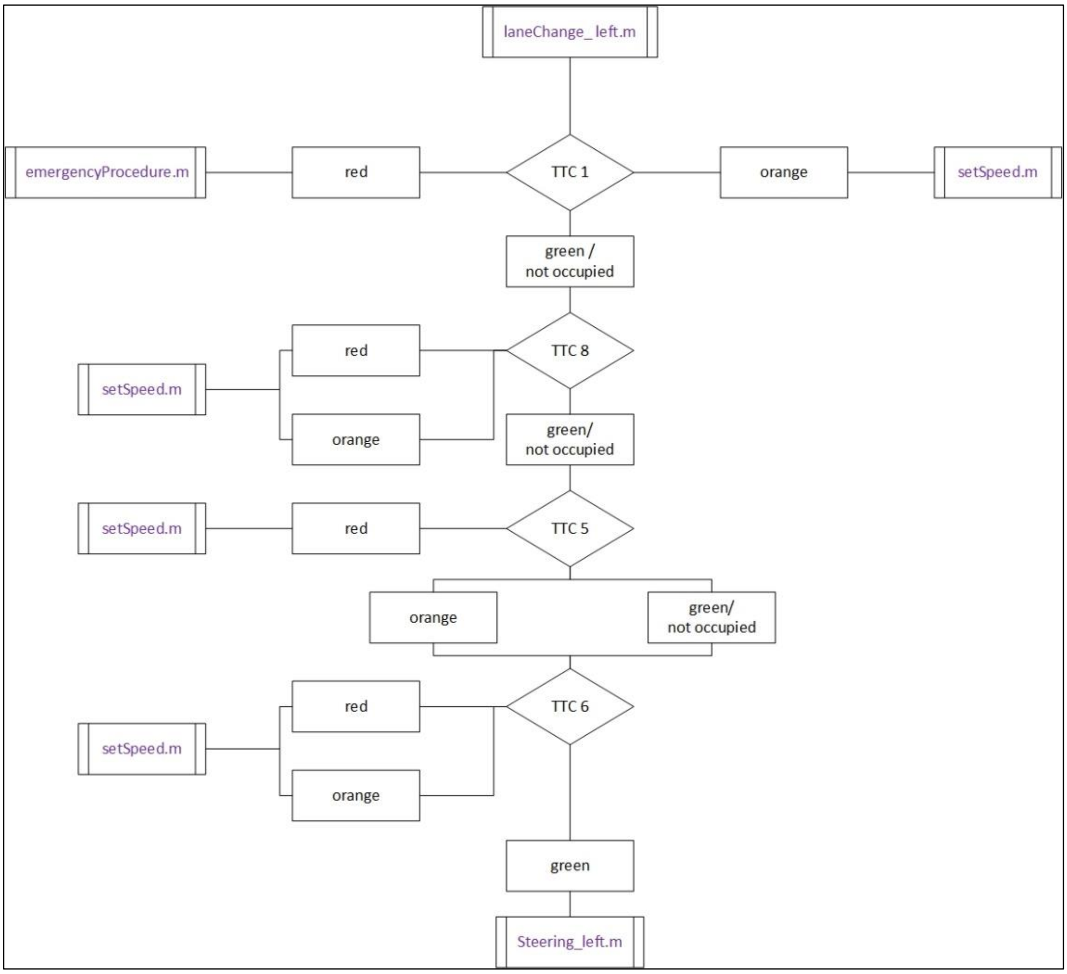


Figure 2-8: Decision tree for lane change to the left

After the general decision of a lane change to the left a closer look is performed as seen in Figure 2-8. As a redundancy the TTC of Space 1 is checked and if this is marked “red” the procedure is stopped immediately and the “Emergency procedure” is started. If the TTC is “orange” the “Set speed” manoeuver is started. In the third and most probable case the TTC of Space 8 is checked. If the TTC is “green” or the space is not occupied Space 5 is checked. If the TTC of Space 5 is “green”, not occupied or “orange” Space 6 is checked. If the TTC of Space 6 is “green”, then the steering manoeuver is started. In all other cases the “Set Speed” procedure is started. Regarding to Space 5, the TTC is observed too, although to keep the safety distance is within the responsibility of the following car, because if the TTC is classified as “red” an overtaking manoeuver of the following car is probable. Therefore no lane change of the Ego-car is started. This assumption is made for Space 6 too and extended to the TTC classification of “orange”, to enable following cars to overtake the Ego-car.

In comparison: The lane change to the right in Figure 2-9, which follows the same principle as the lane change to the left:

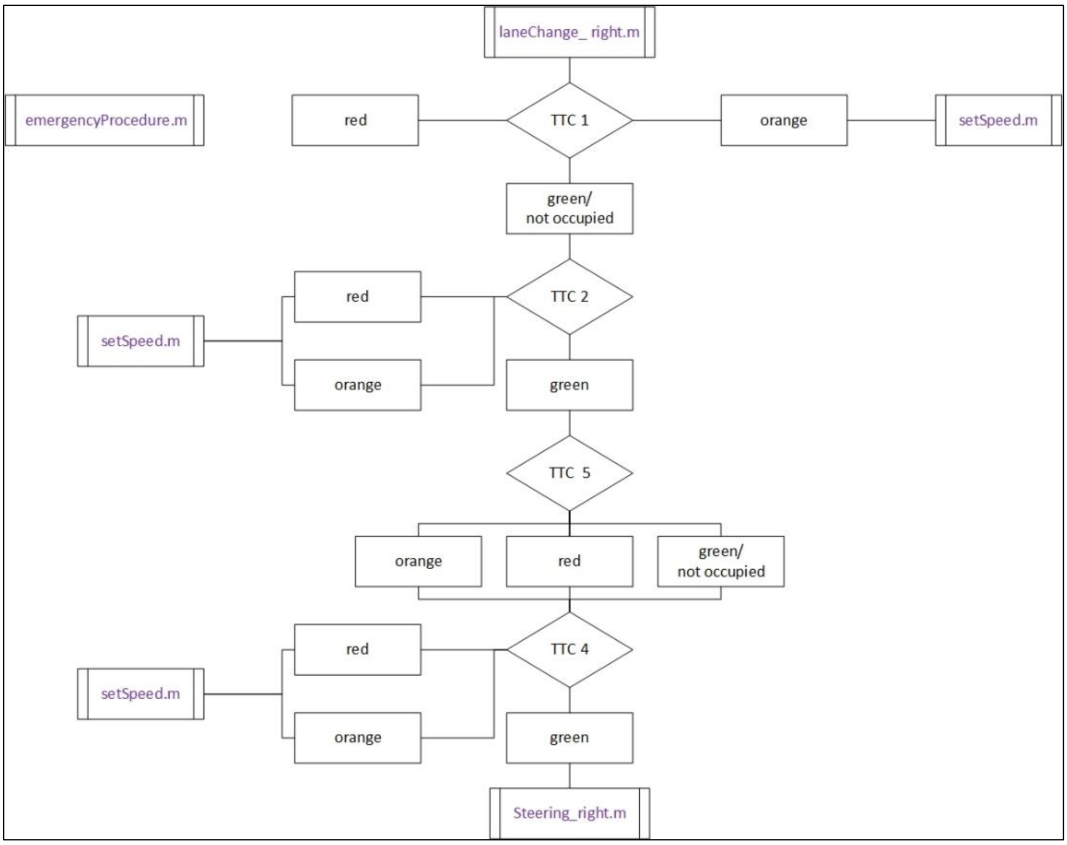


Figure 2-9: Decision tree for lane change to the right

After the final decision whether a lane change manoeuver is possible the direction is handed over to the steering process described in chapter 2.4.1.

If there is a termination condition, as described in chapter 2.6.1 the “Quit lane change” manoeuver as described in chapter 2.4.2 is started.

2.4.1 Steering

After the decision that a steering manoeuver is started the lane change trajectory is calculated.
To reach the goal of a comfortable configuration the lateral acceleration in the general lane changing manoeuver is set to 1 m/s². For a steering manoeuver, a calculated trajectory is necessary which the car can follow. The steering module of Renski [32] is the basis for the steering manoeuver of the trajectory. The module is adapted to the requirements of autonomous driving because a computer can follow the given trajectory exactly.

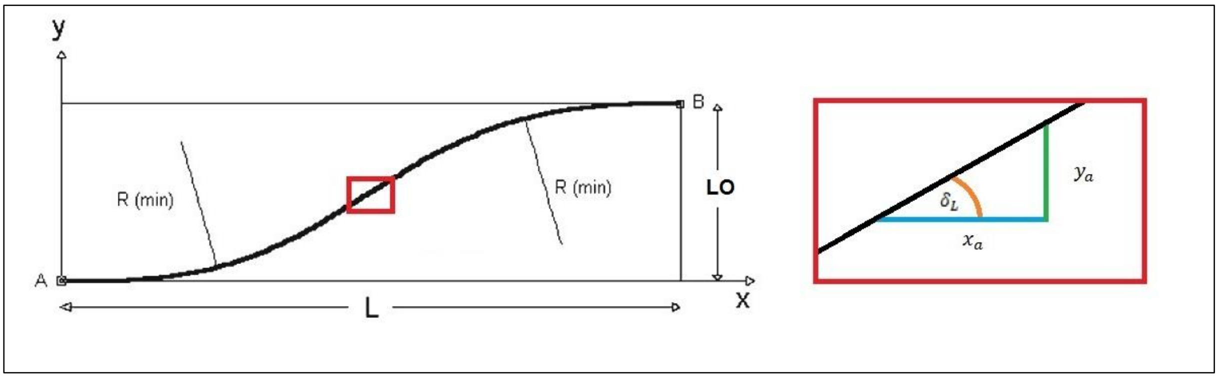


Figure 2-10: Calculation of the steering wheel angle [20, p. 145]

The basis to calculate a steering wheel angle is the steering trajectory. Based on the calculated length of the lane changing manoeuver the *distance in X-direction* x_a of each step (0.015s) is calculated. Related to this length the corresponding offset, the *Y-length* y_a is calculated. As shown in Figure 2-10 and in equation (2-1) the angle between those two directions is calculated and corresponds to the *steering wheel angle* δ_L.

$$tan\ \delta_L = \frac{y_a}{x_a} \tag{2-1}$$

Based on the *steering wheel angle* δ_L. the steering angle for the *left* δ_{LW} and *right front wheel* δ_{RW} can be calculated by means of the Ackermann condition [33, p. 460]. For this a *steering ratio* i_S is needed. In general, the steering ratio for passenger cars is between 14 and 20. Front wheel drive cars have a decrease of the ratio of 17-30% from steering straight to the full steering angle. Furthermore there is the possibility of a variable ratio. A low steering ratio increases the directness of the steering which is a problem at higher velocities. On the other hand, the higher value of the steering ratio is limited to small speed manoeuvers like parking. [33, p. 472]
In the lane change model in AHDAS a variable steering ratio is used. The value is adapted to the velocity of the Ego-car v_{ego} and is empirical optimised by the author. As seen in equation (2-2) the maximum velocity is set with 140 km/h and has a linear behaviour as seen in Figure 2-11.

$$i_S = 10 - (140 - v_{ego}) * 0.04 \tag{2-2}$$

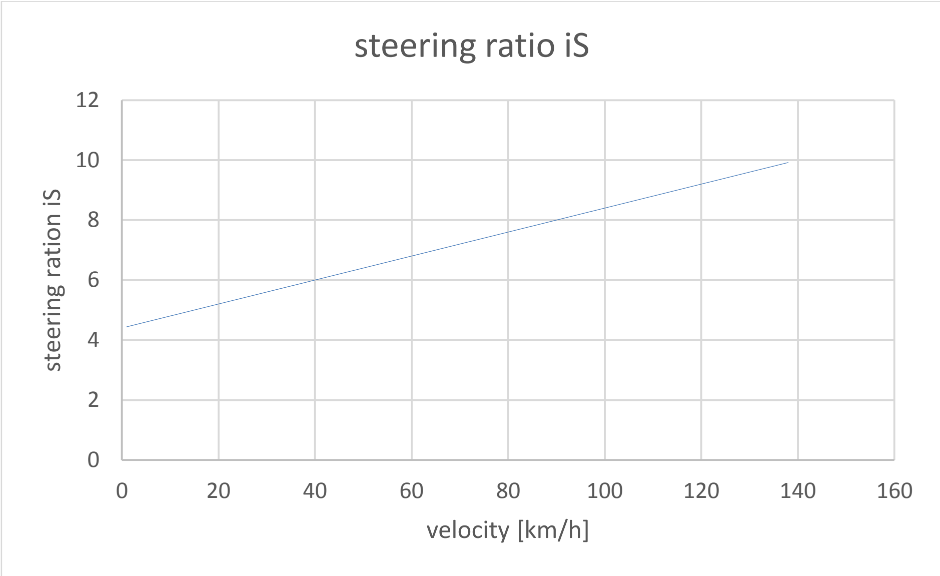


Figure 2-11: Empirical evaluated steering ration iS dependent on the velocity

Concerning the Ackermann condition the *curve outer wheel angle* δ_A is calculated with equation (2-3) depending on the *steering ratio* i_S and the *steering wheel angle* δ_L .

$$\delta_A = \frac{\delta_L}{i_S} \tag{2-3}$$

To calculate the curve inner wheel the Ackermann condition shown in equation (2-4) is used, therefore the car geometry information like the *track width* t_w and the *wheelbase* w_b of the car is necessary and is read from "PC Crash". For this reason the object system OLE is used.

$$cot\delta_I = \cot\delta_A - \frac{t_w}{w_b} \tag{2-4}$$

Thus the *curve inner wheel angle* δ_I is calculated in (2-5): based on the equation (2-4).

$$\delta_I = \arctan\frac{\tan\delta_A}{1-\frac{t_w}{w_b}*tan\,\delta_A} \tag{2-5}$$

Related to the offset, which is calculated, the lane width is the basis. Hence based on the actual Y-position of the Ego-car the final offset is calculated and is basis for all other calculations. Apart from this calculation the offset is adapted. If there is a lane change to the left and the origin lane is not the right one plus 0.5m are added. This adaption is implemented because of the advantage of having a further distance to the car, which is being overtaken. On the other hand, if there is a lane change to the right the offset is adapted too. If there is a lane change to the middle lane, the chosen offset is smaller. Then 0.3m are subtracted, to make sure the car is on the left side of the lane. When changing to the first lane the offset is calculated to drive on the right side of the lane. The information about the driven lane is updated after each lane change manoeuver and stored in the lane counter and is related to the amount of lanes which is set by the user at the beginning.

After finishing the lane change to the left, a time period of 1 second is implemented to minimize the velocity direction angle which remains after the steering process by setting the steering angle to zero. After finishing a lane change to the right for one second the velocity direction angle is set as a negative value at the steering wheels for the same reason than for the lane change to the left. Dependent on the velocity direction angle the velocity direction gets zero after some time steps and as a result the Ego-car goes on straight. After finishing the lane change process the lane counter is updated.

2.4.2 Quit lane change

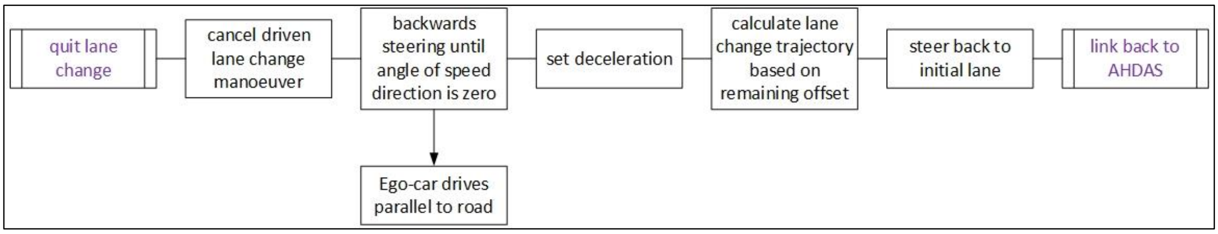


Figure 2-12: Flow chart of the “Quit lane change” manoeuver

There are two scenarios when a lane change manoeuver has to be cancelled. Either a following car on the left side in Space 6 is classified as “red”, “orange” or a higher acceleration rate than 2m/s² in Space 6 is detected. The acceleration rate of 2m/s² is set by the author because of the experience of various simulations and can be adapted. First, the lane change procedure is cancelled. The position of the Ego-car is determined and afterwards the steering angle is set to the neutral position (0°). For this the angle of the velocity direction is used. As a result, the actual negative steering angle is set as wheel steering angle. The velocity direction is exported from “PC Crash” each time step and thus adapted each time step for 3 seconds. For this time period a deceleration of 1 m/s² is set to increase the distance between the Ego-car and the car ahead which should be overtaken.

Afterwards the car drives parallel to the X-direction of the coordinate system and the lane change procedure is started to drive back to the initial lane. To do so the offset based on the actual Y-Position is calculated.

2.5 Set speed

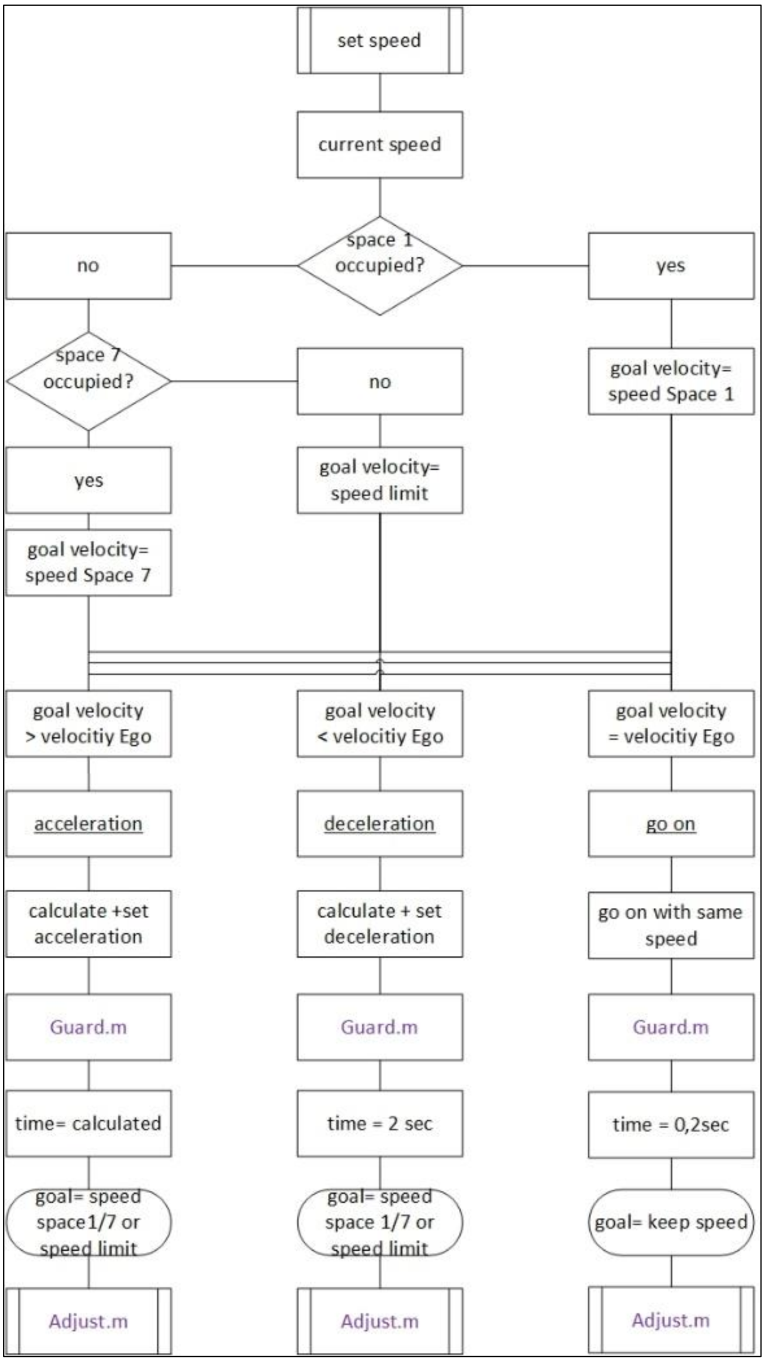


Figure 2-13: Decision tree of set speed procedure

The selection of the driven velocity is based on the one hand on the traffic especially the cars driving ahead, on the other hand naturally on the road traffic regulations. In this context especially Space 7 has to be mentioned because it is relevant in avoiding a forbidden overtaking to the right. This could be possible if the Ego-car drives on the first lane with a higher velocity than another car driving on the middle lane.

The acceleration manoeuver is started as soon as possible. If a slow driving car ahead leaves the own lane to the right lane, the acceleration manoeuver is started right after this car leaves Space 1. Deceleration manoeuvers on the other hand are not set immediately, due to the objectives of driving as fast as permitted. The deceleration manoeuver is started, based on the safety distance and the calculated length of the deceleration manoeuver. For example if a slow driving car reaches Space 1 and no overtaking manoeuver is possible, the car goes on with the initial speed until the relevant distance is reached.

2.5.1 Acceleration

To guarantee fast travelling, acceleration manoeuvers are set. If the car in front is driving faster or if there is an empty road and the Ego-car drives with a lower velocity than permitted, an acceleration manoeuver is set.

$$a = \frac{\Delta v}{\Delta t} \tag{2-6}$$

To catch up to the vehicle ahead the equation (2-6) is used. Referring to the road traffic regulations there should be a safety distance of 2 seconds, to reach this time the acceleration rate is calculated which is needed to close up to the car ahead. If there is no car ahead and the speed limit should be reached the acceleration rate is chosen with $2 m/s^2$. The acceleration rate can be adapted if an environmental friendly driving style is needed. Petros A. [34, p. 279] for example describes an environmental friendly acceleration rate of $1 m/s^2$. In this thesis the acceleration rate is chosen with $2 m/s^2$ to ensure a quick way of driving.

For this purpose the needed time is calculated with the differential speed.

2.5.2 Deceleration

Considering that the Ego-car is a computer-driven car, any reaction times are included into the calculations. But the lag period of the brakes has to be mentioned. Furthermore the needed brake force is provided constantly for the whole braking period. In “PC Crash” the brake lag time is set as a constant value with the half of the full brake force.

For deceleration manoeuvers the deceleration rate is calculated with the equation (2-6) with the time period of 2 seconds and the given differential speed. As a result, the car reaches a safety distance of 2 seconds after the braking manoeuver. If the safety distance gets too short than the deceleration rate is set higher. Therefore the time in the denominator is multiplied by 0.75 to gain a higher deceleration value. After the deceleration manoeuver the velocity is smaller than the required one. Thus after the safety distance is reached, an acceleration manoeuver is initiated to drive with the same speed as the car ahead.

2.5.3 Go on

If there is no other manoeuver like a lane changing required the "go on" sequence is implemented. This sequence consists of a period of 0.2 seconds and the current speed. During this sequence the observation tool "Guard" is operating. After operating the "go on" sequence the "adjust trajectory" procedure is started. The time-period is chosen this short in order to be able to start another manoeuver as soon as possible.

2.6 Other procedures

2.6.1 Guard

To guarantee a continuous observation beside the decision making processes at the beginning of each manoeuver the sub programme "Guard" is implemented. The sub programme observes during all manoeuvers like lane changes or braking procedures the environment in each time step. Thus, differential velocities and relative accelerations are calculated for the car in Space 1. For this the acceleration is calculated to be able to react as early as possible, before reaching the safety distance, when the deceleration rate gets lower than -3 m/s^2. Then an ongoing manoeuver is interrupted and a reaction is set. Furthermore, the velocity difference is calculated to be able to react on a slow driving car moving into the sensor range. The critical velocity difference is 45 km/h. The sub programme observes those figures in the course two steps to eliminate problems during an overtaking process of two cars with a different velocity. Another criterion to stop an ongoing process is a TTC of the Space 1 in "red", which can occur if another vehicle does a lane change in front of the Ego-car.

For lane changing manoeuvers, the behaviour of the vehicle in Space 6 is especially observed. The acceleration rate is calculated and the overtaking process for example is quit if the acceleration in Space 6 is higher than 2m/s^2. To eliminate the problems by lane changes and resulting value leap the relevant cars are also filtered according to their lane. For example, if the Ego-car changes from the right lane to the middle lane the 3rd lane is not relevant.

2.6.2 Adjust trajectory

After the lane change process is finished, often a small yaw angle in the range of 0.1 –0.2° remains whereas on the highway and its speed, high changes in the Y-direction of the Ego-car results.

As a result the adjusting procedure is started after speed changes or straight driving manoeuvers. First the Y-position of the Ego-car is checked and if the offset is more than 0.2m to the middle of the lane than an adaption is started, either to the left or the right side. This is why the offset to the middle of the lane is calculated and handed over to the lane change procedure, as a result the trajectory is calculated and performed. Special settings for the adjustment procedure of the small offsets are a *steering ratio* i_S of 1 for small differences and 2 for an offset of more than 0.5m.

2.7 Emergency procedure

At the beginning of each manoeuver it is checked if the procedure could be performed in a safe way. If there is no possibility to do so the manoeuver isn't started. But if there is a critical situation coming up running a manoeuver, often because of the wrong behaviour of other road users an emergency procedure is implemented.

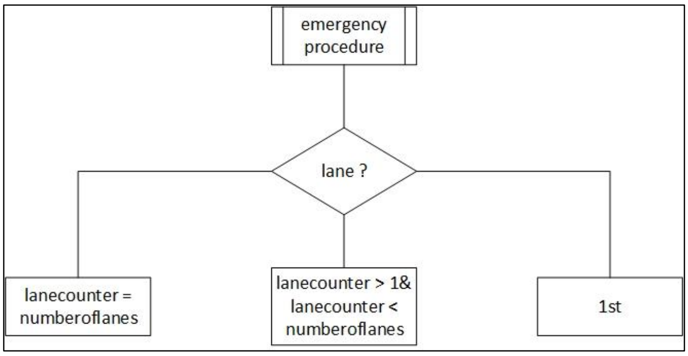


Figure 2-14: Start of the decision tree for the emergency procedure

An emergency procedure is started if the distance between cars ahead are too close or if the "Guard", described in chapter 2.6.1, detects a too high velocity difference or a huge difference of deceleration. If the emergency procedure is started, the driven lane as seen in Figure 2-14 is crucial.

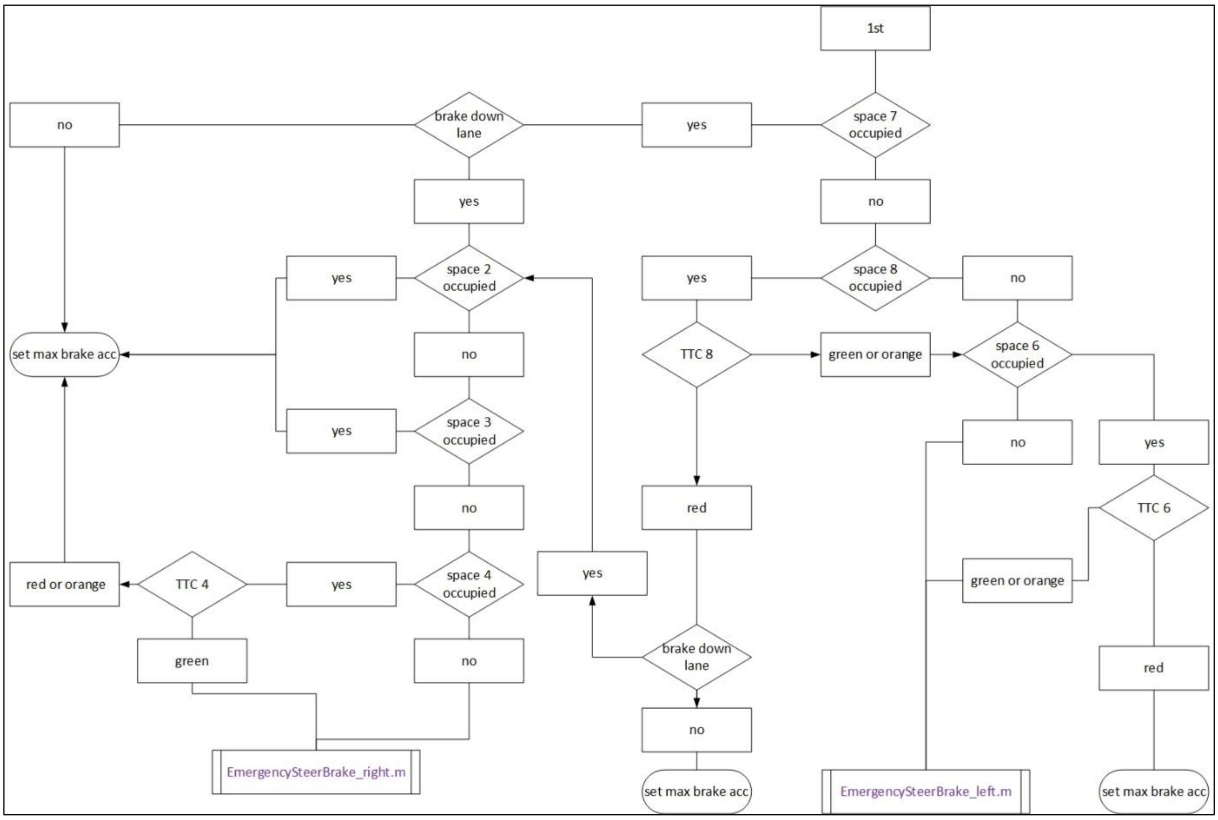


Figure 2-15: Emergency procedure for the 1st lane

If the Ego-car drives on the first lane (Figure 2-15) and an emergency manoeuver is necessary, as seen in Figure 2-15 first the left side is checked if the left side, Space7, is occupied. The right side is checked if there is a breakdown lane. If there is a breakdown lane present, it is checked. The lane has to be free from obstacles. Thus, Space 2 and 3 are checked and of course the following traffic, which could have already evaded to the brake down lane. If the breakdown lane is occupied, no evasion manoeuver is driven but a full brake session is started.

If the left side is not occupied, it is checked, whether there is the possibility to evade to the left. The evading process is possible if there are no cars close on the left side. For this the state of Space 8 and Space 6 is checked. If the TTC is “green” or “orange” an evasive manoeuver is possible, if the TTC is marked “red”, no evasive manoeuver is possible and a full brake session is started.

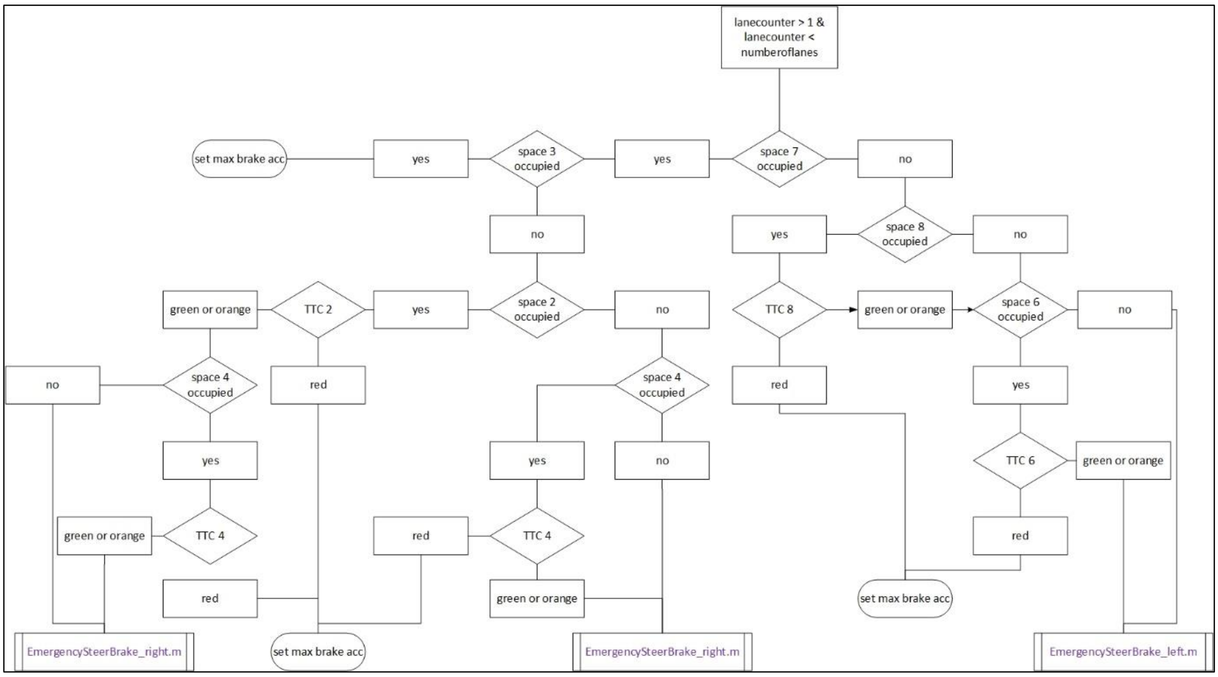


Figure 2-16: Emergency procedure for a middle lane

If the Ego-car drives on a middle lane (Figure 2-16) there are always three possibilities to avoid an accident. First an evasive manoeuver to the left, second an evasive manoeuver to the right and at least a full brake session is possible.

First of all the left side, similar to the 1st lane, is checked and if there is space an evasive manoeuver is driven to the left. Secondly, if there is no possibility to drive to the left lane the right lane is checked. Therefore the same procedure is done than in the emergency procedure for the 1st lane and its breakdown lane. If none of these possibilities is feasible, a full brake session is started.

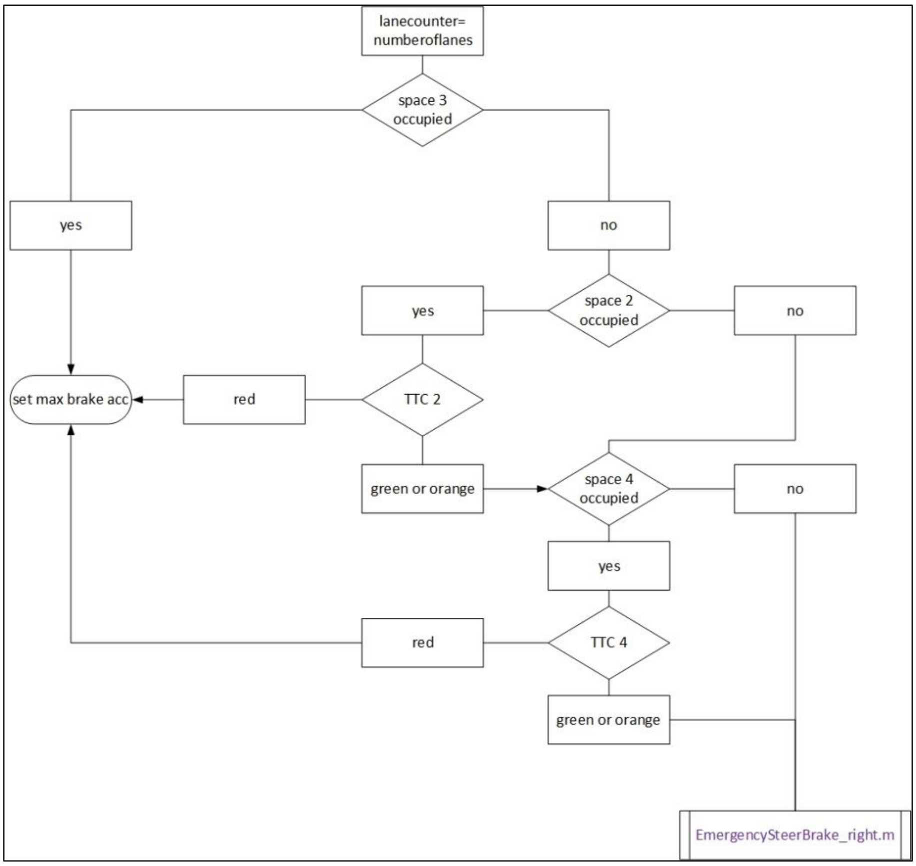


Figure 2-17:Emergency procedure for the left lane

If an emergency situation occurs on the left lane (Figure 2-17), the only possibility is to steer to the right side or start a full brake manoeuver.

If an evasive manoeuver is started the manoeuver of “Brake and steer” as described in chapter 2.7.2 is started. If no evasion is possible, a full brake manoeuver, as described in the same chapter, is performed. After an “Emergency procedure”, the programme stops and the simulation is quit after the Ego-car braked to a velocity of zero.

2.7.1 Brake

If there is no possibility to evade an obstacle a full brake session is set during all implemented manoeuvers. Therefore the maximum deceleration of the car is set until the car stops.

2.7.2 Brake and steer

The brake-steer model is preferred because of a higher chance to prevent a crash and the opportunity to react later and avoid a crash in comparison to the full brake manoeuver. [9, p. 906] Hence if there is a chance to evade an obstacle the steering process is started. In comparison to a normal lane changing manoeuver there is a braking and steering process at the same time. For the emergency procedure and related to the steering trajectory a lateral acceleration is set to 4m/s². The goal is to evade the obstacle completely thus an offset of the linewidth is aspired.

Regarding to the lateral acceleration the braking deceleration is set depending on the driven velocity and based on the calculation of the Circle of Forces in equation (1-4). Therefore the second part of the equation is set to the lateral acceleration, which is set regarding to Figure 1-23, at a high but safe level classified as sporty with a rate of $4m/s^2$. Based on the friction coefficient of 0.7 and the gravity acceleration of $9.81m/s^2$ results in a deceleration rate of $6m/s^2$ which is set for the “brake and steer” manoeuver and allows an evading manoeuver.

3 RESULTS

The autonomous driving process described in the last chapters is checked in some scenarios. To show the functionality, typical traffic situations on highways are tested with the “AHDAS”- tool. Many different scenarios are tested considering the Ego- car has to handle different procedures and is not only driving on the first lane with a constant speed. As a result overtaking processes, speed adaptions and straight go on driving situations are simulated. Furthermore, emergency scenarios are tested to proof their functionality.

3.1 Overtaking manoeuver

To show the functionality a standard overtaking process on the highway is simulated and described in further detail. All relevant decision steps are mentioned. For this a highway with 3 lanes, a breakdown lane and a constant lane width of 3.5m on all lanes is chosen. The speed limit is set to 130 km/h and the Ego-car starts at lane number 1 (right lane) with a speed of 120 km/h. The values are mostly rounded to one decimal place to simplify the readability of the text.

- Start position

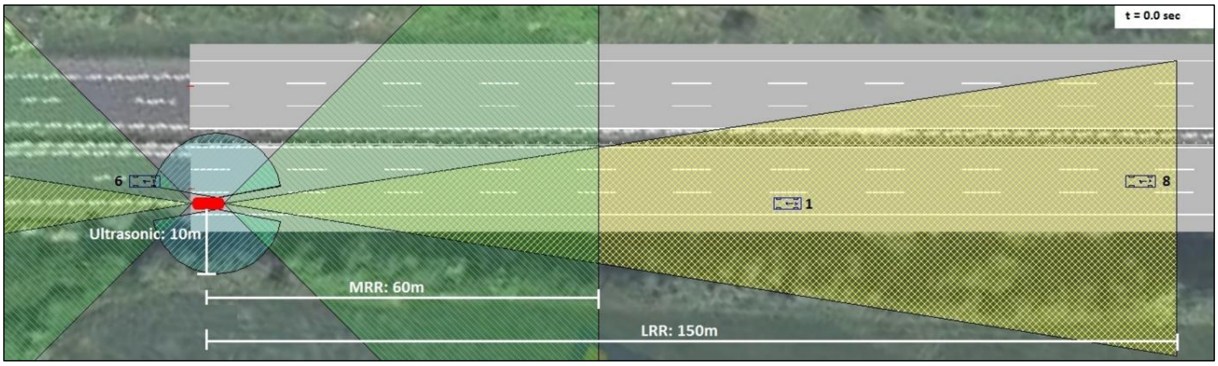


Figure 3-1: Start position

Table 3-1: TTC status: Start position; t= 0s

6	d =5.2 m TTC = 1.25 sec v= 135 km/h	7	d= 140.4 m TTC = 25.4 sec v= 140 km/h	8
5		EGO v = 120 km/h	d= 85.6 m TTC= 15.4 sec v= 100 km/h	1
4		3		2

At the starting position as seen in Figure 3-1 and Table 3-1 the Ego-car is following a car (Space 1) on the first lane with a distance of 90 meters and a differential speed of 20 km/h and a TTC of 15.4 seconds resulting a classification of “green”. Furthermore there is a car overtaking the Ego-car on the second lane (Space 6) with a distance of 5.2 meters to the COG of the Ego-car resulting a TTC classification of “orange”. Another car is driving on the middle lane in front of the Ego-car in space 8 with a distance of 140 meters ahead and a TTC of 25 seconds classified with “green”. All other spaces surrounding the car are not occupied.

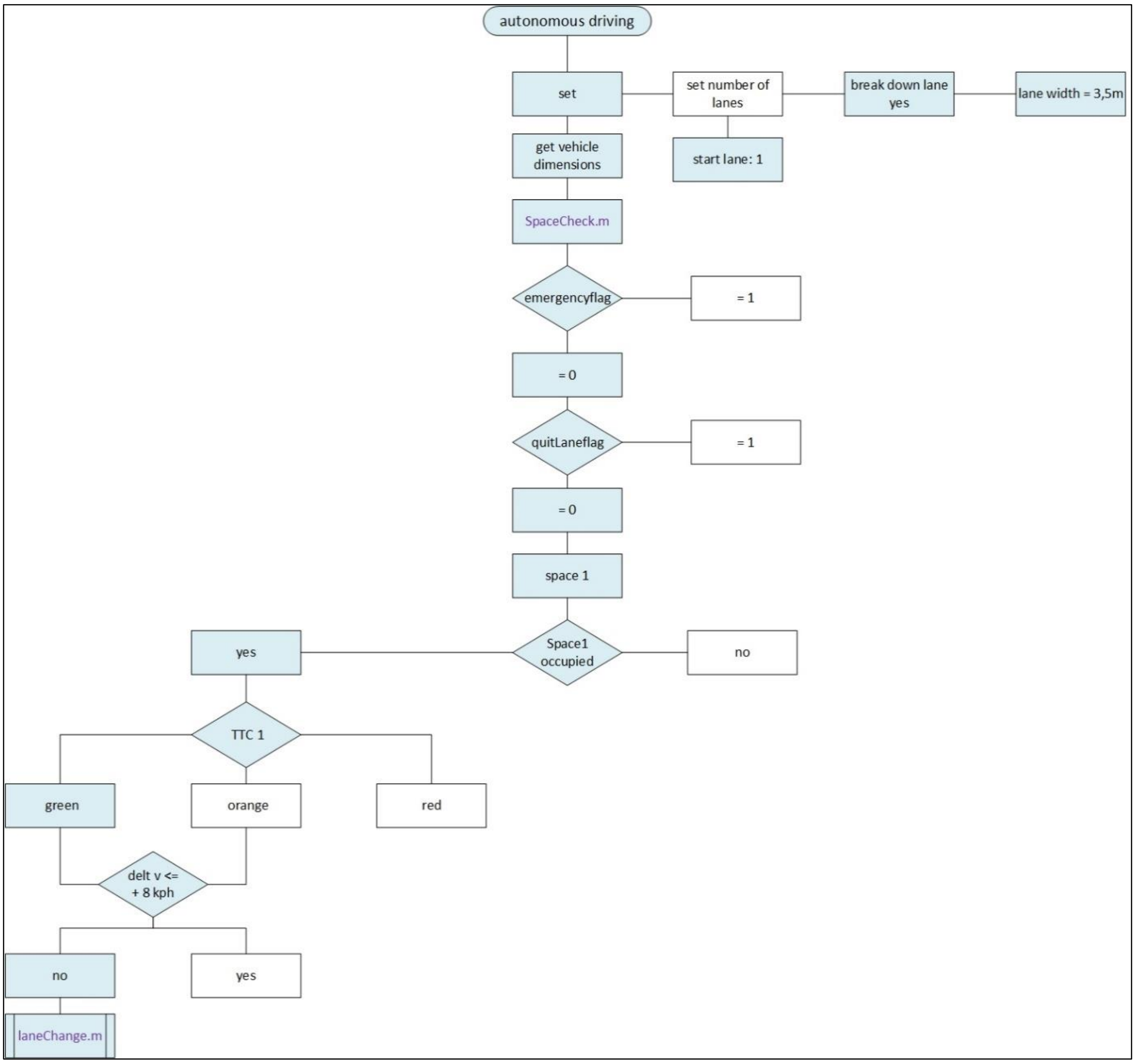


Figure 3-2: "AHDAS": Start decision tree

The algorithm starts with the main decision tree, where the basic settings are set. The “emergency flag” and the “quit lane flag” are naturally zero at the beginning. As a result Space 1 is occupied, classified as “green” and the differential speed is higher than 8 km/h. Thus the next sub programme “Lane change” is chosen.

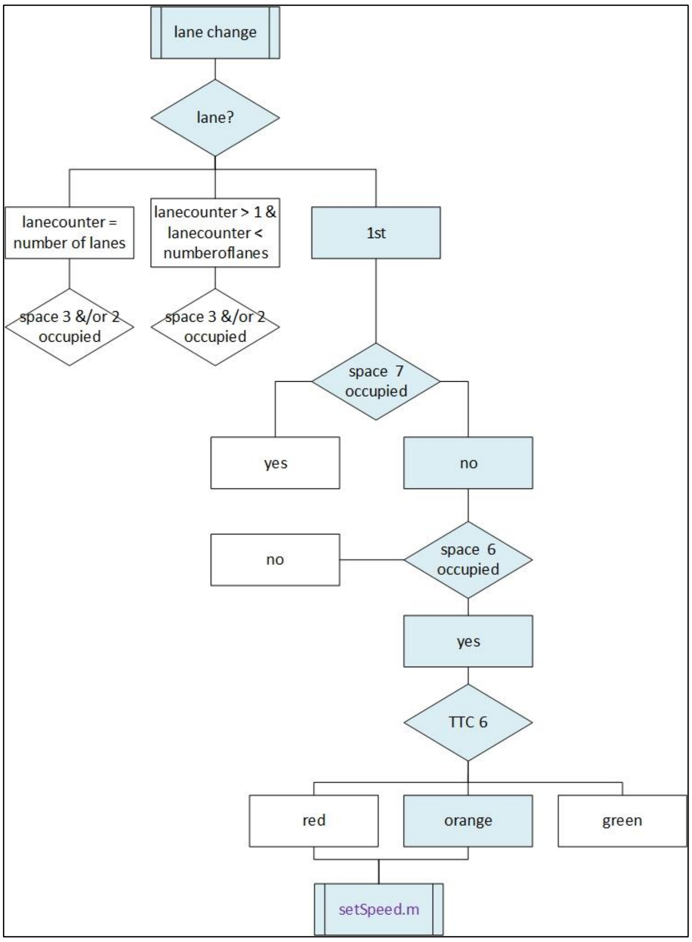


Figure 3-3: "Lane Change"

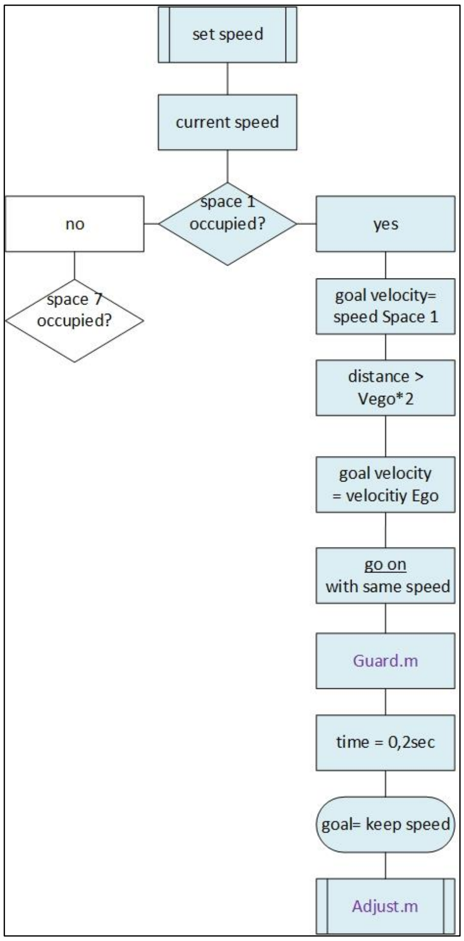


Figure 3-4: "Set Speed"

The Ego-car is driving on the first lane and as mentioned before Space 7 is not occupied. Because of the classification of Space 6 as “orange”, the next sub programme that starts is “Set Speed”.

The sub programme “Set Speed” starts and related to Space 1 the velocity is not changed because of a high distance between the two cars. These three programmes with a duration of 0.2 seconds are revised until the next decision is set:

- 1st point-of-decision

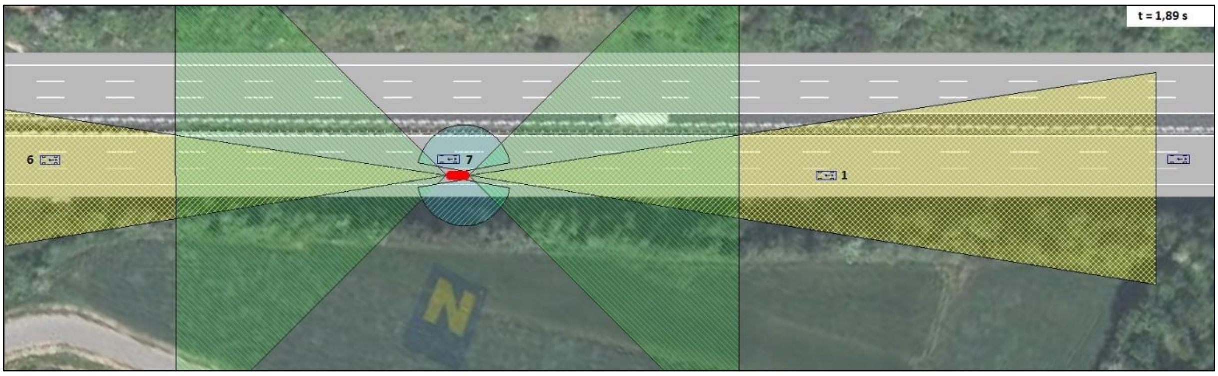


Figure 3-5: Velocity of the Ego-car is adapted to vehicle ahead

Table 3-2: TTC- status of the cars in the sensor range at t= 1.89s

6 **d =85.7 m TTC = 15.45 sec v= 100 km/h**	**occupied** **7**	**8**
5	**EGO** **v = 120 km/h**	**d= 75.1 m TTC= 13.5 sec v= 100 km/h** **1**
4	**3**	**2**

After 1.89 seconds, the Ego- car reaches the safety distance of 66 meters plus 10 meters to reach the right velocity after the deceleration manoeuver, to the car in space 1 as seen in Figure 3-5 and Table 3-2. There is still a car on the left side in Space 7, which means no overtaking process is possible. Furthermore, Space 6 is occupied with a distance of 85 meters and a "green" TTC.

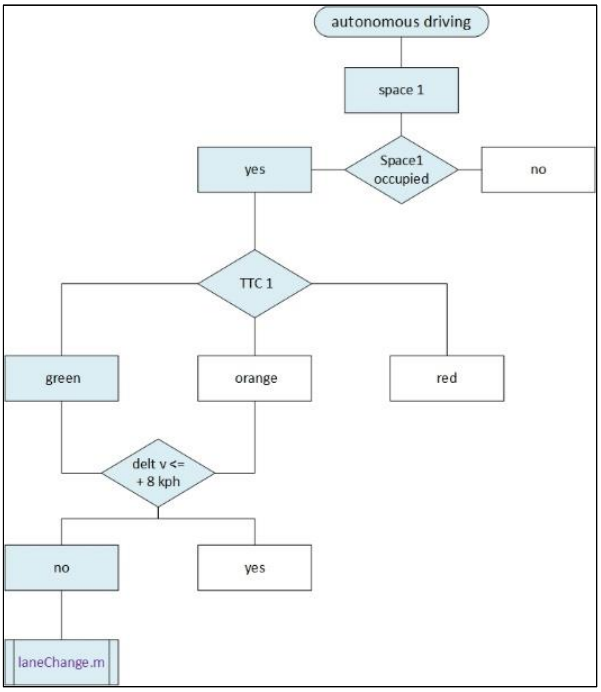


Figure 3-6: "AHDAS" in the loop

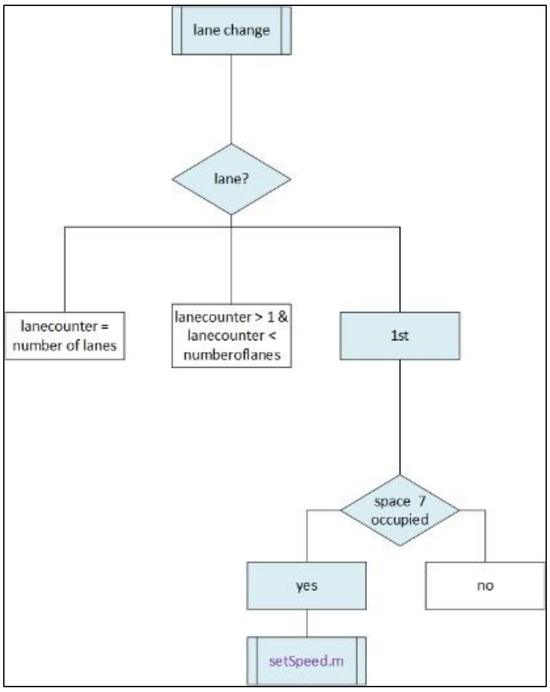


Figure 3-7: "Lane Change" Decision tree

The decision process starts at the beginning with the "AHDAS" programme (Figure 3-6), which excludes the basic settings which were set at the beginning. The special procedure flags are zero, which means they are not shown in Figure 3-6. A "lane change" (Figure 3-7) manoeuver is the result of the first decision tree. As already mentioned Space 7 is occupied hence the "Set Speed" (Figure 3-8) sub programme is started.

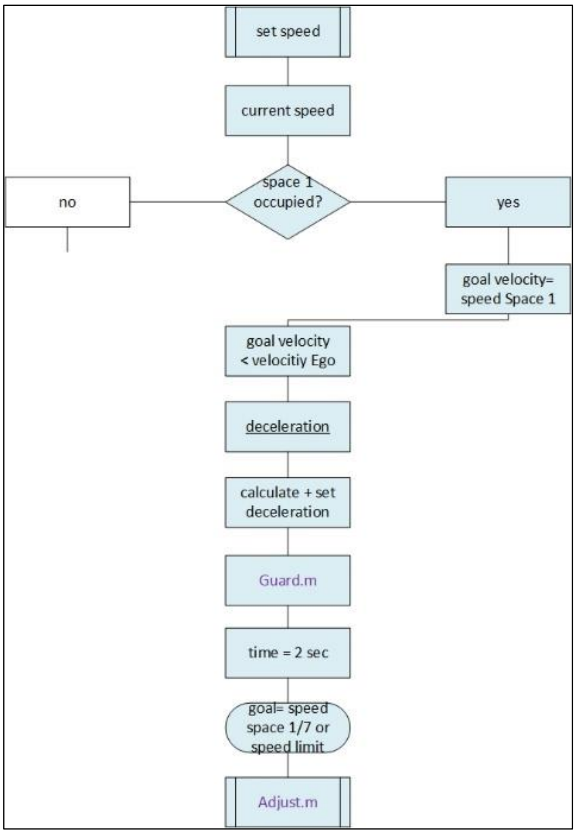


Figure 3-8: "Set Speed" Decision tree: Deceleration

In comparison to the first decision, a deceleration manoeuver is necessary to guarantee the safety distance to the car ahead. Because at this point the distance to the car in Space 1 is the safety distance and the added braking distance. The deceleration is calculated with a deceleration rate of 2.7 m/s² for a time period of 2 seconds. After 2 seconds the aspired position is reached and the Ego-car follows the car in Space 1 with a constant speed of 102 km/h and a safety distance of 68 meters. The algorithm is the same as mentioned in the start position with the sub programme "Go on".

- 2nd point-of-decision

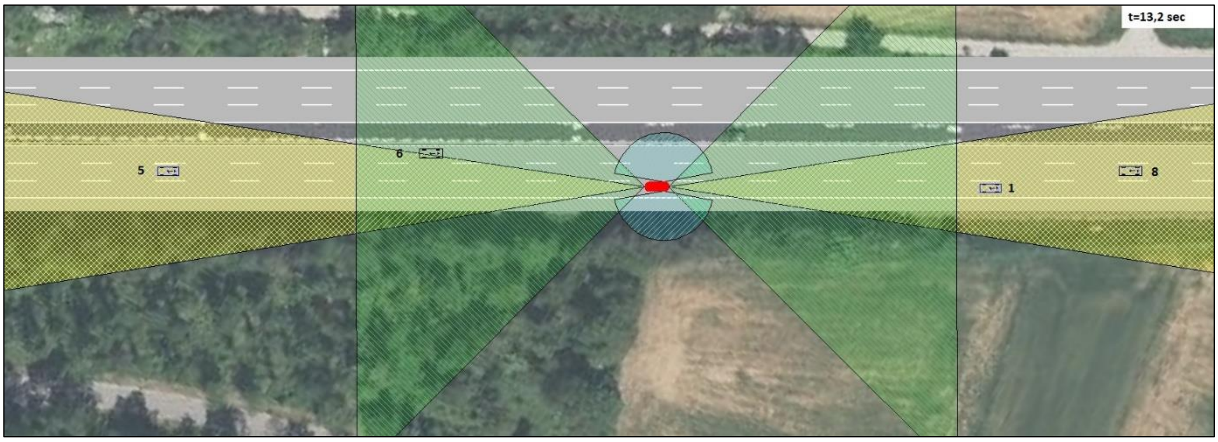


Figure 3-9: Decision to start a lane change is set

Table 3-3: TTC- status of the cars in the sensor range at t= 13.2s

6	d =97,9 m TTC = n.a. v= 100 km/h	7	d= 94,4 m TTC= > 100 sec v= 135 km/h	8
5		EGO v = 102 km/h	d= 63 m TTC= > 100 sec v= 100 km/h	1
4		3		2

After 13.2 seconds as visualised in Figure 3-9 and Table 3-9 the Ego-car is still driving on the 1st lane with 102 km/h. On the left side the relevant car left Space 7 to Space 8 and therefore a distance between those cars is measured as 94.4m and as a result a TTC classification of “green” is evaluated. In Space 6, a following car drives with a distance of about 100m and classified as “green” and the TTC is “not applicable” (n.a.) because the differential speed is negative thus the following car would never collide with the Ego-car. Any other space is occupied.

The “AHDAS” procedure is started and as shown in Figure 3-6 excludes the basic settings which were set at the beginning. Thus Space 1 is occupied and classified with “green”. In this case the differential speed is less than 8 km/h but the speed of the car ahead is less than 120 km/h, thus an overtaking process is started.

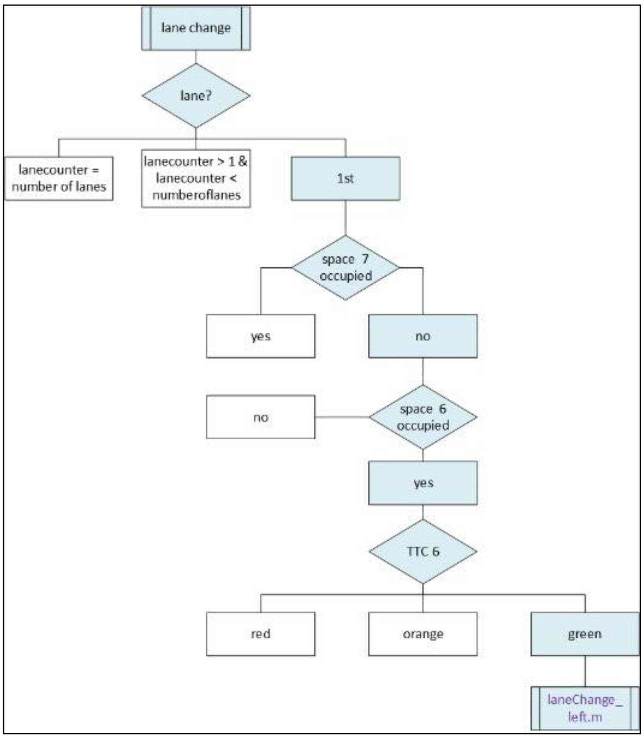


Figure 3-10: "Lane change" Decision Tree

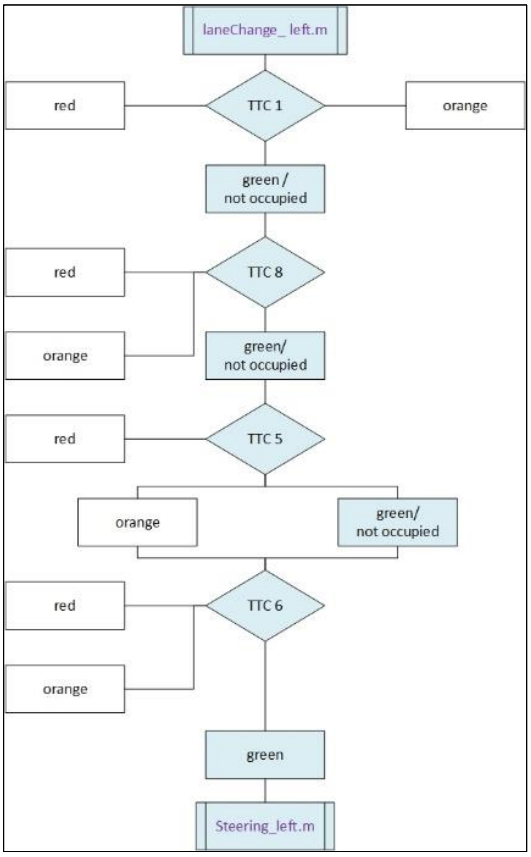


Figure 3-11: "Lane Change to the Left" decision tree

As seen in Table 3-10 Space 7 is not occupied and Space 6 is occupied and classified as “green” thus the sub programme “Lane Change Left” is started. As a result as seen in Table 3-11 all relevant spaces around are either not occupied or classified as “green” thus the steering manoeuver is started. Therefore, with the offset of 3.5meters and the velocity of 102 km/h the trajectory referring the relevant angles is calculated. The speed stays nearly the same for the whole lane changing process, only 0.7 km/h are lost due to friction influences between the tyres and the road surface. The whole lane change lasts 159m and 5.6s and the Ego-car achieves the second lane with a final offset to the first one of 3.2 meters. The driven offset is smaller than the required 3.5m because of problems related to the steering ratio. During the lane changing process a car on the third lane moves into the sensor range and is classified as Space 6 with a differential speed of 38 km/h and a TTC classification of “red”. Thus there is no further lane change process planned the car is not further implement in a decision tree. The “Guard” programme, which supervises each step does not measure any deviation concerning the closer environment of the car.

- 3rd point-of-decision

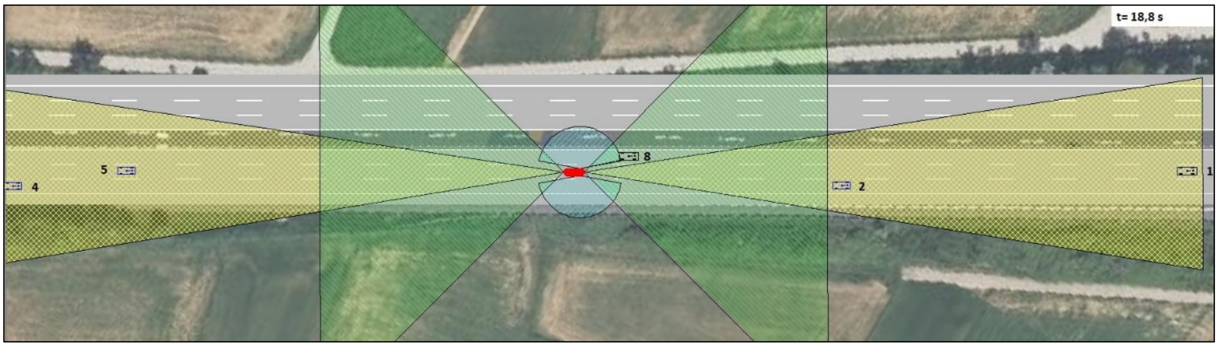


Figure 3-12: Position after lane change and before acceleration

Table 3-4: TTC- status of the cars in the sensor range at t= 18.8s

6		7	d= 8.3 m TTC= 0.8.sec v= 140 km/h	8
5	d =101.2 m TTC = n.a. v= 100 km/h	EGO v = 102 km/h	d= 142.2 m TTC= n.a. v= 135 km/h	1
4	d =127.3 m TTC = n.a. v= 95 km/h	3	d= 59.7 m TTC= 99.5 sec v= 100 km/h	2

When the lane changing process is finished as seen Figure 3-12 in and Table 3-4, after 18.8 seconds the situation is evaluated again so that there is a differential speed of 33 km/h to the car in front (Space 1). Furthermore there is a car on the right side in Space 2 with a classification as “green” and a car on the left side in Space 8 with a classification as “orange”. In the back there are two cars driving in Space 4 and Space 5, both classified as “green”.

The procedure starts again with the “AHDAS” programme as shown in Figure 3-6 and hands over to the sub programme “Lane Change” as seen in Figure 3-13.

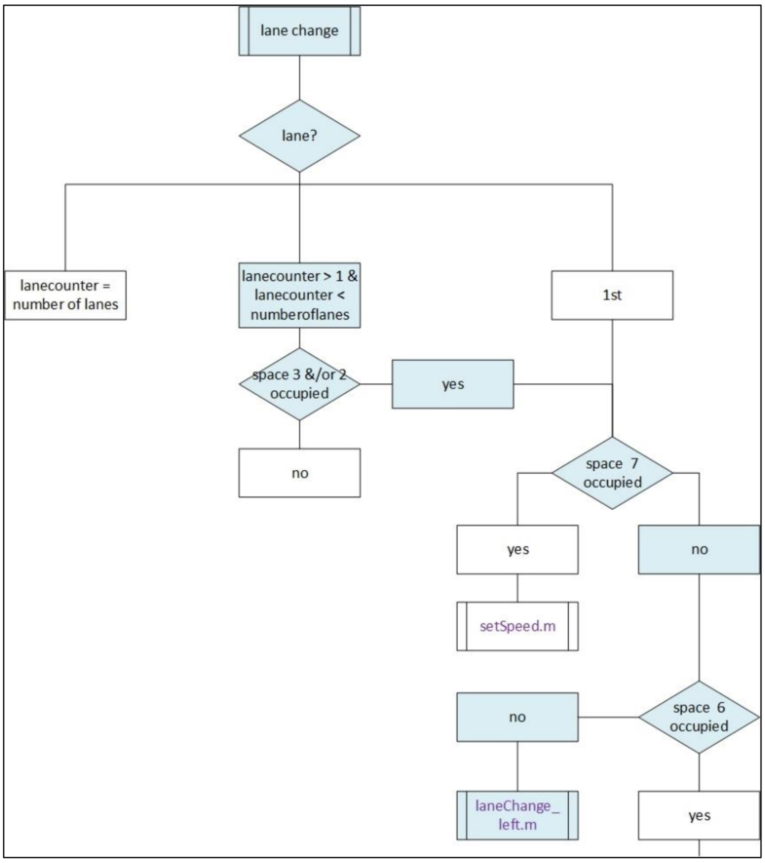


Figure 3-13: "Lane Change": Middle Lane

The car is driving on a middle lane and Space 2 is occupied. Space 7 and Space 6 are not occupied thus the “Lane Change Left” manoeuver is started.

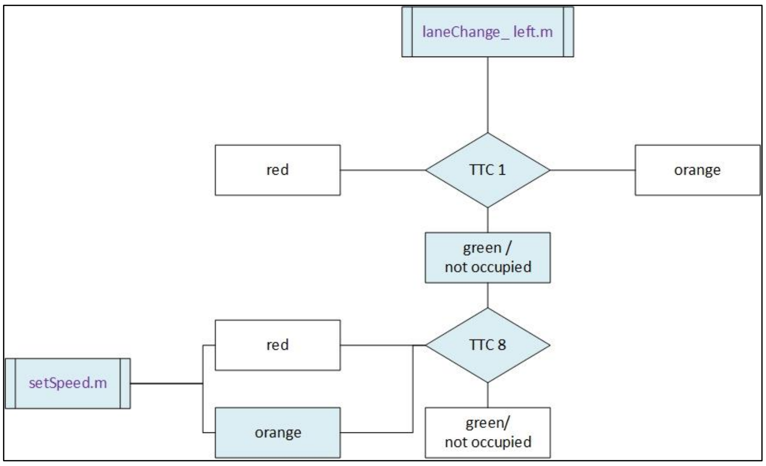


Figure 3-14: "Lane Change to the Left"

In the “Lane Change to the Left” (Figure 3-14) programme, finally the as “orange” classified Space 8 is checked and as a result the “Set Speed” (Figure 3-15) programme is started. No lane change is possible in this case because the car ahead in Space 8 is too close to reach the safety distance after the overtaking manoeuver.

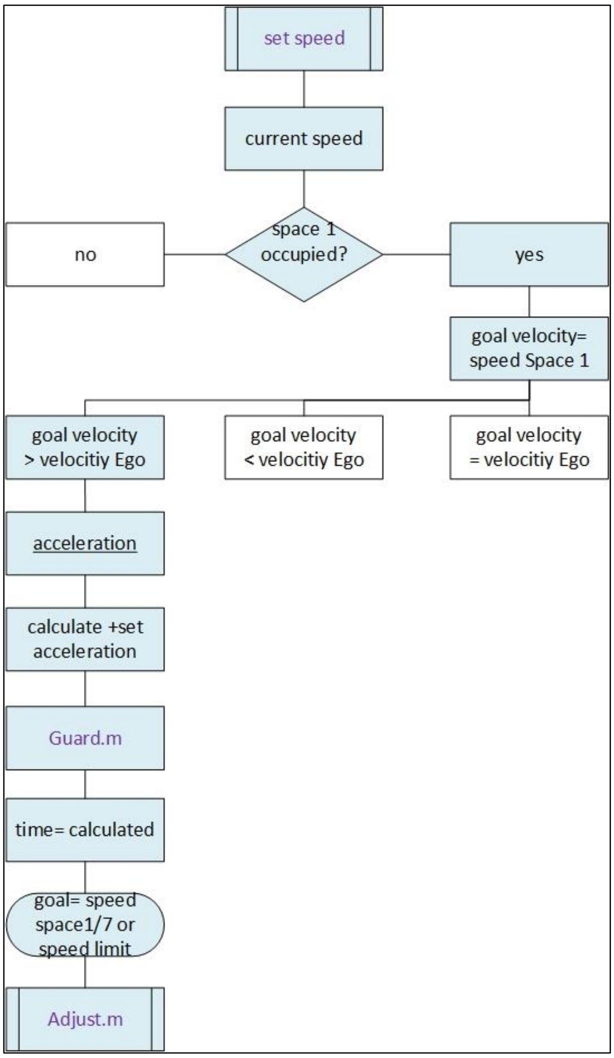


Figure 3-15: "Set Speed": Acceleration

Accordingly no further lane change manoeuver is possible but an acceleration is set. Space 1 is occupied, thus the velocity of the car ahead is the target speed in general but in this case, the car ahead drives 5km/h faster than the speed limit. As a result, the speed limit becomes the goal velocity. An acceleration rate of 2m/s² and a time period of 4.6 seconds is calculated to reach the target speed of 130 km/h. After the overtaking process and the acceleration manoeuver before, a yaw angle of 0.14° remains. As a result after a time period of 10.8 seconds the offset to the middle of the lane amounts 0.6 meters, which means an "adjust" manoeuver starts.

- 4th point-of-decision

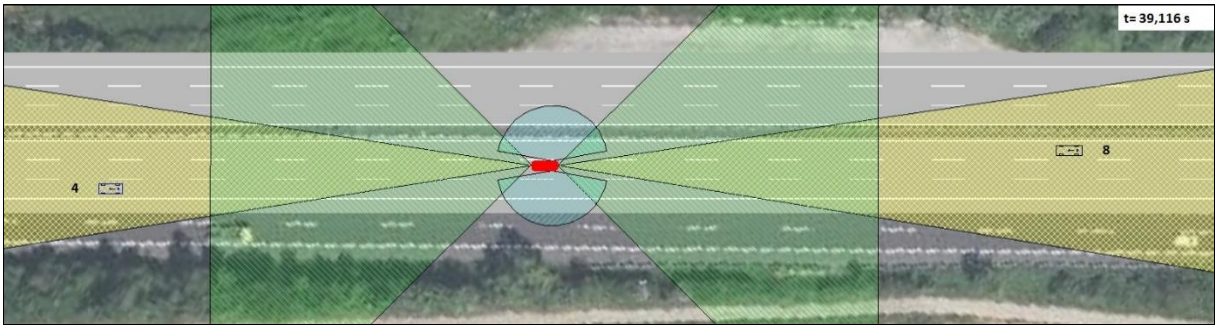


Figure 3-16: Decision to drive back to initial lane is set

Table 3-5: TTC- status of the cars in the sensor range at t=39.116s

6		**7**	**d= 90,7 m** **TTC= n.a.** **v= 140 km/h**	**8**
5		**EGO** **v = 130 km/h**		**1**
4	**d =74,6 m** **TTC = n.a.** **v= 100 km/h**	**3**		**2**

After a total time period of 39.116 seconds the evaluation as shown in Figure 3-16 and Table 3-5 results an occupied Space 8 in the front with a TTC classified in “green”, an occupied Space 4 on the right side with an TTC classified as “green” and a distance between the cars of 74.6 meters.

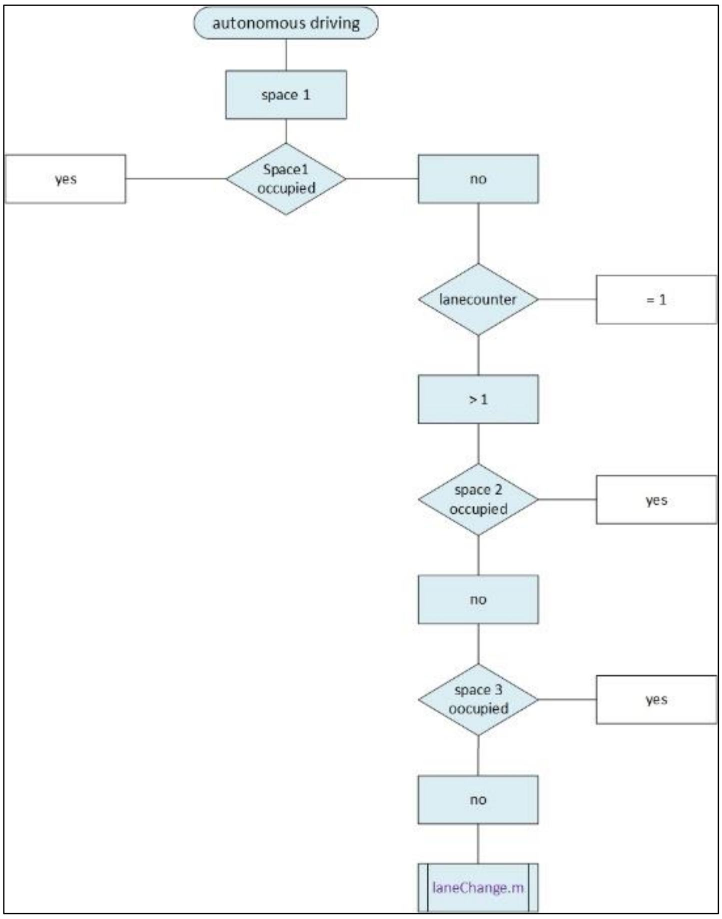


Figure 3-17: "AHDAS": No occupied Space 1

At the beginning the “AHDAS” main programme (Figure 3-17) is started again but in this case Space 1, Space 2 and Space 3 are not occupied and as a result the programme “Lane Change” Figure 3-18 is started.

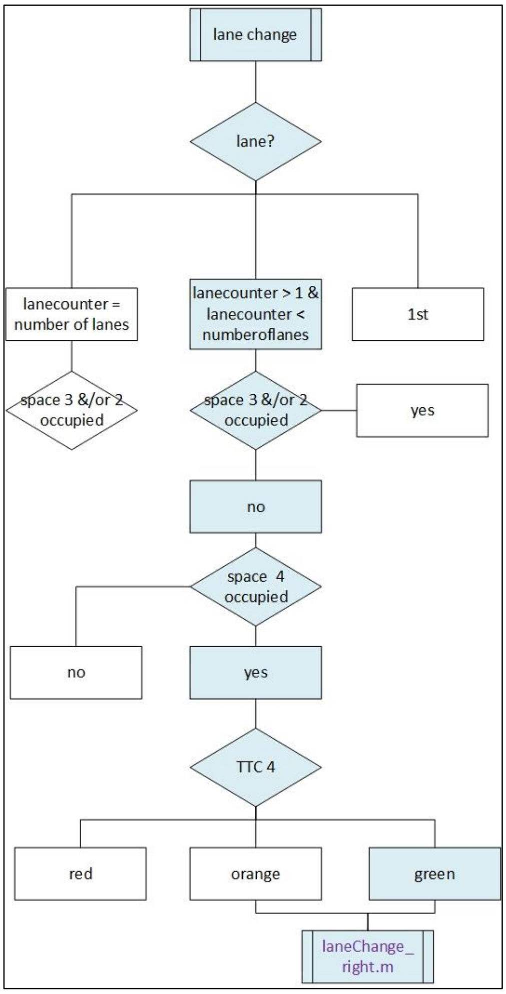


Figure 3-18: "Lane Change": Middle Lane

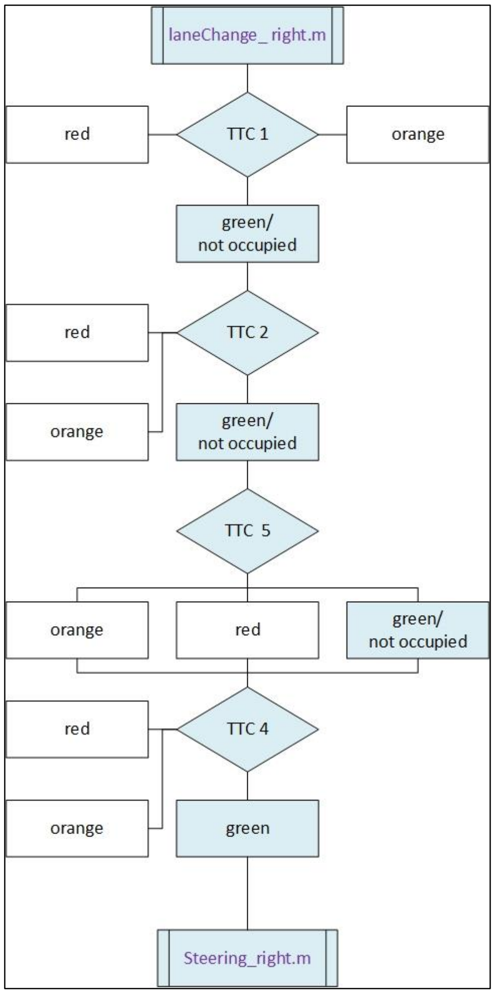


Figure 3-19: "Lane Change to the Right"

The Ego-car is driving on the middle lane and Space 3 or Space 2 are not occupied. Space 4 is occupied and classified as “green”, thus the “Lane Change to the right” programme is started.

As visualised in Figure 3-19 all relevant spaces named in this decision tree are either not occupied or classified as “green”. As a result the overtaking process can be finished and the car can drive back to the initial right lane 1. Therefore, according to the total offset of 4.2 meters to the first lane and a velocity of the Ego-car of 130km/h the lane change trajectory is calculated. The length and the steering angles are calculated again and the steering process is started. After reaching the first lane in a total simulation time of 45 seconds, as seen in Figure 3-20, the car goes on with the maximum velocity related to the speed limit always revising the “Set Speed” procedure.

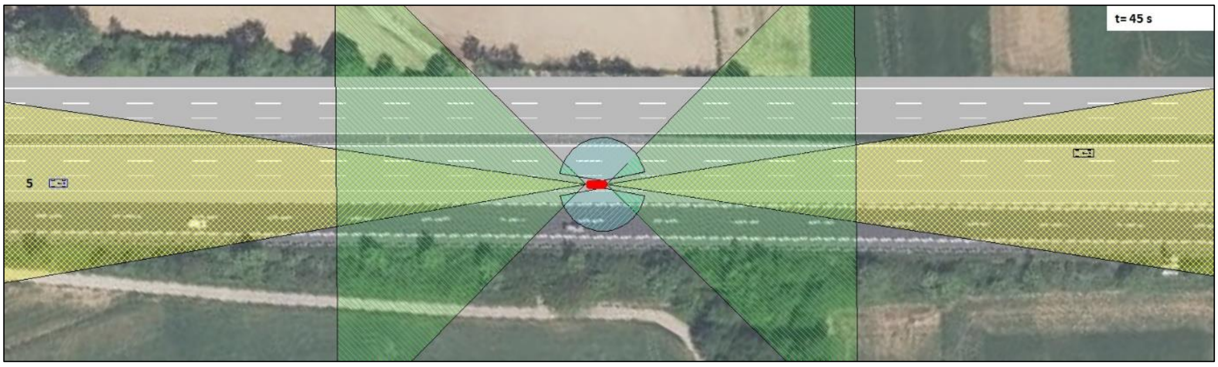


Figure 3-20: Final position on first lane after 45s

3.2 Real Accident

3.2.1 Reconstruction of the Real Accident

For the following example, a real life accident is chosen. The accident is stored in the CEDATU (Central Database for In-Depth Accident Study) database of the Vehicle Safety Institute. [35]

The accident from the database is chosen to show the behaviour of the “AHDAS” tool in a real traffic situation, which leads to an accident, and to compare what the autonomous car does in this situation. The accident happened on a highway in Austria at night in the darkness with no artificial light. It is a straight section with three lanes and a breakdown lane followed of a left bend with a large radius (Figure 3-21 to Figure 3-23). The lane width is about 3.5 meters and the road surface is concrete. No special environment conditions are documented. The road was dry. On the road surface no further traces of the accident were found. A VW Polo was driving on the highway on the second lane with a velocity of about 70 km/h. A following Skoda Octavia driver drove with about 130 km/h on the second lane. The Skoda driver realised the high differential speed too late and rear ended the VW Polo. The Skoda was fully braked at the moment of the impact and the relative velocity at the impact was about 25 to 30 km/h. The whole front of the Skoda was damaged (Figure 3-24 to Figure 3-27.The driver and the passenger of the VW Polo were slightly injured. Due to the braking manoeuver of the Skoda driver, the front of the car moved downwards to the ground and as a result the VW Polo was hit underneath the trunk lid. The VW Polo was damaged on the rear side of the car distributed over the whole width. [35]

Figure 3-21: Highway section where accident happened [36]

Figure 3-22: 350m before the accident site [35]

Figure 3-23: 50m before the accident site [35]

Figure 3-24: Damaged car of accident initiator [35]

Figure 3-25: Damaged car of accident initiator in detail [35]

Figure 3-26: Damage of rear ended car [35]

Figure 3-27: Damage of rear ended car in detail [35]

Figure 3-28: Start position 6.220 seconds before the impact [35]

Based on the reconstruction of the real accident (Figure 3-28) the Skoda drove 6.220 seconds before the impact with 125.8 km/h and the VW with a constant speed of 70 km/h on the middle lane.

Figure 3-29: Start of the deceleration manoeuver of the Skoda driver [35]

Five seconds after the starting position, 1.22 seconds before the impact and with a distance of 13.6m to the car ahead, the Skoda driver starts a full brake manoeuver. Therefore the brake lag time of 0.2s has to be mentioned and as a result at 1.02seconds before the impact the car brakes with a deceleration rate of 7.8m/s². The VW driver still drives with 70 km/h on the second lane.

Figure 3-30: “PC Crash” Reconstruction File: Impact [35]

The Skoda rear-ended the VW after the deceleration time of 1.22 seconds with a velocity of 96.7 km/h. After the collision the VW was accelerated to a velocity of 84.7 km/h and the Skoda had a final velocity of 80.7 km/h.

After the collision both cars stopped, as documented in the police report on the breakdown lane.

3.2.2 "AHDAS"

This scenario is chosen as a basic case to show how an autonomous car would have handled this situation. Due to missing information about the driving route of the involved cars, the presence of any other cars and different statements of the car drivers 4 different scenarios are tested.

- Slow driving vehicle outside the sensor range

In the first scenario the two involved vehicles drive on the second lane with a constant speed. The cars around the Ego-car drive with constant velocities without any changes.

Figure 3-31: "AHDAS" Simulation: start position of the cars on the highway (relevant VW car not in the sensor range)

Table 3-6: TTC- status of the cars in the sensor range at t= 0s

6		**7**	**d= 25.6 m** **TTC= 9.2 sec** **v= 120 km/h**	**8**
5		**EGO** **v = 130 km/h**		**1**
4	**d =25.3 m** **TTC = n.a.** **v= 120 km/h**	**3**	**d= 45.3 m** **TTC= 16.3 sec** **v= 120 km/h**	**2**

As shown in Figure 3-31 and Table 3-6, the Ego-car drives on the second lane with a velocity of 130 km/h. On the right side on the first lane, a car drives with a velocity of 120 km/h in Space 2 with a TTC classification as "orange" and a car on the backside of the car on the right lane in Space 4 with a velocity of 120 km/h and a TTC classification as "orange". On the third lane, another car in Space 8 drives with a velocity of 120 km/h and a classification of "orange". The relevant VW car is not yet in the sensor range of 150m. The "AHDAS" programme starts the sub programme "Go on". One time step (0.015s) later the VW reaches the sensor range and is detected. The calculation of the relative velocity results in a higher relative velocity than 8 and the "Go on" procedure is interrupted. As a result, there is no possibility for an overtaking manoeuver thus a deceleration sequence is set with a deceleration rate of 5.7m/s² for 2.815 seconds. After this manoeuver a velocity of 72.3 km/h is achieved and the Ego-car moves on.

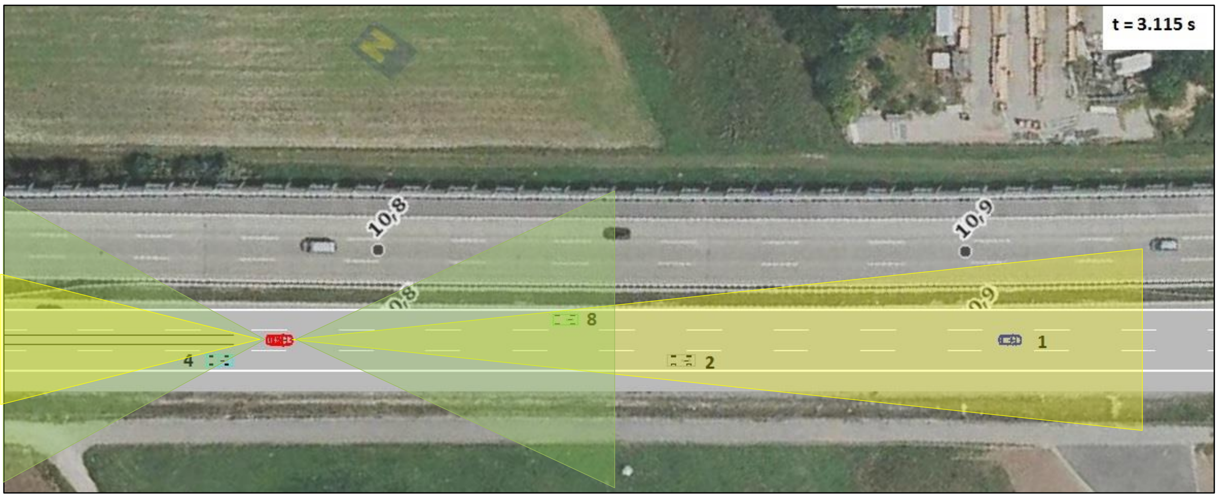


Figure 3-32: "AHDAS" Simulation: Ego-car has the same velocity than the car ahead and decides to start a lane change to the left side

Table 3-7: TTC- status of the cars in the sensor range at t= 3.115s

6		7	d= 44.9 m TTC= n.a. v= 120 km/h	8
5		EGO v = 72.3 km/h	d= 121,8 m TTC= 190 sec v= 70 km/h	1
4	d =5.9 m TTC = 0.4 sec v= 120 km/h	3	d= 64,6 m TTC= n.a. v= 120 km/h	2

After 3.115 seconds (Figure 3-32 and Table 3-7), the car ahead in Space 1 is classified as "green", on the right side Space 2 is occupied and classified as "green". The TTC of Space two is classified as "not applicable"(n.a.) because the relative velocity is negative thus no TTC could be calculated. Space 4 on the back side is classified as "red". On the left side of the Ego-car, Space 8 is occupied and marked "green" with a TTC classified "not applicable". Hence, there is the possibility to overtake the slow

driving car to the left side. At the same time the car in Space 8 overtakes the car in Space 1 on the first lane. A lane changing trajectory is calculated and as a result the steering process to the 3rd lane is started. Finally after 9.964 seconds (Figure 3-33) the overtaking process is finished and the car starts to accelerate to the target speed of the car driving in Space 1 with 120 km/h.

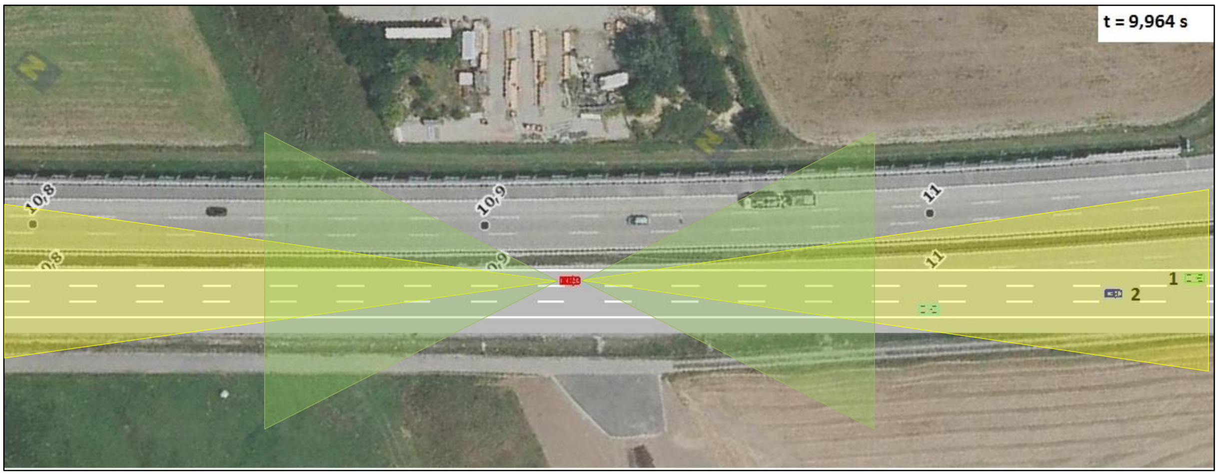


Figure 3-33: "AHDAS" Simulation: after finishing the lane changing process

- Car ahead is in sensor range with less than the safety distance

The assumption in the second scenario is that the car ahead made a lane change and is closer (65.4m) than the safety distance of 72 meters (Figure 3-34 and Table 3-8). All other cars included in the simulation drive with a constant speed.

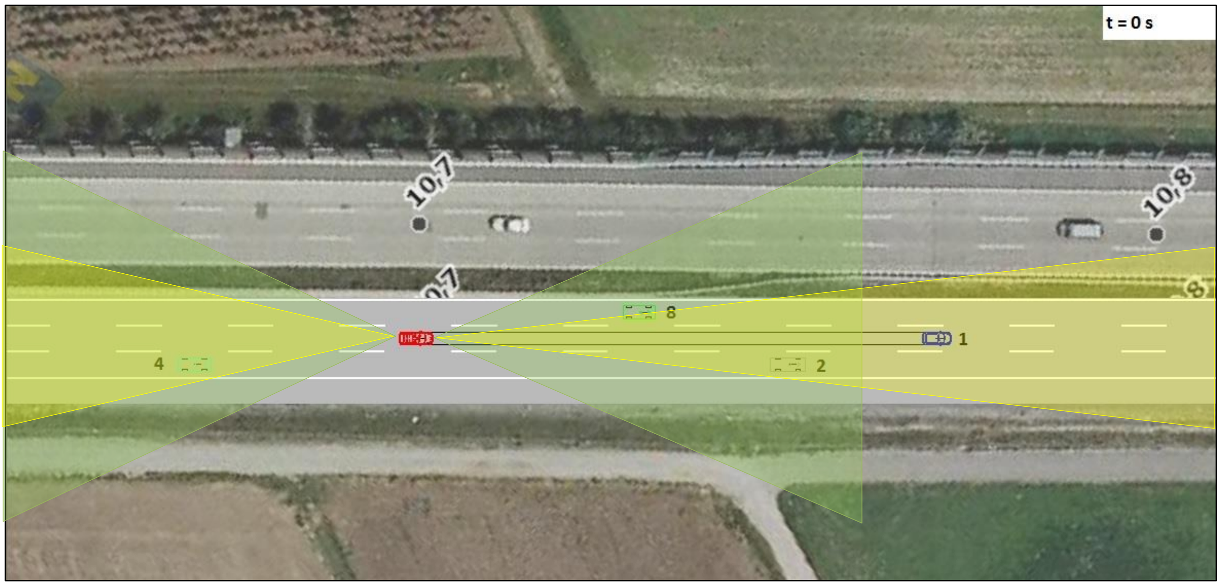


Figure 3-34: "AHDAS" Simulation: car in Space 1 is closer than the safety distance

Table 3-8: TTC- status of the cars in the sensor range at t= 0s

6		7	d= 25.6 m TTC= 9.2 sec v= 120 km/h	8
5		EGO v = 130 km/h	d= 65.8 m TTC= 3.9 sec v= 70 km/h	1
4	d =25.3 m TTC = n.a. v= 120 km/h	3	d= 45.3 m TTC= 16.3 sec v= 120 km/h	2

The Ego-car drives with a velocity of 130 km/h and the car ahead in Space 1 with 70 km/h. The Spaces 1, 2, 4 and 8 are occupied and all marked as a TTC “orange”. Thus, no lane change manoeuver is possible. As a result a deceleration sequence is immediately started. To reach the target speed a deceleration rate of 6,6m/s² for 2.74 seconds is set. Afterwards the Ego-car reaches a velocity of 66.32 km/h. A higher deceleration rate than in scenario one is set because of the shorter distance between the two cars than the safety distance. Thus the time in the denominator is multiplied by 0.75 to gain a higher deceleration value.

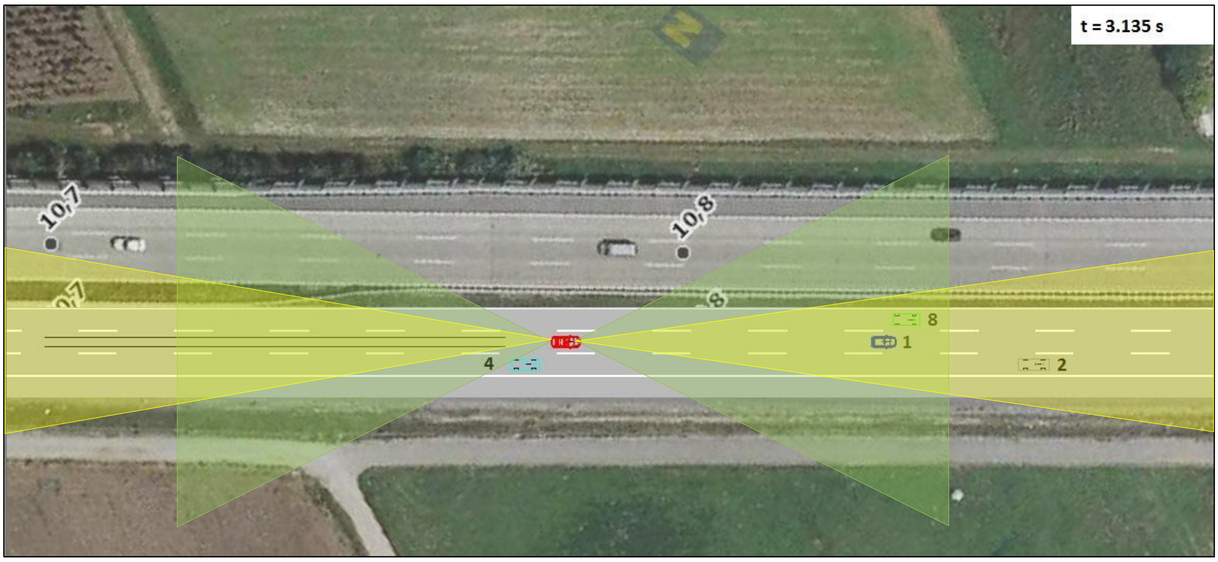


Figure 3-35: “AHDAS” Simulation: After deceleration manoeuver and time step when lane change to the left is started

Table 3-9: TTC- status of the cars in the sensor range at t= 3.135s

6		7	d= 48.9 m TTC= n.a. v= 120 km/h	8
5		EGO v = 66.3 km/h	d= 45.6 m TTC= n.a. v= 70 km/h	1
4	d= 1.9 m TTC = 0.1 sec v= 120 km/h	3	d= 68.6 m TTC= n.a. v= 120 km/h	2

After 3.135 seconds (Figure 3-35) the "Space check" (Table 3-9) results a TTC classification of Space 1, 2 and 8 as "green" and a classification of Space 4 as "red", which means a lane change manoeuver is started again. The car in Space 4 does a forbidden overtaking manoeuver to the right and presents no danger for the Ego-car.

Figure 3-36: "AHDAS" Simulation: After finishing the lane change to the 3rd lane and start of the acceleration process to the target speed

After finishing the lane change manoeuver (Figure 3-36) the target speed is set again.

- Braking manoeuver of the car ahead due to traffic jam/congestion

In the third scenario (Figure 3-37 and Table 3-10), a breaking manoeuver of the slow driving car ahead is simulated, the way it could possibly happen at the end of a traffic jam or congestion, which is not recognised by the car in Space 1. Furthermore, the car ahead is closer than the safety distance.
The same starting situation as in the other scenarios before is set here.

This scenario is not applicable for this real accident because in this case there would be tyre marks on the road and probably a hint in the statements of the drivers but this scenario shows how the autonomous car would have reacted if a traffic jam or congestion takes place.

Figure 3-37: “AHDAS” Simulation: car in Space 1 closer than safety distance; other cars start breaking manoeuver because of a traffic jam or congestion ahead

Table 3-10: TTC- status of the cars in the sensor range at t= 0s

6 d= 55.6 m TTC= n.a. v= 120 km/h	7	8
5	EGO v = 130 km/h	d= 65.8 m TTC= 3.9 sec v= 70 km/h 1
4 d= 25.3 m TTC = n.a. v= 120 km/h	3 occupied	2

The Ego-car drives with 130 km/h the car ahead in Space 1 with 70 km/h and the lanes to the left and to the right are occupied. Thus the Spaces 1, 4 and 6 are classified as “orange” and Space 3 is occupied. Because of the position of the car in Space 1, which is closer than the safety distance a braking manoeuver is started. The braking manoeuver is set with 6.6m/s², as the same as in scenario 2 because the car ahead is not yet braking. At the same time the cars on the other lanes are already braking.

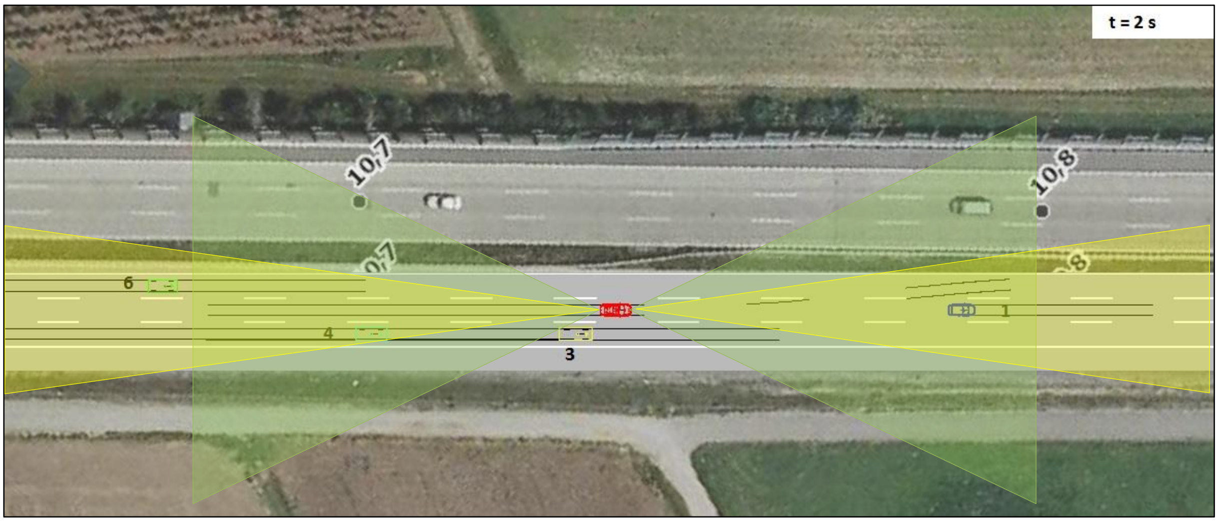


Figure 3-38: “AHDAS” Simulation: Car in Space 1 starts with a full brake manoeuver

Table 3-11: TTC- status of the cars in the sensor range at t= 2s

6	d= 61.3 m TTC= n.a. v= 70.7 km/h	7		8
5		EGO v = 82.3 km/h	d= 45.9 m TTC= 13.4 sec v= 70 km/h	1
4	d= 1.2 m TTC = n.a. v= 70.6 km/h	3 occupied		2

After 2 seconds (Figure 3-38 and Table 3-11) the car ahead in Space 1 starts with a deceleration manoeuver of 6.87m/s². Thus the emergency procedure is started. The situation in this time step: Space 1 and Space 6 with a classification of “green”, Space 4 classified as “orange” and Space 3 is occupied. Because of Space 6 being marked “green” and no further car on the left side an evasion manoeuver to the left side is started. The “AHDAS” always starts an evasion if there is enough space otherwise a full brake manoeuver is set.

After finishing the manoeuver, all cars are stopped and the simulation is quit.

Figure 3-39: “AHDAS” Simulation: After finishing the evasion manoeuver to the left

Due to a lack of information about other road users on the same road section, different scenarios are simulated. The first scenario is the following: If the slow driving car ahead is outside the sensor range the Ego-car starts a deceleration manoeuver at the beginning when the car ahead is detected. After the deceleration, there is enough space to start an overtaking manoeuver and no accident will occur.

If the car ahead is closer than the safety distance the Ego-car decelerates and starts an overtaking process afterwards. The only difference is that the deceleration rate is higher.

To show the emergency procedures of the “AHDAS” programme a deceleration sequence of the car ahead after two seconds is implemented. A traffic jam or congestion ahead is the assumption. This is why the “AHDAS” programme is able to start a braking manoeuver and to evade the braking car ahead to the left.

Compared to the real accident where lack of attention was the presumed cause, the autonomous car is always working with the same degree of attention. This means this type of accident is preventable by an autonomous car.

4 LIMITATIONS

Relevant limitations occur, based on the developed autonomous driving assistant:

- the assistant is used on a straight road section where no bends are implemented
- no acceleration or deceleration lanes are implemented
- no construction sites
- no wrong way drivers can be handled in properly, a collision would be the consequence
- no pedestrians, bicyclists or other forbidden road users on a highway which are not stopped or don't move in driving direction
- no ethical issues are implemented
- the Ego-car moves to the positive x-direction in a cartesian coordinate system
- the middle of the first lane is at the zero point of coordinate system
- no acceleration while an overtaking manoeuver
- for the emergency steer-brake manoeuver, the steering trajectory is calculated at the beginning with its initial speed. Changes in velocity and the resulting change of the trajectory are not taken into account.

By simulating real road accidents an uncertainty remains because of the unknown position and movement of other road users.

As seen in the described overtaking manoeuver in chapter 3.1 the car is able to handle this situation without any problems. According to lane change manoeuvers there are often inaccuracies concerning the steering ratio, which influence the trajectory a lot. Thus the car reaches sometimes not the exact position which is calculated.
Furthermore in chapter 2.6.2 by handling small offset smaller steering ratios are necessary to handle the situation in a feasible way. To eliminate this uncertainty a better solution, for example another possibility to calculate the trajectory, is feasible.

Another limitation is, if Space 7 is occupied and there is a car driving faster in Space 1 than in Space7 than the algorithm allows the Ego-car to overtake on the right side and follows the car in Space 1.

A limitation concerning an "acceleration manoeuver" is that the acceleration rate is not adapted to a certain engine characteristics and is chosen with a fixed value for the whole velocity range.

To show a limitation of the chosen environment observation strategy the following example is described:

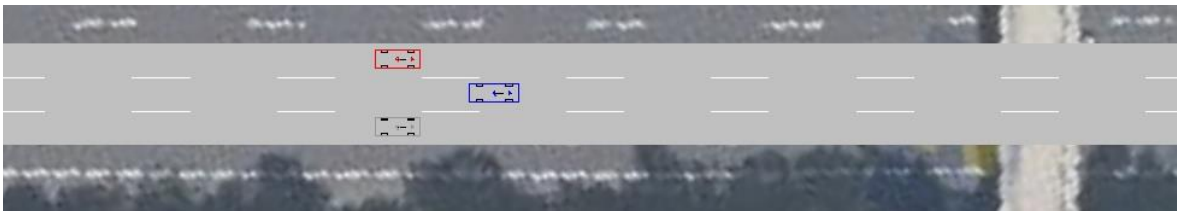


Figure 4-1: Ego-car (red) finishing an overtaking manoeuver on the 3rd lane (t =0s)

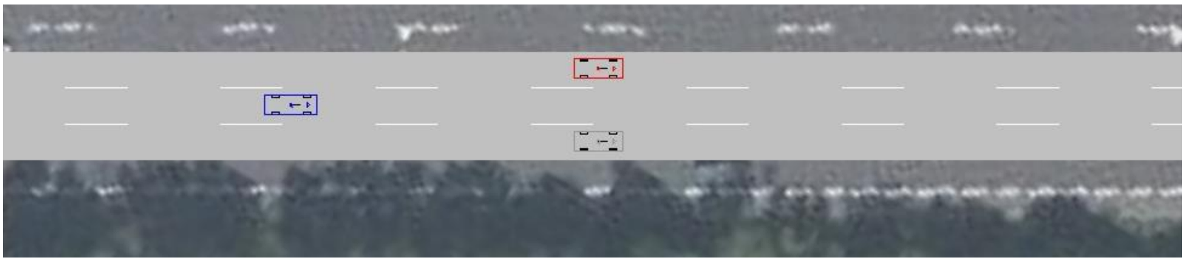


Figure 4-2: Ego-car driving on 3rd lane parallel to the car on the first lane (t=3,572s)

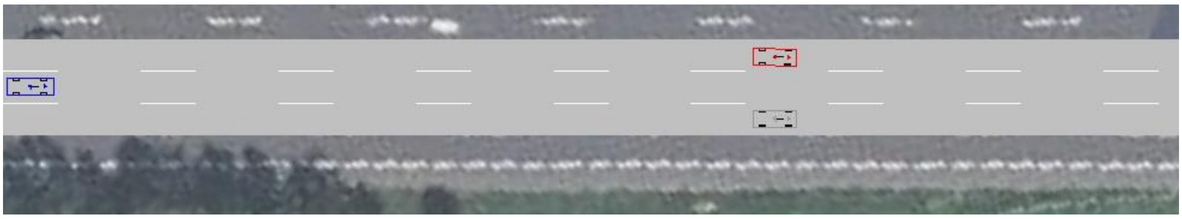


Figure 4-3: Ego-car starts to drive back on the middle lane to finish the overtaking manoeuver (t=8,216s)

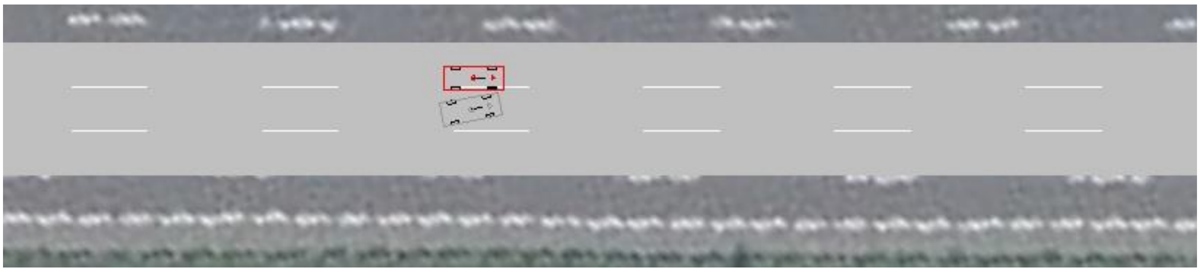


Figure 4-4: Lateral collision because of a lane change of both cars at the same time (t=12s)

The Ego-car drives with 130km/h on the third lane for example after an overtaking process seen in Figure 4-1. After reaching the safety distance to the car in the back (Space 4 with 100 km/h) the Ego-car wants to drive to the middle lane which can be seen in Figure 4-2. At the same time another car driving parallel on the first lane wants to overtake a vehicle ahead on the first lane as shown in Figure 4-3. Thus both vehicles start a lane change manoeuver to the middle lane. Accordingly there is no space observation or classification of the Ego-car two lanes away. Consequently the Ego-car does not “see” the two cars on the first lane. There is also no reaction implemented in the strategy if there is a car moving to the Space 3 with a relative velocity. All in all a lateral collision is the consequence without any reaction of the autonomous Ego-car which is shown in Figure 4-4.

As seen there is a lack of observation in the used model. There is an option to extend the model of the 8 spaces around the Ego-car, which makes some situations easier to handle as there is more detailed information about the environment of the car. Thus, situations like the lane change process of two cars to the same lane could be handled. Evidently, this extension is limited to the range and detection of the implemented sensors.

5 CONCLUSION

In this master thesis, an autonomous driving assistant is created which makes it possible to handle standard or emergency situations on highways. It can be seen that the driving assistant works well under the set boundary conditions and the set requirements.

This model makes it possible to analyse whether a traffic accident would also occur if the car drives autonomously. The driving assistant is designed to act according to the Austrian road traffic regulations and to drive as comfortably and fast as possible. The user can set the following four parameters speed limit, lane width, number of lanes or if there is a breakdown lane or not. All other parameters are chosen automatically.

The relevant situations on highways like acceleration, deceleration or overtaking manoeuvers are solved by using decision trees. To be able to find the right decisions a feasible environment observation is crucial. Therefore the environment is spread up into 8 spaces which are classified with the information of the time to collision.

Furthermore critical situations are detected at the beginning or due to an continuous environment observation also during a driving manoeuver. The critical situations are also handled with decision trees. Nevertheless, the autonomous driving assistant is able to handle slow moving or not moving “objects” which can be added with an object number into the simulation of “PC Crash”. Of course, there is no possibility to divide the obstacles into ones which can be overrun or not.

The changing amount of simulated vehicles is implemented in the decision trees by flexible integration. The autonomous driving assistant was tested on many scenarios, which are described in an overtaking manoeuver and a critical situation where a brake and evasion manoeuver is necessary.
Moreover a real road accident is evaluated and it can be seen that the autonomous car is able to handle the critical situation without any accident as a result.

Generally regarded on the topic autonomous driving the technical possibilities are further developed than the relevant laws. As a result, to implement autonomous driving on the public roads an adaption is necessary. Thus the “Vienna agreement” and the road traffic regulations have to be adapted also concerning vehicle registration or in questions of liability. [1]

6 OUTLOOK

Related to this implemented autonomous highway driving assistant, there is the possibility to implement improvements to also handle conditions that are more complex.
Some ideas on how the assistant can be improved and extended are:

First of all there is the possibility to adapt the driving assistance system to be able to drive bends. The current assistance system works only on straight road sections. Therefore the lane change trajectory has to be adapted to a given bend which leads to an increasing complexity of the calculation of the trajectory. As a result it should be possible to handle “PC Crash” files which are not oriented to the positive x-direction of the Cartesian coordinate system.

Furthermore to improve the behaviour of the autonomous Ego-car and make its behaviour more fluid the trajectory should be adapted to the acceleration. This adaption makes it possible to interact more actively with the other road traffic. Thus, it makes it possible to accelerate into a gap to overtake a vehicle ahead. On the other hand if there is the requirement to quit an overtaking process and the Ego-car has to drive back to the initial lane, the ideal trajectory with a deceleration part could be implemented.

To implement construction sites into the driving assistance model, is another possibility to improve the basic assistance system. For this purpose adequate detection possibilities have to be implemented and the model has to be adapted to handle those special situations (variable speed limits or small lane widths). In general the number of lanes in a road section should be flexible and as a result a narrowing of 3 to 2 lanes should be handled. Another extension concerning road infrastructure are acceleration or deceleration lanes which are also found on highways and which should be implemented.
Concerning the road conditions there are only ideal standard values of dry roads implemented. For this, the velocity of the cars and the lateral acceleration rates have to be adapted to all possible road conditions. For example, another safety distance for snow or icy conditions has to be chosen.

Also inclinations, which has on the one hand an influence on acceleration and deceleration rates should be implemented. On the other hand, they influence the route plan and probably the environmental factor of fuel saving or in the future on the capacity of a battery as well.

The implementation of an obstacle detection, which is already not properly realised in the “AHDAS” tool, can be implemented. For this purpose the detection of obstacles on the road and to classify them as overrun able or not overrun able is a big challenge. A visual object recognition could be feasible to compare the obstacle on the road with a database for example.

Another situation, which could occur on a highway, is a human driver who drives in the wrong direction, which is not implemented in the “AHDAS”. For this situation an algorithm has to be developed to be able to prevent an accident. To classify other possible road users on the highway like bicyclists, pedestrians or game is a part which has to be implemented in a high developed autonomous highway assistant

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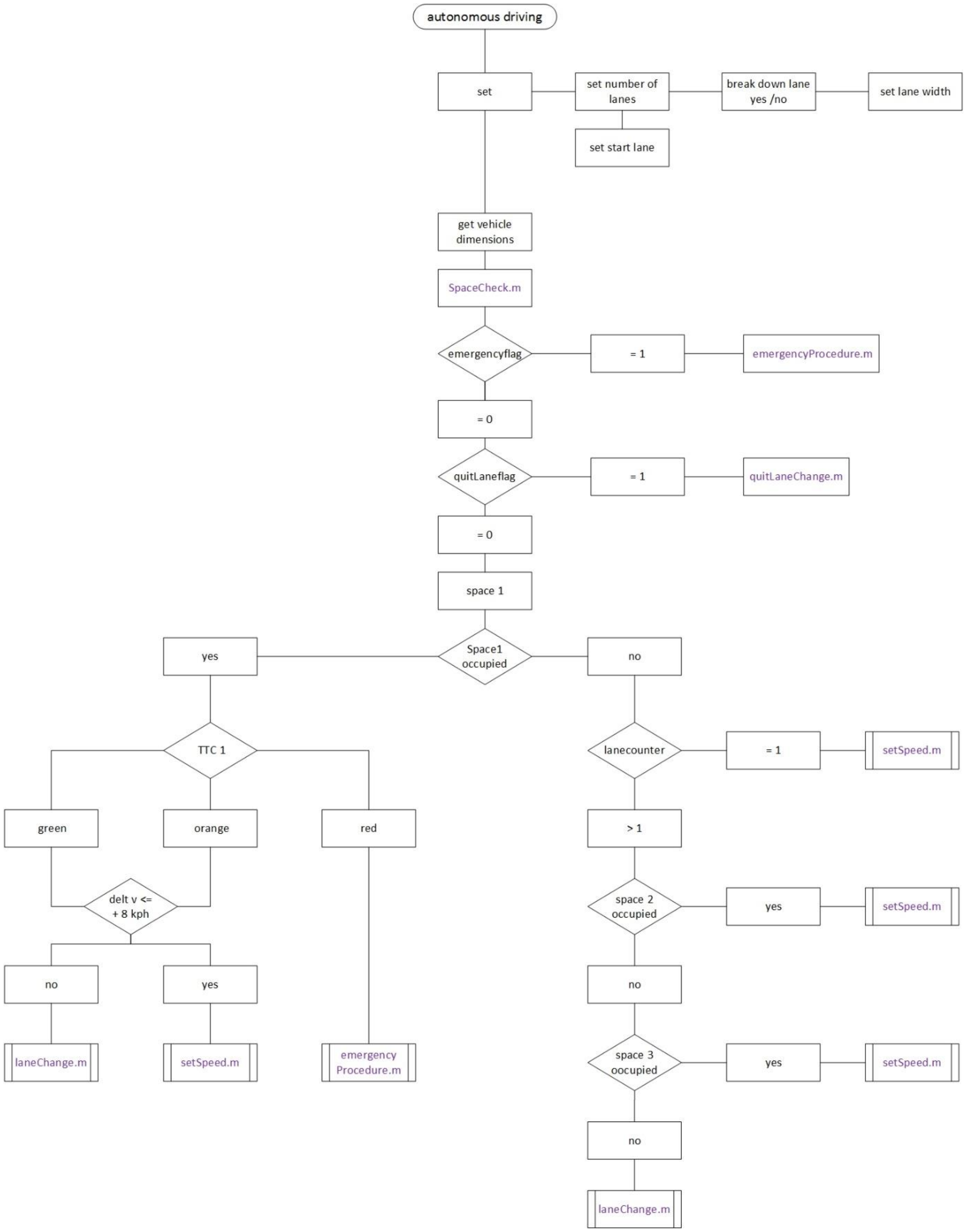
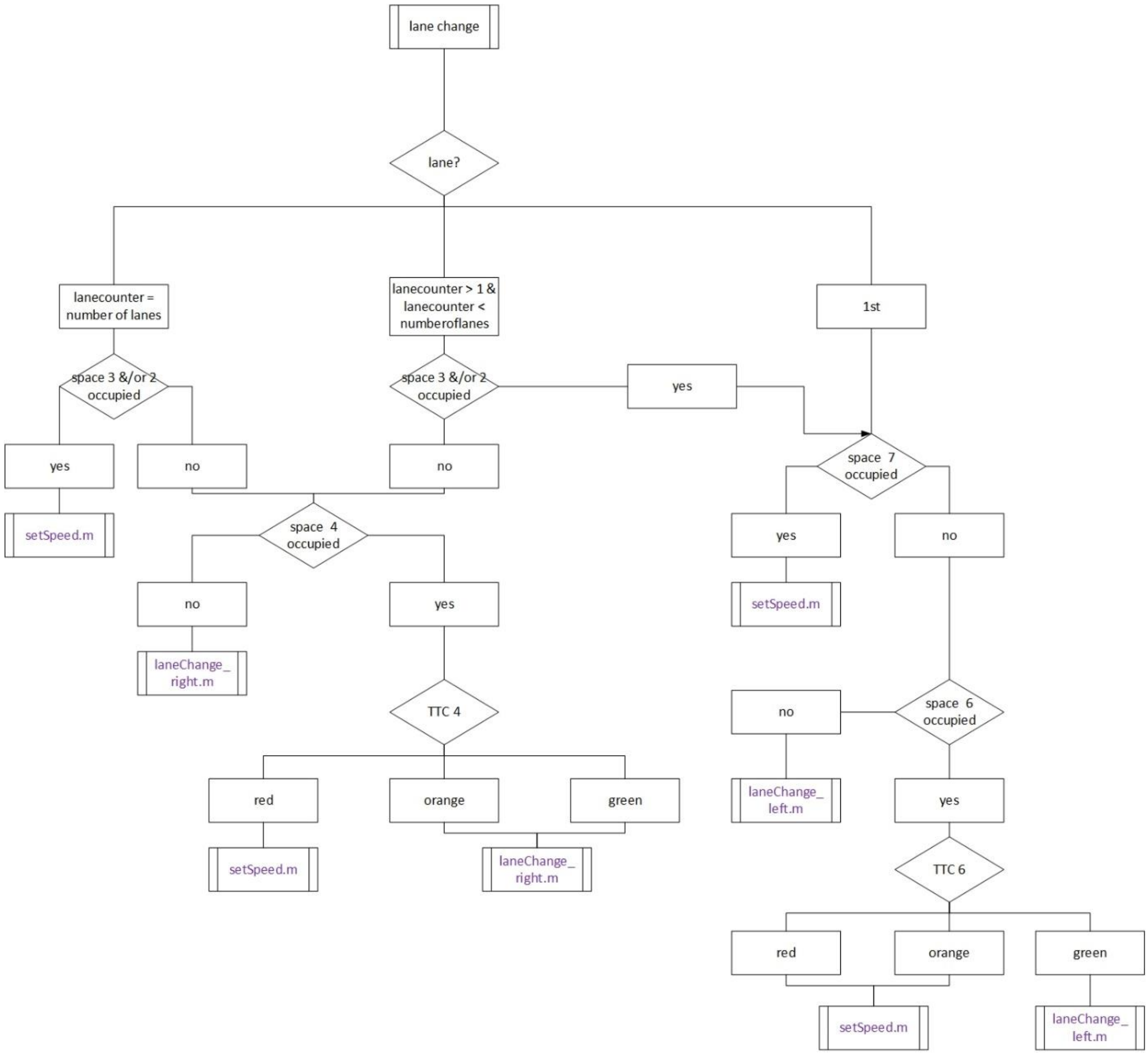
8 APPENDIX

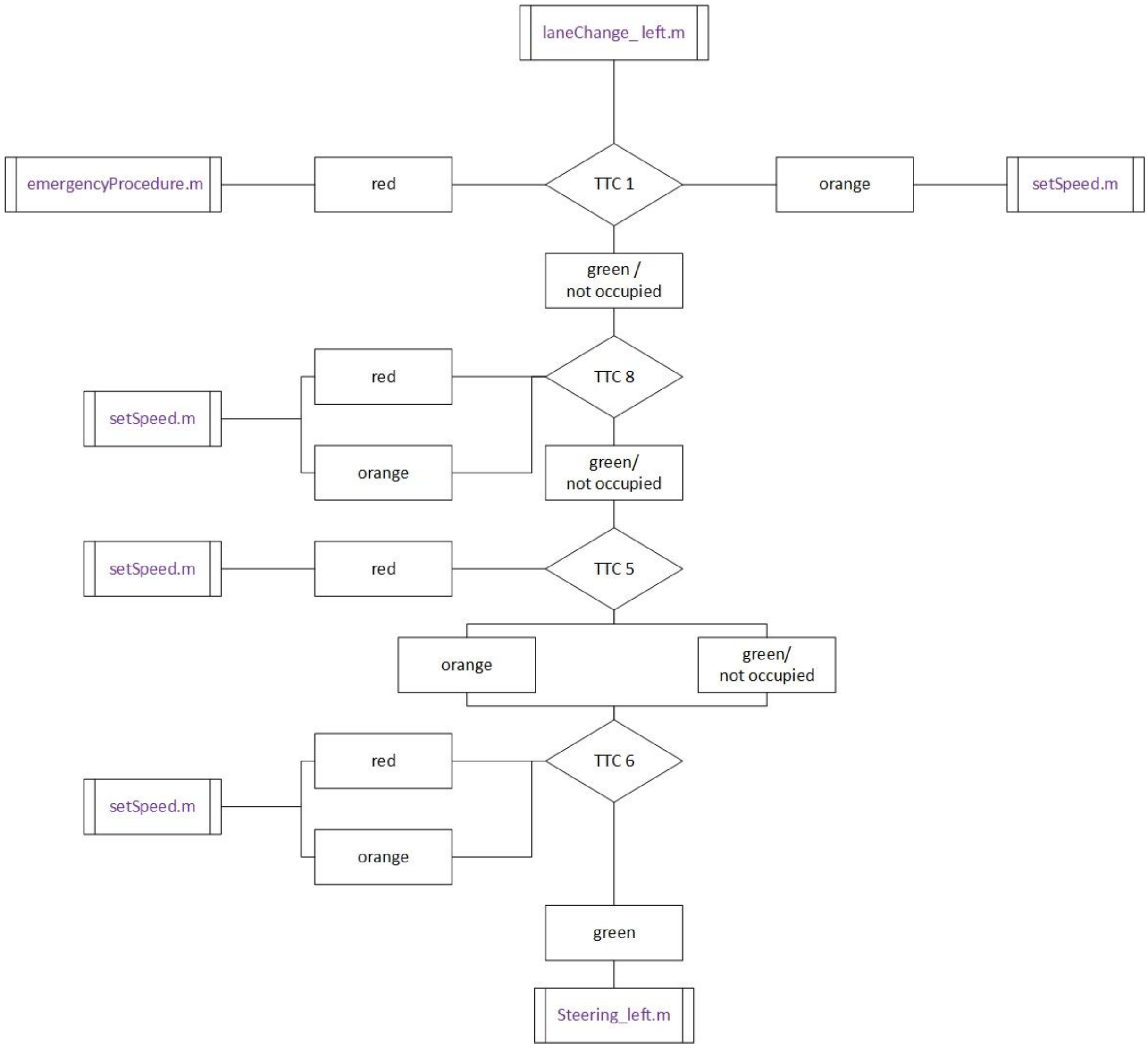
8.1 “AHDAS“



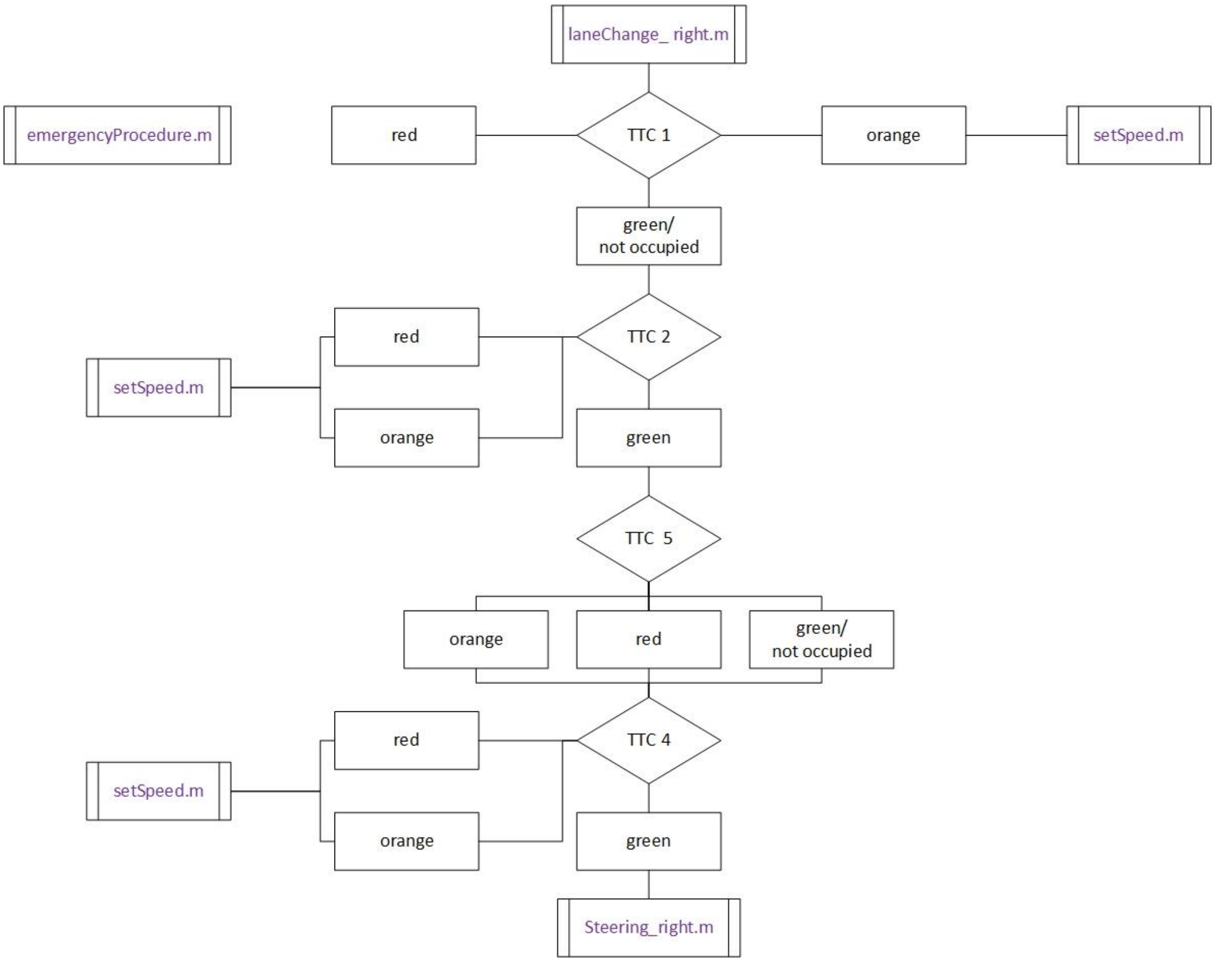
8.2 Lane change



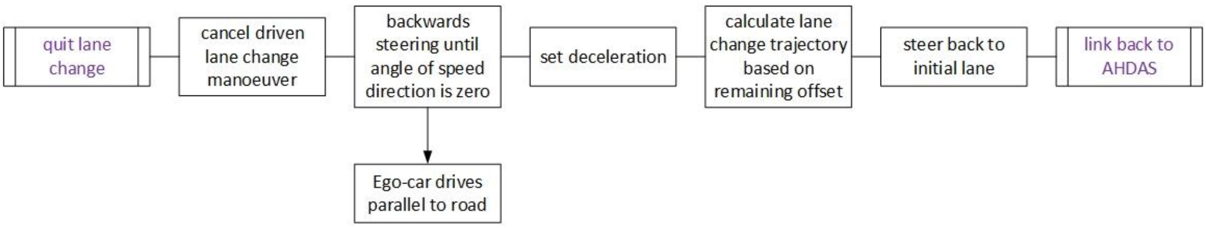
8.2.1 Lane change left



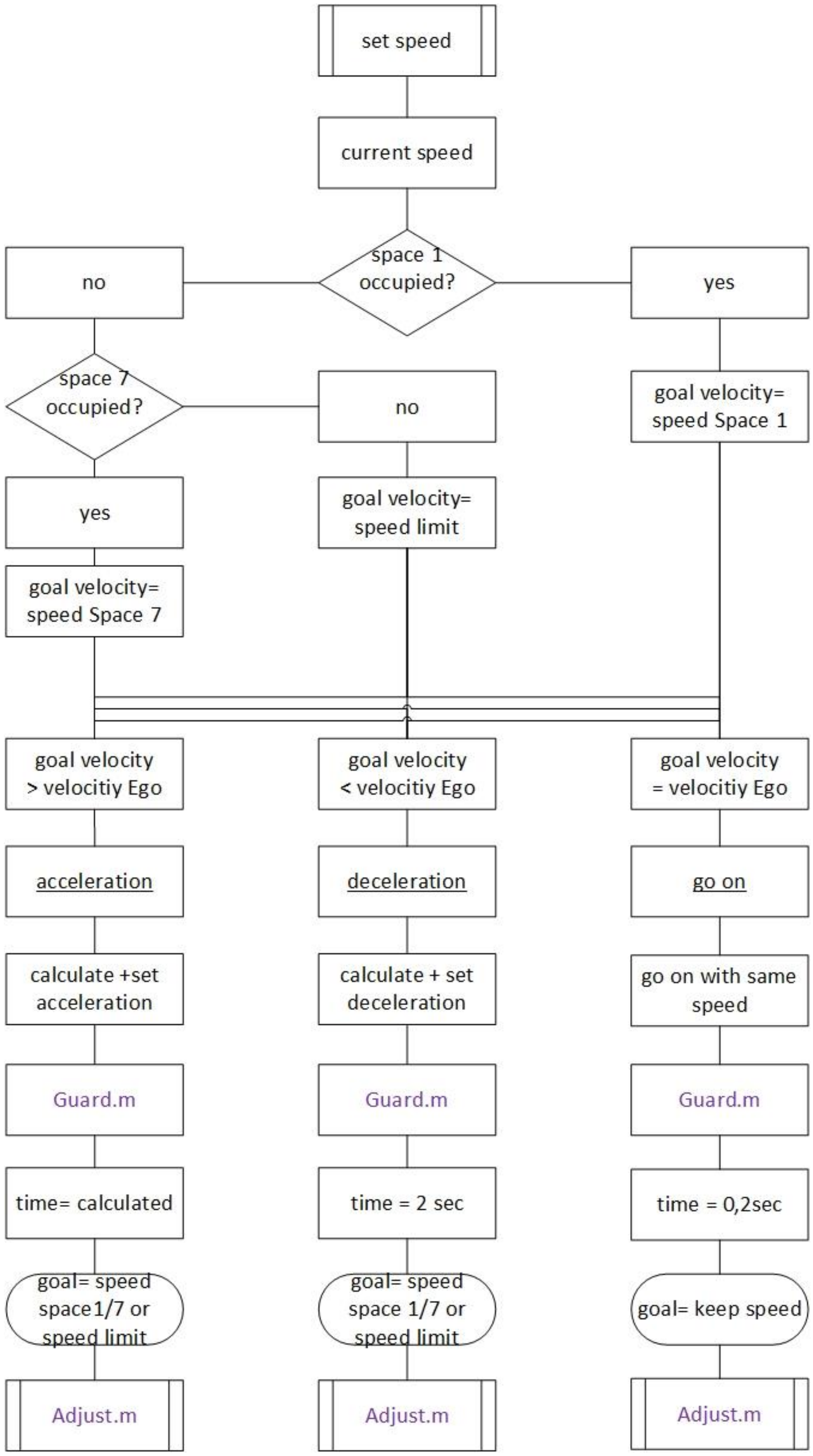
8.2.2 Lane change right



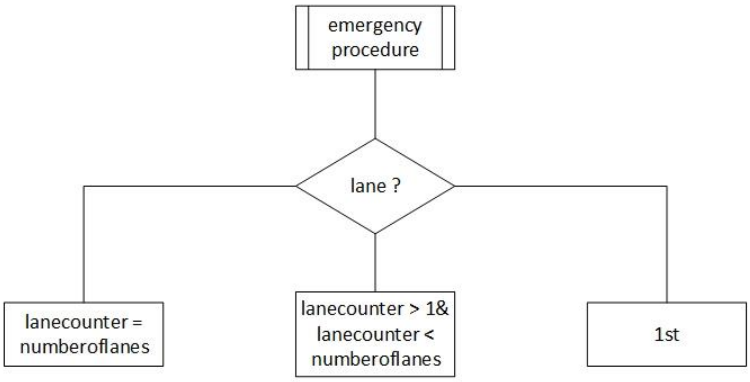
8.2.3 Quit lane change



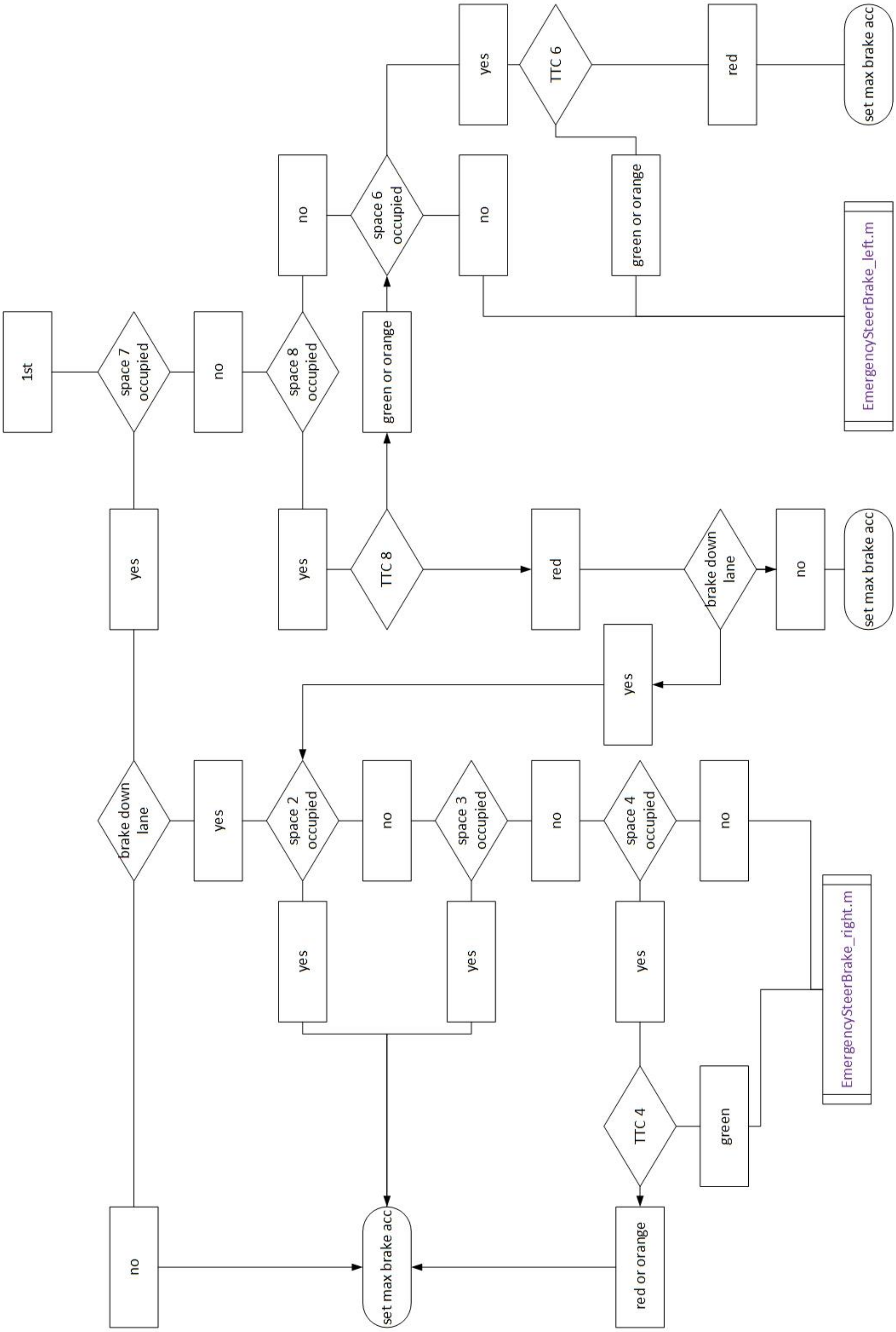
8.3 Set Speed


set speed
current speed
space 1 occupied?
no
yes
space 7 occupied?
no
goal velocity= speed Space 1
yes
goal velocity= speed limit
goal velocity= speed Space 7
goal velocity > velocitiy Ego
goal velocity < velocitiy Ego
goal velocity = velocitiy Ego
acceleration
deceleration
go on
calculate +set acceleration
calculate + set deceleration
go on with same speed
Guard.m
Guard.m
Guard.m
time= calculated
time = 2 sec
time = 0,2sec
goal= speed space1/7 or speed limit
goal= speed space 1/7 or speed limit
goal= keep speed
Adjust.m
Adjust.m
Adjust.m

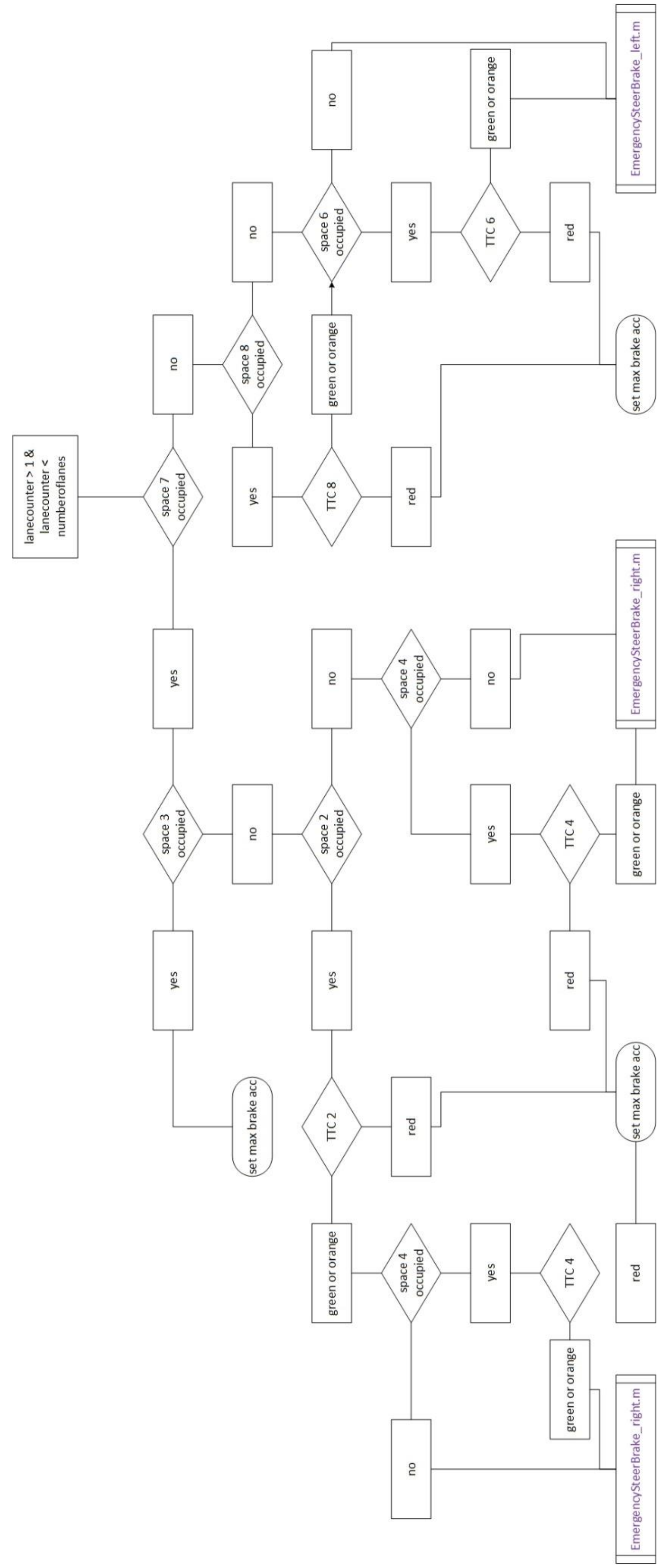
8.4 Emergency procedure



8.4.1 Emergency procedure- Right lane



8.4.2 Emergency procedure- Middle lane



8.4.3 Emergency procedure- Left lane