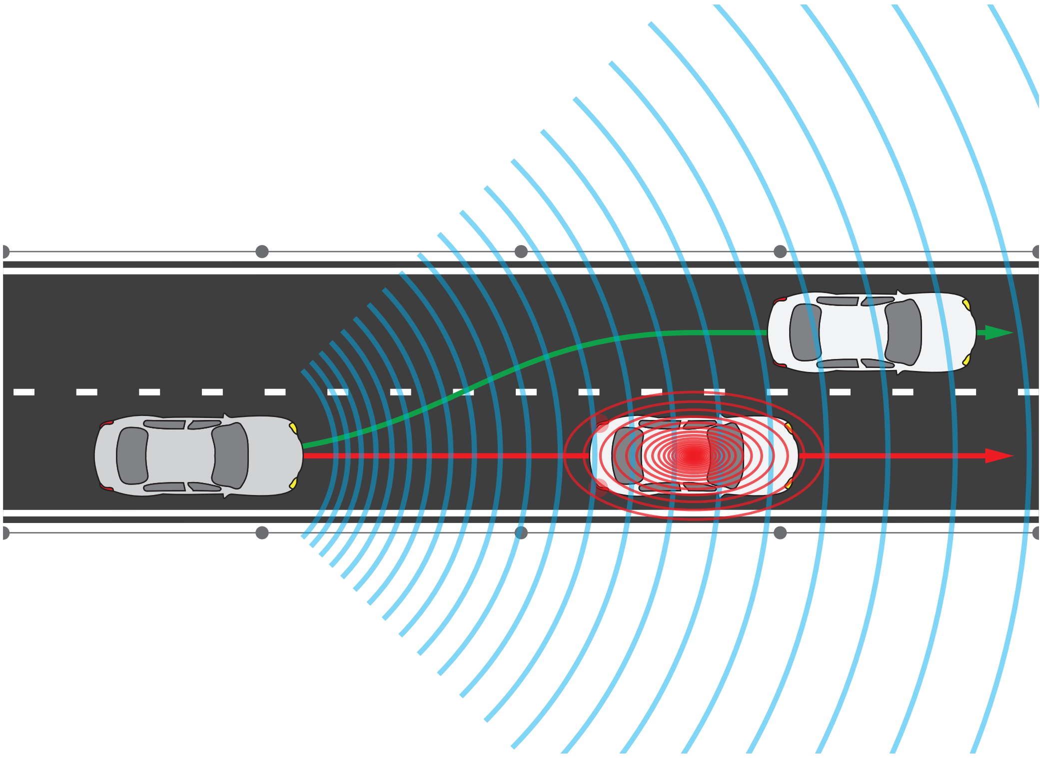

Multi-Target Threat Assessment for Autonomous Emergency Braking

Method based on particle filter for path planning and arithmetically calculated brake intervention evaluation

Master's thesis in System Control and Mechatronics

ANDREAS ANDERSSON

Department of Signals and Systems
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: Possible escape paths for the host vehicle.

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Abstract

While automotive manufacturers are trying their best to decrease the number and severity of road fatalities, the demand for Active safety features increases. Today, Active safety is the way ahead to decrease road fatalities even more and Autonomous Emergency Braking (AEB) and Forward Collision Warning (FCW) play a key role. The foundation of AEB and FCW is Threat Assessment (TA).

This thesis aims to provide an approach to improve the AEB and decrease the risk of road fatalities further than Single-target Threat Assessment is capable of. This is accomplished by evaluating multiple target vehicles and barriers, i.e. Multi-target Threat Assessment. The proposed approach, based on a particle filter, will evaluate the possible escape paths that the driver is expected to manage independently of the traffic scenario.

The particle filter approach solves the Multi-target Threat Assessment (MTTA) with only a few assumptions, making it versatile. However, the method requires more computational power compared to Spline Based Search Tree (SBST). On the other hand, the SBST requires a spline design that may only work in certain scenarios. While the versatility of particle filter presents a possible avoidance path close to a real avoidance maneuver, it also decreases the risk of getting killed in traffic when compared to Single-target Threat Assessment (STTA).

Multi-target Threat Assessment, Active safety, AEB, Automotive, Particle filter, Path planning.

Acknowledgements

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I would also like to thank Simon Andersson and Markus Carlander for interesting discussions regarding algorithms and my implementations.

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Andreas Andersson, Gothenburg, August 2016

Contents

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List of Tables

List of Algorithms

List of Acronyms

AEB Autonomous Emergency Braking. 1–3, 10, 15, 19, 21, 31–33, 47, 49–51

BTN Brake Threat Number. 7, 10, 11, 13, 19, 21, 23, 24, 31, 32, 35, 40, 41, 45, 47, 50

dt Sampling Time. 21

Euro NCAP European New Car Assessment Programme. 1, 2

FCW Forward Collision Warning. 2, 51

MPC Model Predictive Control. 7, 13, 14, 19
MTTA Multi-target Threat Assessment. 2, 3, 9, 10, 13, 19, 32, 39, 40, 48–50

SAT Separating Axis Theorem. 17, 21, 27
SBST Spline Based Search Tree. 7, 13–15, 19, 24, 28, 31, 32, 39, 42, 45–47, 49, 50
SIR Sequential Importance Resampling. 16, 24, 30
SIS Sequential Importance Sampling. 15, 16
STN Steer Threat Number. 10, 13, 15, 19, 24, 27, 28, 30–32, 35, 39–42, 46, 49, 50
STTA Single-target Threat Assessment. 2, 9, 10, 13, 32, 39, 40, 47–49

T Prediction Horizon. 20, 21
TA Threat Assessment. 2, 3, 10, 14, 15, 31, 32, 35, 39, 45, 51
TTC Time To Collision. 13, 37, 47

US NCAP The United States New Car Assessment Program. 1

VCS Vehicle Coordinate System. 5, 21

1

Introduction

The introduction gives a brief understanding of this report's topic and the background of today's Autonomous Emergency Braking (AEB) systems. It will also describe the importance of AEB in traffic accidents.

1.1 Background

Today, Active safety is common in both premium and standard cars. One of the plausible reasons, can be that European New Car Assessment Programme (Euro NCAP) is testing the cars Active safety systems (mainly AEB) and from 2018, active safety requirements will also be introduced in The United States New Car Assessment Program (US NCAP)'s ratings[3]. AEB may initially appear as a collision avoidance function, but in fact, it's mainly used for collision mitigation. According to studies done by the Swedish insurance company Folksam, AEB decreases the severity of injuries with 64% in rear end crashes on roads with speed limits below 50 km/h [4]. By reducing the speed with 10% before collision, the fatality risk can be reduced by 30% [5]. This demonstrates the importance of collision mitigation systems. For a visualization of the fatality risk at different speeds and cases, see figure 1.1.

The reason why AEB only acts as a collision mitigation system is because at high speed, it's more efficient to steer to avoid collision than to brake. So by the time it's

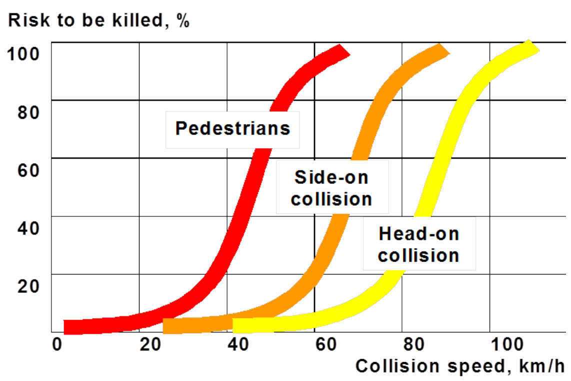

Figure 1.1: The risk of being killed at different impact speeds. The figure is copied from [1]

too late for the driver to avoid collision by steering, it's also too late for braking. And one important thing with Active safety is that it should never interfere with the driver, only assist the driver when needed. So with these matters considered, the car should only apply AEB when collision is unavoidable, i.e. the driver can't avoid the collision with either steering or braking.

1.1.1 Threat Assessment

In some Active safety systems, e.g. AEB and Forward Collision Warning (FCW), Threat Assessment (TA) is key for decision making. The Active safety system evaluates the situation based on the threat other target vehicles causes the host vehicle, i.e. TA. It may also be based on the threat the host vehicle causes the target vehicles. TA is usually split up in two categories; Single-target and Multi-target.

1.1.2 Single-target Threat Assessment

In today's Euro NCAP tests, the scenarios involving cars alone, only require Single-target Threat Assessment (STTA), i.e. algorithms looking solely at one target at the time. So if a steering maneuver is blocked by another target vehicle, the system will not take that into consideration and still draw the conclusion that the driver can avoid the collision by steering. This will result in applying the AEB too late every time.

One approach to evaluate the threat is to calculate how difficult a maneuver is, i.e. calculate threat numbers. The threat number describes how difficult a maneuver is by comparing required action with the capacity of either the car or the driver [2].

1.1.3 Multi-target Threat Assessment

While STTA only looks at one target at the time, multiple targets may still exist in the scenario. Multi-target Threat Assessment (MTTA) looks at all (or some) targets in the field of view and uses that information in the decision making. Either escape paths can be evaluated with that information or MTTA can conclude that an escape path doesn't exist.

MTTA is not required for the current Euro NCAP rating involving cars alone, but it can be important in real life collision situations. An AEB system from 2010 might manage to reduce the speed maximally around 35 - 40 km/h [6], but if the system at an earlier state predicts that the driver is unable to avoid collision, it could be possible to go beyond that limit. The limit exists since it's possible to steer at a later state than brake, to avoid collision at high speeds. To go beyond the limit of 35 - 40 km/h, the steering intervention must be excluded before a braking intervention is too late. By evaluating all targets and barriers, an escape path can be excluded as an option for the driver and the conclusion that braking is the only option can be made. As described in section 1.1, decreasing speed before collision has great impact on fatality outcome. If the system at an early stage can distinguish that the driver has no or little chance to avoid collision, the system can intervene earlier and decrease the impact speed even further, or in a best case scenario, avoid the collision entirely.

This report proposes to use particle filter for calculation of MTTA, where the particle filter designs an avoidance maneuver path. The path is assigned a threat number based on the amplitude of lateral accelerations required to follow it. Instead of lateral accelerations, steer angle and angular velocity can also be used to assign a threat number [7]. However, the different approaches require different models describing the host vehicle's movement.

1.2 Contributions

Methods for MTTA has already been developed, however, they are often based on assumptions on how avoidance maneuvers are designed. This report proposes an MTTA algorithm that handles path planning with only few assumptions which results in a method with high versatility. It consists of a particle filter (section 3.3.2) which estimates an avoidance maneuver by steering. MTTA also requires a method estimating an avoidance maneuver by braking. The proposed method is a modification based on an earlier developed method (section 2.1.1) and allows it to be evaluated arithmetically for increased computational speed (section 3.3.2).

The evaluation of the proposed MTTA will be carried out in three different scenarios described below. The first and third scenarios will demonstrate multi-target case, while scenario two will represent a single-target cases. Results will be based on tests described in section 3.4.

1.2.1 Scope

Several different situations can occur in real life traffic scenarios, but this thesis concentrates on three scenarios in particular. To investigate the essentials of the topic and to test the developed TA and AEB-function, following scenarios are proposed:

1. multilane driving with sudden braking of two adjacent target vehicles.
2. multilane driving with sudden braking of one target vehicle while another target vehicle continues driving.
3. countryside driving with sudden braking of one lead target vehicle while another target vehicle is oncoming in the adjacent lane.

In all scenarios, the braking target vehicles brake with $a = 4\ m/s^2$.

1.2.1.1 Scenario one: Two adjacent target vehicles, both braking

In the first scenario, the host vehicle is driving behind one target vehicle while another target vehicle is driving in the adjacent lane. The target vehicles and the host vehicle drive at constant and equal speed. Due to intense traffic or a potential accident, the target vehicles brakes hard while the driver in the host vehicle is distracted and won't notice the sudden braking of the target vehicles. An avoidance maneuver by steering will be blocked by the target vehicles and barriers next to the road.

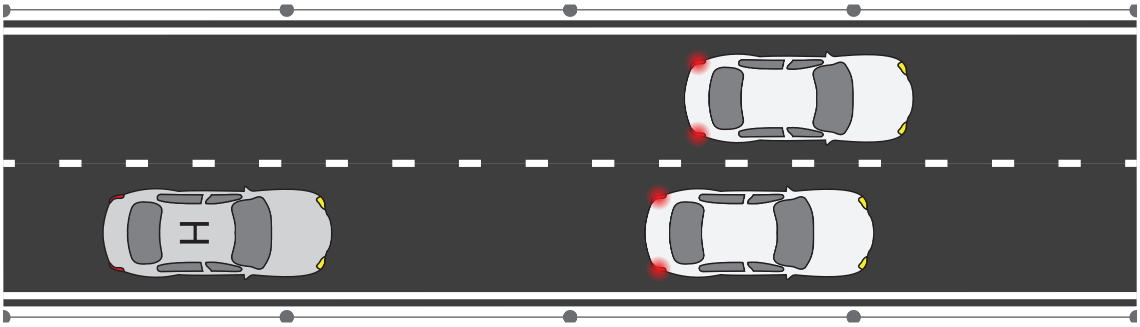

Figure 1.2: Two parallel driving target vehicles that applies the brakes simultaneously and braking to a stop

1.2.1.2 Scenario two: Two adjacent target vehicles, one braking

As in the first scenario, there is intense traffic or a potential accident but it only affects the lane of the host vehicle. The target vehicle in the adjacent lane will therefore continue at constant speed while the target vehicle in the same lane as the host vehicle will brake hard. In this case, an avoidance maneuver by steering will be possible, i.e. a lane change maneuver.

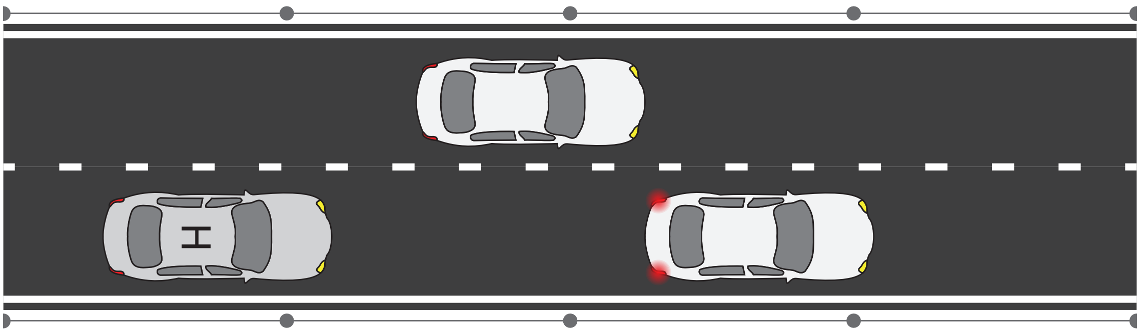

Figure 1.3: Two parallel driving target vehicles where the target vehicle in front of the host vehicle braking to a stop

1.2.1.3 Scenario three: One target vehicle braking, one target vehicle approaching

As in previous scenarios, a target vehicle in front of the host vehicle will brake hard due to intense traffic or a potential accident. But now the adjacent lane has the opposite driving direction. At the time of collision, an oncoming target vehicle will be in the adjacent lane, blocking any steering maneuvers.

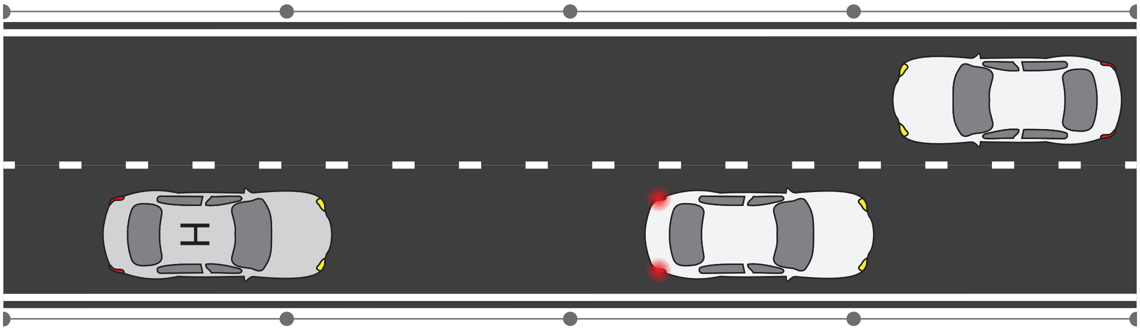

Figure 1.4: Two target vehicles, one oncoming and one in front of the host vehicle. The target vehicle in the host vehicle's lane is braking to a stop.

1.2.2 Limitations

For a more focused report and topic, a couple of limitations are stated:

- only cars are regarded as target vehicles.
- ideal sensor performance.
- the simulation environment (IPG Automotive's CarMaker) is considered to match real life dynamics of cars.
- implementation on embedded hardware is not considered.

1.3 Coordinate system

The coordinate system used in this report is a Vehicle Coordinate System (VCS), meaning the positions of the target vehicles are relative the host vehicle. The global position is unnecessary when developing an active safety feature. The speed and acceleration of the target vehicles are always tangential to the target vehicle itself and the speed and acceleration of the host vehicle is always tangential to the host vehicle itself.

The origin location of VCS may differ between reports. However, in this report, the origin is located in center of the host vehicle's front bumper, figure 1.5. Lateral

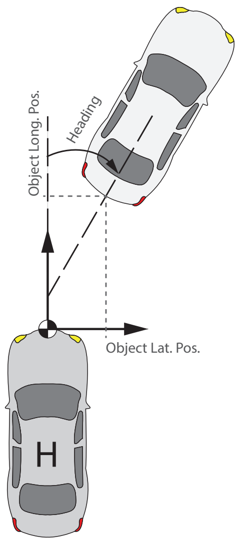

Figure 1.5: Vehicle Coordinate System (VCS) configuration used in the report

and longitudinal positions of the target vehicles are measured from the origin to the center of the rear end bumpers of the target vehicles.

1.4 Thesis outline

The introduction is followed by chapter 2, Theory, where underlying theory needed for the algorithms are described. Also, earlier research and ideas are briefly described. The earlier research presented are Brake Threat Number (BTN) [2], State lattice, Model Predictive Control (MPC) and Spline Based Search Tree (SBST) [8], where BTN and SBST will act as bench mark algorithms for proposed BTN and particle filter method. These researches will be built upon or act as inspiration for the algorithms developed in chapter 3, Method. New methods will be proposed and evaluated. Simulation tests are presented in chapter 4 followed by discussion regarding the results, chapter 5, and finally, conclusion and future work are presented in chapter 6.

2

Theory

In this chapter, earlier developed methods for STTA and MTTA are described together with other theorems and algorithms needed for the development described in the method chapter. An overview of required parts are visualized in figure 2.1.

Figure 2.1: Flow chart describing key parts of a Threat Assessment algorithm

Following sections will describe the underlying theory of the flowchart. Calculations of threat number BTN is described in section 2.1.1 where the theory required for collision detection is described in section 2.3. The calculation of threat number Steer Threat Number (STN) can be computed with STTA, section 2.1.2, or with MTTA, sections 2.1.2.1 to 2.1.2.3. Underlying theory for a particle filter is described in section 2.2.

2.1 Threat Assessment

The key component behind AEB is the TA. The TA evaluates the threat level of other objects in the field of view, e.g. pedestrians, cars, trucks, bikes and so on (only cars are considered in this report). The TA is usually divided into two parts; BTN and STN [2]. Each of those two parts can be calculated by evaluating the effort needed to either brake or steer to avoid collision. As mentioned in section 1.1, TA can be evaluated for each object individually (single-target) or together (multi-target).

2.1.1 Brake Threat Number

The BTN describes how difficult a collision avoidance maneuver by braking is, i.e. the amount of the cars full braking potential that is required. The value BTN <= 1 defines that it's possible to avoid collision by braking and BTN = 0 suggests that there is no threat. To calculate BTN, a couple of variables are initially defined (values collected from [2]):

Table 2.1: Variables for longitudinal dynamics while braking. Values are collected from [2]

	Value	**Unit**
c	0.8	
j_{min}	-10 c	m/s^3
a_{min}	-15 c	m/s^2
t_d	0.08/c	s

The variable a_{min} denotes the largest negative acceleration and j_{min} the largest negative jerk the driver can achieve by braking. Jerk is the derivative of acceleration and it's assumed to be constant while $a > a_{min}$ and the car is braking. The jerk is also assumed to change as a step. The time constant, t_d, is the assumed time delay in the brake system between applied brake signal and the start of the deceleration (t_d changes when the brake signal has been applied already). The unitless constant c denotes what can be expected of the system, i.e. $c = 0.8$ means that the system/car is expected to perform 80% of its full potential.

To calculate the BTN, following equation has been proposed by a patent [9] and several articles [2, 10]:

$$\text{BTN} = \frac{a_{rec}}{\widetilde{a_{min}}} \tag{2.1}$$

where a_{rec} is the required acceleration to achieve relative speed (the difference between the target vehicle's speed (v_t) and the host vehicle's speed (v_h)) $v_t - v_h = 0$ at impact. The calculated required and maximal deceleration is shown in figure 2.2.

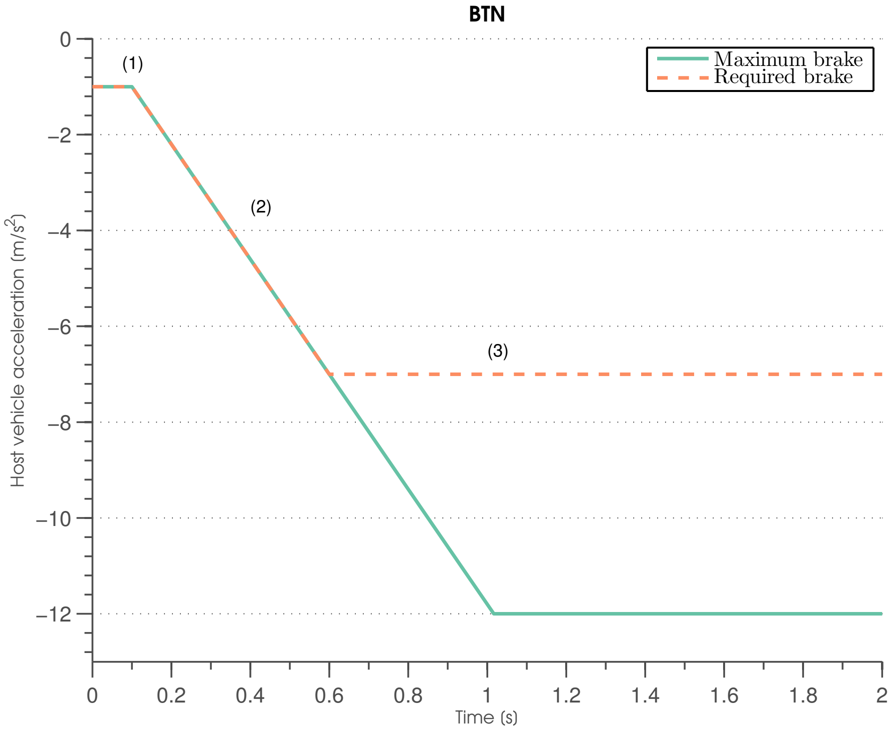

Figure 2.2: Maximum deceleration that can be achieved by the driver compared to the required deceleration to avoid collision

The calculations of BTN according to [2] is as follows: The host velocity

$$v(t_s + t_d) = (v_h + a_h t_d) + a_h t_s + j_{min} \frac{t_s^2}{2} \tag{2.2}$$

describes the part (1) and (2) in figure 2.2. By solving equation (2.2) when $v(t_s + t_d) = 0$ gives

$$t_s = -\frac{a_h}{j_{min}} + \sqrt{\frac{a_h^2}{j_{min}^2} - 2\frac{v_h + a_h t_d}{j_{min}}}. \tag{2.3}$$

and

$$\widetilde{a_{min}} = max(a_{min}, a_h + j_{min} t_s). \tag{2.4}$$

The variables v, a and j denotes the speed, acceleration and jerk and the subscript h denotes the host vehicle while the subscript t denotes the target vehicle.

The calculation of a_{rec} is not straight forward. First of all, there are two different cases to consider when deriving a_{rec}; the target vehicle is moving at collision or the target vehicle is stationary at collision. That is because if the target vehicle is decelerating, the target vehicle is assumed to decelerate until it's stationary and not continue in reverse.

First range and range rate are calculated. The range

$$r(\tilde{t}) = r_0 + (v_t - v_h)\tilde{t} + (a_t - a_h)\frac{\tilde{t}^2}{2} - j_{min}\frac{\tilde{t}^3}{6} \tag{2.5}$$

describes the distance to a specific target vehicle at time t where $\tilde{t} = t - t_d \geq 0$ and

$$r_0 = R_{long} + (v_t - v_h)t_d + (a_t - a_h)\frac{t_d^2}{2} \tag{2.6}$$

where R_{long} is the initial longitudinal range to the target vehicle measured by the host vehicle's sensors. In a similar way, the range rate is formulated as

$$\dot{r}(\tilde{t}) = \dot{r}_0 + (a_t - a_h)\tilde{t} - j_{min}\frac{\tilde{t}^2}{2} \tag{2.7}$$

and

$$\dot{r}_0 = \dot{R}_{long} + (a_t - a_h)t_d. \tag{2.8}$$

The acceleration of the host vehicle while $\tilde{t} \geq 0$ is

$$a_j(\tilde{t}) = a_h + j_{min}\tilde{t}. \tag{2.9}$$

For the case when the target vehicle is moving at collision, the constant acceleration needed to avoid collision is

$$a_m(\tilde{t}) = a_t - \frac{\dot{r}(\tilde{t})^2}{2r(\tilde{t})}. \tag{2.10}$$

Solving $a_j(\tilde{t}) = a_m(\tilde{t})$ gives $\tilde{t} = t_x \geq 0$ and

$$a_{rec} = a_h + j_{min}t_x. \tag{2.11}$$

But this is only valid for the case where the target vehicle is still in motion at collision, i.e. if

$$\begin{aligned} 0 &<= v_t + a_t t_c \\ t_c &= t_x + t_d - \frac{2r(t_x)}{\dot{r}(t_x)} \end{aligned} \tag{2.12}$$

where t_c is the time of collision.

If the statement above isn't valid, i.e. the target vehicle is stationary at collision, the range and the range rate needs to be redefined as

$$r_s(\tilde{t}) = r_0 + r_t - v_h\tilde{t} - a_h\frac{\tilde{t}^2}{2} - j_{min}\frac{\tilde{t}^3}{6} \tag{2.13}$$

where r_0 is described in equation (2.6) and

$$r_t = -\frac{v_t^2}{2a_t} \tag{2.14}$$

and

$$\dot{r}_s(\tilde{t}) = -v_h - a_h t_d - a_h \tilde{t} - j_{min} \frac{\tilde{t}^2}{2}. \tag{2.15}$$

In this case, solving $a_j(\tilde{t}) = a_s(\tilde{t})$ gives $\tilde{t} = t_x > 0$ which is applied in equation (2.11) and finally can BTN be calculated with equation (2.1).

2.1.2 Steer Threat Number

The definition of STN is similar to the definition of BTN and it's included in the patent [9] and the articles [2, 10] as well:

$$\text{STN} = \frac{a_{rec,lat}}{a_{max,lat}} \tag{2.16}$$

where $a_{max,lat} = 7\ m/s^2$ is the maximum lateral acceleration the general driver can perform. A lateral acceleration of $7\ m/s^2$ correspond to driving $\sim$ 30.1 km/h in a roundabout with a radius of ten meters. In STTA, [2] proposes to calculate

$$a_{rec,lat} = \frac{2R_{lat}}{t_c^2} \tag{2.17}$$

where R_{lat} is the required lateral displacement to avoid a collision and t_c is the Time To Collision (TTC).

In STTA it's easy, but $a_{rec,lat}$ is not as easy to calculate in MTTA. In [8], three MTTA methods are investigated and compared; State Lattice, MPC and SBST. The three approaches are described briefly below; sections 2.1.2.1 to 2.1.2.3.

2.1.2.1 State Lattice

State lattice is a graph-based path planning technique that takes kinematic and dynamic constraints into account. This is managed by sampling of state and control spaces [11]. This result in a graph that can be visualized as a grid of nodes on the road connected by edges which describes controllable trajectories (figure 2.3). In each time sample, the algorithm can search for the cheapest collision free path. For instance, the cheapest path can be the path with lowest jerk or acceleration. The maximum acceleration or jerk in that path can be used to calculate STN with equation (2.16).

State lattice easily handles a high number of target vehicles but the precision of the method is directly related to the lattice resolution [8].

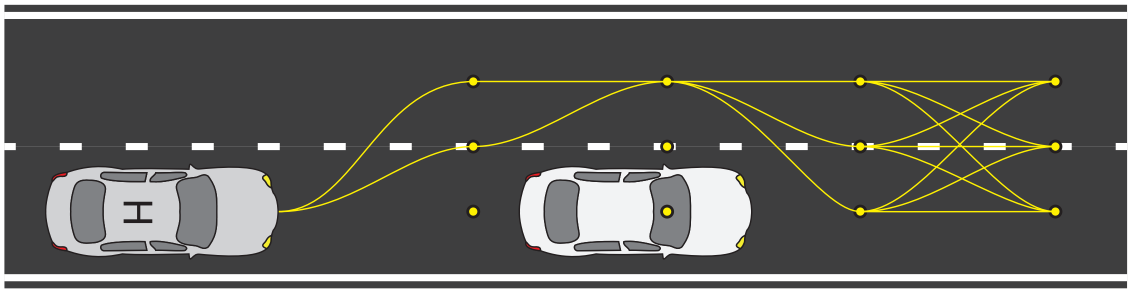

Figure 2.3: State lattice representation where the edges are computed from vehicle dynamics and constraints (This is just an illustration of the splines and the paths are not calculated!)

2.1.2.2 Model Predictive Control

The MPC, is a finite-horizon controller that optimizes the sequence of inputs to minimize a cost function based on predictions of a dynamic model. This is managed while considering the input and state constraints [12].

MPC has the leverage of managing trajectory planning with predictions and constraints. A function is used to describe the safety of a path (or in the general case a cost). Road boundaries (e.g. road edges and barriers) and target vehicles can be constraints for the predicted path, while maximum wheel angle and angle rate can be constraints on the control input. The TA is based on the severity of the control input strategy the MPC proposes.

Yet, solving an MPC for complex scenarios is not a straight forward method and requires a large amount of computational power.

2.1.2.3 Spline Based Search Tree

The third and last approach uses splines for path planning. Splines are a path that is piecewise-defined by polynomials. By using cubic splines, the third derivative of the position, jerk, will be constant throughout one segment. Between segments, jerk is assumed to be able to switch amplitude and sign as a step. The result will be a spline that minimizes jerk, i.e. returns the cheapest path [8]. The nodes are placed next to the target vehicles due to an assumption that the cheapest path is either to go straight or turn and barely touch the target vehicle [10]. To get a differentiable jerk, quintic splines can be used instead [8].

The work flow for SBST proposed by [10] is: all maneuvers passing one target vehicle to the left and to the right are added to a graph. Next, all maneuvers passing two target vehicles to the left respectively to the right are added to the graph. This continues with as many target vehicles as desired, see figure 2.4. With all possible splines placed in a graph, the graph is searched and paths leading to collision are removed. If the graph becomes empty, no steering maneuver is possible to avoid collision. If not empty, the graph is searched for the cheapest path which will be used to calculate STN.

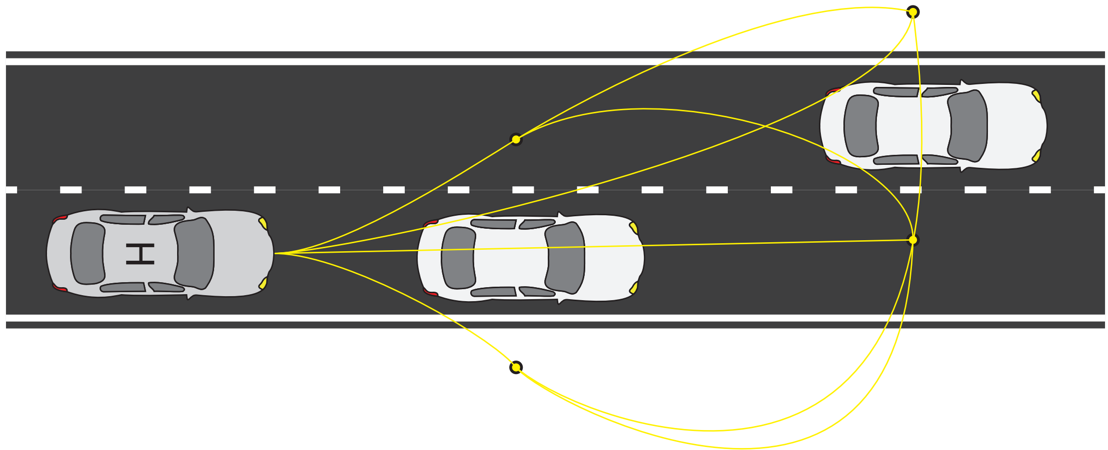

Figure 2.4: Spline representation where the nodes is based on the target vehicles positions. The splines connecting the nodes is an illustration of one possible design. Polynomial order and spline design are adjustable.

The article [8] concludes that the SBST is computationally effective and returns a path sufficient for TA for AEB. However, the path is not equally useful as a reference for an autonomous steering maneuver, since the steep steps in jerk will be uncomfortable for the driver. It also increases in complexity (graph size) with the number of target vehicles considered.

2.2 Particle filter

Gaussian approximations are often used for filtering problems. But some problem's filtering distributions are multi-modal or has some states that may be discrete components, which makes Gaussian approximations inapplicable. In those cases, a particle filter may be more suitable. Particle filter is a method to form Monte Carlo approximations to solutions of Bayesian filter equations [13].

A general algorithm for a particle filter without resampling called Sequential Importance Sampling (SIS) is presented in algorithm 1.

Algorithm 1 Sequential Importance Sampling (SIS)

1: Draw N particles $x_0^{(i)}$ from prior distribution

$$x_0^{(i)} \sim p(x_0), \quad i = 1, ..., N \tag{2.18}$$

and put their weights $w_0^{(i)} = 1/N, \quad \forall i = 1, ..., N$

2: **for** k=1,...,T where T is the period time **do**

3: Draw new particles from the dynamic model

$$x_k^{(i)} = p(x_k | x_{k-1}^{(i)}), \quad i = 1, ..., N \tag{2.19}$$

4: Update weights

$$w_k^{(i)} = w_{k-1}^{(i)} \times p(y_k | x_k^{(i)}), \quad i = 1, ..., N \tag{2.20}$$

y_k is measured states

5: Normalize weights

$$w_k^{(i)} = \frac{w_k^{(i)}}{\sum_{i=1}^{N} w_k^{(i)}}, \quad i = 1, ..., N \tag{2.21}$$

6: **end for**

Particle filters comes in different varieties and Sequential Importance Resampling (SIR) is usually referred to as the *particle filter* [13]. The SIR filter was introduced when resampling was added to SIS. The problem with SIS was that situations could occur where almost all of the particles had zero weight or almost zero weight. This is referred to as the *degeneracy problem* in the literature about particle filtering and prevented the algorithms to be implemented in practical applications.

The resampling procedure refers to when N new samples/particles are drawn from the discrete distribution defined by the particles weights and replaces the old set of particles, $\hat{x_k} \implies x_k$ [14].

The main idea behind the resampling procedure is to remove particles with very low weight and duplicate particles with high weight. The weights are then set to $w_k^{(i)} = 1/N$ to leave the distribution unchanged. The variable $w_k^{(i)}$ is the particle i's weight at time sample k. In SIR, resampling is not carried out every sampling instance, only every n'th sample instance, where n is a design constant, or with *adaptive resampling*. In adaptive resampling, the effective number of particles is estimated by the variance of the weights

$$n_{eff} \approx \frac{1}{\sum_{i=1}^{N} \left(w_k^{(i)}\right)^2}. \tag{2.22}$$

The resampling is then executed when the number of effective particles, n_{eff} is less than a threshold n_{thresh} [13], e.g $n_{eff} < N/10$. The algorithm describing SIR is shown in algorithm 2.

Algorithm 2 Sequential Importance Resampling (SIR)

Draw N particles $x_0^{(i)}$ from prior distribution

$$x_0^{(i)} \sim p(x_0), \quad i = 1, ..., N \tag{2.23}$$

and put their weights $w_0^{(i)} = 1/N, \quad \forall i = 1, ..., N$

for k=1,...,T where T is the period time **do**

Draw new particles from the dynamic model

$$x_k^{(i)} = p(x_k | x_{k-1}^{(i)}), \quad i = 1, ..., N \tag{2.24}$$

Update weights

$$w_k^{(i)} = w_{k-1}^{(i)} \times p(y_k | x_k^{(i)}), \quad i = 1, ..., N \tag{2.25}$$

y_k is measured states

Normalize weights

$$w_k^{(i)} = \frac{w_k^{(i)}}{\sum_{i=1}^{N} w_k^{(i)}}, \quad i = 1, ..., N \tag{2.26}$$

if $n_{eff} < n_{thresh}$, n_{eff} is calculated with equation (2.22) **then**

Draw N particles from the discrete distribution formed by the weights $w_k^{(i)}, \quad i = 1, ..., N$

Replace the old set of particles with the new $\hat{x_k}^{(i)} \implies x_k^{(i)}, \quad i = 1, ..., N$

Set all weights to $w_k^{(i)} = 1/N, \quad i = 1, ..., N$

end if

end for

2.3 Separating Axis Theorem

In order to investigate if collision will occur along the predicted paths, Separating Axis Theorem (SAT) can be used. The theorem states that if two convex polygons can be separated with an axis perpendicular to an edge of either one of the polygons, then no overlap/collision exists [15].

In this case there are two polygons shaped as rectangles, which are convex. A rectangle representing the host vehicle and another representing a target vehicle (one collision investigation for each target vehicle). By projecting the rectangles' corners onto each axis parallel to the rectangles' edges and without overlap between the projected corners, a separating axis exists and no collision has occurred (figure 2.5). If there is an overlap on every axis, then a collision has occurred.

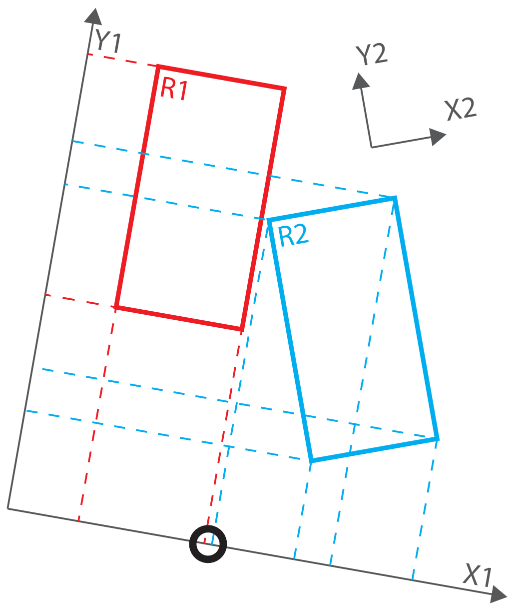

Figure 2.5: Illustration of the Separating Axis Theorem. The corners of both rectangles are projected on the axes (Y1 and X1) parallel to rectangle R1's edges. There are overlaps on the axis Y1 but not on the axis X1, consequently there is an axis perpendicular to X1 that separates the rectangles. Result: No collision.
There is no need to project the corners on axis Y2 and X2 because a separating axis is already located.

Each of the rectangles has four axes perpendiculars to its edges (eight axes together). Two of those are parallel with the other two, so instead of projecting all corners to all eight axes, the corners only needs to be projected on four of them.

By translating and rotating the two rectangles into one of the rectangles local space, no projection needs to be done on that rectangles axis, because the rectangles are already projected in the x- and y-axis. By doing this, the algorithm executes faster and if a separation between the corners can be established on the normal x- and y-axis, no axis projection are required.

3 Method

This chapter presents implemented methods. Initially, how collision detection is implemented with path prediction, section 3.1, followed by arithmetically calculated BTN, section 3.2, based on BTN calculated in section 2.1.1. Later, implementation of SBST, presented in section 2.1.2.3, is proposed followed by particle filter based STN, section 3.3.2. Finally, section 3.4 describes the performed test which results are presented in the chapter Results.

The methods and algorithms used in this report are based on earlier work described in Theory, chapter 2. As for BTN, some modifications have been made for computational improvements and regarding STN, a new approach is proposed. An overview of the entire system is illustrated in the flow chart (figure 3.1).

As mentioned in section 2.1.2, SBST is a computationally effective and sufficient solution to evaluate STN and in [8], the results from the other two methods (MPC and State Lattice) doesn't seem to outperform the SBST-method, i.e. they have similar maximum amplitudes of the lateral acceleration. The article [8] reflects the differences between the algorithms, stating that all of them works for AEB, but some are more suitable as reference for an autonomous steering maneuver, which is not used in this report. On that account, SBST will be used as a benchmark algorithm for STN in this report.

The new approach, to use a particle filter, for STN calculations is developed to avoid the assumptions on how an avoidance path is designed. Also, a new approach to the MTTA problem will be proposed, particle filter. Even though the problem is not a filtering problem, Monto Carlo sampling offered an interesting approach to path planning.

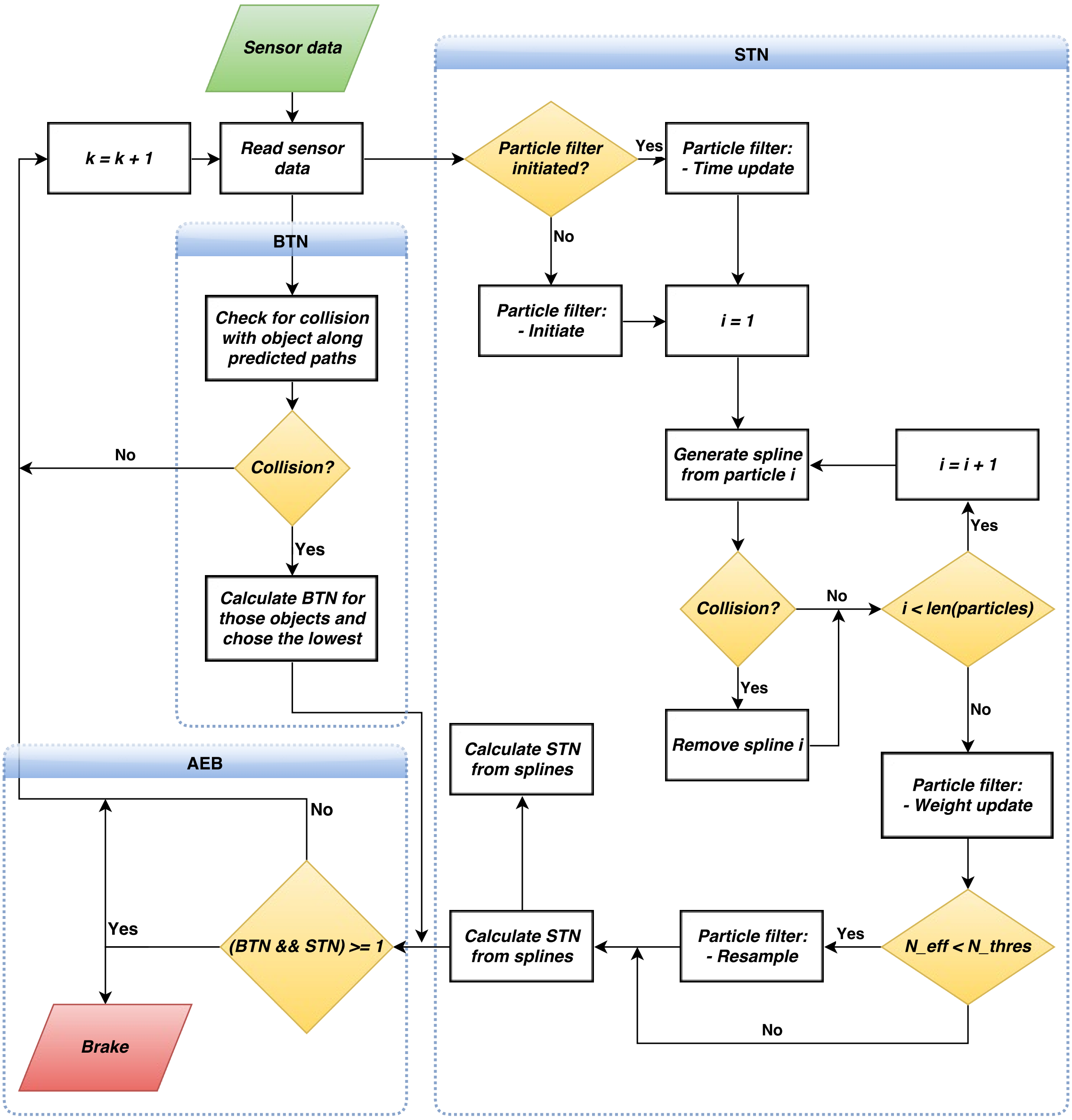

Figure 3.1: Flow chart describing the key components in the proposed threat assessment algorithm

3.1 Collision detection

To investigate if the host vehicle's path will lead to collision with a target vehicle, the future paths of the host vehicle and the target vehicles are desired for comparison.

3.1.1 Path prediction

The path prediction is executed with a model assuming constant acceleration and yaw rate during the prediction horizon. As for the path estimation, a Prediction

Horizon (T) equal to two seconds is used and a Sampling Time (dt) of $0.05s$. Two seconds is higher than the TTC when engaging the AEB in the scenarios and velocities considered in this report. The choosen T and dt results in 40 discrete points with longitudinal and lateral positions

$$\begin{aligned} p_{long,h} &= (v_h t + a_h t^2)\cos(\dot{\theta}_h t) \\ p_{lat,h} &= (v_h t + a_h t^2)\sin(\dot{\theta}_h t) \end{aligned} \tag{3.1}$$

and the heading

$$\theta_h = \dot{\theta}_h t \tag{3.2}$$

where v_h and a_h are the tangential velocity and acceleration of the host and $0 \leq t \leq T$. The initial positions and heading are equal to zero, consequently the coordinate system is VCS (see section 1.3), i.e longitudinal and lateral position and the heading is zero at $t = 0$.

Similar equation remains for the target vehicles, except that initial heading and positions are included. The discrete points with longitudinal and lateral positions will then be

$$\begin{aligned} p_{long,t} &= (v_t t + a_t t^2)\cos(\theta_t + \dot{\theta}_t t) + p_{0_{long,t}} \\ p_{lat,t} &= (v_t t + a_t t^2)\sin(\theta_t + \dot{\theta_{0_t}} t) + p_{0_{lat,t}} \end{aligned} \tag{3.3}$$

and the heading

$$\theta_t = \dot{\theta}_t t + \theta_{0_t} \tag{3.4}$$

A collision between the host vehicle and a target vehicle can now be investigated in each discrete point with SAT (section 2.3).

3.2 Brake Threat Number

The calculation of BTN in section 2.1.1 required numerical calculations and in this section, a BTN that can be solved arithmetically will be presented. The calculation for BTN is as follows:

$$\text{BTN} = \frac{r_c - r_{max}}{r_c}. \tag{3.5}$$

The threat number BTN will be evaluated with equation (3.5) which will evaluate the distance driven ($r_c - r_{max}$) while applying maximum brake until the range rate is zero, with the distance to collision (r_c). This provides a threat number based on the amount of brake capacity required to avoid collision. Both BTN approaches, equation (3.5) and equation (2.1), assume that j_{min} is applied during all brake scenarios independent of necessary acceleration. The variable r_c in equation (3.5) is the longitudinal distance to collision and r_{max} is the longitudinal distance to the target vehicle after a maximum brake intervention.

To calculate r_{max} a couple of steps are essential for the evaluation. First, the time until a_{min} is reached while j_{min} is applied (part (2) in figure 2.2. In this section, “part” followed by a number will refer to that figure!)

$$t_j = \frac{a_{min} - a_h}{j_{min}} \tag{3.6}$$

where a_{min} is the maximum deceleration that can be achieved, j_{min} is the maximum derivative of a, jerk, that can be achieved while braking and a_h is the initial acceleration of the host vehicle. The values for a_{min} and j_{min} are presented in table 2.1.

(Following equations are mostly duplicates of equations from section 2.1.1). In the equations below, range and range rate are calculated. As earlier, h denotes the host vehicle and t denotes a target vehicle. The range

$$r(t) = r_0 + (v_t - v_h)t + (a_t - a_h)\frac{t^2}{2} - j_{min}\frac{t^3}{6} \tag{3.7}$$

where $r(t)$ is the distance to that specific target vehicle at time t in part (2) ($t = 0$ in the beginning of part (2)). The initial range

$$r_0 = R_{long} + (v_t - v_h)t_d + (a_t - a_h)\frac{t_d^2}{2} \tag{3.8}$$

gives the initial condition of the range for part (2) where R_{long} is the initial distance to the target vehicle before part (1). The time constant t_d is the assumed time delay in the brake system between applied brake signal and the start of the deceleration (t_d changes when the brake signal has been applied already) and with the value listed in table 2.1. And in a similar way for the range rate

$$\dot{r}(t) = \dot{r}_0 + (a_t - a_h)t - j_{min}\frac{t^2}{2} \tag{3.9}$$

and

$$\dot{r}_0 = \dot{R}_{long} + (a_t - a_h)t_d. \tag{3.10}$$

If $\dot{r}(t_j) < 0$ then the brakes has to be applied for a longer while, i.e. while $a = a_{min}$ (part (3)). The range rate during part (3) is

$$\dot{r}_a = \dot{r}(t_j) + (a_t - a_{min})t_a \tag{3.11}$$

and solving that equation for $\dot{r}_a = 0$, hence the braking intervention is done, gives

$$t_a = -\frac{\dot{r}(t_j)}{a_t - a_{min}}. \tag{3.12}$$

As in section 2.1.1, two cases are dealt with; the target vehicle is moving at the time of collision and target vehicle is stationary at the time of collision. To investigate if the target vehicle was stationary or not at the collision, equation

$$\begin{aligned} 0 &\leq v_t + a_t t_c \\ t_c &= t_d + t_j + t_a \end{aligned} \tag{3.13}$$

is solved and if it's true, then the target vehicle was moving and

$$r_{max} = r(t_j) + \dot{r}(t_j)t_a + (a_t - a_{min})\frac{t_a^2}{2} \tag{3.14}$$

where $r(t_j)$ is the solution of equation (3.7) for t_j and $\dot{r}(t_j)$ is the solution of equation (3.9) for t_j. Once r_{max} has been calculated, equation (3.5) can be evaluated to compute BTN. If equation (3.13) wasn't true then some new equations needs to be solved instead. First

$$\dot{r}_s(t) = -v_h - a_h t_d - a_h t - j_{min}\frac{t^2}{2}. \tag{3.15}$$

If $\dot{r}_s(t_j) < 0$ then the brakes has to be applied for a longer period of time, i.e. while $a = a_{min}$ (part (3)) as mentioned above. Now

$$\dot{r}_{s_a} = \dot{r}_s(t_j) - a_{min}t_a \tag{3.16}$$

and solving that equation for $\dot{r}_{s_a} = 0$, hence the braking intervention is done, gives

$$t_{s_a} = \frac{\dot{r}_s(t_j)}{a_{min}}. \tag{3.17}$$

The range is now

$$r_s(\tilde{t}) = r_0 + r_t - v_h\tilde{t} - a_h\frac{\tilde{t}^2}{2} - j_{min}\frac{\tilde{t}^3}{6} \tag{3.18}$$

where r_0 is described in equation (3.8) and

$$r_t = -\frac{v_t^2}{2a_t}. \tag{3.19}$$

$$r_{max} = r_s(t_j) + \dot{r}_s(t_j)t_{s_a} - a_{min}\frac{t_{s_a}^2}{2} \tag{3.20}$$

r_{max} can be used in equation (3.5) to calculate BTN.

If $\dot{r}_s(t_j) \geq 0$, then t_j must be recalculated, hence $\dot{r}_s = 0$ before a is saturated to a_{min}. Solving for t_j when equation (3.15) is zero

$$t_{j,1} = -\frac{a_h}{j_{min}} + \sqrt{\frac{a_h^2}{j_{min}^2} + \frac{2(v_h + a_h t_d)}{j_{min}}}. \tag{3.21}$$

The time variable $t_{j,1}$ is then inserted into

$$r_{max} = r_0 + r_t - v_h t_{j,1} - a_h\frac{t_{j,1}^2}{2} - j_{min}\frac{t_{j,1}^3}{6} \tag{3.22}$$

and r_{max} can be used in equation (3.5) to calculate BTN.

If $\dot{r}(t_j) \geq 0$, then

$$t_{j,2} = \frac{a_t - a_h}{j_{min}} + \sqrt{\frac{(a_t - a_h)^2}{j_{min}^2} + \frac{2\dot{r}_0}{j_{min}}} \tag{3.23}$$

and if

$$0 \leq v_t + a_t t_c \\ t_c = t_d + t_{j,2} \tag{3.24}$$

then

$$r_{max} = r_0 + (v_t - v_h)t_{j,2} + (a_t - a_h)\frac{t_{j,2}^2}{2} - j_{min}\frac{t_{j,2}^3}{6} \tag{3.25}$$

and r_{max} can be used in equation (3.5) to calculate BTN.

If equation (3.24) was false, then equation (3.21) and equation (3.22) are calculated and afterward used in equation (3.5). The threat number BTN is now evaluated and what remains is STN which is evaluated in the next section.

3.3 Steer Threat Number

The calculation of STN will be carried out according to suggested equation in section 2.1.2

$$\text{STN} = \frac{a_{rec,lat}}{a_{max,lat}}. \tag{3.26}$$

The acceleration $a_{rec,lat}$ is evaluated with two different approaches. The first one is the SBST. But that method depends on assumptions on where the switching of the jerk levels are taking place, i.e. assumptions on how an avoidance maneuver is designed. To avoid those kinds of assumptions, a particle filter, i.e. SIR-filter, are introduced to find paths at random and iterate those until they have converged.

3.3.1 Spline Based Search Tree

The splines consists of “cubic splines” which results in constant jerk between the nodes. A result is that the jerk will be minimized with the assumption that it can be applied as a step. This is preferred due to the goal to minimize the acceleration. The cubic splines are

$$\begin{aligned} \frac{d^3y}{dx^3} &= (-1)^{i+1}k \\ \frac{d^2y}{dx^2} &= (-1)^{i+1}kx + a_{i,2} \\ \frac{dy}{dx} &= (-1)^{i+1}k\frac{x^2}{2} + a_{i,2}x + a_{i,1} \\ y(x) &= (-1)^{i+1}k\frac{x^3}{6} + a_{i,2}\frac{x^2}{2} + a_{i,1}x + a_{i,0} \end{aligned} \tag{3.27}$$

where y and x denotes lateral and longitudinal positions and i denotes the segment index. To calculate the coefficients $a_{i,j}$ and k, the number of segments and equality conditions for the transitions between the segments needs to be established. To do so, an avoidance maneuver design is required.

Defining a maneuver that uses the smallest amount of lateral acceleration to avoid collision independent on scenario is not an easy task, if not even impossible. Some assumptions may be satisfying in certain scenarios and worse in others.

Two maneuvers will be evaluated in this report; constant turn in one direction (one segment spline) (figure 3.2), and a s-shaped spline (three segments spline) (figure 3.3). The resulting accelerations in those two maneuvers are compared in figure 3.4.

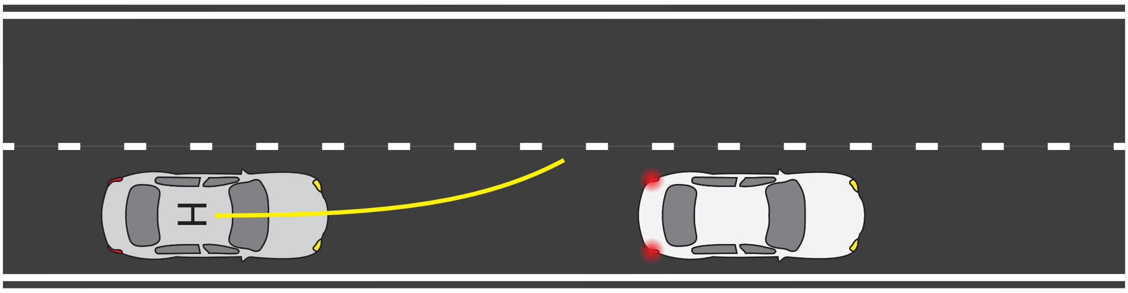

Figure 3.2: One segment spline

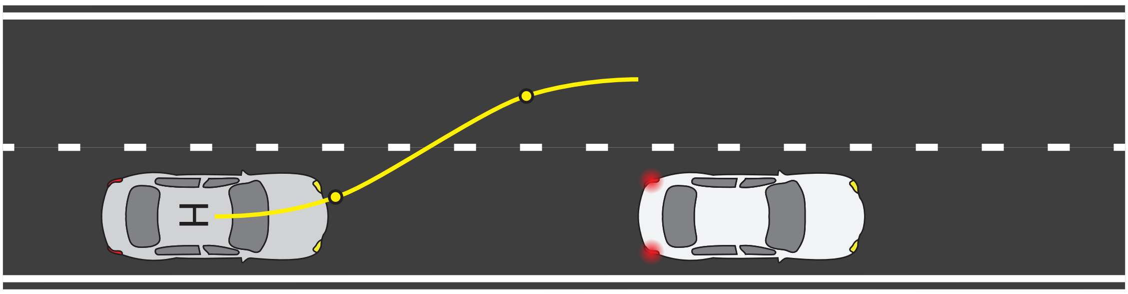

Figure 3.3: Three segment (s-shaped) spline

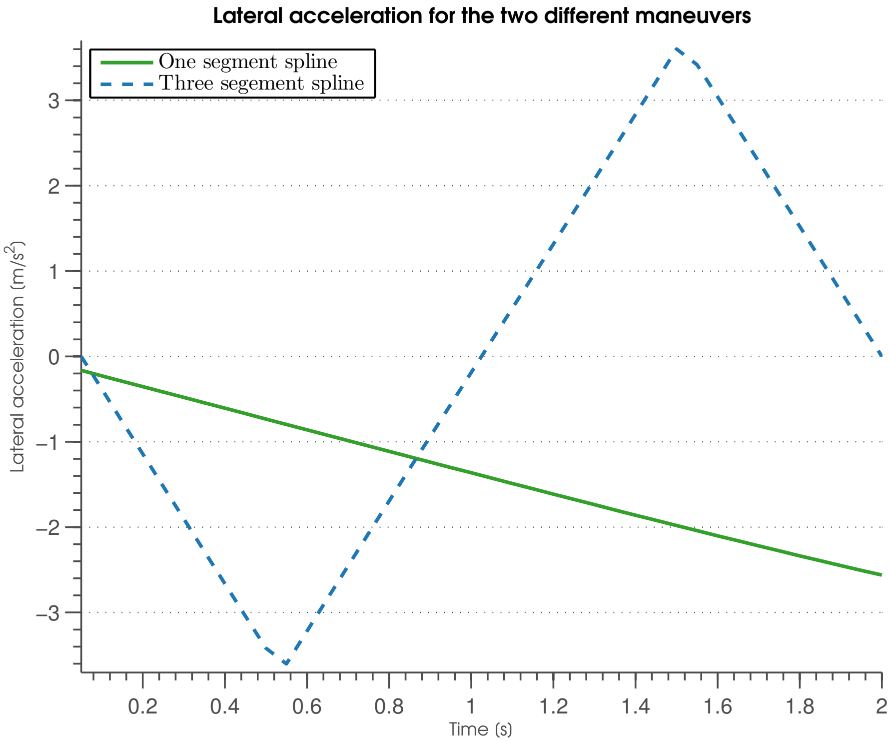

Figure 3.4: The lateral acceleration to avoid the target vehicle in front of the host with a maneuver to the left

To solve equation (3.27) with the one segment spline is rather straight forward. Four coefficients $(k, a_{1,2}, a_{1,1}, a_{1,0})$ require four equality constraints. What's known for an avoidance maneuver to the left is the start (the host vehicle's front right corner) and end position (the target vehicle's rear left corner), the host vehicle's speed, heading and yaw rate. For a maneuver to the right the host vehicle's front left corner and the target vehicle's rear right corner is used instead. These combined results in four constraints to solve the linear system

$$\begin{bmatrix} \frac{x_0^3}{6} & \frac{x_0^2}{2} & x_0 & 1 \\ \frac{x_e^3}{6} & \frac{x_e^2}{2} & x_e & 1 \\ \frac{x_0^2}{2} & x_0 & 1 & 0 \\ x_0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} k \\ a_{1,2} \\ a_{1,1} \\ a_{1,0} \end{bmatrix} = \begin{bmatrix} y_0 \\ y_e \\ \frac{dy_0}{dx_0} \\ \frac{d^2y_0}{dx_0^2} \end{bmatrix} \tag{3.28}$$

where x_0 and y_0 is the longitudinal and lateral start position of the spline, x_e and y_e is the longitudinal and lateral end position of the spline. $\frac{dy_0}{dx_0}$ and $\frac{d^2y_0}{dx_0^2}$ are given by equation (3.29), and equation (3.30).

$$\frac{dy_0}{dx_0} = \tan\theta_0 \tag{3.29}$$

where θ is the heading and equation (3.29)'s derivative

$$\frac{d^2y_0}{dx_0^2} = \frac{\dot{\theta}_0}{v_h}\frac{1}{\cos^2\theta} \tag{3.30}$$

where v_h is the host vehicle's speed.

For the three segment spline, the same conditions are applied but additional six are needed due to ten (instead of four) unknown coefficients. The additional conditions state that y, $\frac{dy}{dx}$ and $\frac{d^2y}{dx^2}$ will remain equal in the transition between the end of previous segment and in the start of the next segment. These constraints results in the linear system

$$\left[\begin{array}{c|ccc|ccc|ccc} -\frac{x_0^3}{6} & \frac{x_0^2}{2} & x_0 & 1 & 0 & \dots & \dots & \dots & \dots & 0 \\ -\frac{x_0^2}{2} & x_0 & 1 & 0 & \dots & \dots & \dots & \dots & \dots & 0 \\ -x_0 & 1 & 0 & \dots & \dots & \dots & \dots & \dots & \dots & 0 \\ -\frac{2x_1^3}{6} & \frac{x_1^2}{2} & x_1 & 1 & -\frac{x_1^2}{2} & -x_1 & -1 & 0 & \dots & 0 \\ -\frac{2x_1^2}{2} & x_1 & 1 & 0 & -x_1 & -1 & 0 & \dots & \dots & 0 \\ -2x_1 & 1 & 0 & 0 & -1 & 0 & \dots & \dots & \dots & 0 \\ \frac{2x_2^3}{6} & 0 & \dots & 0 & \frac{x_2^2}{2} & x_2 & 1 & -\frac{x_2^2}{2} & -x_2 & -1 \\ \frac{2x_2^2}{2} & 0 & \dots & 0 & x_2 & 1 & 0 & -x_2 & -1 & 0 \\ 2x_2 & 0 & \dots & 0 & 1 & 0 & 0 & -1 & 0 & 0 \\ -\frac{x_e^3}{6} & 0 & \dots & \dots & \dots & \dots & 0 & \frac{x_e^2}{2} & x_e & 1 \end{array}\right] \begin{bmatrix} k \\ a_{1,2} \\ a_{1,1} \\ a_{1,0} \\ a_{2,2} \\ a_{2,1} \\ a_{2,0} \\ a_{3,2} \\ a_{3,1} \\ a_{3,0} \end{bmatrix} = \begin{bmatrix} y_0 \\ \frac{dy_0}{dx_0} \\ \frac{d^2y_0}{dx_0^2} \\ y_1 \\ \frac{dy_1}{dx_1} \\ \frac{d^2y_1}{dx_1^2} \\ y_2 \\ \frac{dy_2}{dx_2} \\ \frac{d^2y_2}{dx_2^2} \\ y_e \end{bmatrix}. \quad (3.31)$$

One spline (either the one segment or the three segments) is calculated to pass each target vehicle of interest to the left and to the right. Then a combination is done to add splines after each other that passes two target vehicles (and more if desired) on all combination of sides. All of these combinations are added to a graph that can be search for the cheapest spline that doesn't lead to collision with barriers or target vehicles. The collision detection for target vehicles is carried out with SAT (section 2.3). For barriers, all corners of the host vehicle can be investigated. If one or more are on the wrong side, collision has occurred.

When the splines that leads to collision has been erased, the splines left are paths that avoids collision (if splines no longer exists, no maneuver is possible). To evaluate the easiest spline to follow, STN is desired, then the lateral acceleration throughout the splines must be calculated. According to [16], the lateral acceleration can be approximated as

$$a_{lat} \approx \kappa \cdot v_h^2 \quad (3.32)$$

where v_h is the host vehicle's speed and the curvature

$$\kappa = \frac{\frac{d^2y}{dx^2}}{(1 + \frac{dy}{dx}^2)^{\frac{3}{2}}}. \quad (3.33)$$

Each spline will then get a STN by inserting $a_{rec,lat} = \max(a_{lat})$ in equation (3.26) and the spline with the lowest STN determines the STN of the scenario.

3.3.2 Particle filter

The SBST-method depends on its assumptions and maneuver designs. To avoid assumptions on how a perfect maneuver is carried out, an algorithm designing and evaluating the path by itself, is desirable. The particle filter makes those features possible, even though the problem itself, is not a filtering problem. The particle filter makes an initial guess, evaluates it, changes the guesses based on that evaluation and updates it according to the measurements. Therefore an algorithm that can manage to solve the path planning on its own is established.

The particle filter is not living a life of its own, it demands configuration and later tuning to perform as desired. The key part is how to evaluate a suitable path. In this case, a suitable path is a path that has low lateral accelerations and avoids collisions.

For a particle filter, a high particle weight induce that the particle has a high plausibility to survive the resampling. If a particle has the weight zero, then it has no plausibility to survive the resampling at all. Initially, particles that create a spline leading to collision, will be given weight zero.

The goal is to find an avoidance maneuver that is as simple as possible to carry out. In this case (the STN calculation in section 3.3), the lateral acceleration is a measurement of that. So the particles that create splines with low lateral accelerations, should be given high weights. That can be implemented in multiple ways, e.g. from the sum of the accelerations or jerks. But that gave splines with large steps in jerk large weights, while a log barrier function (equation (3.39)) gave them smaller weights. The log barrier function resulted in a particle filter that managed to find solutions until STN ≤ 1 with less particles.

The particle needs a couple of states to produce a spline. As in [10], the jerk is applied as a constant signal between nodes and assumed to be able to switch amplitude and sign at the nodes separating the segments. The states are as follows:

$$\begin{bmatrix} j_0 \\ \vdots \\ j_N \\ dt_0 \\ \vdots \\ dt_N \\ h_0 \\ \vdots \\ h_{N-1} \end{bmatrix} \tag{3.34}$$

where $j_{0:N}$ is the jerk, $dt_{0:N}$ is the duration in time and $h_{0:N-1}$ is the duration offset in each segment in the spline. A condition for the states

$$T = \sum_{i=0}^{N-1} (dt_i + h_i) + dt_N \tag{3.35}$$

where T is the time horizon and decided in beforehand.

The optimal magnitude of the jerk levels $j_{0:N}$ are unknown, so an initial guess is made

$$j_i = \mathcal{N}(0, \sigma_j^2), \quad \forall i = 0, ..., N \tag{3.36}$$

where $\mathcal{N}$ is the normal distribution. The mean value is $\mu = 0$, hence a maneuver can be either to the left or to the right and σ_j is the standard deviation. The standard deviation is a design parameter to get satisfying splines in all situations where an avoidance maneuver is possible.

The time variables $dt_{0:N}$ are placed where a switch of jerk is assumed suitable (figure 3.5). The assumptions in this report conclude that a switch of jerk is assumed to be suitable beside a target vehicle and half the distance (in time) to that target vehicle. The final spline always lasts until the end of the time horizon T, equation (3.35).

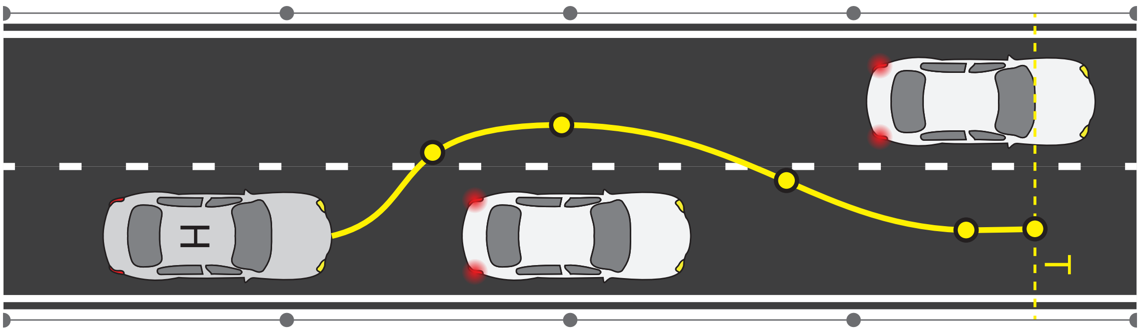

Figure 3.5: The position of the nodes depends on the target vehicles' position. A node is placed next to a target vehicle and another between that node and the previous. A final node is placed at the end of the prediction horizon.

The assumption that the switching of jerk is carried out when next to a target vehicle and half way there, might be incorrect, or only correct in some cases. The duration offset gives some flexibility to those assumptions by moving the switching point back and forth

$$h_i = \mathcal{N}(0, \sigma_h^2), \quad \forall i = 0, ..., N \tag{3.37}$$

where $t_i = dt_i + h_i$ for each spline. The splines

$$\begin{aligned}
\dddot{y} &= j_i \\
\ddot{y} &= j_i t + a_{i,2} \\
\dot{y} &= j_i \frac{t^2}{2} + a_{i,2} t + a_{i,1} \\
y &= j_i \frac{t^3}{6} + a_{i,2} \frac{t^2}{2} + a_{i,1} t + a_{i,0}
\end{aligned} \tag{3.38}$$

where $a_{i,2}$ is the lateral acceleration, $a_{i,1}$ is the lateral velocity and $a_{i,0}$ is the lateral position at the beginning of each segment, hence at $t = 0$.

The weighting function was defined as a weight $= 0$ meaning collision has occurred and otherwise the weight is calculated with a log barrier function

$$g(j_i) = -\log(-|j_i| - j_t) + \log(j_t) \tag{3.39}$$

where j_t is the "jerk threshold". The chosen threshold should be greater than maximum possible lateral jerk. If the threshold is set to the exact maximum possible jerk, those splines will reach a substantially low weight and probably vanish in the resample. In all possible maneuvers survival is desired and STN is required to reach the value one at least every time an avoidance maneuver is possible, therefore some margin is desired. The weight of the particle is

$$w = \frac{1}{\sum_{i=0}^{N} g(j_i)} \tag{3.40}$$

where $g(j_i)$ is calculated with equation (3.39).

The particle filter follows the work flow of the SIR-filter, algorithm 2. The time update works as follows:

Algorithm 3 Time update for the implemented Sequential Importance Resampling (SIR) filter

---

1: Calculate time to target vehicles TV_k, where the TV's is ordered in ascending order from $i = 0 \rightarrow$nTargetVehicles
2: Store the old duration values $odt_{0:N-1} = dt_{0:N-1}$
3: **for** $k = 0, ..., k_f$ where $k_f = \frac{N-1}{2}$ is the number of included objects in the spline configuration **do**

$$\begin{aligned} dt_{2k} &= \frac{TV_k}{2} \\ dt_{2k+1} &= \frac{TV_k}{2} \end{aligned} \tag{3.41}$$

4: **end for**
5: **for** $i = 0, ..., N-1$ **do**

$$h_i = h_i + \mathcal{N}(0, \sigma_{h,u}^2) \tag{3.42}$$

6: **end for**
7: Calculate the remaining time until the time horizon T is reached

$$dt_N = T - \sum_{i=0}^{N-1} (dt_i + h_i) \tag{3.43}$$

8: Update the jerk levels according to the change of duration time
9: **for** $i = 0, ..., N$ **do**

$$j_i = \frac{6a_{i,1}odt - 6a_{i,1}dt + 3a_{i,2}odt^2 - 3a_{i,2}dt^2 + j_i odt^3}{dt^3} \tag{3.44}$$

10: **end for**

---

where equation (3.44) is derived from the expression that the lateral positions should be equal before and after the change of duration of the spline

$$j_i \frac{odt^3}{6} + a_{i,2}\frac{odt^2}{2} + a_{i,1}odt + a_{i,0} = j_{0_i}\frac{dt^3}{6} + a_{i,2}\frac{dt^2}{2} + a_{i,1}dt + a_{i,0} \tag{3.45}$$

and j_{0_i} is the jerk applied in the previous time step.

When all particles/splines are calculated, the spline with the lowest maximum acceleration is searched for. This acceleration will be named $a_{rec,lat}$ and give the STN through equation (3.26).

Now the TA is complete after both BTN and STN are calculated.

3.4 Tests and verification

In order to test the performance of the methods and whether the assumptions are maintained or not, test runs are desirable. However to test real life AEB-scenarios are dangerous, expensive and the reproducibility is low. A workaround for all of the above, without neglecting reliable results, is to use simulations in a well-developed environment with life-like dynamics. In this report, IPG Automotive's simulation software CarMaker is used for this purpose. It opens up the possibility for multiple repeated tests and fast development. Also, the software can be connected to Simulink for easy integrations with MATLAB or run compiled c-code.

For all test cases involving the particle filter, 300 particles will be used. Fewer particles increase the computational speed but may lower the quality of the results.

The sections below represents the sections in the chapter 4, Results.

3.4.1 Method comparisons

The developed methods are evaluated with methods developed in earlier research. The arithmetically calculated BTN will be evaluated with BTN described in section 2.1.1 and the particle filter based STN will be evaluated with STN calculated in section 3.3.1, SBST.

3.4.1.1 Brake Threat Number

To test that the arithmetically computed BTN perform as well as BTN described in section 2.1.1, BTN is observed while approaching a target vehicle (scenario one, figure 1.2). Both the host vehicle and the target vehicle drive in the same lane at 70 km/h. The target vehicle suddenly brakes with an acceleration of 4 m/s^2. The host vehicle maintains the initial speed and the test continues until BTN = 1 is passed for both methods.

Only one scenario is required, because the target vehicle in the host vehicle's lane acts the same in all three scenarios.

3.4.1.2 Steer Threat Number

The comparison of the particle based STN and the STN calculated in section 3.3.1 (SBST) involves all the scenarios. Both types of spline designs will be used in comparison with the particle filter.

In all the scenarios, the host vehicle and the target vehicles will start with a speed of 70 km/h. In scenario one, both target vehicles will brake with an acceleration of 4 m/s^2. In scenario two and three, only the lead vehicle in the host vehicle's lane will brake with an acceleration of 4 m/s^2, while the other target vehicle will continue driving without braking.

3.4.2 Brake intervention evaluation

To test if MTTA perform better than STTA, the scenario one and three will be compared to scenario two. In scenario two, only one target vehicle acts as a threat to the host vehicle, so it resembles a single-target scenario. At high speeds, the MTTA is supposed to perform as a STTA in scenario two, but outperforms it in scenario one and three. In those two scenarios, MTTA is supposed to realize that an avoidance maneuver for the driver by steering isn't possible leaving braking as the only option to avoid collision.

3.4.2.1 Collision avoidance

To verify the TA's (figure 3.1) performance (BTN and STN both integrated in the AEB together), CarMaker is set up to run all the three scenarios (section 1.2.1) at different speeds (30, 50, 70, 90 and 110 km/h). The AEB is activated if the threat numbers are > 1 or if BTN > 1 and no avoidance maneuver is possible. The result will demonstrate the performance of the MTTA but also compare it to STTA.

The target vehicle in front of the host vehicle always starts three seconds further down the road and when the target vehicles brake, they brake with $a = 4\ m/s^2$.

3.4.2.2 Particle filter based Steer Threat Number

By only looking at whether a collision did or didn't occur can be misleading when drawing conclusions. If the TA rules out an avoidance maneuver by steering too early, the system will have more time to avoid collision, but it could be an early brake intervention, i.e. braking while the driver may still have control of the situation. This is key part in active safety applications, to never interfere with the driver while he/she may have control of the situation, since that could lead to huge discomfort for him/her.

To evaluate this, scenario two is used with the same configuration as in section 3.4.1.1 and the driver in CarMaker is programmed to do an avoidance maneuver as late as possible. An early brake intervention is triggered if the system activates the brakes when an avoidance maneuver by steering is still possible. If a steering maneuver is initiated, the AEB is disengaged.

4

Results

The proposed TA, i.e. particle filter based STN and arithmetically calculated BTN, is evaluated with earlier research in section 4.1. The performance of the TA is presented in section 4.2.

4.1 Method comparisons

The TA (figure 3.1) is evaluated with earlier research in scenarios described in section 1.2.1.

4.1.1 Brake Threat Number

Both approaches (the numerically and the arithmetically calculated BTN) crosses the threshold ($BTN = 1$) at the same time (figure 4.1), so they commence braking simultaneously and neither of them outperforms the other when looking at timing of brake decision. But the proposed approach (section 3.2) is faster to calculate due to the fact that it can be calculated arithmetically and therefore has an advantage over the numerically calculated BTN.

Comparison between the two approaches for 30, 50, 90 and 110 km/h are included in appendix B.

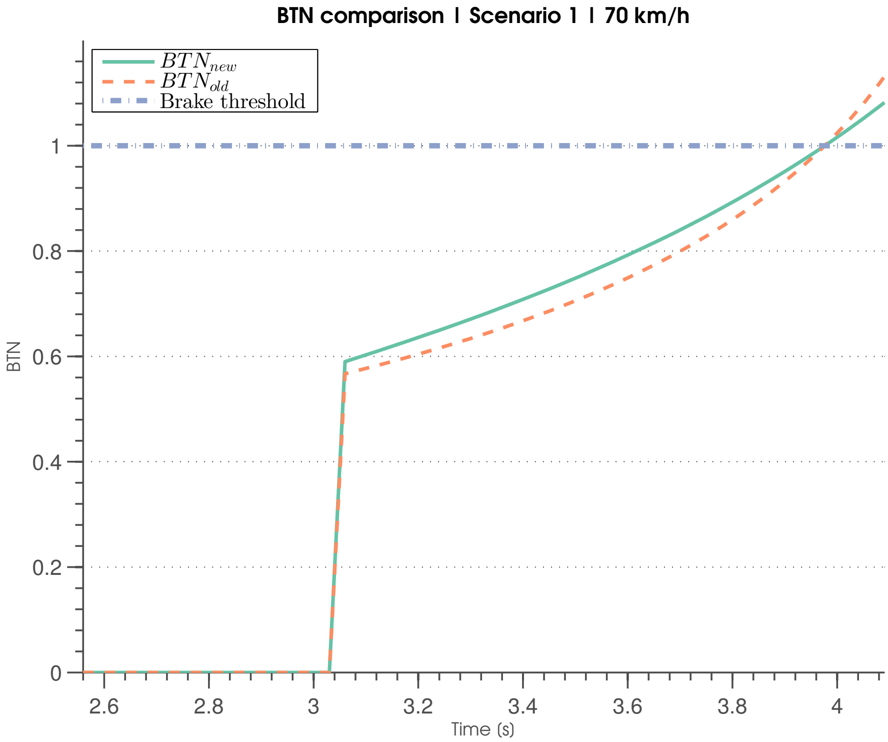

Figure 4.1: A comparison between numerically calculated Brake Threat Number (BTN) (BTN_{old}) and arithmetically calculated Brake Threat Number (BTN) (BTN_{new}). The Brake threshold indicates $BTN = 1$

4.1.2 Steer Threat Number

For scenario one, figure 4.2, all three methods come to the conclusion that an avoidance maneuver is no longer possible after approximately 3.5s (which is correct due to the path being blocked in both lanes). In figures 4.2 to 4.4, the threshold is the limit for when a steering maneuver is no longer possible to avoid collision. The end point of the lines shows when there are no paths avoiding collision.

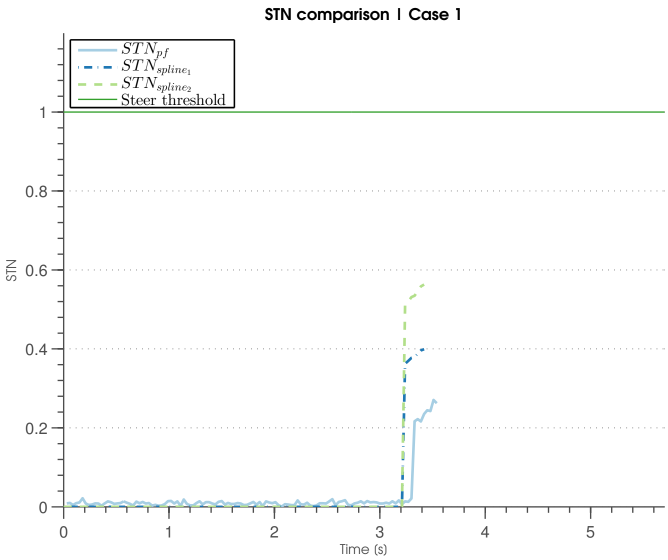

Figure 4.2: Steer Threat Number (STN) for scenario one where STN_{pf} is the particle filter based method, STN_{spline_1} is the Spline Based Search Tree (SBST) with one segment spline and STN_{spline_2} is the SBST with three segment (s-shaped) spline.

While an avoidance maneuver wasn't possible in scenario one, the case is different in scenario two. The target vehicle to the left of the host vehicle continues at constant speed, leaving a steering maneuver to the left lane possible to avoid collision with the target vehicle braking in the host vehicle's lane. The result is shown in figure 4.3 where all methods finds an avoidance maneuver. All methods state that the critical threshold $STN = 1$ is reached at different times. The two segment (s-shaped) spline, STN_{spline_2} in figure 4.3, crosses first. This is not unexpected due to its larger accelerations throughout the spline compared to the one segment spline (figure 3.4). The particle filter base method crosses last, i.e. the particle filter state that an avoidance maneuver by steering is possible at a lower TTC.

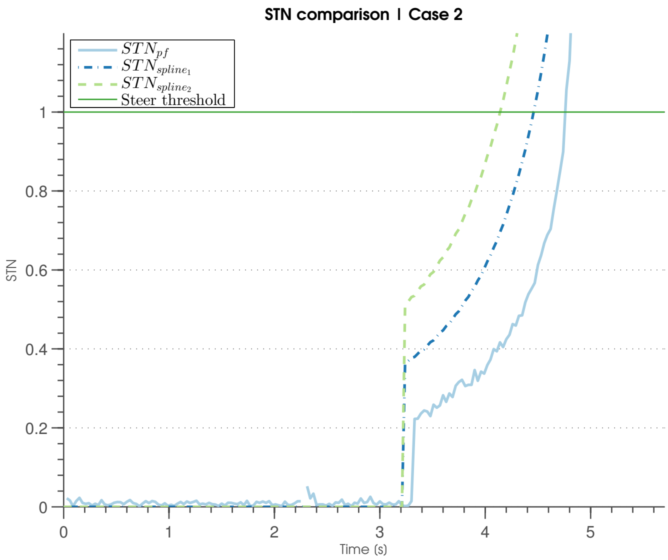

Figure 4.3: Steer Threat Number (STN) for scenario two where STN_{pf} is the particle filter based method, STN_{spline_1} is the Spline Based Search Tree (SBST) with one segment spline and STN_{spline_2} is the SBST with three segment (s-shaped) spline.

In scenario three, as in scenario one, an avoidance maneuver will be blocked by a oncoming vehicle in the adjacent lane. But this time it's an approaching target vehicle blocking the lane change. Yet again, figure 4.4, all three methods manage to realize that an avoidance maneuver is not possible.

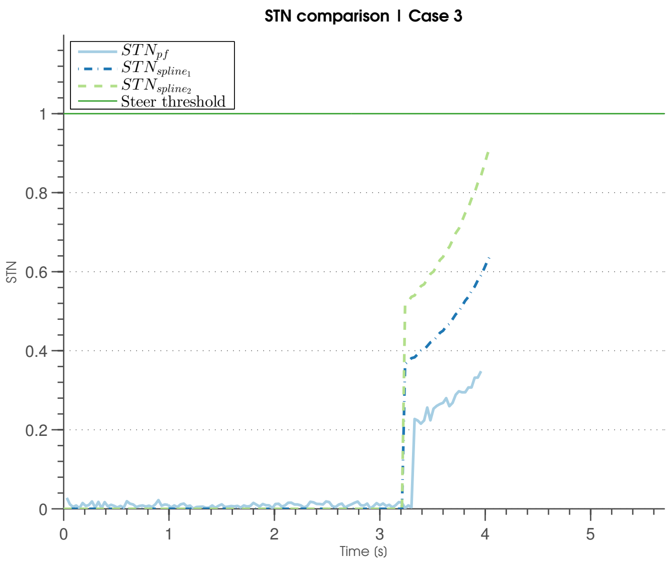

Figure 4.4: Steer Threat Number (STN) for scenario three where STN_{pf} is the particle filter based method, STN_{spline_1} is the Spline Based Search Tree (SBST) with one segment spline and STN_{spline_2} is the SBST with three segment (s-shaped) spline.

All three figures 4.2 to 4.4 states that no avoidance maneuver is possible simultaneously, however, the compared methods STN values differ in amplitude. A conclusion between which method is closest to a true avoidance maneuver is not possible in those figures. An investigation of the performance of the particle filter based STN is presented in section 4.2.2.

The particle filter based STN, figures 4.2 to 4.4, is not as smooth as the implementations of SBST. This is expected because the particle filter generates a lot of guesses and chooses the collision free path with the lowest STN value. Therefore, the chosen path in one time sample may differ from the chosen path in the next, while SBST uses the same spline design between all time samples.

4.2 Brake intervention evaluation

The MTTA algorithm's purpose is to avoid or mitigate collisions and decrease the impact speed at least equal to an STTA algorithm. Scenario two will act as a single-target evaluation. The speed reduction and early brake interventions will be investigated at different speeds.

4.2.1 Collision avoidance

The results of these tests are presented in table 4.1 where data are extracted from a report generated in CarMaker, appendix A. The table presents whether the TA managed to avoid collision or not. This table represents the performance of the TA for the three scenarios, section 1.2.1.

Table 4.1: A summary of the system performance test for the three scenarios at different speeds (the speed denotes the initial speed of the host vehicle and target vehicles)

Scenario	Speed	Collision avoided	Impact speed	Speed reduction	TTC at AEB intervention
1	*30 km/h*	Yes		30 km/h	0.80 s
	50 km/h	Yes		50 km/h	1.15 s
	70 km/h	Yes		70 km/h	1.45 s
	90 km/h	Yes		90 km/h	1.70 s
	110 km/h	Yes		110 km/h	1.85 s
2	*30 km/h*	Yes		30 km/h	0.80 s
	50 km/h	Yes		50 km/h	1.00 s
	70 km/h	No	29.4 km/h	40.6 km/h	1.00 s
	90 km/h	No	52.7 km/h	37.3 km/h	0.90 s
	110 km/h	No	66.5 km/h	43.5 km/h	0.90 s
3	*30 km/h*	Yes		30 km/h	0.80 s
	50 km/h	Yes		50 km/h	1.15 s
	70 km/h	Yes		70 km/h	1.45 s
	90 km/h	Yes		90 km/h	1.70 s
	110 km/h	Yes		110 km/h	1.95 s

Collision is avoided at all different speeds in scenario one and three due to the fact that an avoidance maneuver by steering is blocked by a target vehicle in the adjacent lane. The system can therefore brake when needed. In scenario two, the system manages to avoid collision at speeds $\leq$ 50 m/s^2 and above that speed collision occurs. Even though collision occurs, it manages to decrease the collision impact with roughly 40 km/h and this increases the possibility to survive tremendously according to diagram in figure 1.1.

The results are as expected, MTTA avoids collision for scenarios when an avoidance maneuver by steering isn't possible, and decreases impact speed with $\sim$ 40 when an avoidance maneuver by steering is possible (as a STTA, section 1.1.3).

How BTN and STN perform during the three scenarios (70 km/h) is visualized in figure 4.5, figure 4.6 and figure 4.7. The figures shows when braking and steering respectively are no longer possible and when the brakes could be applied.

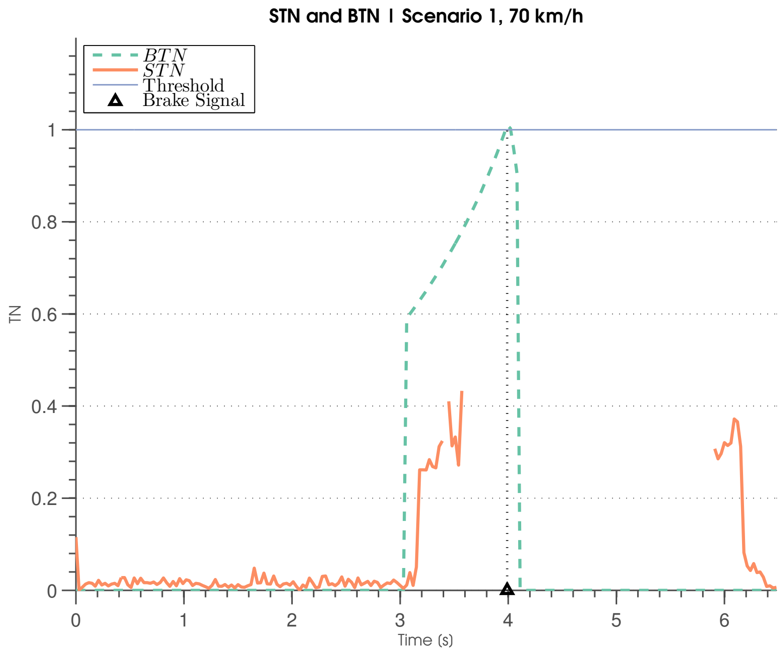

Figure 4.5: Brake Threat Number (BTN) and Steer Threat Number (STN) for scenario one. "Brake signal" is triggered if both threat numbers are > 1 or if BTN> 1 and no avoidance maneuver is possible, i.e. no line.

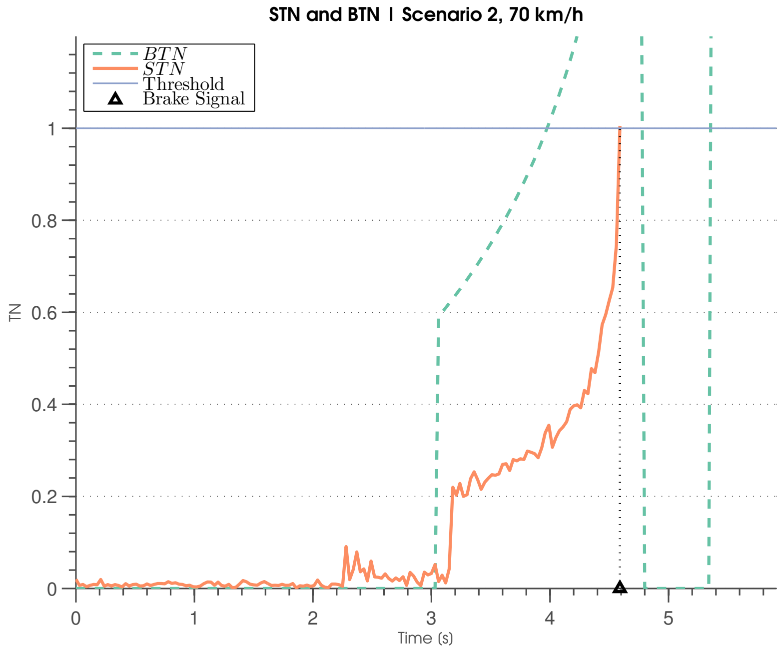

Figure 4.6: Brake Threat Number (BTN) and Steer Threat Number (STN) for scenario two. The “Brake signal” is triggered if both threat numbers are > 1 or if BTN> 1 and no avoidance maneuver is possible, i.e. no line.

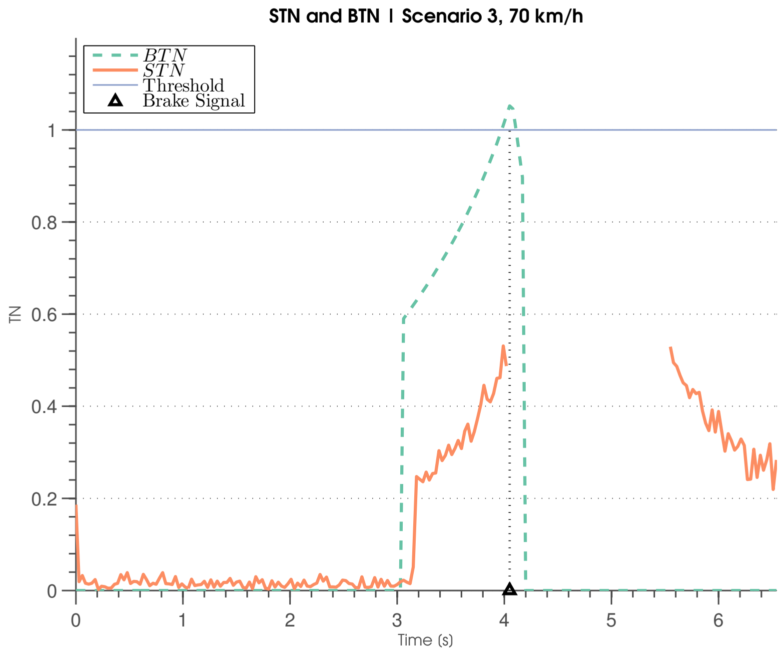

Figure 4.7: Brake Threat Number (BTN) and Steer Threat Number (STN) for scenario three. “Brake signal” is triggered if both threat numbers are > 1 or if BTN> 1 and no avoidance maneuver is possible, i.e. no line.

The system managed to avoid collision at low speeds, but failed at high speeds for scenario two. By comparing BTN and STN for scenario two and the speeds 70 km/h (figure 4.6) and 30 km/h (figure 4.8), it's clear that an avoidance maneuver by steering is easier than braking at high speeds and the opposite regarding low speeds.

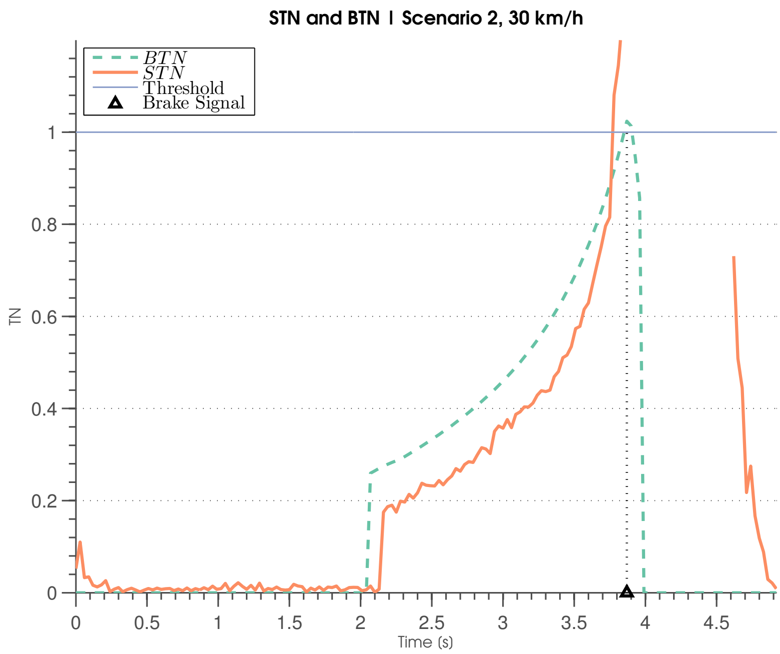

Figure 4.8: Brake Threat Number (BTN) and Steer Threat Number (STN) for scenario two. The "Brake signal" is triggered if both threat numbers are > 1 or if BTN> 1 and no avoidance maneuver is possible, i.e. no line.

4.2.2 Particle filter based Steer Threat Number

In the comparison between particle filter method and SBST (figures 4.2 to 4.4) the particle filter state that less lateral acceleration was required to avoid collision by steering for all t's and scenarios. But a validation with an avoidance maneuver is required to determine if these results are reliable. The results of those maneuvers are summarized in table 4.2. The results of the test at 70 km/h can be seen in figure 4.9, while figures for the other speeds can be seen in appendix C.

According to these tests, the particle filter works well in cases when speed is ≤ 70. At the speeds 90 and 110, the particle filter triggers an early brake interventions, i.e. brakes even though the driver can avoid collision. This because the particle filter's path planning failed to find the path that CarMaker used. But despite that, SBST state that a steering maneuver is required even earlier (figures 4.2 to 4.4), at all speeds. So the particle filter based STN is more correct than SBST when evaluating avoidance maneuvers by steering.

Table 4.2: The time variable TTC_{AEB} denotes at what TTC the AEB was activated and TTC_{steer} denotes at what TTC an avoidance maneuver by steering was still possible according to CarMaker. The variable t_{diff} is the difference between the two TTC values.

Speed	*Early brake intervention*	TTC_{AEB}	TTC_{steer}	t_{diff}
30 km/h	No	0.90 s	1.05 s	0.15 s
50 km/h	No	0.85 s	0.95 s	0.10 s
70 km/h	No	0.85 s	0.90 s	0.05 s
90 km/h	Yes	0.90 s	0.85 s	- 0.05 s
110 km/h	Yes	1.05 s	0.85 s	- 0.20 s

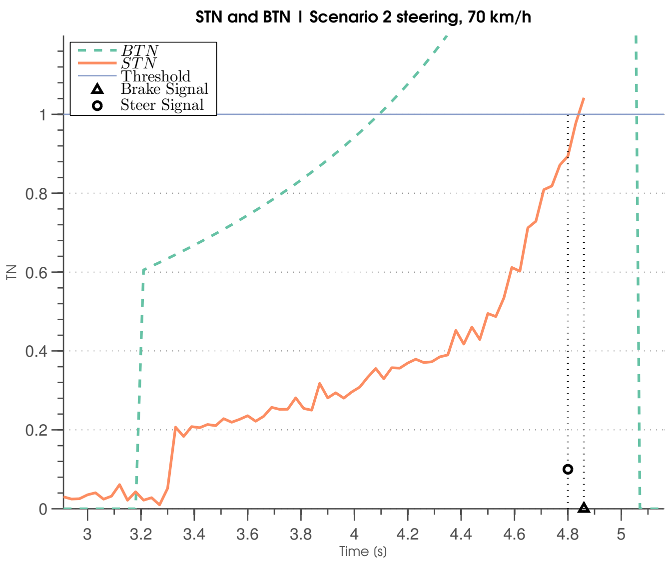

Figure 4.9: Brake Threat Number (BTN) and Steer Threat Number (STN) for scenario two. “Brake signal” is triggered if both threat numbers are > 1 or if BTN> 1 and no avoidance maneuver is possible, i.e. no line. The “Steer Signal” is triggered when the driver initiate the steering maneuver.

5

Discussion

Below, discussions regarding the obtained results are presented together with descriptions and reflections of performed tests.

5.1 Brake Threat Number

In section 4.1.1, the figure shows that the two different approaches gave different results. However, the most critical part, crossing the threshold, happened simultaneously. The differences when BTN $\neq 1$ occur because numerically calculated BTN calculates the brake intervention needed to barely touch the target vehicle, while proposed BTN calculates brake distance until range rate is zero while applying maximum (for the general driver) brake. Nevertheless, the main result was that equal performance was reached (crossing the threshold simultaneously) with less computational power, which can be a huge advantage in the automotive applications. The price of the cars is of significant importance and of course highly influenced by the accessories in the car. So being able to draw equal conclusions with less need of processor power are of great value.

Also, the TA only measures the distance in longitudinal direction, because all scenarios are rear-end collision scenarios on straight roads. This means that the TA is limited to only deliver true results when that's the case. If the road has a curvature, the result can be misleading, stating that the distance is shorter than the actual path. Still, that difference is negligible in many scenarios.

5.2 Steer Threat Number

The results (in section 4.1.2) show that SBST always deliver smooth and reliable outcomes, compared to the particle filtering method that present non-smooth results and occasionally fails to find a solution. A smooth curve is desirable because future values will prove easier to predict. However, an increased number of particles would increase the particle filter's smoothness. Yet, the particle filter showed itself to deliver almost the same results as the tested steering avoidance maneuvers carried out in CarMaker. Therefore, with SBST the brake decision would occur too early every time, creating early brake interventions at all speeds because both the one segment spline and the three segment (s-shaped) spline reached same STN as the particle filter faster (figure 4.3).

This may be misleading as results for SBST. The results only state that the assumptions on how to design the spline wasn't ideal. Regardless, it shows that the assumptions are critical to the outcome. Even though an improved design of the spline may perform ideal in one case, it may differ from the perfect spline in the next. This highlights the best feature of the particle filter based method, it ability to adapt to each and every situation.

5.3 Steering maneuvers in CarMaker

In section 4.2.2, the tests involving steering maneuvers in CarMaker showed some unsatisfying results for the particle based STN. On the other hand, the steering maneuvers were calibrated to precisely avoid the braking target vehicle. Starting a steering maneuver that late in real life, will not be in combination of confidence and margin for the driver and a brake intervention will probably not be distinguished as an early brake intervention from the drivers perspective. In this degree the test may be too extreme and real life test may show result without early brake interventions.

The performance of a steering maneuver will also be influenced by the awareness of the driver, the tires' conditions, road surface and so on. Also, in CarMaker, all those factors were optimal. However, it's unlikely that these factors will be optimal simultaneously in real life.

5.4 Particle filter for Steer Threat Number

As mentioned earlier, the particle filter is not dependent on true assumptions of the perfect steering maneuver. It's also versatile, shows rapid convergence (section 4.1.2) and is not limited to rear-end collision scenarios on straight roads. Further, it should handle curved roads, intersections, crossing path scenarios and so forth.

Despite all the favorable arguments for the particle filter, its performance and chances of finding a solution depends on sufficient amount of particles. The more particles, the more guesses may be closer to the perfect avoidance path, but also increases the calculation time. All in all, there is a trade-off between calculation speed and reliability.

5.5 Spline Based Search Tree

One of the problems occurring for SBST is that the path isn't evaluated during the entire prediction horizon since, it stops next to the last target vehicle (figure 2.4). It assumes that the exit conditions of the end of the spline prevents the rest of the path from leading to collision. For the three segment (s-shaped) spline, the heading of the host vehicle at the end of the spline is equal to the heading of the host vehicle in the beginning of the spline. This only works well on straight roads. In a curve, it may end with collision into a barrier after the spline has ended. Designing the spline to reach equal heading as the target vehicle may be a more reliable assumption. In other words, the target vehicles are assumed to follow the road, so if the host vehicle travels in the same direction, it will also follow the road.

As for the one segment spline, the case is even worse. In that case, no assumptions of heading is applied on the end of the spline (figure 2.4), which may lead (or even probably) to collision into the barrier within the prediction horizon. Extending the spline until the end of the prediction horizon may be difficult since that requires an assumption on where to end the spline.

Adding more assumptions to the spline also requires a higher order of polynomials. That will not automatically lead to a spline with minimized jerk, which was a key feature of the cubic splines. How to achieve minimized jerk for a quintic spline is handled in [8].

5.6 Time To Collision for scenario one and three

In table 4.1, the TTC values for scenario one and three are identical for the speeds between 30-90 km/h but differ with $0.1s$ for the speed 110 km/h. The reason is that the target vehicles aren't driving at the same longitudinal distance in scenario one. The target vehicle drives slightly ahead of the target vehicle in the host vehicle's lane. Therefore, an avoidance maneuver is possible for a short time, preventing the AEB to engage at BTN $= 1$, while for scenario three, the host vehicle can never safely turn into the adjacent lane.

5.7 Multi-target Threat Assessment performance

Collision was avoided for speeds ≤ 50 in all scenarios. However, at higher speeds in scenario two (which represents a single-target scenario), collisions occurred and the impact speeds were about 30, 55 and 65 km/h for starting speeds 70, 90 and 110 km/h (see table 4.1). According to the graph in figure 1.1, this results in approximately 0 %, 2.5 % and 5 % risk of getting killed in a head-on collision. This can be compared to the case if no brakes were applied: about 10 %, 60 % and 100 %. This concludes that an AEB system with STTA increases the risk of survival substantially, while the MTTA pushes the numbers to 0% for scenarios when a steering maneuver to avoid collision isn't possible. The minor difference in results between STTA and MTTA can still save many lives.

6

Conclusion

The summary of the result in regard of the Contributions (section 1.2) will be presented in this chapter. Also, potential future work is presented.

6.1 Contribution

Performance of the particle filter based STN. The particle filter based STN generates more accurate STN values when compared to steering maneuvers than the SBST. This leads to fewer early brake interventions which mean no brake interventions when the driver may have control of the situation, i.e. less discomfort for the driver.

Does MTTA AEB contribute to increased chance of survival in comparison with STTA AEB? The answer is yes. For the scenarios considered in this report (section 1.2.1) the MTTA algorithm will avoid collision entirely when a steering maneuver is blocked by target vehicles and/or barriers. This is shown in the results where collision was avoided for scenario one and three, while collision was a fact for scenario two at higher speeds. All three scenarios appear the same for STTA algorithms since the car, in the host vehicle's lane, acts equally in all the scenarios. Therefore, the result for scenario two represents the expected results in scenario one and three as well.

6.2 Future work

Even though the result are positive for the particle filter approach, some parts still requires improvements and modifications for increased performance. Further more, a better developed AEB is desired in order for the system to be implemented in an embedded system.

6.2.1 Drivable surfaces

In this report, all surfaces not blocked by either target vehicles or barriers are considered drivable surfaces. The scenarios for when MTTA can fulfill its purpose are limited by this. In some cases, no barriers exist but the area next to the road is still not drivable, or the barrier may be far from the road edge. This can lead to the algorithm stating that the driver can squeeze the car in between the target vehicle and the barrier, even though the driver would avoid this. Consequently, a more in depth investigation is required to distinguish what a drivable surface is. However, that may put high demands on the sensing systems as well. This will increase the number of scenarios when the MTTA is of use.

6.2.2 More complex weighting function

A more complex weighting function may result in more reliable results from the particle filter. While this report's weighting function only evaluates the amplitude of the splines jerk, the distance to the target vehicles may also add important information. For a steering maneuver, the spline with the highest particle weight will probably be the spline closest to the target vehicle it's avoiding. By decreasing the particle weight for splines close to the target vehicles, the spline with the greatest chance of survival in resampling, will not be the spline with lowest STN, but a spline with better possibility to avoid collision in the next time step as well. The spline closest to the target vehicles also have a significant risk of leading to collision in the next time sample, which is undesirable.

6.2.3 Spline Based Search Tree

The results showed that the particle filter method performs better than SBST, but SBST is faster to compute. In a car with low processing power, this means that SBST can be a suitable choice, if the spline design is improved. Further, a combination of spline designs can be used to get closer to the perfect steering maneuver in most scenarios.

6.2.4 Autonomous Emergency Braking and Forward Collision Warning

Knowing when to brake and how hard, are critical to avoid collision by braking. The AEB in this report either brake at maximum capacity or not at all. Adding pre-brake and controlled brake pressure during an braking intervention are also possible. The threat number gives a scale of severity of the situation from a drivers perspective. Even though the BTN = 1, the car may have some margin left and maximum brake isn't required.

The threat numbers can also be used to activate FCW, hopefully resulting in the driver taking care of the situation before the AEB is required. FCW warns the driver with sound and/or lights that a dangerous situation is about to occur. The information of the simplest spline may also be used to guide the driver in the direction to turn to avoid collision.

6.2.5 Collision avoidance by steering

Instead of using TA as collision mitigation AEB, the spline from the particle filter may be used for steering interventions, which can open up the possibility to avoid collision entirely in all three scenarios. However, this requires sensing systems that can detect target vehicles on all sides and road surfaces to ensure safe maneuvers.

In the case of using the spline as reference line for a steering maneuver, the constant jerk assumption may not hold. In this case a higher order spline with differentiable jerk signal may be required for safe maneuvers.

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A

Appendix

Result Summary

Overall Results

Number of Tests:	15	100.0 %	
Tests passed:	12	80.0 %	
Tests skipped:	0	0.0 %	
Tests with warning:	0	0.0 %	
Tests failed:	3	20.0 %	
Tests with error:	0	0.0 %	
Tests not executed:	0	0.0 %	

Detailed Results

ID	Test	Result
1	Case1	
1.1	30 km/h	
1.2	50 km/h	
1.3	70 km/h	
1.4	90 km/h	
1.5	110 km/h	
2	Case2	
2.1	30 km/h	
2.2	50 km/h	
2.3	70 km/h	
2.4	90 km/h	
2.5	110 km/h	
3	Case3	
3.1	30 km/h	
3.2	50 km/h	
3.3	70 km/h	
3.4	90 km/h	
3.5	110 km/h	

Detailed Results

1

Test # 1
Case1

Characteristics

Name	Description
Impact speed	
TTC	

Name	# 1	# 2	# 3	# 4	# 5
Impact speed [km/h]	0.0000e+000	0.0000e+000	0.0000e+000	0.0000e+000	0.0000e+000
TTC [s]	8.0000e-001	1.1500e+000	1.4500e+000	1.7000e+000	1.8500e+000

Criteria

Name	Description
Collision	

Name	# 1	# 2	# 3	# 4	# 5
Collision	✓	✓	✓	✓	✓

1.1

Test # 1.1	Result
Case1 └ 30 km/h	Passed

General Information

TestRun	
Name:	Case1
Description:	

Resultfile
Results not saved

Characteristics

Name	Value
impact_speed [km/h]	0.000000
TTC_AEB [s]	0.800000

Criteria

Name	Result
Collision	✔

1.2

Test # 1.2	Result
Case1 └ 50 km/h	✔ Passed

General Information

TestRun	
Name:	Case1
Description:	

Resultfile
Results not saved

Characteristics

Name	Value
impact_speed [km/h]	0.000000
TTC_AEB [s]	1.150000

Criteria

Name	Result
Collision	✔

1.3

Test # 1.3	Result
Case1 └ 70 km/h	Passed

General Information

TestRun	
Name:	Case1
Description:	

Resultfile
Results not saved

Characteristics

Name	Value
impact_speed [km/h]	0.000000
TTC_AEB [s]	1.450000

Criteria

Name	Result
Collision	✔

1.4

Test # 1.4	Result
Case1 └ 90 km/h	Passed

General Information

TestRun	
Name:	Case1
Description:	

Resultfile
Results not saved

Characteristics

Name	Value
impact_speed [km/h]	0.000000
TTC_AEB [s]	1.700000

Criteria

Name	Result
Collision	✔

1.5

Test # 1.5	Result
Case1 └ 110 km/h	✔ Passed

General Information

TestRun	
Name:	Case1
Description:	

Resultfile
Results not saved

Characteristics

Name	Value
impact_speed [km/h]	0.000000
TTC_AEB [s]	1.850000

Criteria

Name	Result
Collision	✔

2

Test # 2
Case2

Characteristics

Name	Description
Collision speed	
TTC	

Name	# 1	# 2	# 3	# 4	# 5
Collision speed [km/h]	0.0000e+000	0.0000e+000	2.9450e+001	5.2711e+001	6.6525e+001
TTC [s]	8.0000e-001	1.0000e+000	1.0000e+000	9.0000e-001	9.0000e-001

Criteria

Name	Description
Collision	

Name	# 1	# 2	# 3	# 4	# 5
Collision	✓	✓	✗	✗	✗

2.1

Test # 2.1	Result
Case2 └ 30 km/h	✔ Passed

General Information

TestRun	
Name:	Case2
Description:	

Resultfile
Results not saved

Characteristics

Name	Value
c_speed [km/h]	0.000000
TTC_AEB [s]	0.800000

Criteria

Name	Result
Collision	✔

2.2

Test # 2.2	Result
Case2 └ 50 km/h	Passed

General Information

TestRun	
Name:	Case2
Description:	

Resultfile
Results not saved

Characteristics

Name	Value
c_speed [km/h]	0.000000
TTC_AEB [s]	1.000000

Criteria

Name	Result
Collision	✓

2.3

Test # 2.3	Result
Case2 └ 70 km/h	Failed

General Information

TestRun	
Name:	Case2
Description:	

Resultfile
Results not saved

Characteristics

Name	Value
c_speed [km/h]	29.449759
TTC_AEB [s]	1.000000

Criteria

Name	Result
Collision	

2.4

Test # 2.4	Result
Case2 └ 90 km/h	Failed

General Information

TestRun	
Name:	Case2
Description:	

Resultfile
Results not saved

Characteristics

Name	Value
c_speed [km/h]	52.710735
TTC_AEB [s]	0.900000

Criteria

Name	Result
Collision	

2.5

Test # 2.5	Result
Case2 └ 110 km/h	Failed

General Information

TestRun	
Name:	Case2
Description:	

Resultfile
Results not saved

Characteristics

Name	Value
c_speed [km/h]	66.525055
TTC_AEB [s]	0.900000

Criteria

Name	Result
Collision	

3

Test # 3
Case3

Characteristics

Name	Description
Collision speed	
TTC	

Name	# 1	# 2	# 3	# 4	# 5
Collision speed	0.0000e+000	0.0000e+000	0.0000e+000	0.0000e+000	0.0000e+000
TTC [s]	8.0000e-001	1.1500e+000	1.4500e+000	1.7000e+000	1.9500e+000

Criteria

Name	Description
Collision	

Name	# 1	# 2	# 3	# 4	# 5
Collision	✔	✔	✔	✔	✔

3.1

Test # 3.1	Result
Case3 └ 30 km/h	✔ Passed

General Information

TestRun	
Name:	Case3
Description:	

Resultfile
Results not saved

Characteristics

Name	Value
c_speed	0.000000
TTC_AEB [s]	0.800000

Criteria

Name	Result
Collision	✔

3.2

Test # 3.2	Result
Case3 └ 50 km/h	✔ Passed

General Information

TestRun	
Name:	Case3
Description:	

Resultfile
Results not saved

Characteristics

Name	Value
c_speed	0.000000
TTC_AEB [s]	1.150000

Criteria

Name	Result
Collision	✔

3.3

Test # 3.3	Result
Case3 └ 70 km/h	✔ Passed

General Information

TestRun	
Name:	Case3
Description:	

Resultfile
Results not saved

Characteristics

Name	Value
c_speed	0.000000
TTC_AEB [s]	1.450000

Criteria

Name	Result
Collision	✔

3.4

Test # 3.4	Result
Case3 └ 90 km/h	✔ Passed

General Information

TestRun	
Name:	Case3
Description:	

Resultfile
Results not saved

Characteristics

Name	Value
c_speed	0.000000
TTC_AEB [s]	1.700000

Criteria

Name	Result
Collision	✔

3.5

Test # 3.5	Result
Case3 └ 110 km/h	✔ Passed

General Information

TestRun	
Name:	Case3
Description:	

Resultfile
Results not saved

Characteristics

Name	Value
c_speed	0.000000
TTC_AEB [s]	1.950000

Criteria

Name	Result
Collision	✔

B

Appendix

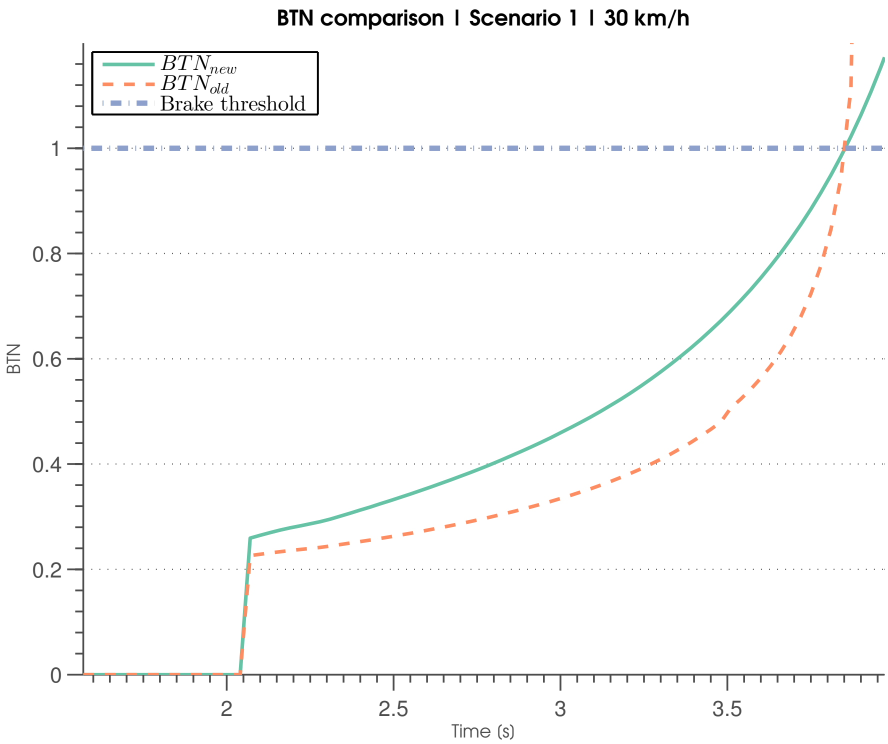

Figure B.1: A comparison between numerically calculated Brake Threat Number (BTN) (BTN_{old}) and arithmetically calculated Brake Threat Number (BTN) (BTN_{new}). The Brake threshold indicates $BTN = 1$

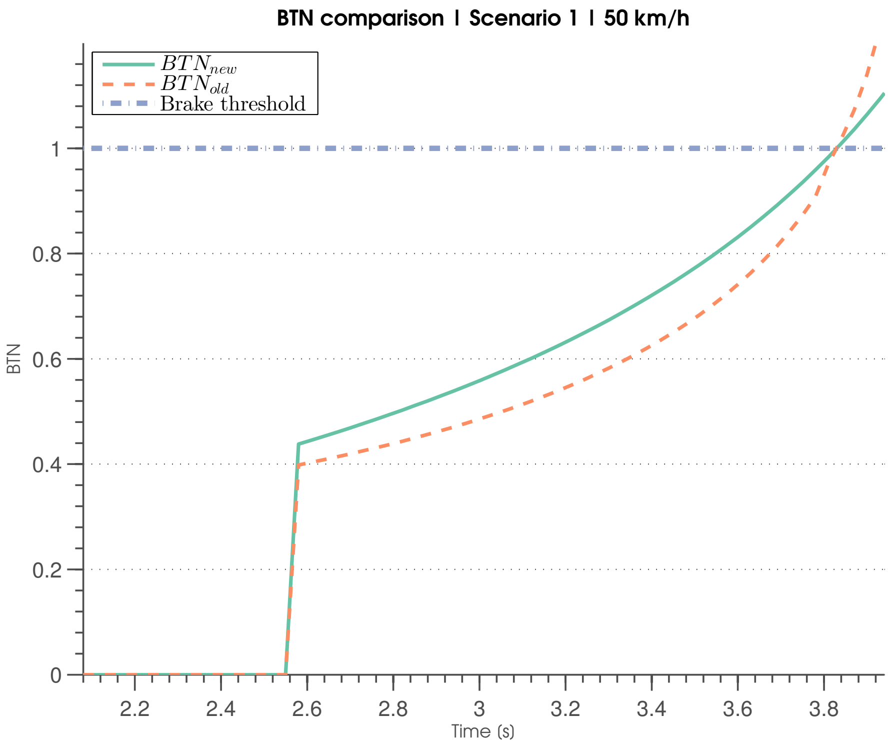

Figure B.2: A comparison between numerically calculated Brake Threat Number (BTN) (BTN_{old}) and arithmetically calculated Brake Threat Number (BTN) (BTN_{new}). The Brake threshold indicates $BTN = 1$

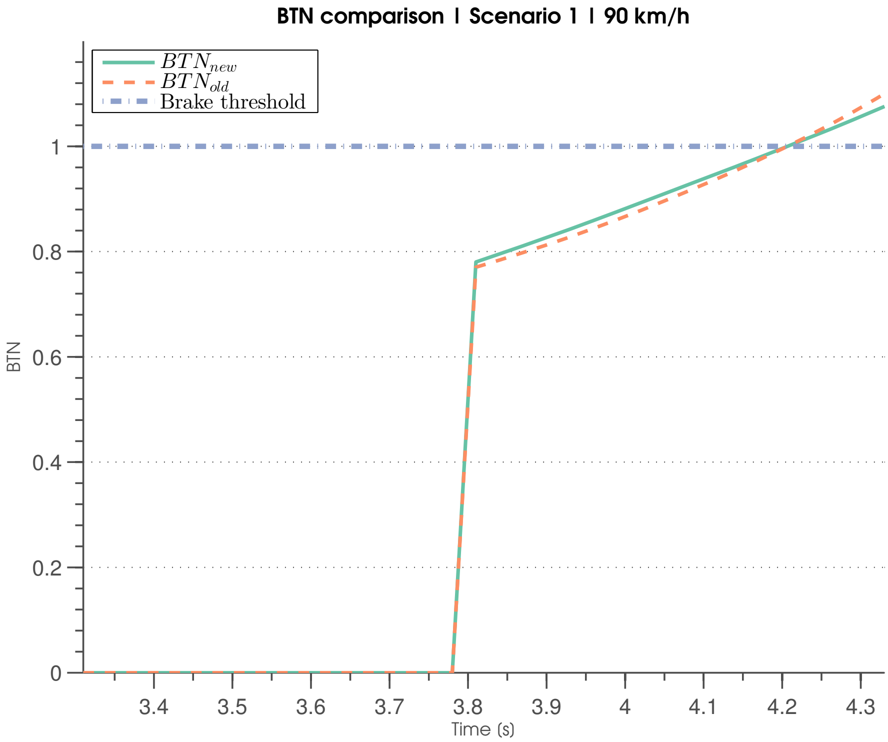

Figure B.3: A comparison between numerically calculated Brake Threat Number (BTN) (BTN_{old}) and arithmetically calculated Brake Threat Number (BTN) (BTN_{new}). The Brake threshold indicates $BTN = 1$

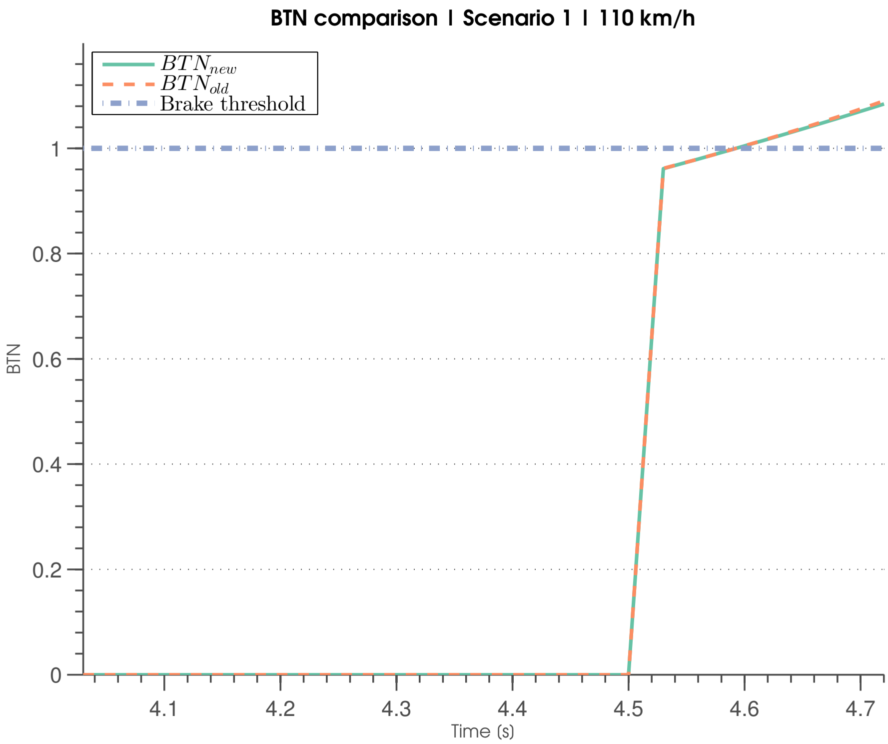

Figure B.4: A comparison between numerically calculated Brake Threat Number (BTN) (BTN_{old}) and arithmetically calculated Brake Threat Number (BTN) (BTN_{new}). The Brake threshold indicates $BTN = 1$

C

Appendix

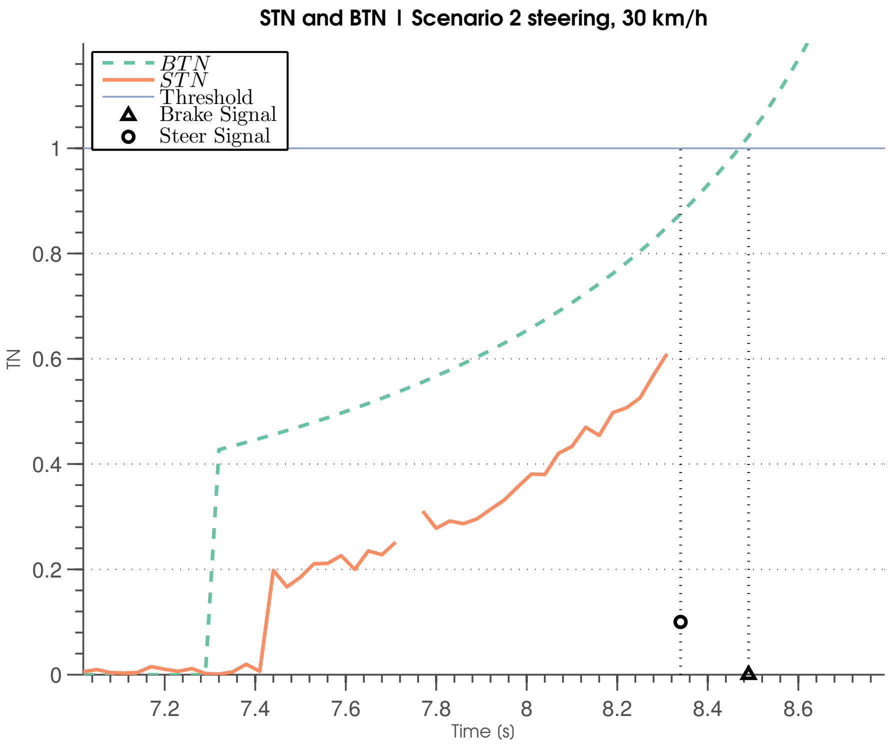

Figure C.1: Brake Threat Number (BTN) and Steer Threat Number (STN) for scenario two. "Brake signal" is triggered if both threat numbers are > 1 or if BTN> 1 and no avoidance maneuver is possible, i.e. no line. The "Steer Signal" is triggered when the driver initiate the steering maneuver.

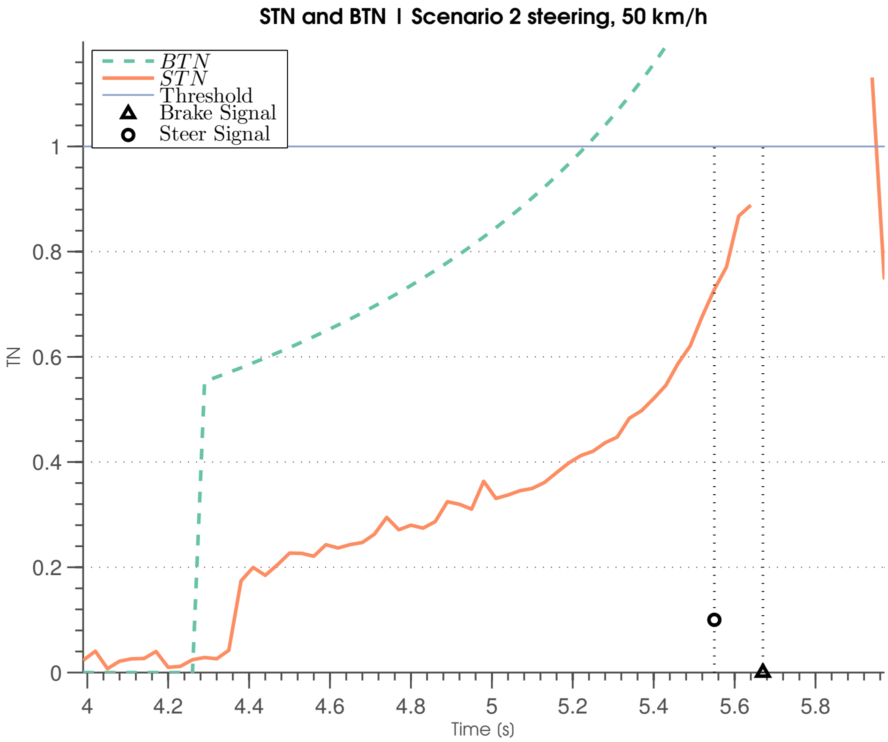

Figure C.2: Brake Threat Number (BTN) and Steer Threat Number (STN) for scenario two. "Brake signal" is triggered if both threat numbers are > 1 or if BTN> 1 and no avoidance maneuver is possible, i.e. no line. The "Steer Signal" is triggered when the driver initiate the steering maneuver.

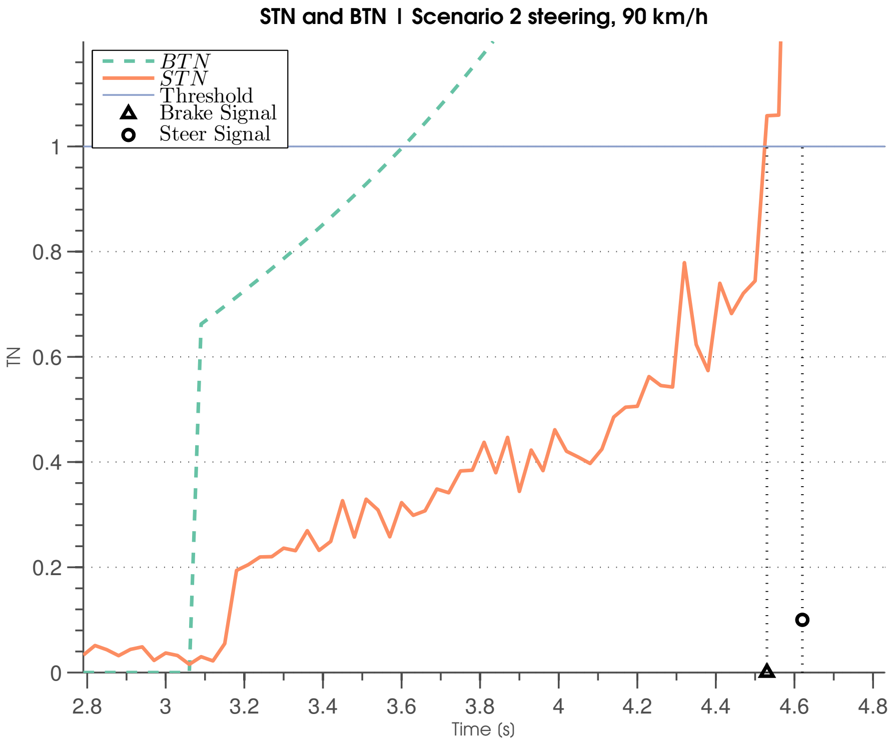

Figure C.3: Brake Threat Number (BTN) and Steer Threat Number (STN) for scenario two. “Brake signal” is triggered if both threat numbers are > 1 or if BTN> 1 and no avoidance maneuver is possible, i.e. no line. The “Steer Signal” is triggered when the driver initiate the steering maneuver.

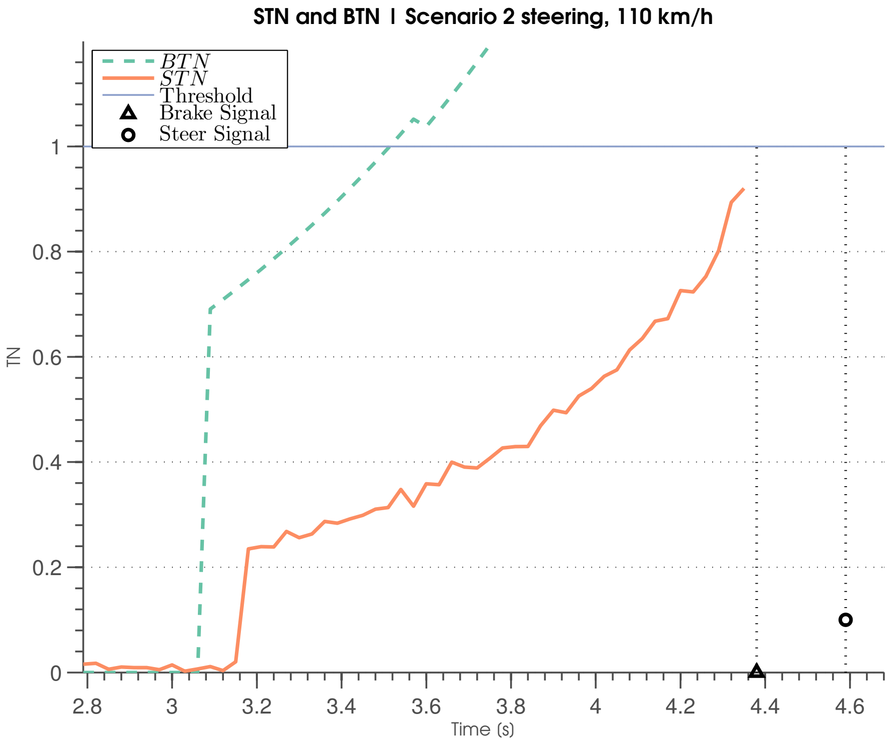

Figure C.4: Brake Threat Number (BTN) and Steer Threat Number (STN) for scenario two. "Brake signal" is triggered if both threat numbers are > 1 or if BTN> 1 and no avoidance maneuver is possible, i.e. no line. The "Steer Signal" is triggered when the driver initiate the steering maneuver.