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Adjacent Lane Collision Warning System for Truck with Trailer in a Simulated Environment

Model-based development of a warning system in a simulated environment using threat assessment

Master's thesis in Systems, Control and Mechatronics

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Gothenburg, Sweden 2019

Master's thesis 2019:NN

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Cover: Scenario created using IPG TruckMaker showing a collision scenario between trailer and adjacent vehicle.

Typeset in LaTeX
Gothenburg, Sweden 2019

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Abstract

The car industry has seen increased demands for Advances Driver Assistance Systems (ADAS) to improve safety of for the own vehicle and for vulnerable road users (VRUs) such as pedestrians and bicyclists. ADAS is makings its way into the truck industry as well, and these systems are needed since accidents with trucks often lead to serious injuries or casualties [1]. Auto emergency brake system and lane keeping assist already exist for trucks but are mostly used to avoid rear end collisions or when a pedestrian walks out in front of the truck. However for trucks some accidents occur from collision with the trailer. When a tractor-trailer combination is driving through sharp turns the trailers wheels and body moves differently than the tractor itself, giving it a different orientation. Hence even though the tractor is kept in the ego lane, and is in no danger of collision, the trailer can potentially collide with an adjacent car. Through vehicle position prediction using the bicycle model and knowledge of the road ahead, threat assessment can be performed to evaluate risk of collision with adjacent vehicles. Actions such as braking and warning the driver are evaluated using threat assessment, and all of the implemented solutions are tested in a simulated environment. The results shows potential for real world implementation of such an active safety system in a truck that can avoid or minimise the damage between tractor-trailer and other road users.

Keywords: Articulated vehicle, tractor, trailer, Advanced Driver Assistance system, truck, vulnerable road users, active safety, vehicle motion modelling, adjacent vehicle, collision avoidance, Truckmaker.

Acknowledgements

First we would like to thank our supervisors Andreas Andersson and Karin Brötjefors at Aptiv. Andreas Andersson had insight on the topic and helped us find a task to work on. Without his support and knowledge this thesis would never have been made possible. They have both provided continuous help with discussing the subject, implementation and writing throughout the entire process.

We would also like to thank our examiner Jonas Fredriksson at Chalmers Tekniska Högskola. His expertise has provided us with insight that has helped us make difficult decisions and made this an overall better thesis.

Lastly we would like to thank IPG automotive for providing us with a license for their simulation software TruckMaker. TruckMaker has enabled us to carry out all of our testing, implementations and evaluation in an easy and controlled environment.

Jonas Lundberg, Gothenburg, June 2019
Henrik Eriksson, Gothenburg, June 2019

Contents

List of Figures

Abbreviations and wordings
Abbrevations:
GPS - Global Position System
Hitch(-point) - Connection(-point) between tractor and trailer.
ALCWS - Adjacent Lane Collision Warning System
EBV - Emergency Brake Value
LMP - Lane Margin Path
COG - Centre of Gravity

Wordings:
Truck - truck with an attached semi-trailer.
Tractor - pulling vehicle
Trailer - semi-trailer.

1
Introduction

This chapter will give an overview of this thesis, the subsections will introduce the problem and the scope of the thesis.

1.1 Background

Active safety systems have been around for several years now, for example on the US market Volvo XC60 started with its low speed collision avoidance system as a standard feature in 2010 [2]. All active safety systems are meant to avoid or reduce the severity of accidents when the driver is unable to do so. Because these system help drivers when they are incapable of handling current situation, a newer name is Advanced Driver Assistance Systems(ADAS). In later years, vehicle safety rating organization euro NCAP only give highest rating to cars with ADAS systems implemented. In year 2014 euro NCAP decided that cars will also be scored for their autonomous emergency brake system [3] and can only get the highest safety rating with this kind of system. Many car consumers want to keep them and their families safe when driving, hence these consumers want and buy safe cars. This has caused ADAS development to thrive in the car industry.

Before decision making actions from some ADAS is used, such as AEB, Threat Assessment (TA) is typically performed, see e.g. [15]. For vehicles, TA can be described as surroundings are monitored and analysis for potential threats of the current situation is repeatedly done. From the TA, decisions are made whether to intervene or not, an intervention could be braking, steering or warning. An example of decision making from the TA could be when driving and a pedestrian suddenly walks out in front of the vehicle. The vehicle should warn the driver when the pedestrian is potentially still sufficiently far away so that the driver should be able to react to it and if the pedestrian is to close to the vehicle the vehicle should automatically brake. It there are other vehicles behind the vehicle, braking too hard too early may cause other kind of accidents. This is the kind of problems the TA should analyze. TA can be seen as a decision algorithm that uses traffic situations as input data and outputs warnings or actions.

Cars are not alone on the roads, heavy vehicles such as trucks are also common. Due to the nature of trucks being heavier and bigger, accidents involving trucks more frequently lead to fatal or severe injuries. In Sweden around 50-60 % of all casualties from truck accidents [1] are head on collisions when cars are trying to pass the longer vehicle. Other common accidents are when trucks are driving through sharp turns and the trailers wheels move differently than the tractor wheels, this trailer offset can then collide or squeeze adjacent traffic participants. Most truck drivers should be able to solve these situations but many traffic accidents occur due to driver distractions as seen in [17], yielding the need for an ADAS system.

This thesis will present the design of an ADAS system for a tractor with semi-trailer negotiating sharp curves. The active safety system will be called Adjacent Lane Collision Warning System (ALCWS) throughout the thesis. To develop ALCWS, first a model of the tractor and trailer position will be created. Nearby traffic will also be modelled and future states will be predicted. For each time step, the simulation runs a threat assessment algorithm which will evaluate the collision risk from the predicted states. If threat level reaches a certain limit, actions will be taken to prevent a collision. These actions will be implemented first as a signal to warn the driver and after that create a closed loop system and a brake controller to prevent the collision.

1.2 Aim and objectives

The aim is to develop and implement ALCWS that warns the driver when the truck is on a path to collide with the adjacent traffic. If the truck driver does not take action when warned, the ALCWS should apply full brake to minimize severity of the collision. The objective is that the final implemented system should be able to accurately predict the movement of the traffic, tractor and semi-trailer based on the future road curvature. From these predictions perform a TA to determine if the predicted paths will intersect with traffic in the adjacent lane and take appropriate action. The TA should give a warning before the crash and give a brake request to apply full brake if the crash is unavoidable.

1.3 Scope

The scope of the project is limited to two situations when accidents related to cutting corners occur. The first situation is that the trailer will in some cases cut into the adjacent lane, this can occur at two lane roundabouts or at speed reducing chicanes during roadworks. The second situation is when a truck takes a right turn, the tractor has to drive into the adjacent lane to clear the right corner with the trailer. The truck will then occupy both lanes and need to be aware of road users next to it before occupying both lanes. Longer trucks has to do this to avoid cutting the corner with the trailer and hitting e.g a traffic light pole. The situations are visulized in in Fig. 1.1 and Fig. 1.2.

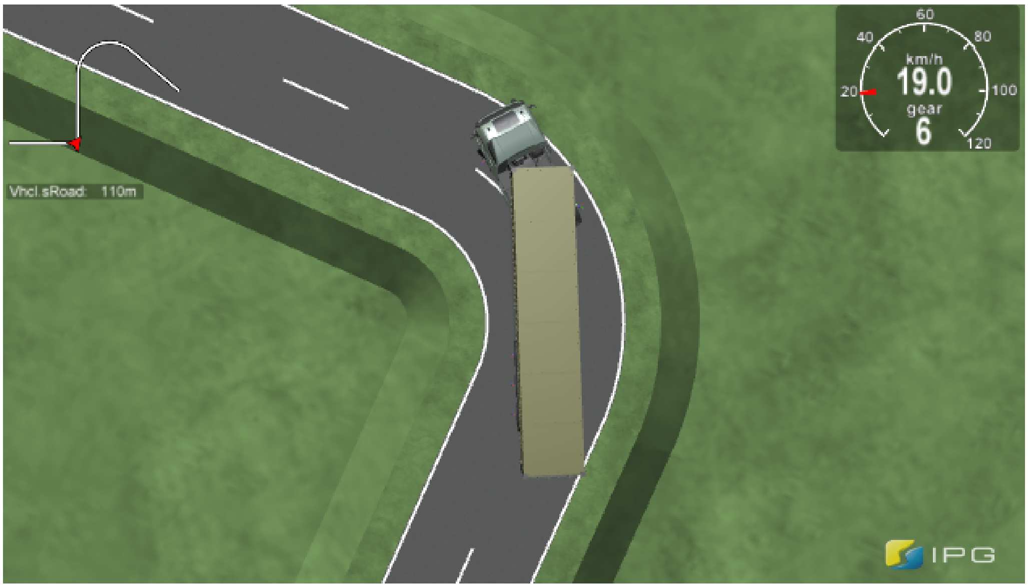

Figure 1.1: Screenshot from TruckMaker giving a visual description of how the trailer can cut the adjacent lane and potentially collide with adjacent traffic

Figure 1.2: Screenshot from TruckMaker giving a visual description for the second problem, where the truck has to enter and even cover the adjacent lane for the trailer to not cut into the corner.

The two cutting corner situations can be described using two test scenarios, a left turn and a right turn with various radii. The testing scenarios from the two corners are refined in the following list:

- Sharp left turn with collision. 90 degrees, 10 meter radius.
- Sharp right turn with collision. 90 degrees, 10 meter radius.
- Left turn without collision. 90 degrees, 45 meter radius.

All of these scenarios are used to test and verify the performance of ALCWS, where the first two will test how well it warns and brakes, while the last two will be for testing that no false warnings are given. Only one adjacent road user will be considered for the purpose of this thesis.

1.4 Limitations

Some limitations are used throughout the project to limit the scope:

- Sensors perform ideally, i.e no noise. Yields precisely known position of ego vehicle and adjacent road users.
- Performance on embedded hardware for real-time operation is not considered.
- Only a truck and semi-trailer combination is considered.
- Only corners with exact radius through the corner are considered.
- Steering actions or other autonomous drive options will not be implemented, only braking action and warning.
- All vehicles are assumed to be squares, i.e rounding of corners are not considered.
- Only right-hand traffic is considered.

There exist computer vision algorithms to detect the road curvatures and radar solutions to scan for nearby cars. With these components, the developement and implementation of the ADAS for the scenarios mentioned in background would seem possible and the limitations mentioned above should not limit the possibility to implement the system in real trucks and hopefully it will save lives.

1.5 Benefits of having Adjacent Lane Collision Warning System

Benefits of having a working ALCWS are many with the biggest main motivator being that it would be life and injury saving. There is also environmental and financial savings to be made. Environmental because a crash cause broken vehicles, both the truck and adjacent ones. This is bad for the environment as new parts need to be created unnecessarily or whole cars/trailers may be scrapped and be shipped to the junkyard. Financial winnings are there for the car owner as the car will not be in the accident to begin with and there will not be any hassle with insurances.

Trucks are usually driven for logistic companies and disruptions to the usage of the trucks are directly missed income as there may not be spare trucks to use and the driver may need days off e.t.c. It is also beneficial on a bigger level then the two vehicles involved, when accident happen on heavily traffic roads big queues can build up which is both bad for environment and cost money for everyone. Also emergency services personnel will be occupied with the crash instead of taking care of other things.

1.6 Outline of the thesis

The vehicle models used for estimating future positions will be detailed in chapter 2. It includes the kinematics of a tractor trailer combination, the velocity model and a braking model.

In chapter 3, theoretical preliminaries, the equations and more technical calculations will be described. This chapter serves to provide a greater understanding of the implemented functions in the following chapters.

Chapter 4, Adjacent Lane Collision Warning System (ACLWS), contains all the implemented functions and how they will be used together to create ALCWS. It starts off with a brief introduction to the softwares used for simulation and modelling as well as the test scenarios in which it all is evaluated. After the introduction a more detailed description of how the vehicle models are used to predict future positions, how collisions are detected and how threat assessment is made based on these predictions.

The results will be presented in chapter 5 showing the performance of the predictions as well as the system as a whole. The performance presented is position predictions accuracy, estimated time of impact in relation to actual time of impact, user warning signal activation, emergency braking and ALCWS.

Chapter 6 contains the conclusions drawn based upon the final results of the thesis.

The discussions chapter 7 discusses limitations of the project and potential future implementations and uses of implemented functions and ALCWS as a whole.

2
Modelling

This chapter aims to describe modelling of both adjacent car and tractor as well as extending the tractor with a trailer. Last section in this chapter describes how stopping distance for a vehicle is modelled.

2.1 Vehicle dynamics modelling

The vehicle dynamics modelling can range from very complex 3-D models taking tyre flexing during braking and accelerating into account, down to simpler models where the vehicle is lumped into a single particle that moves freely in a plane. For the purposes of this project a commonly used vehicle model, called the bicycle model, [5] and [6], is used. The bicycle model sums the two front wheels together to a single wheel. For trucks the number of rear wheels can differ, no matter how many rear wheels there is, the bicycle model sums them together to one unique wheel at the centre of the axles, see Fig. 2.1.

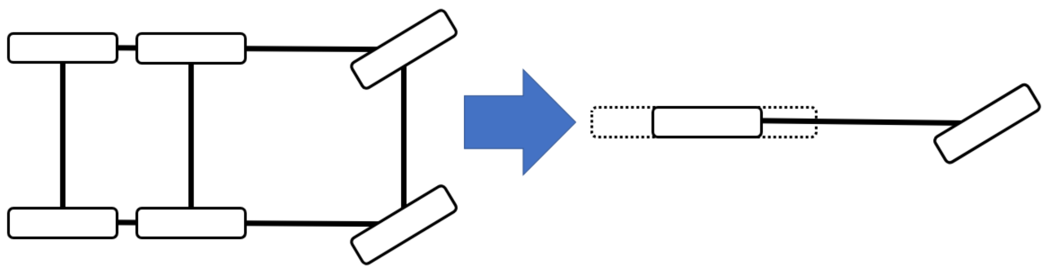

Figure 2.1: Explanatory figure of how the 6 wheeled tractor is summarized to two unique wheels.

The bicycle model can also have varying levels of complexity with friction coefficients, tire cornering stiffness [7] et.c., down to just be the speed in two directions and its angle. However, as only position and orientation dynamics is sought a rather simple model is used.

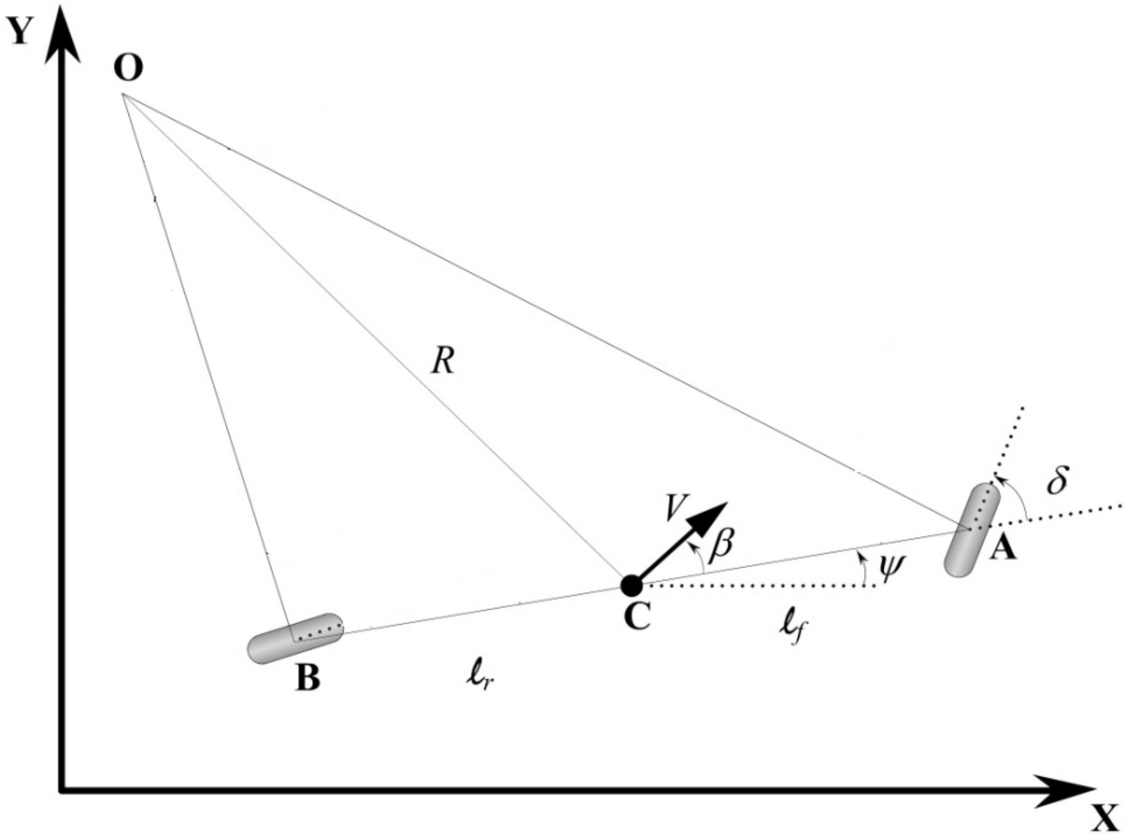

Figure 2.2: Visual description of the tractors bicycle model. Figure is edited from [6].

From Fig. 2.2, equations to describe the motion of the tractor can be derived:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\Psi} \end{bmatrix} = \begin{bmatrix} cos(\Psi + \beta) \\ sin(\Psi + \beta) \\ 1/R \end{bmatrix} V. \tag{2.1}$$

where x and y are the position of the centre of gravity (COG) in the X-Y plane, Ψ is the yaw angle, β is the side slip angle, R is the radius of the curve and V is the vehicle velocity. The radius R of the curve is assumed to be a known variable for this project. For real world scenarios this could be provided from sensor input. Ψ is known through continuous integration of $\dot{\Psi}$. Ψ in the current time step is also available through the output of TruckMaker. Side slip angle is the angle between the vehicle angle and the direction of movement. An example of when side slip angles occur is icy road turn when a car slides on the road sideways. Hence side slip can occur when the road friction coefficient is low, the velocity is high, when the turn is very sharp or a combination of the three. So even though the vehicle is pointing in the direction of the curve its direction of movement is a wider curve. Finding the slip angle β is done through estimation of the steering angle, δ from

$$\delta = \frac{L}{R}. \tag{2.2}$$

where L is the total length between axles of the vehicle or

$$L = l_f + l_r. \tag{2.3}$$

where l_r and l_f are the distance between rear/front axle and COG respectively. Finally yielding the equation of the side slip angle as:

$$\beta = arctan(\frac{l_r tan(\delta)}{L}) \tag{2.4}$$

Extending the model to include dynamics of the trailer adds an angle describing the angular displacement between the trailer and tractor, as visualised in Fig. 2.3.

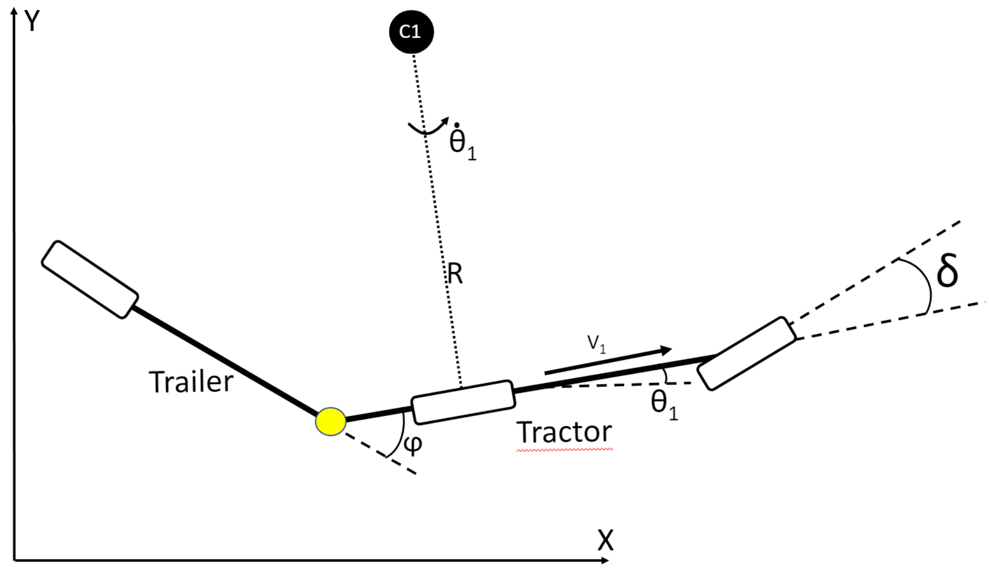

Figure 2.3: Extending the bicycle model with a trailer.

Since there is a limited amount of literature about side slip angle estimation for trailers, and the corners are driven through at low velocities, the side slip angle will be disregarded for the trailer. Using the geometry between the trailer-tractor combination we get the following equations of motion:

$$\dot{\varphi} = (\frac{b_2 + a_n cos(\varphi)}{b_2})(\dot{\Psi} - \frac{sin(\varphi)V}{b_2 + a_n cos(\varphi)}) \tag{2.5}$$

with a_n being the distance between the tractor rear wheel axle and the hitch point, and b_2 between the trailer wheel axle and the hitch point. The angle φ is derived from integration of $\dot{\varphi}$.

For estimating the distance travelled a constant velocity model is used [10]. It is a linear model where only the distance travelled is taken into account and velocity is assumed constant. Creating a state vector as $X(t) = [s \;\; v]$, with s as distance and v as current velocity, the state update equation can then be defined as

$$X(t + \Delta t) = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix} X(t). \tag{2.6}$$

2.2 Stopping distance for vehicles

When talking traffic safety, stopping distance is a common topic. Stopping distance, [13], is defined as:

$$\textit{stopping distance} = \textit{reaction distance} + \textit{brake distance} \tag{2.7}$$

where *reaction distance* is the driven distance it takes for the driver to hit the brake after seeing something on the road where braking is needed and *brake distance* is the distance it takes for the vehicle to come to a full stop after applying the brakes. Hence reaction distance is velocity dependent, whilst reaction time is constant. Reaction time averages, vary depending on source/study, see e.g. [13] and [14]. A common number between sources is that the 85th percentile driver, typically has a reaction time from 0.5 seconds to 1.5 seconds, this number varies also with age and the amount of distractions. This is purely reaction time, for evaluating traffic situation and then make a decision the reaction time would be slightly longer. Based on this, *reaction distance* can be defined as

$$\textit{reaction distance} = vt, \tag{2.8}$$

where v is the velocity in m/s and t is the reaction time. The *brake distance* can be calculated, using the model in [13], as:

$$\textit{brake distance} = 0.1v + \frac{v^2}{2a} \tag{2.9}$$

where a is the deceleration constant that can be found by taking gravity times the friction constant. The friction constant will depend on road conditions, different tyres et.c. The first term in (2.9) is to account for the fact that when pushing the brakes there is some delay before full deceleration is achieved, here assumed to be 0.1 s. Hence from these equations it can be found that the stopping distance is dependant on the velocity.

3
Theoretical Preliminaries

In this chapter a theoretical background is provided for chapter 4, where the system ALCWS is explained and implemented.

3.1 Cubic spline

Spline is a term used for many different kinds of data interpolation, the one used for this project is based on the Cubic spline model. This is a third order polynomial which can be used to describe a trajectory between two or more points. The polynomial for a cubic spline $S_i(x)$ on each sub-interval i is then on the form:

$$S_i(x)|_{x_i} = \frac{a_i(x-x_i)^3}{6} + \frac{b_i(x-x_i)^2}{2} + c_i(x-x_i) + d_i, \quad [x_i \leq x \leq x_{i+1}]. \tag{3.1}$$

For two points a single polynomial trajectory can be created, as illustrated in Fig. 3.1.

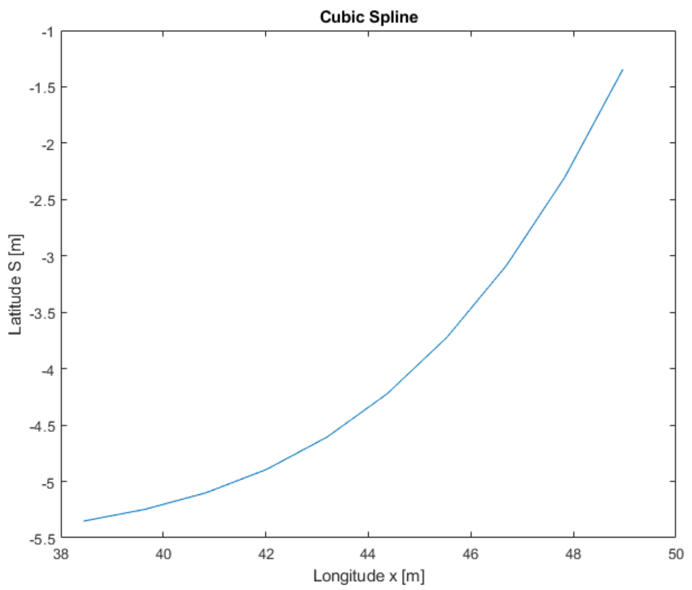

Figure 3.1: A spline derived from two points.

By using three or more points, piece-wise polynomials can be created where each interval is evaluated separately.

The spline is used to describe the lateral position along the road and x denotes the longitudinal position. Analyzing the first and second derivative of the spline gives information about the spline which can later be used to calculate curvature as explained in Section 3.2. Expressing this in equations gives:

$$\frac{dS_i(x)}{dx}|_{x_i} = \frac{a_i(x-x_i)^2}{2} + b_i(x-x_i) + c_i \tag{3.2}$$

$$\frac{d^2S_i(x)}{dx}|_{x_i} = a_i(x-x_i) + b_i \tag{3.3}$$

$$\frac{d^3S_i(x)}{dx}|_{x_i} = a_i \tag{3.4}$$

and by looking at the third derivative, we can see that the jerk is constant along an interval allowing for a smooth trajectory to a desired position, [11].

3.1.1 Radius and curvature from a spline function $\mathbf{S_i(x)}$

For a given function, the radius is known to be equivalent to the inverse of the curvature of the function [8]:

$$R \equiv \frac{1}{|\kappa|} \tag{3.5}$$

and the curvature is known as the change of the tangential angle ϕ over the arc length, [9]:

$$\kappa \equiv \lim_{\Delta s \to 0} \frac{\Delta\phi}{\Delta s} = \frac{\frac{\Delta\phi}{\Delta t}}{\frac{\Delta s}{\Delta t}} = \frac{\frac{\Delta\phi}{\Delta t}}{\sqrt{(\frac{\Delta x}{\Delta t})^2 + (\frac{\Delta y}{\Delta t})^2}} = \frac{\frac{\Delta\phi}{\Delta t}}{\sqrt{x'^2 + y'^2}} \tag{3.6}$$

By using the following relation:

$$tan(\phi) = \frac{\Delta y}{\Delta x} = \frac{\Delta y}{\Delta t}\frac{\Delta t}{\Delta x} = \frac{y'}{x'} \tag{3.7}$$

The numerator of (3.6) can be expressed as [9]:

$$\frac{\Delta\phi}{\Delta t} = \frac{x'y'' - y'x''}{x'^2 + y'^2} \tag{3.8}$$

Inserting (3.8) into (3.6) gives:

$$\kappa = \frac{x'y'' - y'x''}{(x'^2 + y'^2)^{\frac{3}{2}}} \tag{3.9}$$

For a two-dimensional curve as is the case with the spline functions the equation can be expressed as:

$$\kappa = \frac{\frac{d^2y}{dx^2}}{[1 + (\frac{dy}{dx})^2]^{\frac{3}{2}}} \tag{3.10}$$

Now that the curvature is calculated the radius can be found by inverting (3.10) as shown by the relationship in (3.5):

$$R = \frac{[1 + (\frac{dy}{dx})^2]^{\frac{3}{2}}}{\frac{d^2y}{dx^2}}. \tag{3.11}$$

For the splines explained previously, the $\frac{dy}{dx}$ is the same as equation (3.2) and $\frac{d^2y}{dx^2}$ as equation (3.3). This would give us the radius of a spline as:

$$R_{S_i(x)} = \frac{[1 + (\frac{dS_i(x)}{dx}|_{x_i})^2]^{\frac{3}{2}}}{\frac{d^2S_i(x)}{dx}|_{x_i}}. \tag{3.12}$$

3.2 Lateral acceleration from curvature

When doing sharp turns especially with vehicles that have high COG such as trucks, lateral acceleration is of interest. High lateral acceleration can cause the vehicle to skid, roll over or give discomfort for the driver. From classical mechanics, also known as centripetal force, a particle travelling at constant speed along a curve has an acceleration normal to its path, according to

$$lateral\ acceleration = v^2/R = v^2\kappa \tag{3.13}$$

with R being the road radius and κ being the curvature, as described in the previous subsection.

3.3 Creating boundary boxes for the tractor and trailer

A global coordinate system is used for tracking the tractor position and rotational angle. The positions is just a point positioned in the COG of the tractor, but by combining the point with the rotation angle a bounding box for the tractor can be found. By using transformation matrices the corner points of the truck can be found, and with these points edges can be created. The transformation matrix in 2-D is according to

$$T(a,b,\lambda) = \begin{bmatrix} cos(\lambda) & -sin(\lambda) & a \\ sin(\lambda) & cos(\lambda) & b \\ 0 & 0 & 1 \end{bmatrix}, \tag{3.14}$$

where λ is the rotation angle of tractor or trailer and a and b are the magnitudes of translation in x and y of the vehicle bodies COG. Looking at the schematic picture in Fig. 3.2, (X_c, Y_c) is the only given point, hence the rest of the points need to be calculated.

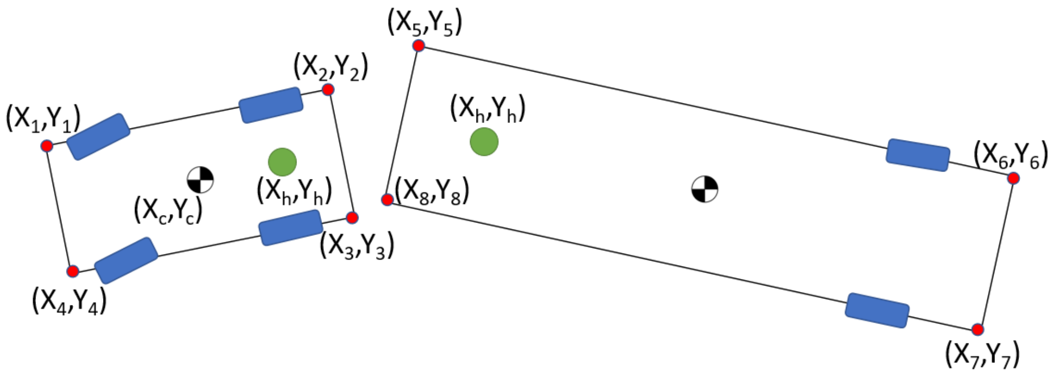

Figure 3.2: Schematic figure of the boundary boxes of the tractor and trailer. The checker patterned circle is the global coordinate, green circle is the hitch point and small red circles are corners.

For the tractor the corner points and hitch point can be found as

$$\begin{bmatrix} X_i \\ Y_i \end{bmatrix} = T(a_i, b_i, \lambda) \begin{bmatrix} X_c \\ Y_c \end{bmatrix}, \quad i = 1, .., 4. \tag{3.15}$$

The hitch point can be found through

$$\begin{bmatrix} X_h \\ Y_h \end{bmatrix} = T(a_h, b_h, \lambda) \begin{bmatrix} X_c \\ Y_c \end{bmatrix}. \tag{3.16}$$

Having access to the hitch point, corner points for the trailer will be calculated as

$$\begin{bmatrix} X_i \\ Y_i \end{bmatrix} = T(a_i, b_i, \lambda_t) \begin{bmatrix} X_h \\ Y_h \end{bmatrix}, \quad i = 5, .., 8. \tag{3.17}$$

Adjacent road users are given boundary boxes in the exact same way as the tractor boundary box is created using different a,b and λ in (3.14).

3.3.1 Determining if the trailer stays in ego-lane

By doing estimation of how the tractor will drive through a curve, the angle between tractor and trailer can be estimated using the bicycle model. Through iterative calculations at each time step it can be determined if the trailer overlaps with the adjacent lane. This overlap check, is done by making two lines, one along each side of the trailers long side, see Fig. 3.3.

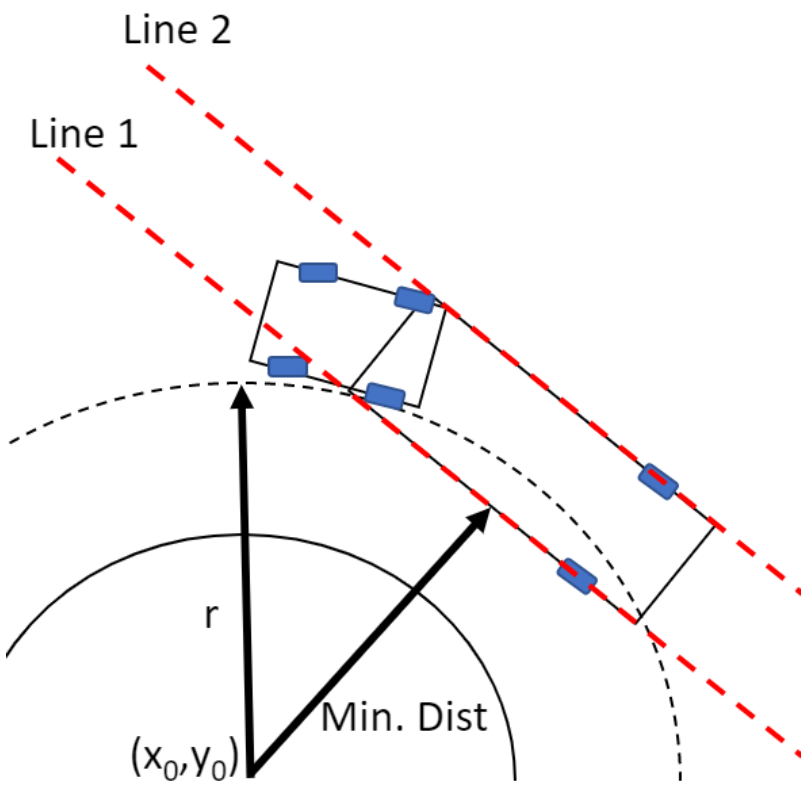

Figure 3.3: Figure describing the calculation to find the condition for if the trailer leaves its lane.

These lines are derived through knowing the position of each of the corners of the trailer and calculating the line that goes between these two points. Deriving these two lines gives the possibility to check the minimum distance to a point from the lines by using (3.18).

$$Minimum\ distance_i = \frac{|a_i x_0 + b_i y_0 + c_i|}{\sqrt{a_i^2 + b_i^2}} \quad i = 1, 2 \tag{3.18}$$

where x_0 and y_0 are the coordinates that the minimum distance is calculated from. By selecting these coordinates as the centre of the circle representing the corner, the condition to see if the trailer leaves its lane is

$$Minimum\ distance_i < r \quad i = 1, 2 \tag{3.19}$$

where i is each of the lines for the trailer and r_i the radius for each side of the trailer. This condition is straight forward and if this condition is not fulfilled the trailer is estimated to stay inside its lane and no actions should be taken.

4
Adjacent Lane Collision Warning System

This project is using Matlab/Simulink for algorithms and data analysis. ALCWS gathers data from TruckMaker and sends input back to TruckMaker for warning and brake requests. In each time step a path prediction of the trailer and the surrounding vehicles is generated. From this path and from known velocities the future position of the vehicles is calculated. Threat assessment is made based on these calculations. If the truck enter a curve when an adjacent car is close, with a possibility of collision, the threat assessment should trigger an output that there is a high risk of collision. Once this has been done an action will be implemented to give a brake request when collision is unavoidable to minimize damage. The test system together with the implementation is described by Fig. 4.1.

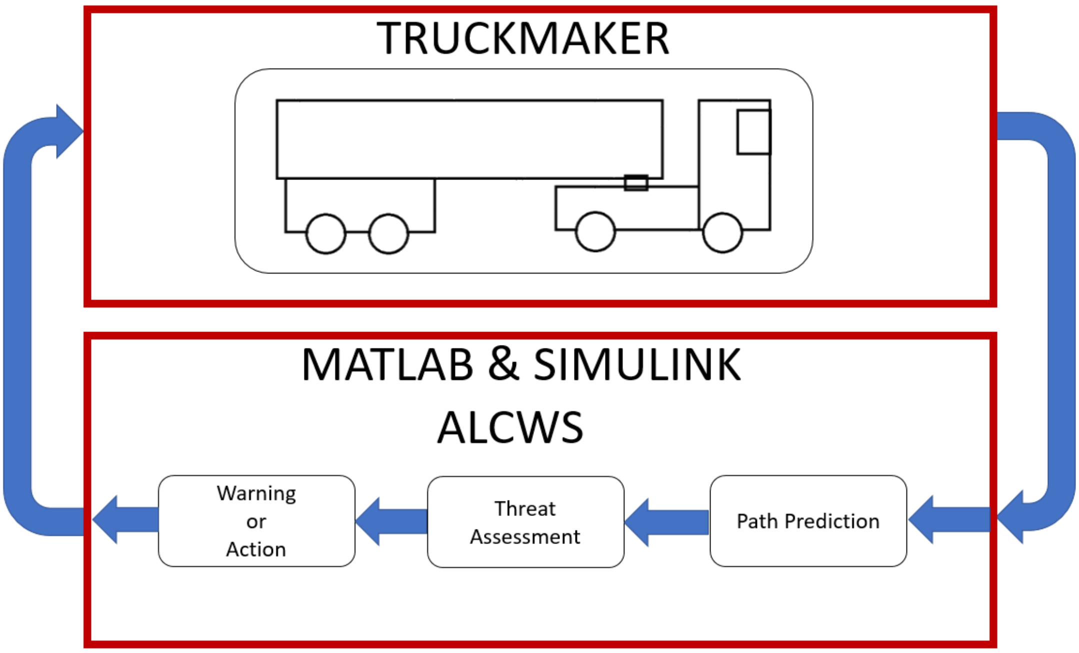

Figure 4.1: Flowchart of where the algorithms are implemented.

The following sections and their corresponding subsections will go through the different subsystems in Fig. 4.1. Section 4.1 will go through information about TruckMaker and how it is used. Section 4.2 will cover the topic of how path prediction is performed in this project. Section 4.3 describes the implemented threat assessment algorithm. The last section of this chapter will be about how the threat assessment is used to either give a warning or a brake request to TruckMaker.

4.1 TruckMaker

TruckMaker is a simulation software provided by the company IPG-automotive [4] that is used for testing and development of ALCWS. It is a vehicle simulation software that can be used for developing active safety features. TruckMaker offers the possibility of connecting the simulation software with Simulink and MATLAB. This connection enables the possibility to read the environment data directly in Simulink and intercept the vehicle control signals to tailor the driving behaviour. TruckMaker offers virtual real time simulation with simulation of multiple vehicles at the same time, with ego-dynamics, different road conditions and driver behavior. TruckMaker also generates 3-D simulations so the user can observe the vehicle behaviour in real-time.

When using simulation softwares such as TruckMaker, concept development will be quicker as it removes complications of hardware installation and fault searching in such systems. Due to the dangerous nature of the problem scenarios, TruckMaker enables testing of the different scenarios. Because performing these tests safely would be highly complicated with a real truck and real cars. Therefore the main focus in the thesis can be kept to position/orientation prediction, threat assessment, collision warning and collision avoidance/mitigation in a simulation environment.

The problem scenarios, described earlier appear on many roads around the world, hence limitations to the number of turns is needed. Test track scenarios are created in TruckMaker. These are used to limit the testing during development and as verification platform. Four different tests will be used as described in Chapter 1. In Fig. 4.2 on the left the two test tracks for one sharp left hand turn and one problem free left hand turn can be seen. The two figures on the right in Fig. 4.2 are the right hand turns also using one problem free and one sharp problematic turn.

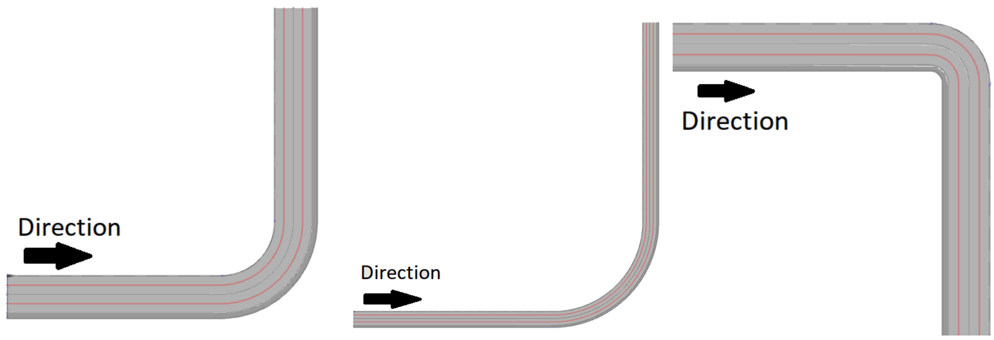

Figure 4.2: The different test tracks used for development

4.2 Path prediction

This section will contain information about how the models and sensor data is used to estimate future positions of the tractor, trailer and adjacent vehicles. These estimations are called path predictions. It also contains a subsection on how alternative paths are created as possible avoidance maneuvers when driving.

4.2.1 Estimation of future positions of tractor and trailer

State predictions of the tractor and the trailer are performed by using the bicycle model. By integrating position and orientation, using the bicycle model equations giving current speed and upcoming curvature as inputs. States during the prediction time, i.e time horizon can be found. The time horizon is set to three seconds. A sample time (Δt) is used within this time horizon to gather state values throughout the prediction. The total number of state predictions will then be

$$N = \frac{time\ \ horizon}{\Delta t}. \tag{4.1}$$

The path prediction is algorithmically described in in Alg. 1.

Algorithm 1: Position and orientation prediction

Input : $x_0, y_0, \psi_0, \varphi_0$,velocity,radius
Data: N,Δt
Output: X,Y,Ψ,Φ
init: $X_0 = x_0, Y_0 = y_0, \bar{\Psi}_0 = \psi_0, \bar{\Phi}_0 = \varphi_0$
for k = *0 in N* **do**
    Find distance*
    Find radius†
    Find steer angle and slip angle •
    Find $dx, dy, d\psi, d\varphi$ ⊗
    $X_{k+1} \longleftarrow X_k + dx\Delta t$
    $Y_{k+1} \longleftarrow Y_k + dy\Delta t$
    $\Psi_{k+1} \longleftarrow \Psi_k + d\psi\Delta t$
    $\Phi_{k+1} \longleftarrow \varphi_k + d\varphi\Delta t$

* Distance travelled is found using the constant velocity model (2.6).
† Radius ahead of the truck is found in a data set containing radius for all distances.
• Steer angle and side slip angle is found using bicycle model equations (2.2) and (2.4).
⊗ $dx, dy, d\psi$ is found using bicycle model equation (2.1) and $d\varphi$ the trailer equation (2.5). By removing (2.5), the algorithm can instead be applied to adjacent road users.

A visualization showing current state of the truck as well as the predictions can be seen in Fig. 4.3.

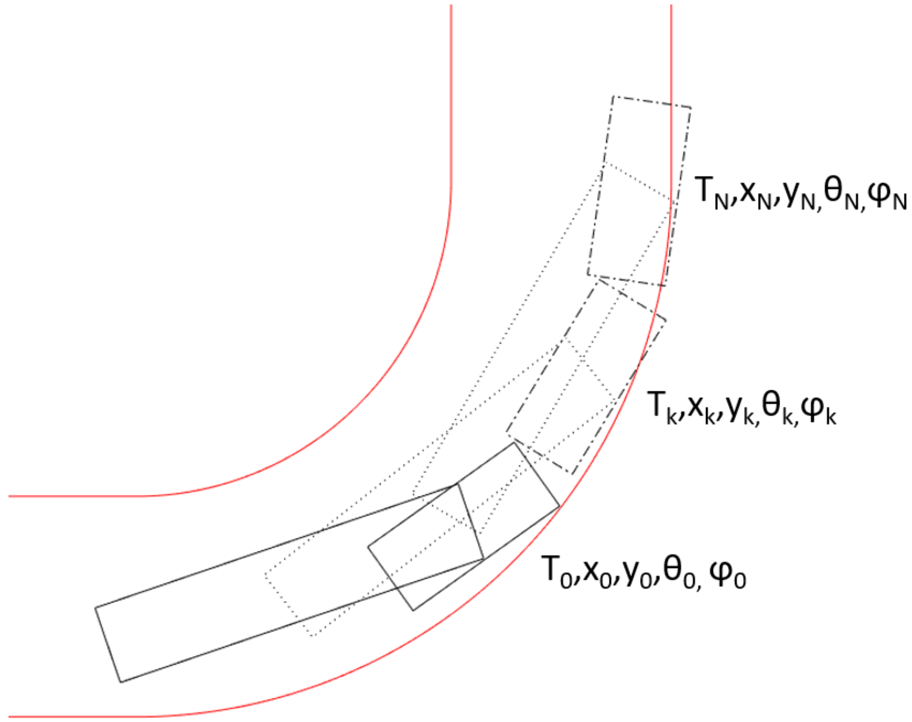

Figure 4.3: Plot of current and two predicted position and orientation of truck. Showing the current position, the position at K time steps and the final predicted position at time step N.

In Fig. 4.3, the curved lines are road lines, the solid polygons are tractor and trailer at its current position and orientation. Dash-dotted polygons are predicted tractor positions at time step k and at end of time horizon time step N. Dotted polygons are the trailer predictions at each of the predicted tractors respective time steps.

4.2.2 Alternate path creation

In the previous section the process of creating a predicted path based on current heading is described. For some scenarios the current path will lead to a trailer overlap into the adjacent lane, that might be compromising other vehicles. In this section the creation of lane margin path (LMP), and how it may lead to a collision free trajectory for the tractor is explained. LMP is an alternate path which aims to follow the outmost edge of the curve, because this lead to a minimal lane overlap while staying in the ego lane as seen in Fig. 4.4, where both the current path and this wider path is shown and detailed further in the equations below.

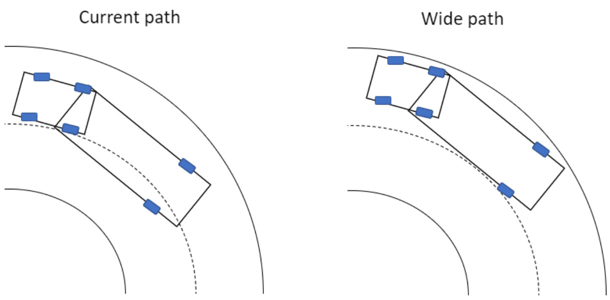

Figure 4.4: Showing a tractor in two different driving scenarios with varying levels of lane overlap from the trailer.

The idea is that the turning radius can be increased with an offset, l, up to a margin determined by the road width

$$r_m = r_0 + l \tag{4.2}$$

where r_0 is the original turning radius if left unchanged. The offset l depends on if a right turn, $r \geq 0$, or left turn ,$r < 0$, is coming up

$$l = \begin{cases} -l_m & \text{for } r \geq 0 \\ r_m & \text{for } r < 0 \end{cases} \tag{4.3}$$

where l_m is left margin and r_m is right margin. The tractors new position becomes:

$$\begin{bmatrix} x_m \\ y_m \end{bmatrix} = \begin{bmatrix} x_0 \\ y_0 + l \end{bmatrix} \tag{4.4}$$

where x_m and y_m are the updated coordinates and the wider path the tractor is following throughout the curve is determined by r_m.

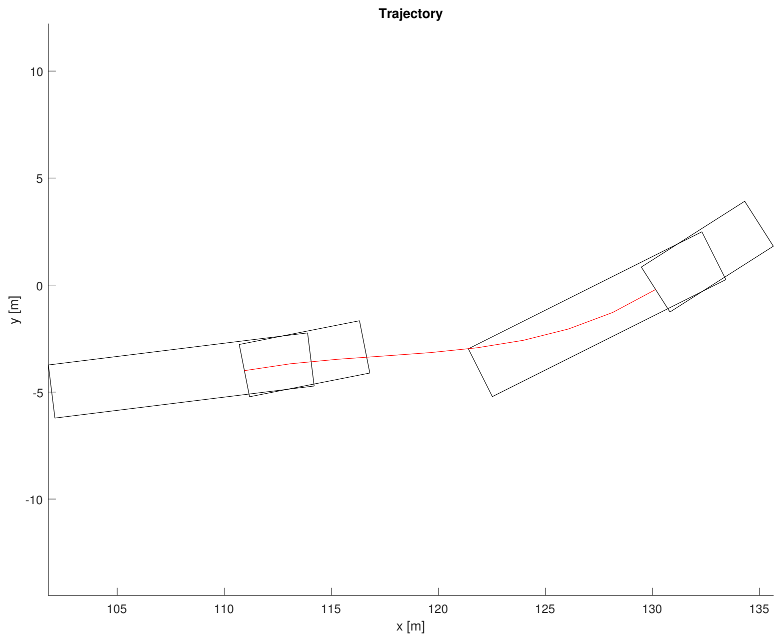

Figure 4.5: The created path from current position to LMP. Using a spline, that start in the current position and ends at LMP.

As the LMP starts at an offset, there is no predetermined path from the current position to this improved wider path. To address this a trajectory is created to join the current heading with the LMP as seen in Fig. 4.5. The trajectory is created using a cubic spline as explained in section 3.1. This spline is well suited as it is created using the desired position, the current heading angle and has a constant level of jerk along the trajectory allowing for a smooth path to follow. There are six initializing values, the first four: y_i, y_{i+1}, x_i, x_{i+1} are the start and end points of the spline in the x- and y-coordinate system. The last two: $\frac{dS_i(x)}{dx_i}$, $\frac{dS_{i+1}(x)}{dx_{i+1}}$ are the spline derivative which affects the heading of the vehicle and can be expressed as a result of (3.7):

$$\frac{dS_i(x)}{dx_i} = tan(\theta_i) \tag{4.5}$$

where the angle θ_i is the direction where the tractor is currently heading and θ_{i+1} represents the tractor heading at the end point. The spline coefficients can be found from an equation system containing the states and derivatives. The equations can be described as two matrices, A and b as seen below:

$$A = \begin{bmatrix} \frac{x_i^3}{6} & \frac{x_i^2}{2} & x_i & 1 \\ \frac{x_{i+1}^3}{6} & \frac{x_{i+1}^2}{1} & x_{i+1} & 1 \\ \frac{x_i^2}{2} & x_i & 1 & 0 \\ \frac{x_{i+1}^2}{2} & x_{i+1} & 1 & 0 \end{bmatrix}, \ b = \begin{bmatrix} y_i \\ y_{i+1} \\ tan(\theta_i) \\ tan(\theta_{i+1}) \end{bmatrix} \tag{4.6}$$

Finally the spline coefficients from Chapter 3 section 3.1 are found by solving the equation system:

$$\begin{bmatrix} a_i \\ b_i \\ c_i \\ d_i \end{bmatrix} = A \backslash b \tag{4.7}$$

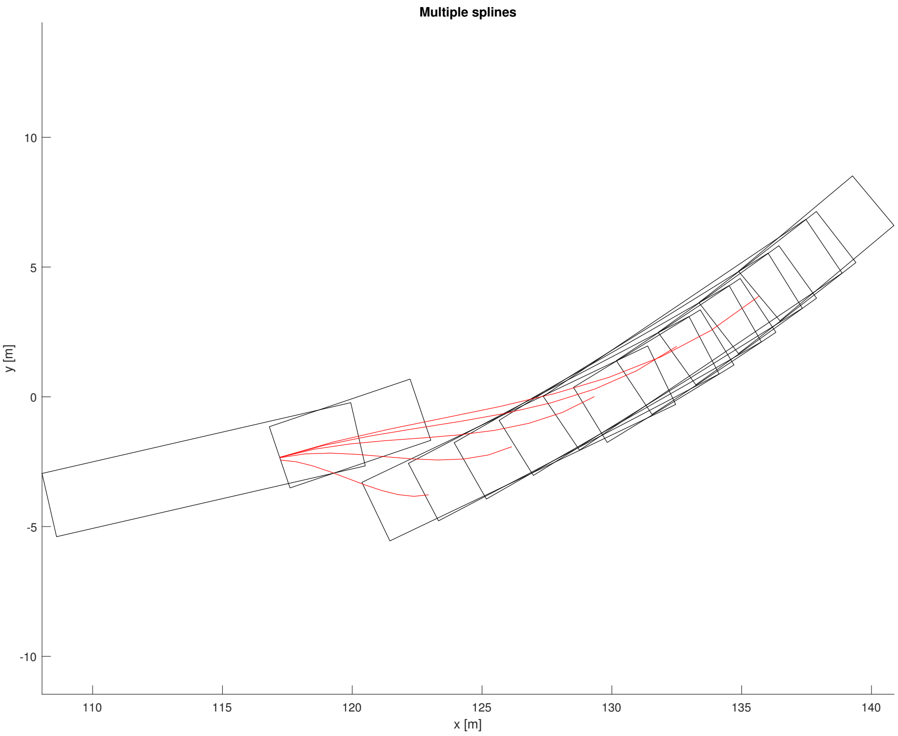

Figure 4.6: Five splines created for different trajectories to the alternate path.

For each position, five splines are created for different time steps along the alternate path. This is to evaluate different trajectories separately, as some may be suitable to follow in order to avoid a collision but others may still result in a collision. The splines are evenly spaced along the time steps of the estimated path as can be seen in Fig. 4.6. After creating five splines each of them are evaluated to verify if they are possible for the tractor to follow. This is done by calculating the curvature κ, equation 3.10. The curvature is then used to estimate the lateral acceleration of the vehicle , $a_{lat} = v^2\kappa$, where any values over a set threshold of 3.5 m/s^2 are considered unusable [16]. Splines with values above the threshold are discarded.

4.3 Threat Assessment

This section will go into detail about how the threat level is evaluated based on the predicted movement and position of the vehicles. Furthermore, the cause of action taken following the threat assessment will be described.

4.3.1 Threat-based cause of action

This section aims to explain and motivate the cause of action taken based on the future predictions. When a driver enters a corner, he or she seldom follows it completely uniformly. As the predictions are based on the current heading and the position of the tractor this could result in unnecessary warnings or actions as the driver might be aware of the situation and is planning on steering away to take a wider path, hence avoiding the impending crash. For such situations it is important to not step in and take control as the driver could have managed without interference. In order to only step in when necessary a multi-layered threat assessment system is used.

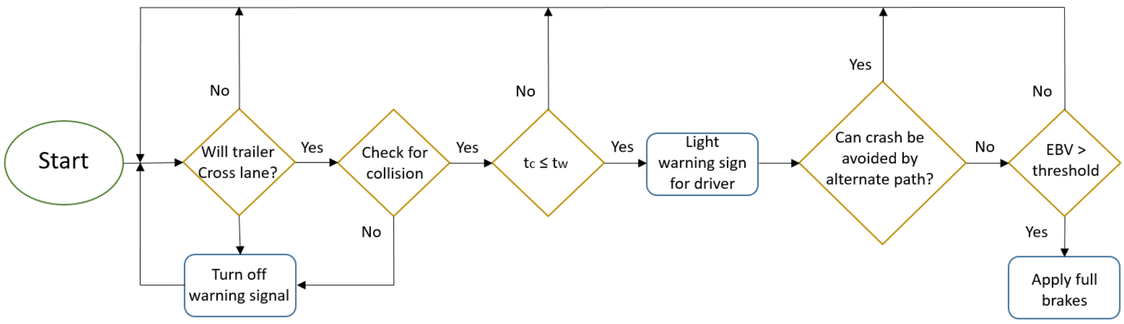

Figure 4.7: Flow chart of the developed threat assessment algorithm.

The threat assessment system is depicted in the flow chart seen in Fig. 4.7. Each point will be further explain in the following list:

1. **Will trailer cross lane?** The first sequence evaluates if the trailer will cross into the adjacent lane. If this is the case then the collision evaluations will start.
2. **Check for collision** If lane crossing has been confirmed then predictions are made for the current path. All these truck position predictions at different time steps are compared to those of the adjacent car. If any prediction at the same time step is overlapping a collision has been detected. If no collisions are detected, then the truck is in no immediate danger and we return to step 1 to evaluate collision risk for the next time step. If however the truck is on a collision path then precautions such as the brakes could start pressurizing to reduce the brake-lag effect. Further evaluation will be made in the next step.
3. $\mathbf{t_c \leq t_w}$ A crash has been predicted. Whether to warn the driver or not is evaluated as detailed in section 4.4.1 depending on the predicted time of impact in relation to the appropriate warning time based on the reaction and braking time.
4. **Can crash be avoided by alternate path?** By now it is known that the crash will occur if the tractor continues on this path and a warning is issued, but is there another way to avoid collision? In this part of the sequence the possibility of driving an alternate path as calculated in section 4.2.2 is evaluated. If the alternate path is safe to follow according to the current predictions, and the calculated spline path is collision free, then it is still

possible to avoid a collision and no further action will be taken based on the predictions made in this time step. If a collision cannot be avoided by following an alternate path, then the algorithm continues to the braking evaluation.

5. **EBV > threshold** At the current state a crash will occur and there is no possibility for the driver to steer away from the situation. The only option left is to lower the velocity of the vehicle. In this step the braking threshold is evaluated, if it is larger than the threshold then the brakes will be applied as a last resort to avoid or mitigate a collision. If it is lower then the threshold value then the evaluation starts over for the next time step and the driver still has time to manually reduce the speed.

The reasoning behind this approach is to not intervene unless it is absolutely necessary. A system that steps in, in situations where a crash could have been avoided by the driver could create a distrust in the system. Furthermore, by braking other dangerous situations could occur as there could be other vehicles behind the trailer that might be affected by a sudden braking action. Aside from these side effects another reason is that as the time horizon increases, i.e. how far ahead in time the crash is predicted, the accuracy of the model decreases. We do not want to apply a full brake based on a prediction too far into the future, but rather save it for more immediate threats.

4.3.2 Collision detection

To evaluate if a crash will occur the position and orientation of both the adjacent vehicle and the tractor and trailer has to be taken into account. In Fig. 4.8 the actual position of the truck, trailer and adjacent vehicle is displayed. Both tractor and trailer are checked for collision. The tractor needs to be considered when taking the right hand turn, because in that scenario the tractor is first to enter the adjacent lane. Furthermore, the tractor and trailer will be regarded as a 2D object moving in only x- and y-direction.

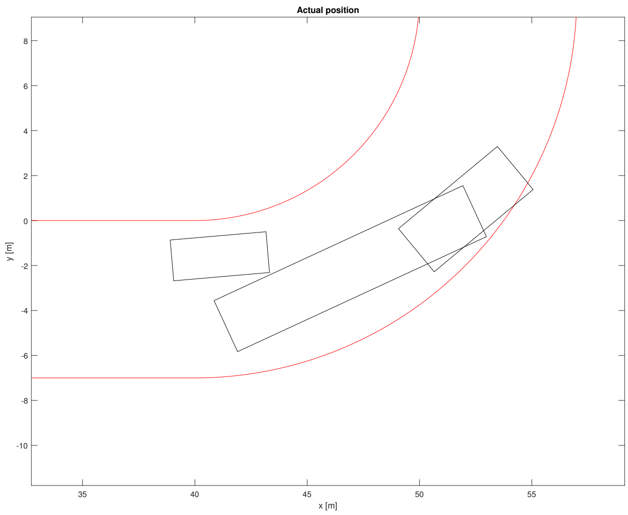

Figure 4.8: Snapshot from the simulated crash case.

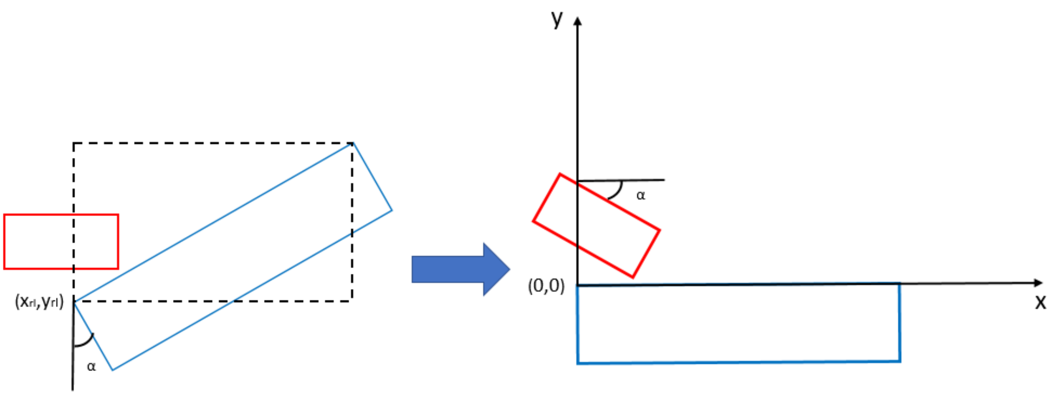

Figure 4.9: Rotation of the trailer and adjacent vehicle coordinate system. The large box is the trailer, small box is adjacent vehicle.

When evaluating a potential crash scenario, rectangular bounding boxes are used to describe the dimensions of the vehicles. To determine if a crash will occur, the position of the corners on the trailer are used as bounding limits, if one corner of the vehicle is inside of the bounding box limits, a crash is predicted. In Fig. 4.9 it is displayed how the coordinates of the trailer and adjacent vehicle are rotated and translated so that the origin is at the rear left corner of the trailer (x_{rl}, y_{rl}).

This gives a fixed bounding box values corresponding to the width and length of the trailer. The overlap is estimated from the adjacent vehicles relative position to the trailer. In Alg. 2 the entire sequence of translating, rotating and comparing the border values is explained:

Algorithm 2: Collision detection from adjacent vehicle corner overlap

Input : $P_{truck}*, P_{adjacent}*, \Psi$
Output: $collision, t_c$
begin
    $collision = False$
    $[x_{max}, y_{max}] = [trailerLength, 0]$
    $[x_{min}, y_{min}] = [0, -trailerWidth]$
    for i = *1 to* n **do**
        `/* Translate coordinates to a new origin located in real left trailer corner */`
        $\begin{bmatrix} x_{rl,i} \\ y_{rl,i} \end{bmatrix} = [P_{truck,i}(1,4), P_{truck,i}(2,4)]$
        $P_{adjacent,i} = P_{adjacent,i} - \begin{bmatrix} x_{rl,i} \\ y_{rl,i} \end{bmatrix}$
        `/* Create rotation matrix and rotate coordinates */`
        $T = \begin{bmatrix} cos(\Psi_i) & -sin(\Psi_i) \\ sin(\Psi_i) & cos(\Psi_i) \end{bmatrix}$
        $P_{adjacent,i} = T^\intercal P_{adjacent_i}$
        `/* Determine if overlap occurs */`
        for j = *1 to 4* **do**
            if $P_{adjacent,i}(1,j) < x_{max}$ **and** $P_{adjacent,i}(1,j) > x_{min}$ **and** $P_{adjacent,i}(2,j) < y_{max}$ **and** $P_{adjacent,i}(2,j) > y_{min}$ **then**
                $collision = True$
                $t_c = dt \cdot i$

* $P_{truck}, P_{adjacent}$ contains x- and y-coordinates of the bounding box corners on the form $P = \begin{bmatrix} x_{fl} & x_{fr} & x_{rr} & x_{rl} \\ y_{fl} & y_{fr} & y_{rr} & y_{rl} \end{bmatrix}$

4.4 Warning or action

This section will describe how the evaluations for warning and action are performed. First the algorithm for warning or action for ALCWS will be shown, then separate parts of the algorithm will be described further in the subsequent subsections.

4.4.1 Driver collision warning

When issuing a warning for the driver, a model based on the velocity of the tractor and the average reaction time as explained in section 2.2 is used. The time of warning before impact is calculated as follows:

$$t_w = t_r + t_s \tag{4.8}$$

where t_r is the average reaction time of 1.5 seconds, [14], t_s is a variable used to describe how the braking time rises with as the speed increases. t_s is calculated from a linear function of the speed starting at values larger than 10 km/h as 1.5 seconds should be sufficient to react with the low braking periods for lower speeds given the average reaction time, that is 1.5 seconds.

$$t_s = \begin{cases} 0 & \text{for } v < 10km/h \\ t_b(v-10) & \text{for } v \geq 10km/h \end{cases} \tag{4.9}$$

The time of warning t_w, then becomes longer, earlier warning, as the vehicle speeds up, reaching the end of time horizon at 40 km/h. t_b is parameter for braking time at varying velocities and has to be changed depending on vehicle. i.e. a tuning parameter, in this case it is experimentally determined to 0.5. This is to ensure that the driver has enough time to not only react to a threat, but also give the driver a chance to avert the situation as a greater braking time is needed. A warning will be given when the following condition is satisfied:

$$t_c \leq t_w \tag{4.10}$$

where t_c is the predicted time to impact.

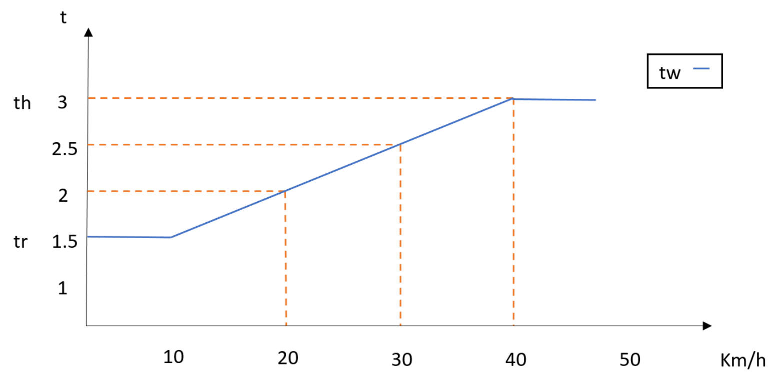

Figure 4.10: Graph showing how early ALCWS will display a warning for the driver.

In Fig. 4.10 the warning time is shown as a function of velocity. As the time horizon is set to 3 seconds the maximum warning time is reached at 40 km/h where any predicted collision will yield a warning signal.

4.4.2 Emergency braking evaluation

When performing an emergency brake, the velocity is reduced to zero over a short period of time. This will in turn affect the predicted future positions and may have potential repercussions. As mentioned in the previous section the estimated braking time is used to evaluate at which time instant the vehicle will come to a full stop. This combined with the predicted path from the bicycle model will be used to evaluate whether a crash with the adjacent vehicle will occur when applying full brakes. This alone is not enough to evaluate if the situation requires emergency braking. If the tractor is driving ahead of the adjacent vehicle then braking using this evaluation alone would result in a crash that could have been avoided by simply continuing to drive. To circumvent this, three additional layers are added to the emergency braking evaluation:

Compare to the original predictions To ensure that the crash is not created as a result of the braking, the predictions will be analysed together with the original collision predictions. If no collision is predicted, then there is no reason to use the brakes as the curve can be completed at the current velocity without causing a collision. The brakes will only be applied if a collision is predicted in a shorted period of time into the future in the original prediction than in the braking predictions.

Parallel or ahead If the adjacent vehicle is coming up behind the trailer at a greater velocity it is possible to predict a future crash in the original predictions as the car would catch up to the trailer if the velocity was kept constant. Further it could also predict a crash when braking as stopping would cause the vehicle to run into the trailer. So as a third layer to the evaluation the vehicle has to be parallel or ahead of the trailer to avoid causing a collision by applying the brakes.

Maximum time period As predictions are just estimations of where the vehicles will be in the future, they do not correlate completely to reality. Looking further into the future will give larger margins of error, for this reason the braking predictions will be limited to predictions up to 1.5 seconds into the future as emergency braking is a very drastic measure. 1.5 seconds is roughly the time it takes to stop at 30 km/h with the current tractor-trailer setup, meaning that for velocities higher than this a collision will occur, although at a lower velocity than if no brakes had been applied at all.

To put all of this into a simpler form, a mathematical model is used to do the brake evaluation and find an Emergency Brake Value (EBV),

$$f(t_C, t_B, P_A, P_T) = \frac{t_B}{1.2 t_C} sign(P_A - P_T) = EBV \tag{4.11}$$

where t_B represents the predicted time to impact from the emergency brake evaluation and has a maximum allowed value of 1.5 seconds, t_C is the time to impact from the original predictions. P_A is the position of the front of the adjacent vehicle that has the highest longitudinal value in the frame of the trailer, and P_T is the position of the rear of the trailer, i.e. 0 in the frame of the trailer. These values are found when performing collision detection as seen in section 4.3.2, see Fig. 4.9.

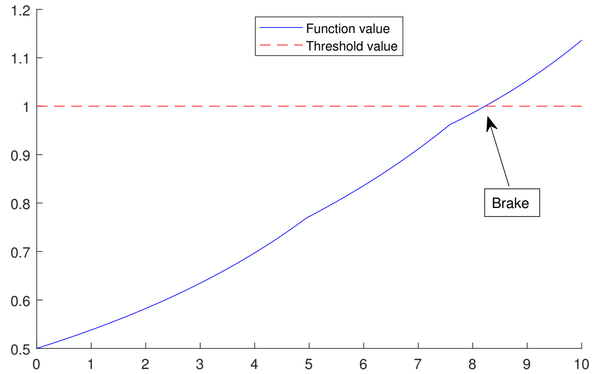

Figure 4.11: Graph showing an example of how the EBV value passes the threshold value and a brake request is given.

In Fig. 4.11 the function value is calculated in equation (4.11). When the function value is larger than the threshold value of 1, the brakes will be applied. The function will have a larger magnitude than the threshold value when $1.2t_C > t_B$ using a 20% margin. When the adjacent vehicle is behind the trailer, the sign of the function will be negative and the threshold value will not be exceeded.

5

Results

ALCWS manages to provide warnings in advance, estimates position and orientation for future time steps, evaluates an alternate driving path and, as a last resort, applies the brakes to minimize collision damage. This chapter will present the performance of these functions, as well as ALCWS as a whole.

5.1 Evaluation scenarios

The corners detailed in the scope in section 1.3, chapter 1 are the ones the evaluation will be conducted on, that is the following corners:

- Sharp left turn with collision. 90 degrees, 10 meter radius. This turn is evaluated using three different velocity profiles.
  - Using constant velocity
  - Constant velocity until right before the turn, where the accelerator is applied to give acceleration.
  - Constant velocity until right before the turn where no throttle is given, causing a deceleration.
- Sharp right turn with collision. 90 degrees, 10 meter radius.
  - Using varying velocity.
- Left turn without collision. 90 degrees, 45 meter radius.
  - Using constant velocity.

ALCWS will be tested at constant vehicle velocity in both the curve with a 10 meter radius, as well as the 45 meter radius to see how well it operates at different radii.

ALCWS will be tested in scenarios where the velocity varies up to and during the curve. One scenario is where the tractor is accelerating up until the corner, and another where the vehicle is decelerating when going into the the curve. This is to see to which extent the predicted time of impact is affected by changes in velocity of the vehicle as a constant velocity model is used.

Through the right turn a very low velocity around 8 $\pm$ 4 km/h is used as low velocity is required to handle the very sharp cornering. As such any significant acceleration or deceleration will be hard to produce and is therefore disregarded during the evaluation of the right turn.

5.2 Sharp left turn

This section will show the results of the left turn with a 10 meter radius. In figure 5.1 the turn and a collision scenario can be seen.

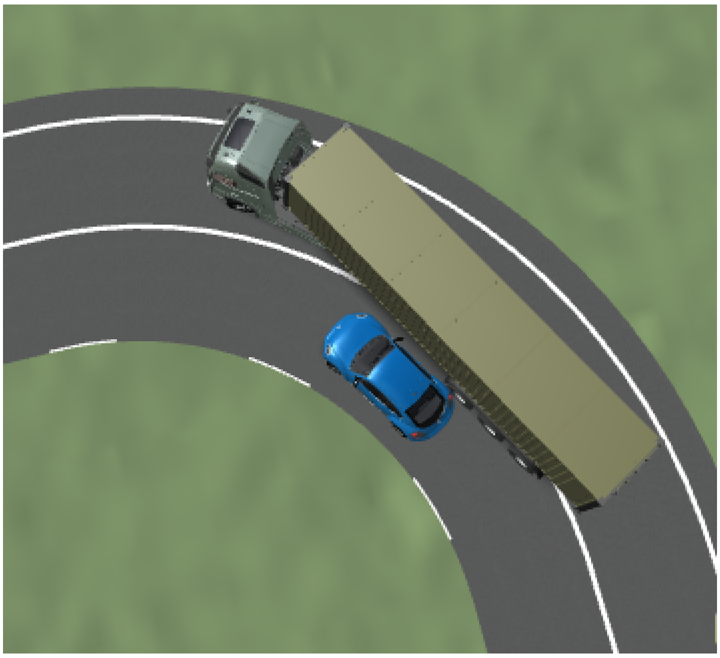

Figure 5.1: The sharp left turn causing a collision with adjacent vehicle.

5.2.1 Path Prediction Accuracy

When performing the threat assessment the accuracy of the prediction is of importance. If the predictions are wrong, the warning accuracy will also suffer. To evaluate prediction accuracy the mean, RMS and peak values are calculated. First constant velocity will be evaluated, then while accelerating in the turn and lastly the test is performed while decelerating in the turn.

In the following tables the positional accuracy and angular accuracy based on world coordinates is defined using mean value, RMS value and peak value. The values are found using the predicted position and angle at 1.5 seconds and 3 seconds, and comparing these with the actual position and angle that actually occurred after said 1.5 seconds and 3 seconds respectively.

Case: Constant velocity

Table 5.1: Distance errors between prediction and actual values.

Time horizon	1.5s	3s
Mean X distance error[m]	0.1822	1.7047
RMS X distance error[m]	0.3433	0.7692
Peak X distance error[m]	0.8203	1.8110
Mean Y distance error[m]	-0.2524	0.4989
RMS Y distance error[m]	1.3232	2.7368
Peak Y distance error[m]	1.9726	2.2498

Table 5.2: Angle errors between prediction and actual values.

Time horizon	1.5s	3s
Mean Ψ error[rad]	-0.0203	-0.0149
RMS Ψ error[rad]	0.0536	0.0506
Peak Ψ error[rad]	0.1488	0.1273
Mean Φ error[rad]	-0.0051	0.0087
RMS Φ error[rad]	0.0269	0.0315
Peak Φ error[rad]	0.0788	0.0939

Case: Acceleration in turn

Table 5.3: Distance errors between prediction and actual values.

Time horizon	1.5s	3s
Mean X distance error[m]	0.5763	-1.8064
RMS X distance error[m]	0.8211	2.6493
Peak X distance error[m]	1.3873	2.8037
Mean Y distance error[m]	0.2532	-0.9051
RMS Y distance error[m]	0.4491	1.3489
Peak Y distance error[m]	1.0266	2.7307

Table 5.4: Angle errors between prediction and actual values.

Time horizon	1.5s	3s
Mean Ψ error[rad]	-0.0157	0.0222
RMS Ψ error[rad]	0.0515	0.0807
Peak Ψ error[rad]	0.1529	0.2300
Mean Φ error[rad]	-0.0052	0.0216
RMS Φ error[rad]	0.0244	0.0459
Peak Φ error[rad]	0.0693	0.1319

Case: Deceleration in turn

Table 5.5: Distance errors between prediction and actual values.

Time horizon	1.5s	3s
Mean X distance error[m]	−0.2342	0.8514
RMS X distance error[m]	0.7454	2.0830
Peak X distance error[m]	1.2125	2.8263
Mean Y distance error[m]	0.0391	0.4754
RMS Y distance error[m]	0.3256	1.9179
Peak Y distance error[m]	1.1065	2.3983

Table 5.6: Angle errors between prediction and actual values.

Time horizon	1.5s	3s
Mean Ψ error[rad]	−0.0345	−0.1150
RMS Ψ error[rad]	0.0801	0.2327
Peak Ψ error[rad]	0.2658	0.7906
Mean Φ error[rad]	−0.0135	−0.0311
RMS Φ error[rad]	0.0494	0.0823
Peak Φ error[rad]	0.1633	0.2352

5.2.2 Collision prediction performance

The following graphs will show at which point a collision occurs in the simulation as well as at which point in time the collision was believed to occur, based on the predictions made with 1.5 and 3.0 seconds time horizon to evaluate the performance regarding time of impact.

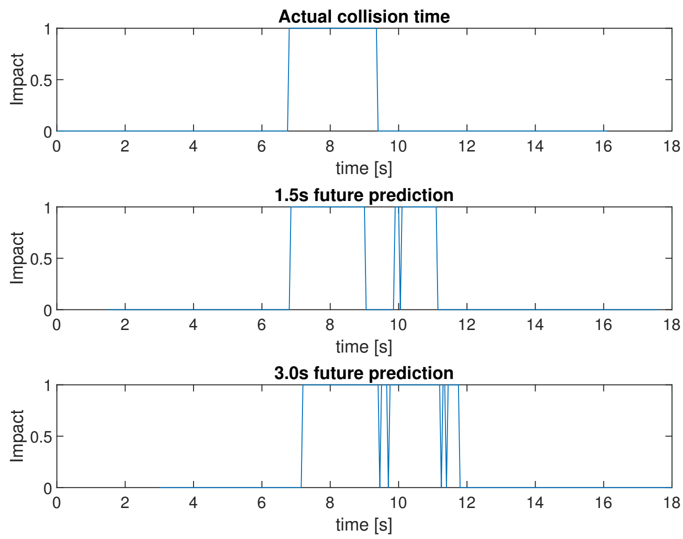

Figure 5.2: Test run at constant velocity with a time horizon of 3 seconds

Constant velocity: In Fig. 5.2 both vehicles are moving at 20 km/h during this test and the predictions are all very close to the actual time of impact with a small deviation on the three second prediction. As the collision occurs the adjacent vehicle slows down to a halt in the simulation environment, hence the longer crash period than first predicted as the car is no longer driving out of the corner at this point.

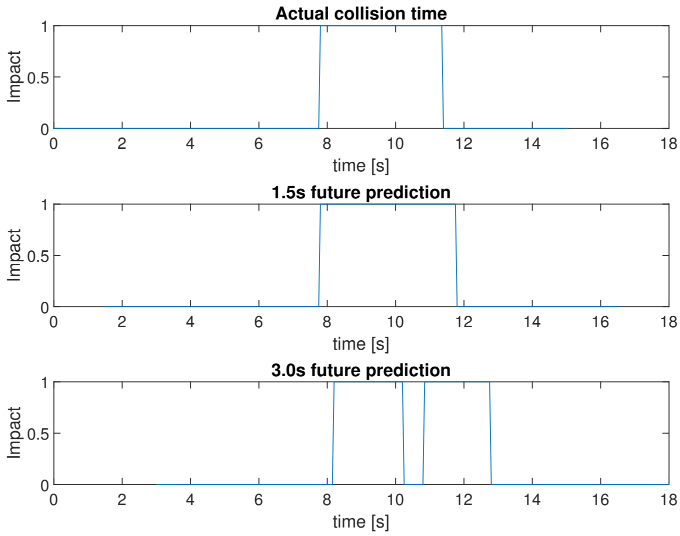

Figure 5.3: Test run at constant velocity with a time horizon of 3 seconds.

Acceleration: In Fig. 5.3 the second test run is shown where the adjacent vehicle is accelerating until the corner, some slight variations in the predictions can be seen. This is partly because a constant velocity model is used, so the initial collision predictions are made further into the future as the car had a lower velocity at that point in time. The error is low though at less than half a second for the three second prediction.

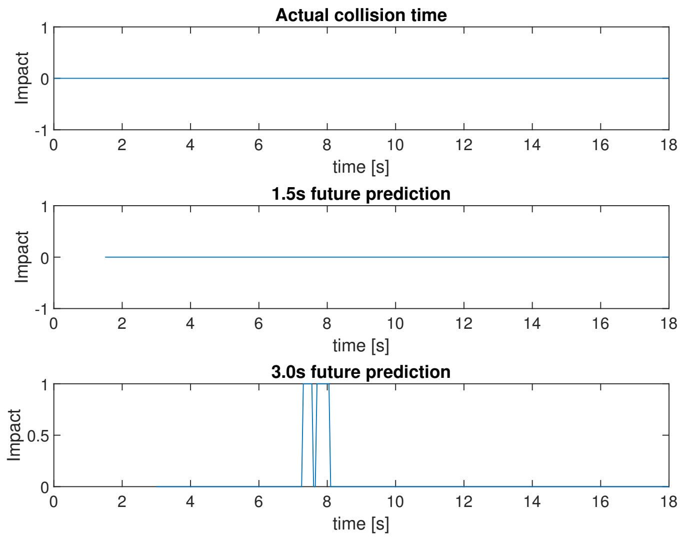

Figure 5.4: Test run at constant velocity with a time horizon of 3 seconds.

Deceleration In Fig. 5.4 the case where a deceleration occurs during the cornering. Again the performance is decent with the prediction when time of collision occur and actual time of collision are less than half a second.

	Constant	Acceleration	Deceleration
Actual time of collision	6.8	7.9	0
Predicted time of collision with 1.5 seconds horizon	6.8	7.9	0
Predicted time of collision with 3.0 seconds horizon	6.8	8.1	7.5

Table 5.7: Table of collision time and predicted collision time.

In table 5.7 a short summary of the actual collision time, and predicted time of impact occurs from the three figures shown above.

5.2.3 Driver warning performance

The warnings given to the driver can be seen in table 5.8 showing the times when warnings were given and when collisions occurred in the three different acceleration profiles.

	Time of warning [s]	Time of collision [s]	Duration of warning [s]
Constant velocity	5.05	6.8	1.75
Accelerating	5.95	7.8	1.85
Decelerating	5.25	7	1.75

Table 5.8: Table of driver warning times.

As can be seen in the table warning duration's are highly similar for the three cases. The desired duration of warning for the speeds used in this test would be around two seconds, since the velocity is varying between 18 km/h and 22 km/h.

5.2.4 Lane margin path performance

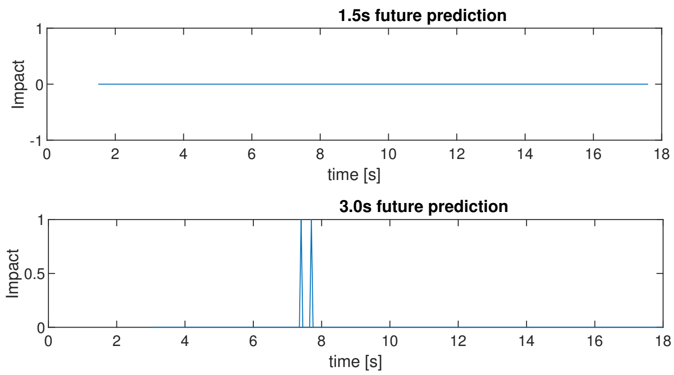

Figure 5.5: Test run with constant velocity using a time horizon of 3 seconds

In Fig. 5.5 the tractor follows the regular path through the 10 meter radius curve at a constant velocity while evaluating the LMP. The predictions at 1.5 seconds shows no indication that a collision will occur along the improved path. For the 3 second prediction horizon it does predict that a collision will occur. No real time collision is shown as the tractor follows the actual path, where we know a collision will occur and is of no interest in this context.

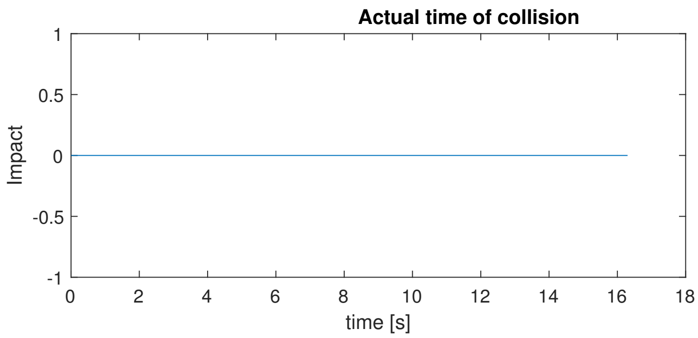

Figure 5.6: Real-time crash evaluation when following the outer line of the curve.

In Fig. 5.6 the real-time crash evaluation of the vehicles is performed as the tractor is controlled to follow the outer line of the curve during a test run. This is done to verify whether the predictions above are accurate. In this case we can see that 1.5 second predictions were indeed correct, and that the collision predicted at 3 seconds was incorrect. The alternate path can be followed for this tractor-trailer combination in a 10 meter radius curve without causing a collision, although the 3 seconds prediction does provide a false collision detection.

5.2.5 Emergency braking value performance

In the following figures the emergency braking value is plotted together with the brake request and time of collision. It can be observed that the brake request is following the EBV-function threshold. In all three cases the speed is taken down to below 5 km/h at the time of collision. The graphs shows similar performance in all three cases.

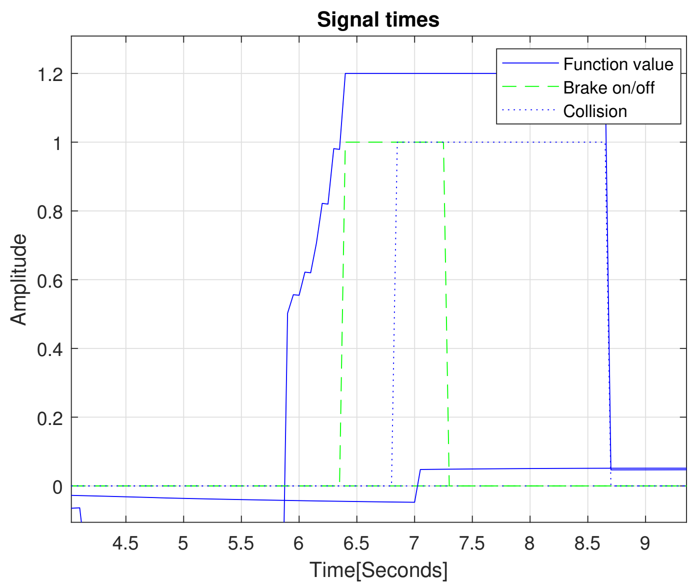

Figure 5.7: Plot of the EBV-value, the brake signal and time of collision when using a constant velocity throughout the turn.

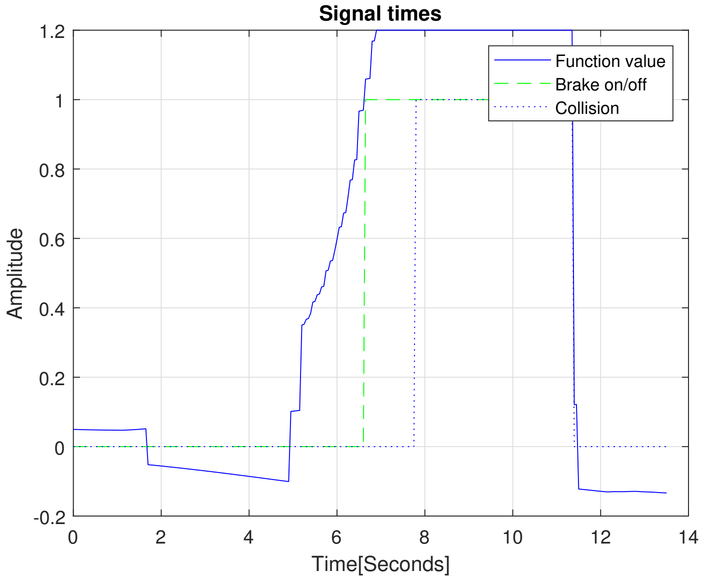

Figure 5.8: Plot of the EBV-value, the brake signal and time of collision when accelerating at and through the turn.

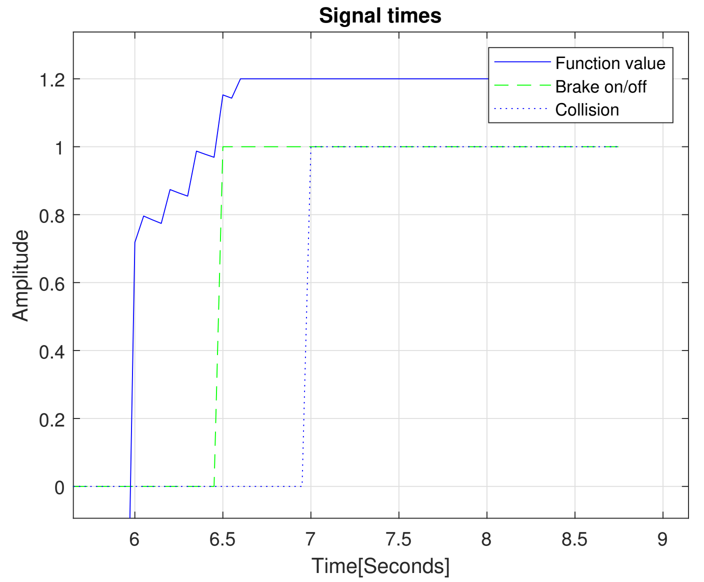

Figure 5.9: Plot of the EBV-value, the brake signal and time of collision when decelerating at and through the turn.

5.3 Wide left turn

This section contains results from the wider 45 meter radius left turn. A screenshot from Truckmaker can be seen in Fig. 5.10. The adjacent car has a higher velocity than the truck and passes it around half way through the turn.

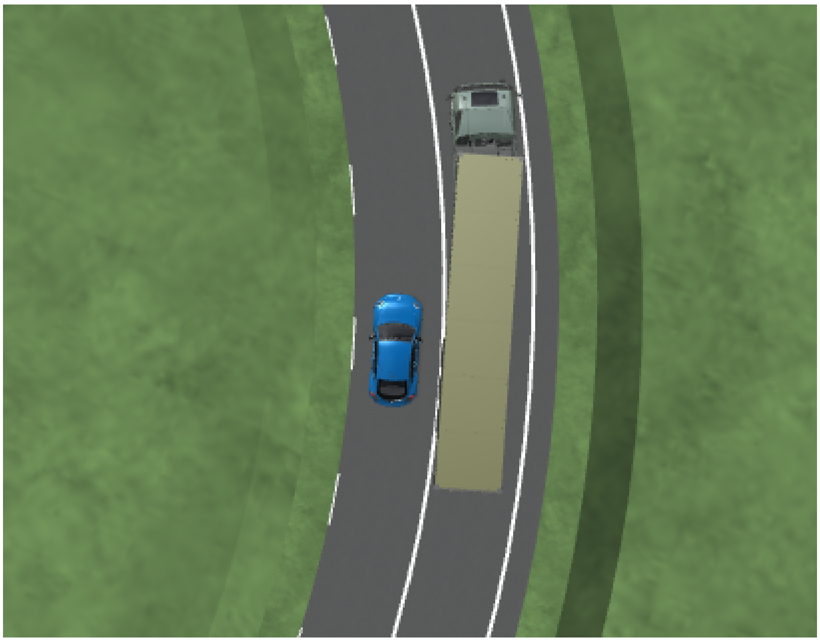

Figure 5.10: Screenshot from Truckmaker where the car passes the truck, in the wider 45 meter radius left turn.

5.3.1 Path Prediction Accuracy

The accuracy will be measured in the same way as is done in section 5.2.1 but this time for the wider 45 m radius curve.

In the following tables the position and angular accuracy is presented.

Table 5.9: Distance errors between prediction and actual values.

Time horizon	1.5s	3s
Mean X distance error[m]	0.1065	−0.0412
RMS X distance error[m]	0.3865	0.9900
Peak X distance error[m]	1.1011	2.4565
Mean Y distance error[m]	0.3019	−0.6836
RMS Y distance error[m]	0.3859	0.8194
Peak Y distance error[m]	0.6421	1.1094

Table 5.10: Angle errors between prediction and actual values.

Time horizon	1.5s	3s
Mean Ψ error[rad]	0.0130	0.0286
RMS Ψ error[rad]	0.0368	0.0554
Peak Ψ error[rad]	0.1133	0.1336
Mean Φ error[rad]	0.0057	0.0074
RMS Φ error[rad]	0.0168	0.0181
Peak Φ error[rad]	0.0497	0.0554

5.3.2 Collision prediction performance

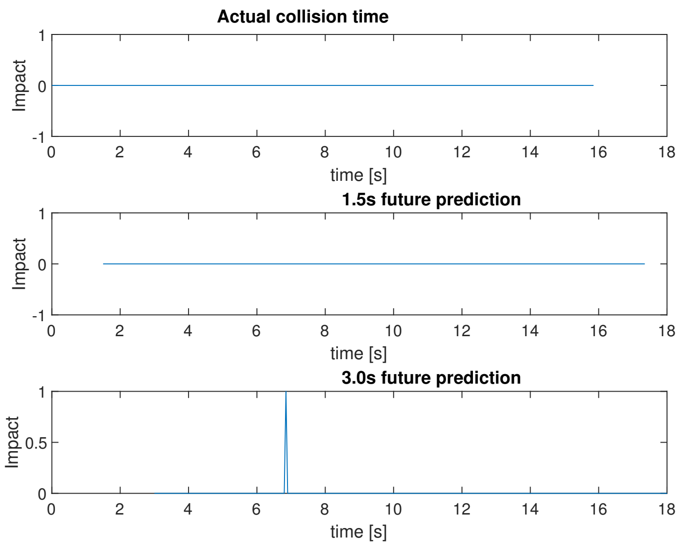

Figure 5.11: Test run at constant velocity with a time horizon of 3 seconds.

Constant velocity: In Fig. 5.11 both vehicles are moving at a constant pace through the wide corner of 45 meters. No collision occurs, but a predictions using the 3 seconds time horizon indicates that a collision would occur. As no collision occurs only the constant velocity will be presented in this section as both acceleration and deceleration only should affect the predicted time of impact.

5.3.3 Driver warning performance

A warning is given at 2.7 seconds into the simulation and held for 0.95 second, see Fig. 5.12. No collision does occur, hence a warning should not have been given.

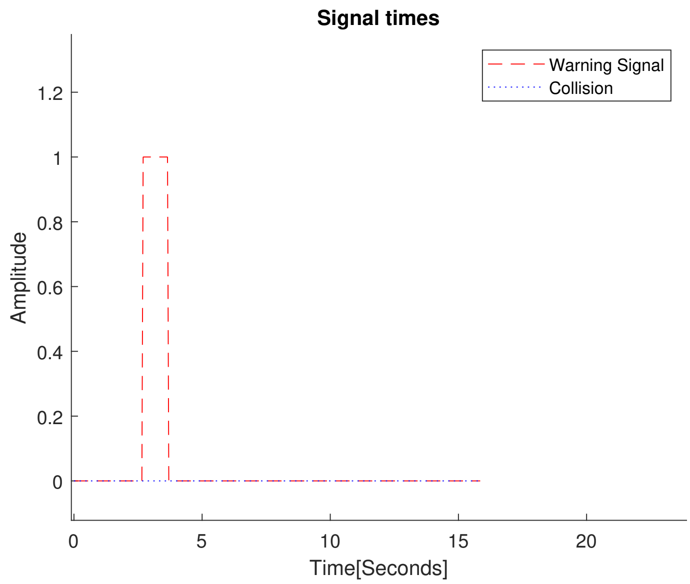

Figure 5.12: Graph of warning signal(on/off) and collision, which does not occur.

5.3.4 Emergency braking value performance

In the following Fig. 5.13 the EBV is tested in this wider 45 meter turn. And it can be observed that no brake is applied. Which may seem a bit odd since the EBV-value crosses the threshold(values > 1). But a small hold is also in the system which requires the EBV-value to stay over the threshold for more than one sampling instance (this is to make it slightly more robust against these kind of events and if noise would be present). Which in this case it does not, hence the brake is not triggered.

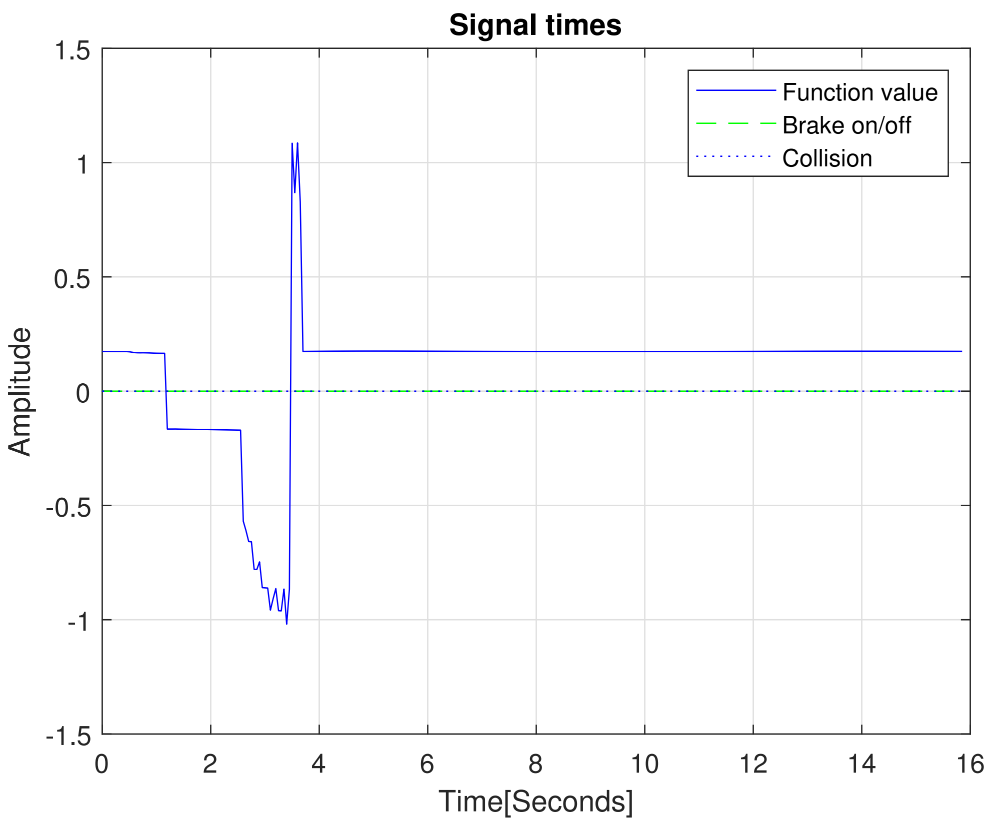

Figure 5.13: Plot of the EBV-value, the brake signal and time of collision when using a constant velocity throughout the turn.

5.4 Sharp right turn

The sharp right hand turn also has a 10 meter radius. In order to clear the corner the truck needs to occupy both lanes. The path given for the truck to follow is manually set up in Truckmaker. In figure 5.14 the path can be seen on the left as the dotted line in the plan view. On the right a screen shot from Truckmaker as the truck is going through the corner.

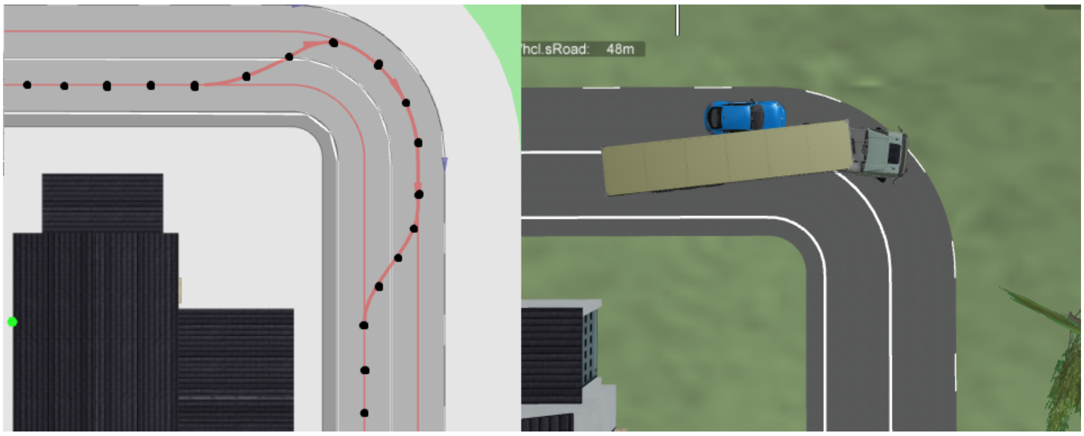

Figure 5.14: Two screenshots from Truckmaker. On the left, path through the corner(dotted). On the right, a screenshot as the truck is passing the corner causing a collision with adjacent vehicle.

5.4.1 Path Prediction Accuracy

The accuracy will be measured in the same way as is done in section 5.2.1 but this time for the sharp right turn.

Table 5.11: Distance errors between prediction and actual values.

Time horizon	1.5s	3s
Mean X distance error[m]	0.0392	−0.2525
RMS X distance error[m]	0.5769	1.3605
Peak X distance error[m]	2.3862	5.1631
Mean Y distance error[m]	−0.0472	0.0619
RMS Y distance error[m]	0.2407	0.5589
Peak Y distance error[m]	0.7456	1.3277

Table 5.12: Angle errors between prediction and actual values.

Time horizon	1.5s	3s
Mean Ψ error[rad]	0.0156	0.0309
RMS Ψ error[rad]	0.1020	0.1384
Peak Ψ error[rad]	0.3058	0.5930
Mean Φ error[rad]	0.0032	0.0061
RMS Φ error[rad]	0.0751	0.0858
Peak Φ error[rad]	0.2598	0.3100

5.4.2 Collision prediction performance

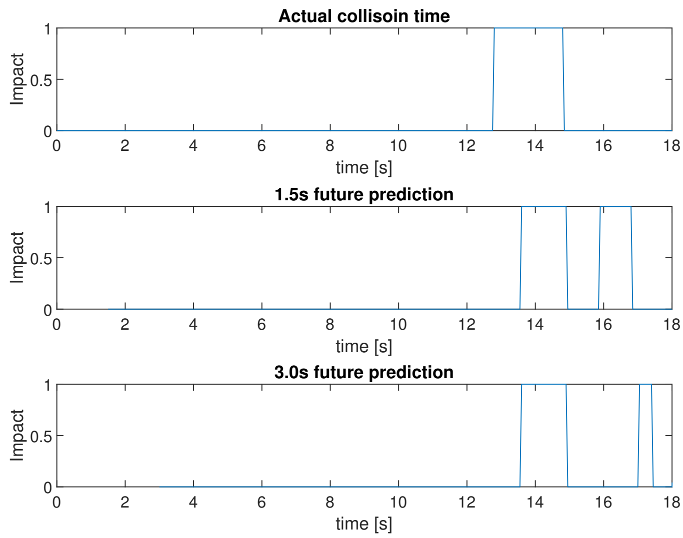

Figure 5.15: Test run at constant velocity with a time horizon of 3 seconds.

In figure 5.15 the predicted time of impact is compared to the actual time of impact. As can be seen the actual time of impact occurs just before the 13 second mark, but the predicted time of collision occurs roughly 0.5 seconds further into the future. .

5.4.3 Driver warning performance

In table 5.13 is the warning time for the right turn.

	Time of warning [s]	Time of collision [s]	Duration of warning [s]
Constant velocity	11.6	12.8	1.2

Table 5.13: Table of driver warning times.

The desired warning time for this scenario is the minimum warning time, that is 1.5 seconds.

5.4.4 Emergency braking value performance

A test is done with the emergency brake system activated. Result of the test can be seen in Fig. 5.16.

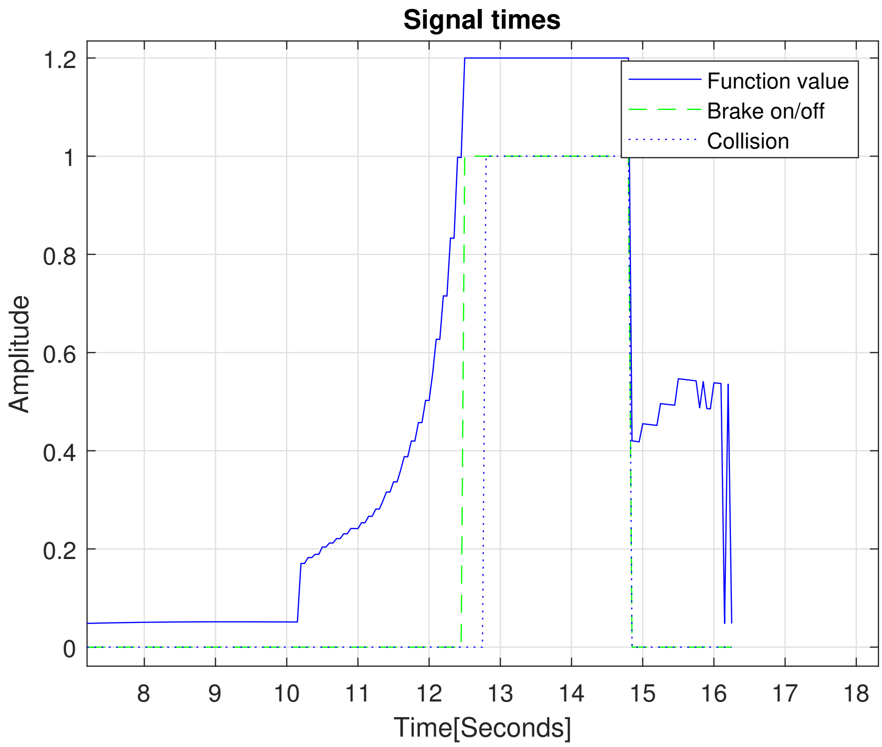

Figure 5.16: The emergency braking value, as well as the brake and collision signals.

As can be seen the brake is again triggered before collision. The speed of the truck going into the turn is around 10 km/h so even though the time between braking and collision the speed of the truck still reaches zero.

5.5 Discussion

5.5.1 Path Prediction Accuracy

From the results presented in Section 5.2-5.4, the errors may seem large with peak errors of around two meters, which would correspond to roughly half the width of the road. The peak errors are seen after the collision would have occurred. In the first scenario the collision occur at 7 seconds where the position error is less than 0.5 meters. Hence, the predictions for our warning purposes are therefore deemed accurate enough, while the prediction performance for the whole scenario is poor. Influences to these errors can come from:

- Slightly unpredictable driving behaviour from TruckMakers' driver model, where it does not drive entirely centered in its lane.
- In very sharp corners, small deviations from the assumed radius will give quite large errors at the end of the time horizon. The integral part of the prediction

(recursively calculating forward from the current angle) stacks up the error.

- After passing the corner and the road is straight again, problems will occur if the truck or the predictions close to the truck have an angle that are not aligned with road heading. The later predictions will go straight out from this angle which may give a large error at the end of time horizon prediction. This can be seen Fig. 5.17. The final prediction should be centered in the right lane but due to a small angle of the truck the prediction is overlapping into the adjacent lane.

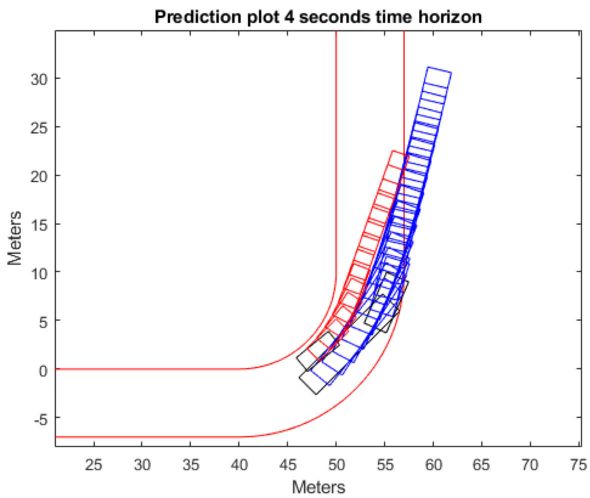

Figure 5.17: A plot of the predictions using a time horizon of four seconds to show angle errors at end of the turn.

Even though, the prediction performance would be one of the most important parts when implementing the function in a real truck, the main purpose of this thesis is the warning algorithm. Predictions could be improved given more time or different approaches to the topic. Ways to improve the predictions are discussed under section Future Work.

One conclusion drawn from the predictions results is the trade off between accuracy and prediction time. Long prediction time is needed to be able to give warnings with enough time for the driver to react to the warning. But a longer time horizon, yields higher level of degradation in path prediction accuracy.

5.5.2 Collision prediction performance

The collision prediction provides varying results depending on the scenario at hand. At constant velocities the predicted time of impact is very accurate, it does however suffer some deviations when quick acceleration, or deceleration are made. This is reasonable since a constant velocity model is used which only relies on the current velocity of the host and adjacent vehicle, and not how it changes over time. Even with changes in velocity it does however manage to predict within a reasonable time window from the actual time of collision, and could still be used in a meaningful way to assess the threat level of the situation.

For the sharp left turn it seems to make the most correct predictions. In the 45 meter radius curve it has some problems with the three second predictions where it makes an error in predicting that a collision will occur for a short period of time. For the right turn it suffers from rather large errors even at the 1.5 second predictions. This could be a result of the very sharp cornering that is executed, as the predictions are made based on the curvature of the upcoming trajectory. For these very low curvature values some additional inaccuracies could possibly occur.

5.5.3 Driver warning

These results are quite interesting. Even though the path prediction is a bit off, the collision prediction is still decent and gives good results for the warnings. All warnings are given ahead of time with a good margin of time. The warning time however is not entirely according to what is expected, equation (4.9). They are slightly below the value, which is not too unexpected since the equation defines the maximum value for the warning time, although it is the desired time. The two previous prediction functions would have to perform optimally to yield the desired signal warning length.

5.5.4 Emergency braking value & auto-emergency brake

The emergency braking is performing as intended in the given scenarios, where it always slow down the velocity of the truck a lot before the collision. Once again, this function is also heavily dependent on previous functions performance, which means that ALCWS performance also comes down to the performance of the path prediction.

5.6 Results summary and implications for real world implementation

Throughout the result section, it has been shown that the predictions and actions taken, i.e. braking and warning the driver, has been mostly successful in the test scenarios. The estimated time of impact is nearly identical to the actual time of impact. However, they do suffer from slight deviations during accelerations or decelerations as a constant velocity model is used. This should not pose any big implications in real world applications as the estimations will simply be updated in the next time step and adjusted accordingly and the automatic braking should only be applied when crash is already unavoidable.

Section 5.5.1 shows some limitations for the pose and position prediction if the heading angle of the vehicle deviates from the heading of the road. These deviations will affect ALCWS as it uses the predictions as a basis for warning the driver and applying brakes. These deviations reach their peak values for predictions of the vehicles after the corner is finished, i.e. when the danger of lane overlap is over.

This means that the predictions made for after the corner could simply be disregarded. However, as shown in Section 5.3, there are false detections in the 45 meter radius curve. Ideas of how to combat these false detections and improve upon the predictions will be presented in the following chapter.

5.7 Limitations and assumptions

Some limitations are known right now. Many of these limitations should be solvable given more time and development. Some assumptions made during the development will not be applicable for a real world implementation.

- Preview distance. In good conditions and on straight roads it may be possible to perfectly assess how the road looks. But during a sharp corner the road could be outside of view from the sensors, hence it will be hard to accurately estimate the road curvature and by extension predict future vehicle positions.

- Known heading. As we have designed the test scenarios and the path taken by both the truck and the adjacent vehicle we always know in which direction that the vehicles will turn. This might be problematic in junctions e.t.c where we can not really be sure that the truck is going to turn, nor how wide the turn through the corner will be. Looking at indicators, GPS and steering angle may be one way to predict driver intention. Still might be problematic in a large junction where there will be a big number of ways of how the driver performs the turn.

- Shape of the road. In the simulation the road is always perfectly wide, the radius is constant throughout the curve, the straights are straight, the lane widths are exact and the lateral slope is always zero. No roads will be this perfect in the real world. Hence some adaptions may be needed.

- Only one vehicle used as traffic, the considerations done are only when there is a car in the adjacent lane and it is going to be a collision. However in real traffic there might be several cars in the adjacent lane. Also not only in the adjacent lane but also behind and in front of the truck, hence the emergency braking may be a bad option in that case. This is a limitation that was decided for the scope of this project. Given more time exploration of adding more traffic should be doable.

- Different loads yields different brake distances. Hence an unloaded and loaded truck are viewed the same in the braking model, and if the equipage is heavier the braking distance will be longer and may cause a crash. As of today the truck and trailer do not share any information. But solutions for this has started in the industry [12] and soon also trailer might become smart and communicate with the tractor. From this parameters such as length and loads could be communicated to the active safety systems.

- Road conditions change in real world driving, especially on the northern hemisphere where there are snowy roads, wet roads and dry roads. Hence steering and braking performance of the truck will change over the course of a day and with even bigger changes over the course of a year. This could perhaps be solved by using road conditions models where perhaps vision data could be used to estimate road friction/condition.

- System stability analysis should be performed on ALCWS to ensure that it always functions properly. The different number of test tracks was throughout this project reduced to the different test scenarios described in the method chapter.

Some of the features should already be possible to implement, such as detection of lane cutting and prediction of colliding with stationary objects at low speed. The model needs to be tested against real roads with real trucks in order to know how the system would perform.

6
Conclusions and Future Work

6.1 Conclusions

It has been shown that implementing a system such as ALCWS as suggested in this thesis should be possible. Referring back to the aim and objectives in Section 1.2 and Chapter 4 describing the implementation of the developed ALCWS system.

- The path prediction provides an estimation of the future positions of the host- and adjacent vehicle given reliable sensor data describing the environment. The predictions have been used to estimate time of impact and manages to do so, but as time increases the deviation from the actual travelled path increases. Ways to address the increasing deviations will be discussed in Future work following this section.

- The threat assessment is made based on the predictions which evaluates when to warn the driver in the event that a potential collision is detected or when to apply brakes. This works well in the simulated scenarios with a known driver model.

- The development of an alternate path, LMP, was successful and yields a separate set of predictions from the outmost part of the road. During the testing on the sharp left turn, LMP could successfully evaluate that it could follow the outer side of the curve without causing a collision with the adjacent vehicle.

- The ADAS ALCWS works as intended based on the inputs from the TA. It follows the sequences as specified in section 4.3.1. The result is a system that determines in which order the commands should be evaluated and how the use the TA.

6.2 Future work

In this section potential improvements and additions to the current model will be discussed and why these are logical steps for a real world implementation of ALCWS.

6.2.1 Driver model & assumed heading

ALCWS currently uses a bicycle model which assumes the vehicle will follow a predetermined path along the road during the its predictions. It uses the current heading, position and velocity as initial inputs and follows a curve using a constant curvature. A real driver may choose to start then corner extra wide and then make a tighter turn and cut through parts of the corner. Further investigation should be made to see if there exist a general behaviour of drivers that could be expressed as a model to be used together with the bicycle model for a more advanced prediction model. Another approach would be to assume that the tractor heading is the same as the heading of the road itself. This way, even if the driver decides to drive out to the edge of the road before entering the curve, the heading used for the predictions will remain constant up until the curve. This will result is more consistent predictions and could improve the accuracy at longer time horizons.

6.2.2 Generalised warning signal

In its current state, ALCWS warns the driver when an apparent threat occurs based on a relatively short time horizon extending to a maximum of 3 seconds. To give the driver more headroom to react another layer could be added which warns if a tight curve is coming up which could lead to a compromising position. This could be based on road curvature readings at greater distances or GPS readings and help the driver to completely avoid ending up on an collision course.

6.2.3 Driving intervention

With improved models for more precise predictions it could be possible to intervene in the driving in more ways than just braking at the last second. An example would be to slowly adjust the vehicle to the outer side of the curve using autonomous driving so that the vehicle can pass safely with no risk of collision. It could also be realised through gently braking the tractor.

6.2.4 Multiple vehicle detection

A real world implementation would require multiple vehicle detection and evaluation of how braking intervention could affect the surrounding traffic participants.

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