Methods for Improving Radar Maneuver Detection for Tangentially Moving Targets

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Abstract

This master thesis has been done in the field of Advanced Driver Assistance Systems and presents a method to assist cross traffic at road junctions. An accurate tracking of crossing objects is necessary in order to assist traffic at road junctions. At Continental, the stable tracking of crossing objects is available, but the system still gives false alarms for non-colliding objects (e.g. Target Braking at crossroads). Hence the main focus of this thesis is on the reduction of false alarms for non-colliding objects. Radar based Maneuver Detection function has been developed for Crossing Emergency Brake Assist system, which uses radar measurement parameters to detect the maneuvering of target objects in order to differentiate between collision and non-collision cases. Different crossing scenarios have been created in a Matlab environment and the algorithm is tested. Secondly, the algorithm is tested by using the measurement data from real recordings and evaluation is made. The proposed algorithm has reliably detected the non-collided objects (in normal cases) and helped in reducing the false alarm rate significantly.
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<td>Anti-lock Braking Systems</td>
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<tr>
<td>ACC</td>
<td>Adaptive Cruise Control</td>
</tr>
<tr>
<td>ADAS</td>
<td>Advanced Driver Assistance Systems</td>
</tr>
<tr>
<td>AEB</td>
<td>Automatic Emergency Braking</td>
</tr>
<tr>
<td>AUTOSAR</td>
<td>AUTomotive Open System ARchitecture</td>
</tr>
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<td>BAS PLUS</td>
<td>Brake Assist System PLUS</td>
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<td>BSM</td>
<td>Blind Spot Monitoring</td>
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<td>CA</td>
<td>Collision Avoidance</td>
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<td>CMA</td>
<td>Cumulative Moving Average</td>
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<tr>
<td>CTA</td>
<td>Cross Traffic Assist</td>
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<td>CW</td>
<td>Collision Warning</td>
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<td>EBA</td>
<td>Emergency Brake Assist</td>
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<td>EMA</td>
<td>Exponential Moving Average</td>
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<tr>
<td>LDW</td>
<td>Lane Departure Warning</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
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<td>MMA</td>
<td>Modified Moving Average</td>
</tr>
<tr>
<td>NCAP</td>
<td>New Car Assessment Program</td>
</tr>
<tr>
<td>NHTSA</td>
<td>National Highway Traffic Safety Administration</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
<tr>
<td>PCS</td>
<td>Pre-Collision Safety</td>
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<tr>
<td>RADAR</td>
<td>RAdio Detection And Ranging</td>
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<tr>
<td>SMA</td>
<td>Simple Moving Average</td>
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<tr>
<td>TTC</td>
<td>Time to Collision</td>
</tr>
<tr>
<td>V2I</td>
<td>Vehicle to Infrastructure</td>
</tr>
<tr>
<td>V2V</td>
<td>Vehicle to Vehicle</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organization</td>
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<td>WMA</td>
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1 Introduction

The desire to build safer vehicles and roads to reduce the number of road accidents leads to the development of Advanced Driver Assistance Systems. These systems use different sensors to monitor the environment and perform certain actions to provide active and passive safety to the passengers and road occupants. Radar based maneuver detection function has been developed for Crossing Emergency Brake Assist system to assist the traffic at road junctions.

1.1 Motivation

Mobility is the basic necessity of mankind. In the last few decades, the automotive industry has flourished a lot and made people’s life easier for mobility but on the other hand, the increased in road traffic has negative repercussions on road capacity, energy and road safety etc. According to WHO report 2010, approximately 1.24 million people are killed each year in road accidents worldwide which is the eighth leading cause of death globally and almost 50 million get injured. Statistics has shown that these numbers will increase drastically, if no preventive measures are taken (cf. [1], p. 1-12). There are three main reasons of road accidents; poor road, unsafe vehicle and bad driving. Both road infrastructure and vehicle safety has been improved much in past years but the human behavior has not improved much. That is why more than 80% of road accidents result from driver’s loss of attention during driving such as talking on telephone, eating, drinking or smoking etc. (cf. [2]). Road accidents result not only in loss of human lives but also it damages the property. So vehicle manufacturers and their suppliers have made it their goal to avoid such accidents or at least to reduce their effects as much as possible. Studies have shown that reasonable number of accidents can be avoided by recognizing a potential hazard insufficient amount of time period and by performing suitable driving actions. Such actions can be accomplished in two ways either by giving alarm signals to the driver or by automatic control of the vehicle (cf. [3]).

According to NHTSA around 25% of road accidents happen at road junctions. These accidents are caused due to various reasons but the main reasons are due to driver distraction or misjudgment (cf. [2]). In the past, OEM’s used to provide safety relevant
functions in the longitudinal direction only. But nowadays, OEM’s are focusing more and more towards safety relevant functions to react on tangentially moving targets, e.g. Crossing Assist and Crossing Emergency Brake Systems, in order to avoid or to reduce these numbers of road junction accidents. Assisting the cross traffic at road junction is very challenging and demands lots of dedication in research and development work. As a research oriented and hard working person, this challenging task motivated me a lot to use my skills and knowledge in an effective way to bring innovation into the market.

1.2 Problem Formulation

Cross Traffic Assist (CTA) is a safety system and one of the applications of Advanced Driver Assistance Systems which continuously monitors the cross traffic in city junctions. If this system detects any kind of hazardous situations, it gives warning signals to driver through acoustic or optical means, so that the driver can do safety measures. If driver does not apply brakes, the system intervenes and takes the control of the whole vehicle and do appropriate actions to provide active or passive safety to the vehicle and driver respectively.

Continental is developing a radar based CTA for series vehicles. The stable tracking of crossing objects is available, but the main focus is the reduction of false alarms for non colliding objects (braking at crossroads). CTA function requires an accurate tracking of tangentially moving objects in order to discriminate between use cases (collision:
brake/warning desired) and misuse cases (object stops at road border etc: no brake/warning shall occur). Camera sensor is extremely useful to detect lateral maneuvers of objects but camera does not operate well during bad weather or at night. Therefore false alarm performance must be maintained in radar only mode. In the past, automotive radar systems were primarily used for longitudinal functions (e.g. ACC, EBA) where the high range accuracy and velocity measurement capability of the radar proved its strength. The current challenge for radar system is to accurately track the tangential moving objects, which help in determining the lateral maneuvers (acceleration/deceleration) of target objects in order to discriminate between collision and non-collision cases.

1.3 Objectives of the Thesis

The scope of this project consists of reliably detecting lateral maneuvers (acceleration/deceleration) of target vehicles by using radar sensor and reducing the false alarm rate of the system for crossing scenarios, while maintaining the use-case performance high.

1.4 Organization of Thesis

Chapter 1 introduces the reader about ongoing developments in the field of Advanced Driver Assistance Systems, its advantages in daily life and challenges it is facing these days. Then it describes the main problem in detail and objectives of this thesis work.

Chapter 2 gives some background knowledge of Radar sensor systems, its measurement parameters and limitations. It also gives an overview of Radar based ADAS. Then it gives brief introduction of approaches стратегий which can help in detecting the maneuvering of target vehicles and in the end discuss about some work related to it.

Chapter 3 begins with the description of main work which has to be done, state of the art work and finally explains the concept of this thesis work in detail.

Chapter 4 describes the algorithm which has been implemented for detecting lateral maneuvers of crossing vehicles.

Chapter 5 contains the theoretical and real results of all the assumed crossing scenarios and finally evaluates these results.
Chapter 6 draws conclusion of the thesis work and describes directions for future work.
2 Technical Background

This chapter contains all the technical background related to radar technology that has been used in the research and development of this thesis work. It gives the brief introduction of Radar based Advanced Driver Assistance Systems. It also entails brief description of the techniques used in the development of algorithms and assist in enhancing their performance.

2.1 Radar

RADAR is an acronym for Radio Detection and Ranging (cf. [4]). As the name depicts, it is an object detection system that uses electromagnetic waves to determine the range, angle and radial velocity of an object which comes in its range. It is mostly used to detect the aircrafts, ships, missiles; road vehicles etc. Typically a radar module consists of transmitter, receiver, radar antenna; duplexer, signal processing unit and indicator (cf. [5]). The basic operating principle of radar is shown in Figure 2.

The transmitter generates the electromagnetic waves which are then radiated into the free space by the radar antenna. These transmitted waves are reflected back from the object and picked by the radar antenna and sent to receiver. Duplexer connects the radar antenna to the transmitter during transmission of radio waves and to the receiver during receiving of reflected signals. The reflected signal is called ECHO and it’s a very weak
signal which is then amplified by the receiver. The signal processing unit then evaluates this ECHO signal and extracts the useful information regarding the object (cf. [6]).

2.1.1 Measurement Parameters

This section describes some measurement parameters that receive from radar sensor and gives information about the target.

**Range**

Radar transmits the radio waves with sufficient power into the space. If the radar has directional antennas, then the radio waves are focused in one direction only and propagate in this direction with speed of light. If these radio waves strike an obstacle in its path, then part of the energy of the waves is reflected back to the radar which then evaluates the information contained in it. The distance between the radar and the target object (obstacle) can be calculated from the runtime of the radio wave. The actual range of the target object from the radar is known as slant range and it is line of sight distance between the radar and the target object (cf. [6]).

\[ s = v \cdot t \]  

(1)

Where ‘s’ is the distance travelled by the radio wave during its flight, which is ‘2R’ because it travels from radar to target object and back before detection. Where ‘v’ is the velocity by which the radio wave is travelling which is equal to the speed of light \( c_0 = 3 \times 10^8 \text{ m/s} \). The Equation 1 will become,

\[ 2R = c_0 \cdot t \]  

(2)

Hence the range will become as,

\[ R = \frac{c_0 \cdot t}{2} \]  

(3)

**Radial Velocity**

Radial velocity of an object is the rate of change of distance of that object with respect to the radar antenna. When electromagnetic waves are reflected back from an object to radar antenna, it gives the radial velocity if an object is moving towards or away from the radar. If an object is moving then its absolute velocity can be decomposed into two components; the velocity along the radial direction (which is also known as radial
velocity) and the velocity perpendicular to that radial direction. The diagonal of the rectangle which is formed by these two components is the absolute velocity vector of an object. Hence the radial velocity is the part of absolute velocity. It can also be seen in the Figure 3, where the green arrow shows the radial velocity, blue arrow shows the tangential velocity and the red arrow is the absolute velocity of the plane. The rate of change of distance will be zero if object is stationary or moving along the perpendicular direction (at Point B in Figure 3), hence the radial velocity will be zero. The Doppler frequency only occurs if the radial velocity is not zero. If the rate of change of distance between the object and radar antenna is decreasing (when the object is approaching) then the radial velocity will be negative and if it is increasing (object is moving away) then the radial velocity will be positive (cf. [6]).

![Figure 3: Velocity Components](image)

**Azimuth Angle**

The angle at which target is located can be determined from the directivity of the antenna. Directivity is defined as the ability of the antenna to focus the transmitted energy in a certain direction. When a reflected signal (ECHO) is received at the receiver, both the azimuth angle and elevation angle of the target from the radar can be calculated by measuring the angle at which the antenna is pointing at that time (cf. [6]).
Changing the antenna orientation can be accomplished either mechanically or electronically without moving parts (beam forming).

**Radar Cross Section**

The ability of radar to detect a target object is defined by the radar cross section. It is a measure of the ratio of backscattered power density of the ECHO signal from the target towards radar to the power density of the signal intercepted by target object. It is denoted by ‘\( \sigma \)’ and has a unit of \( \text{m}^2 \). Radar cross section \( \sigma \) is defined by the Equation 4 (cf. [6]),

\[
\sigma = \frac{4 \cdot \pi \cdot r^2 \cdot S_r}{S_t}
\]  

(4)

Where

\( \sigma \) = measure of the target object’s ability to reflect radar signals towards radar receiver, in \( \text{[m}^2\text{]} \)

\( S_t \) = power density of the signal intercepted by target object, in \( \text{[W/m}^2\text{]} \)

\( S_r \) = backscattered power density of the ECHO signal in the range \( r \), in \( \text{[W/m}^2\text{]} \)

2.1.2 Limitations of Radar

Apart from its advantages, radar has some shortcomings too. There are certain things that radar cannot perform, for example detecting lane markings on the road, detecting and reading traffic signs on the boards, reliably detecting pedestrians at the road junction and performing lighting function as desired according to the traffic and environment conditions (cf. [7]).

But the main limitation of radar which is of our interest is; when target object is moving tangentially with respect to radar then there is no radial velocity measurement from it. Radar sees the target object as a stationary object because of no Doppler frequency (cf. [6]). Hence the absolute velocity of target object must be determined from the azimuth angle change. But the accuracy of azimuth angle limits the accuracy of absolute velocity of target object.
2.2 Advanced Driver Assistance Systems

Advanced Driver Assistance Systems (ADAS) are intelligent on board systems (real-time embedded systems) which have been developed by automotive manufacturers and their suppliers to help the driver during all phases of driving to provide comfort, driving efficiency and road safety etc. (cf. [8], p. 12). ADAS systems consist of at least one sensor, an evaluation unit and at least one actuator.

These systems sense the surrounding environment of a vehicle through powerful sensors (Radar, Camera etc.), evaluate the gathered information and activate the required actuators (brakes, warning LED etc.). Safety is the critical aspect of these designs and is provided by giving alerts to the driver against any potential hazard or by taking control of the vehicle. Examples of such systems are Collision Warning (CW), Lane Departure Warning (LDW), Anti-lock Braking Systems (ABS), Collision Avoidance (CA) and Emergency Brake Assist (EBA) etc. While comfort is provided by giving useful information and by reducing driver’s fatigue through systems like Adaptive Cruise Control (ACC), Night Driving Assist and Navigation Systems etc (cf. [3]).

2.3 Radar Based ADAS

Radar based Advanced Driver Assistance Systems are characterized by the use of short range (<50m), mid range (~100...150m) and long range (>=200m) radars to analyze the environment around the car. Depending upon the transmitter/receiver antenna position
(front, rear and side) and software/algorithm, these systems can address the following applications to provide pure driving safety and driving comfort (cf. [10]),

### 2.3.1 Adaptive Cruise Control

It is an autonomous cruise control system which is installed on road vehicles to provide comfort to the drivers while driving. Mostly it is used on highways where it uses long range radar sensor to detect the other vehicle in front and automatically adjust the speed of the vehicle to maintain a safe distance (cf. [11]).

### 2.3.2 Blind spot Monitoring

It is a collision warning system which is installed on road vehicles to provide safety to the drivers while driving. This system can use different sensors (like short range radar etc) to detect the other vehicles located on the side and rear of the vehicle and give warning to driver in the form of acoustic or visual signal (cf. [12]).

![Figure 5: Forward Looking Radar Application (ACC)](image)

### 2.3.3 Automatic Emergency Braking

It is a collision avoidance system which is installed on road vehicles to provide safety to the vehicle occupants and its surroundings. Depending on the application (in city or highway), different radar sensors are used to detect the hazardous situations and gives warning signals to drivers. If driver does not act within the safety time, the system intervenes and applies brakes automatically to avoid collision or to reduce the effects of collision (cf. [13]).
2.4 Curve Smoothing (Fitting) Methods

Here are some basic techniques that can be used to remove the spikes and to refine the received signals.

**Simple Moving Average (SMA)**

A simple moving average (SMA) is formed by computing the average (mean) of Input data over a specified number of periods. SMA is usually defined as the un-weighted mean of the previous ‘n’ data (\(I_{14}\)).

For taking an example of simple equally weighted running mean for n-test samples of data, let’s consider if those data samples are \(I_M, I_{M-1}, \ldots, I_{M-(n-1)}\) then the formula would be formulized as (\(I_{14}\)),

\[
SMA = \frac{I_M + I_{M-1} + \ldots + I_{M-(n-1)}}{n} = \frac{1}{n} \sum_{i=0}^{n-1} I_{M-i}
\]  

(5)

**Exponential Moving Average (EMA)**

Exponential Moving Averages (EMA), also known as an exponentially weighted moving average (EWMA), can be specified in two ways - as a percent-based EMA or as a period-based EMA. A percent-based EMA has a percentage as its single parameter while a period-based EMA has a parameter that represents the duration of the EMA. The formula for an exponential moving average is (\(I_{14}\)),

\[
EMA(\text{current}) = ( (\text{Input data}(\text{current}) - EMA(\text{prev}) ) \times \text{Multiplier}) + EMA(\text{prev})
\]  

(6)

**Weighted Moving Average (WMA)**

A weighted average is any average that has multiplying factors to give different weights to data at different positions in the sample window. Mathematically, the moving average is the convolution of the datum points with a fixed weighting function (\(I_{14}\)).

While performing technical analysis of data, a weighted moving average (WMA) has the specific meaning of weights that decrease in arithmetical progression (\(I_{14}\)),

\[
WMA = \frac{np_M + (n-1)p_{M-1} + \ldots + 2p_{(M-n+2)} + p_{(M-n+1)}}{n + (n-1) + \ldots + 2 + 1}
\]  

(7)
**Cumulative Moving Average (CMA)**

A cumulative moving average can be defined as the arrival of data in an ordered datum stream, and one would like to get the average of all of the data up until the current datum point. As each new data input receives, the average input at the time of the occurrence can be calculated for all of the occurrences up to that point using the cumulative average, typically an equally weighted average of the sequence of n values $x_1, \ldots, x_n$ up to the current time $([14])$,

$$CMA_n = \frac{x_1 + \cdots + x_n}{n} \quad (8)$$

The brute-force method to calculate this would be to store all of the data and calculate the sum and divide by the number of datum points every time a new datum point arrived. However, it is possible to simply update cumulative average as a new value, $x_{n+1}$ becomes available, using the formula $([14])$.

$$CMA_{n+1} = \frac{x_{n+1} + n \cdot CMA_n}{n + 1} \quad (9)$$

**Modified Moving Average (MMA)**

Modified moving averages are similar to simple moving averages. The first point of the modified moving average is calculated the same way the first point of the simple moving average is calculated. However, all subsequent points are calculated by first adding the new input data and then subtracting the last average from the resulting sum. The difference is the new point, or modified moving average $([15])$.

### 2.5 Trendline for Detection Methods

Trendlines are used to give indications about the pattern of the data and also it indicates when a trend in the data has changed. To see the trend in the data, any of the following six trendlines or regression types can be chosen but the type of data determines which trendline should be used.

**Linear Trendline**

A linear trendline is a best fit straight line that is used when we have a data set of simple linear values. The slope of the straight line determines either the trend in the data is increasing or decreasing at a steady rate (cf. [16]).
**Logarithmic Trendline**
A logarithmic trendline is a best fit curved line that is used when the rate of change in data values is increasing or decreasing rapidly and then become stable (cf. [16]).

**Polynomial Trendline**
A polynomial trendline is a curved line and it is used when the data is constantly changing over time. The order of the polynomial can be varied according to the number of variations in the data (cf. [16]).

**Power Trendline**
A power trendline is again a curved line and it is used when the data is constantly increasing at a specific rate. If the data contains zero or negative values then this power trendline cannot be used or created from the data (cf. [16]).

**Exponential Trendline**
An exponential trendline is a curved line and it is used when the data is increasing or decreasing at a very high rate. If the data contains zero or negative values then this exponential trendline cannot be used or created from the data (cf. [16]).

**Moving Average Trendline**
A moving average trendline is used to remove the spikes or fluctuations in the data set and shows the pattern of the data very clearly (cf. [16]).

### 2.6 Related Work

Due to recent developments in safety requirements for crossing scenarios and global NCAP safety ratings, every OEM is now focusing on developing safety systems for crossing objects and pedestrian protection. From 2016 onward, Autonomous Emergency Braking and pedestrian protection systems have become standard equipments in every new car (cf. [17]). Mercedes-Benz has already developed a safety system ‘BAS PLUS with Cross Traffic Assist’ in 2013, which not only avoid collisions from rear side but also avoid collisions from the front side with the help of Stereo Camera and Radar sensors (cf. [18]). Similarly Toyota has introduced a Pre-Collision Safety (PCS) system to avoid front side collisions in 2015, which is also Radar and Camera based fusion system (cf. [19]). Companies like Audi (cf. [20]) and Continental
(cf. [21]) have already introduced Radar based Rear Cross Traffic Alert systems for parking assistance.

2.7 Summary

In this chapter, the basic theory of radar sensor has been presented. It also describes in detail some of its useful measurement parameters and its limitations with respect to its applications in automotive field. Next it also includes the basic description of Advanced Driver Assistance System, its advantages in daily life and some examples of the radar based ADAS systems. Some methods have been explained to reduce the noise in the signals and to see the trend of the data. This chapter ends by highlighting some related work to this master thesis.
3 Methodology

This chapter describes the concept of the whole research and development conducted in this thesis. It highlights the main problem area of the cross traffic assist function and addresses the solution to enhance the performance of the function.

3.1 Description of Main Work

The main focus of this thesis work is to develop a radar based maneuver detection function for Crossing EBA to assist crossing objects at road junction and to reduce the false alarm rate for misuse cases. The function performance is defined by two parameters; Detection Rate and False Alarm Rate. Detection Rate relates to the Use Case (collision: brake/warning desired) and False Alarm Rate relates to the Misuse case (object stops at road border etc: no brake/warning shall occur). Detection Rate is; how often the system detects the collision at road junction between ego vehicle and crossing vehicle when these are moving on a collision course, and in this case ego vehicle must stop in order to avoid collision. Whereas the False Alarm Rate is; the crossing vehicle brakes and stops at stop line, the ego vehicle makes full brakes too while in this case the ego vehicle should not apply brakes. This is very critical as ‘Misuse case’ happens very often and will put others lives in danger, whereas the high Detection Rate saves lives.

![Figure 6: Crossing EBA Function Division](image)
Hence the challenge is to **reduce the False Alarm Rate** as much as possible while maintaining the high detection rate. This is because if some of the use cases are lost, the system is still saving lives but not endangering any life. So the red cloud in the Figure 6 is the major concern.

To reduce the false alarms it is necessary to track the tangential moving objects accurately by using radar sensor, which can only be achieved if the system knows the accurate lateral maneuvers (acceleration/deceleration) of the target vehicle.

### 3.2 State of the Art

One way of determining target maneuver is to know about the absolute velocity of the target vehicle, its actual location and its orientation. Once these three parameters are known, the time to collision can be calculated to find out either there will be a collision or not when ego vehicle reaches road junction. Radar measurements do not provide the absolute velocity of target vehicle directly; it can only be estimated through its measured parameters. The Figure 7 shows the scenario of a target with velocity ‘\(v\)’ moving at an orientation of ‘\(\alpha\)’. The projection of the velocity along the X axis and Y axis are ‘\(v_x\)’ and ‘\(v_y\)’ respectively. The measured radial velocity by the radar is ‘\(v_{rad}\)’ at an azimuth angle of ‘\(\theta\)’ (*cf. [22]*).

![Figure 7: Formation of Radial Velocity Vector](image-url)
The radial velocity $v_{rad}$ is the projection of the object velocity vector ‘v’ on the azimuth axis. By decomposing $v_x$ and $v_y$ along the radial direction it can be derived that

$$v_{rad} = v_x \cos \theta + v_y \sin \theta$$  \hspace{1cm} (10)

The value of $v_{rad}$ and $\theta$ is known from the measurement. The object velocity values $v_x$ and $v_y$ must be determined. From the above Equation 10 no unambiguous solution can be derived in the general case. To solve Equation 10 with 2 unknowns another assumption (equation) is needed ([22]).

For longitudinal moving objects (ACC use-case) the simplest assumption would be $v_y = 0$. However, for arbitrary moving objects (crossing object) a more refined assumption must be made. The second equation can be derived by forcing a minimization condition. It must be noted that the condition must be such that the value of either $v_x$ or $v_y$ must not go towards infinite for all possible values of $\theta$. After the determination of projections of velocity vector $v_x$ and $v_y$ along x-axis and y-axis respectively, orientation angle $\alpha$ can be derived from the following equation ([22]),

$$\alpha = \frac{v_y}{v_x}$$  \hspace{1cm} (11)

And finally the velocity vector by,

$$v = v_x \cos \alpha + v_y \sin \alpha$$  \hspace{1cm} (12)

Minimization condition needs values of $v_x$ or $v_y$ estimated from the kalman tracker (cf. [22]). Due to propagation of uncertainties of the parameters, kalman tracker does not provide the accurate velocity values; hence the sudden change in the absolute velocity of the target vehicle cannot be determined accurately, which leads to false alarms. Hence this method has not been chosen to detect the target maneuvering (braking etc.), while it is effective in those cases when the collision happens (usually vehicles collide with the same speed as these are moving before collision) and has been used to calculate the time to collision (ttc).
3.3 Concept

Other way of determining target maneuver is by evaluating the behavior of radar measurement parameters. Continental radar gives measurements of different parameters but the most interesting parameters to check the target maneuver are the Radial Velocity \( V_{rad} \), Azimuth Angle \( \text{Azi} \) and Range \( R \). Radial velocity has better accuracy than the other radar parameters; hence it is reliable and can be evaluated.

**Radial Velocity**

Equation 10 can be modified to calculate the radial velocity of the target object (plane) as,

\[
V_{rad} = (v_x \cos \theta + v_y \sin \theta) - v_{obs} \cos \theta
\]  

(13)

Where \( v_{obs} \) is the velocity of the observer (radar station), \( \theta \) is the azimuth angle between observer and target object which can be determined from the current positions of observer and target object in the following way,

\[
\theta = \tan^{-1} \left( \frac{y_{tar} - y_{obs}}{x_{tar} - x_{obs}} \right)
\]  

(14)

Where \( v_x \) and \( v_y \) are the projections of target object’s velocity vector on the x-axis and y-axis respectively and calculated from the following equations,

\[
v_x = v \cos \alpha
\]  

(15)

\[
v_y = v \sin \alpha
\]  

(16)

Where \( v \) is the velocity of target object and \( \alpha \) is the orientation angle at which the target object is moving on a frame of reference.

Now let’s look at the problem and try to theoretically find out the behavior of the radial velocity \( V_{rad} \) for the crossing scenarios. Before going into detail one thing should be noted here, Crossing EBA can face many scenarios in real life in which it has to decide between collision and non-collision cases and take actions. Collision cases are straightforward to detect because mostly in these cases both the vehicles are moving with almost constant speeds. But non-collision cases can be of different types, e.g. crossing target vehicle apply brakes and stops at stop line or it passes by the ego vehicle before...
ego vehicle reaches the junction etc. Hence non-collision case can be further split up into two categories as shown in Figure 8.

Figure 8: Crossing EBA Problem Division

Hence there are three categories of crossing scenarios now; first when Ego and Target vehicles are moving on a collision course and have a collision, secondly when Ego and Target vehicles are moving on a collision course but the target vehicle apply brakes and stops at stop line and thirdly when Target vehicle is Passing By Ego vehicle at road junction without having a collision. The behavior of radial velocity would be different when the speed of the target vehicle is different. Hence to theoretically find out the radial velocity behavior for the three assumed scenarios, two assumptions have been made. First, when target vehicle is moving with constant speed (zero acceleration). Secondly, when target vehicle is moving with variable speed (constant acceleration and deceleration), while ego vehicle speed will remain constant in all the test cases.

3.3.1 Non-Accelerated Motion

First of all, the behavior of the radial velocity will be checked for the three assumed scenarios of Crossing EBA when both ego vehicle and target vehicles are moving with constant speeds. For simplicity, it is assumed that both vehicles are moving with same constant speed and the target vehicle is crossing ego vehicle at 90° angle according to AUTOSAR standard. The reference frame is taken from the radar location which is installed at the center of the front bumper of ego vehicle.
a. Collision

Let’s say there is a collision scenario as shown in Figure 9 in which ego vehicle (yellow car) and target vehicle (red car) are moving with constant speed of 10 m/s in x-direction and y-direction respectively and collide after 20 s at the road junction. The starting positions of ego vehicle \((x_{ego}, y_{ego})\) and target vehicle \((x, y)\) can be calculated from the following equation of motion,

\[
s = v t + \frac{1}{2} at^2
\]  

(17)

![Figure 9: Collision Scenario](image)

The radial velocity of the target vehicle in Collision Scenario can be calculated from the following equation which is modified from Equation 13 as,

\[
v_{rad} = (v_x \cos \theta + v_y \sin \theta) - v_{ego} \cos \theta
\]  

(18)

Here ‘\(v_{ego}\)’ is the actual velocity of ego vehicle (observer) and is already known, theta \((\theta)\) is the azimuth angle between ego vehicle and target vehicle and can be determined from the current positions of vehicles as,

\[
\theta = \tan^{-1} \left( \frac{y - y_{ego}}{x - x_{ego}} \right)
\]  

(19)
Velocity ‘v’ of the target vehicle and orientation angle ‘α’ at which the target vehicle is moving on a reference frame are already known beforehand. Hence ‘vₓ’ and ‘vᵧ’ can be calculated from Equation 15 and Equation 16 respectively. So all parameter values are known, the behavior of radial velocity (vₚ) can be seen in the Figure 10.

Figure 10 shows the results of radial velocity of target vehicle, when it is colliding with ego vehicle and it is plotted against the distance along y-axis. Target vehicle start at some distance from negative y-direction (x-axis) and stop at y equals to zero (road junction) when the collision occurs. Radial velocity is negative because the rate of change of distance is decreasing (target vehicle is moving towards ego vehicle). The radial velocity remained constant throughout the collision course until the collision happened at y equals to zero. It can also be derived from the radial velocity equation.

According to Equation 18, radial velocity depends on four parameters; target vehicle velocity (v) which is constant and given, orientation (α) which is also known and remained same throughout the course, ego vehicle velocity (vₑ₀) which is also constant and given, azimuth angle (θ) which also remained constant (in this case 45°) because the rate of change of distance of each vehicle to the junction point remained the same. Hence radial velocity remained constant until the target vehicle collided with ego vehicle and stopped at y equals to zero. When both vehicles collided with each other and stopped, the radial velocity also became zero.
b. Target Brake

Now let’s say there is a non-collision scenario in which ego vehicle (yellow car) and target vehicle (red car) are moving with same speed of 10m/s from the same distance in x-direction and y-direction respectively. Target vehicle applies brakes before reaching the road junction and stops at stop line as shown in Figure 11, while ego vehicle reaches the road junction in 20s. The starting positions of ego vehicle \((x_{ego}, y_{ego})\) and target vehicle \((x, y)\) can be calculated from the following equation of motion,

\[
s = vt + \frac{1}{2}at^2
\]

Here ‘\(v_{ego}\)’ is the velocity of ego vehicle (observer) and is already known, theta \((\theta)\) is the azimuth angle between ego vehicle and target vehicle and can be determined from the current positions of vehicles as,

\[
v_{rad} = (v_{x} \cos \theta + v_{y} \sin \theta) - v_{ego} \cos \theta
\]

The radial velocity of the target vehicle in Target Brake Scenario can be calculated from the following equation which is modified from Equation 13 as,
Velocity ‘v’ of the target vehicle and orientation angle ‘α’ at which the target vehicle is moving on the reference frame is already known beforehand. Hence ‘v_x’ and ‘v_y’ can be calculated from Equation 15 and Equation 16 respectively. So all parameter values are known, the behavior of radial velocity (v_rad) can be seen in the Figure 12.

\[
\theta = \tan^{-1} \left( \frac{y - y_{ego}}{x - x_{ego}} \right)
\]  

(22)

Figure 12 shows the results of radial velocity of target vehicle, when it is moving on a collision course but apply brakes and stops at stop line. If the target vehicle had not applied brakes, it would have collided with the ego vehicle. Target vehicle start at some distance from negative y-direction (x-axis) and stop at stop line (y = -2). Radial velocity is negative because the rate of change of distance is decreasing (target vehicle is moving towards ego vehicle). When ego vehicle and target vehicle are moving with constant velocities and on a collision course, the radial velocity remains constant and when target vehicle start applying brakes to stop at stop line, the radial velocity graph starts increasing at that point, and going towards zero because the target vehicle is going to stop at stop line. The radial velocity in Figure 12 has not completely drops to zero because at this point in time, ego vehicle has reached road junction while the target vehicle is still slowing down and has some speed which will eventually drops to zero. If the target vehicle applies soft brakes, the radial velocity graph will start increasing slowly and this change in curve will shift towards left. If it applies hard brakes, the
radial velocity graph will increase very abruptly and this change in curve will shift towards right.

c. **Target Pass By**

Now let’s say there is another non-collision scenario in which ego vehicle (yellow car) and target vehicle (red car) are moving with constant speed of 10m/s in x-direction and y-direction respectively for 20s. Ego vehicle reaches the road junction position in 20s while target vehicle passes the ego vehicle at the road junction for about 2s earlier as shown in Figure 13.

The starting positions of ego vehicle \((x_{ego},y_{ego})\) and target vehicle \((x,y)\) can be calculated from the following equation of motion,

\[
s = v t + \frac{1}{2} at^2
\]  

(23)

The radial velocity of the target vehicle in Target Pass By Scenario can be calculated from the following equation which is modified from Equation 13 as,

\[
v_{rad} = (v_x \cos \theta + v_y \sin \theta) - v_{ego} \cos \theta
\]  

(24)
Here ‘v\textsubscript{ego}’ is the velocity of ego vehicle (observer) and is already known, theta (θ) is the azimuth angle between ego vehicle and target vehicle and can be determined from the current positions of vehicles as,

\[
\theta = \tan^{-1}\left(\frac{y - y\textsubscript{ego}}{x - x\textsubscript{ego}}\right)
\]  

(25)

Velocity ‘v’ of the target vehicle and orientation angle ‘α’ at which the target vehicle is moving on the reference frame is already known beforehand. Hence ‘v\textsubscript{x}’ and ‘v\textsubscript{y}’ can be calculated from Equation 15 and Equation 16 respectively. So all parameter values are known, the behavior of radial velocity (v\textsubscript{rad}) can be seen in the Figure 14.

![Radial Velocity Behavior](image)

**Figure 14:** Radial Velocity Behavior in Target Pass By Scenario

Figure 14 shows the results of radial velocity of target vehicle, when it is passing by ego vehicle on a cross road and it is plotted against the distance along y-axis. Target vehicle start at some distance from negative y-direction (x-axis) and pass by ego vehicle at ‘y’ equals to zero (road junction) few seconds earlier. Radial velocity is negative because the rate of change of distance is decreasing (target vehicle is moving towards ego vehicle). The radial velocity graph is gradually increasing in the beginning but rapidly increased in the end when target vehicle is about to cross the ego vehicle path (road junction). The radial velocity is not remaining constant because one of the parameter in the radial velocity Equation 21 is changing throughout the course now, which is azimuth angle (θ). The azimuth angle (θ) is changing in this scenario because of the difference of the rate of change of distance of each vehicle to the junction point.
When the target vehicle is far from the road junction point, the azimuth angle ($\theta$) is decreasing slowly; hence radial velocity ($v_{rad}$) is changing slowly. If the target vehicle crosses the ego vehicle at road junction just fraction of time earlier, the radial velocity graph will shift towards right and the increase in radial velocity graph will be very abrupt closer to road junction ($y=0$). The radial velocity is not zero when the target vehicle is tangential or at road junction ($y = 0$) because the frame of reference (ego vehicle) is moving. The radial velocity at road junction ($y=0$) is equal to the velocity of reference frame (ego vehicle) and it is negative because it is moving towards the target vehicle.

![Radial Velocity Behavior](image)

**Figure 15:** Combined Radial Velocity Results

This Figure 15 shows the combined results of radial velocity behavior of target vehicle for all the three scenarios which have been described above for non-accelerated motion. The plot shows the results of radial velocity until both or any one of the vehicle has reached the road junction. The change in radial velocity behavior is now quite evident for the non-collision scenarios (Target Pass By, Target Brake). But radial velocity in a collision course remains constant until the collision happened at road junction and it is interested to know the behavior of radial velocity just before the ego or target vehicle reaches the road junction (0, 0). Hence the collision and non-collision cases can be differentiated from the behavior of radial velocity. For collision case, it remains constant; while for non-collision cases, it starts changing when the target apply brakes.
or pass by. So if the change in radial velocity behavior is accurately and timely detected, crossing EBA will not give any false alarms.

3.3.2 Accelerated Motion

Now let’s try to check the behavior of radial velocity (Vrad) for the three scenarios when ego is moving with constant speed while target vehicle is moving with variable speed (constant acceleration and deceleration). For simplicity, it is assumed that target vehicle is crossing ego vehicle at 90° angle according to AUTOSAR standard. The reference frame is taken from the radar location which is installed at the center of the front bumper of ego vehicle.

a. Collision

Let’s say there is a collision scenario as shown in Figure 16 in which ego vehicle (yellow car) is moving in x-direction with constant speed of 10m/s while target vehicle (red car) is moving in y-direction with initial speed of 10m/s and has a constant acceleration and deceleration of 0.2m/s² and collide after 20s at the road junction. The starting positions of ego vehicle (x_ego, y_ego) and target vehicle (x, y) can be calculated from the following equation of motion,

\[ s = v \cdot t + \frac{1}{2} a t^2 \]  

(26)

![Figure 16: Collision Scenario with Accelerated Motion](image)
The radial velocity of the target vehicle in Collision Scenario with Accelerated Motion can be calculated from the following equation which is modified from Equation 13 as,

\[ v_{rad} = (v_x \cos \theta + v_y \sin \theta) - v_{ego} \cos \theta \]  

(27)

Here ‘v_{ego}’ is the constant velocity of ego vehicle (observer) and is already known, theta (θ) is the azimuth angle between ego vehicle and target vehicle and can be determined from the current positions of vehicles as,

\[ \theta = \tan^{-1} \left( \frac{y - y_{ego}}{x - x_{ego}} \right) \]  

(28)

Velocity ‘v’ is the current velocity of the target vehicle and orientation angle ‘α’ at which the target vehicle is moving on a reference frame is already known beforehand. Hence ‘v_x’ and ‘v_y’ can be calculated from Equation 15 and Equation 16 respectively. So all parameter values are known, the behavior of radial velocity (v_{rad}) of target vehicle on a collision course when it has a constant acceleration of 0.2m/s^2 can be seen in the Figure 17.

\[ \text{Figure 17: Radial Velocity Behavior in Collision Scenario with Target Acceleration} \]

Figure 17 shows the results of radial velocity of target vehicle, when it is moving on a collision course with constant acceleration and collides with constantly moving ego vehicle at road junction. Radial velocity is plotted against the distance along y-axis. Target vehicle start at some distance from negative y-direction (x-axis) and stop at ‘y’
equals to zero (road junction) when the collision occurs. Radial velocity is negative because the rate of change of distance is decreasing (target vehicle is moving towards ego vehicle). The radial velocity is decreasing constantly because the rate of change of distance is decreasing with constant increasing rate. It can also be derived from Equation 27. When both vehicles collided with each other and stopped, the radial velocity becomes zero.

The behavior of radial velocity \(v_{\text{rad}}\) of target vehicle on a collision course when it is moving with constant deceleration of \(0.2\text{m/s}^2\) can be seen in the Figure 18.

![Radial Velocity Behavior](image)

**Figure 18**: Radial Velocity Behavior in Collision Scenario with Target Deceleration

Figure 18 shows the results of radial velocity of target vehicle, when it is moving on a collision course with constant deceleration and collides with constantly moving ego vehicle at road junction. Radial velocity is plotted against the distance along y-axis. Target vehicle start at some distance from negative y-direction (x-axis) and stop at ‘y’ equals to zero (road junction) when the collision occurs. Radial velocity is negative because the rate of change of distance is decreasing (target vehicle is moving towards ego vehicle). The radial velocity is increasing constantly because the rate of change of distance is decreasing with constant decreasing rate. It can also be derived from the Equation 27. When both vehicles collided with each other and stopped, the radial velocity becomes zero.
b. Target Brake

Let’s say there is a non-collision scenario in which ego vehicle (yellow car) is moving in x-direction with constant speed of 10m/s while target vehicle (red car) is moving in y-direction with initial speed of 10m/s and has a constant acceleration and deceleration of 0.2m/s$^2$ for 20s. Target vehicle applies additional brakes before reaching the road junction and stops at stop line as shown in Figure 19, while ego vehicle reaches the road junction in 20s. The starting positions of ego vehicle ($x_{ego}, y_{ego}$) and target vehicle (x,y) can be calculated from the following equation of motion,

$$s = vt + \frac{1}{2}at^2$$  \hspace{1cm} (29)

![Figure 19: Target Brake Scenario with Accelerated Motion](image)

The radial velocity of the target vehicle in Target Brake Scenario with Accelerated Motion can be calculated from the following equation which is modified from Equation 13 as,

$$v_{rad} = (v_x \cos \theta + v_y \sin \theta) - v_{ego} \cos \theta$$  \hspace{1cm} (30)
Here ‘\(v_{\text{ego}}\)’ is the velocity of ego vehicle (observer) and is already known, theta (\(\theta\)) is the azimuth angle between ego vehicle and target vehicle and can be determined from the current positions of vehicles as,

\[
\theta = \tan^{-1}\left(\frac{y - y_{\text{ego}}}{x - x_{\text{ego}}}\right)
\]

Velocity ‘\(v\)’ of the target vehicle and orientation angle ‘\(\alpha\)’ at which the target vehicle is moving on the reference frame is already known beforehand. Hence ‘\(v_x\)’ and ‘\(v_y\)’ can be calculated from Equation 15 and Equation 16 respectively. So all parameter values are known, the behavior of radial velocity (\(v_{\text{rad}}\)) of target vehicle in a Target Brake scenario when it is moving initially with constant acceleration of 0.2m/s\(^2\) before applying brakes can be seen in the Figure 20.

![Radial Velocity Behavior](image)

**Figure 20**: \(v_{\text{rad}}\) Behavior in Target Brake Scenario with Target Acceleration

Figure 20 shows the results of radial velocity of target vehicle, when it is moving on a collision course with constant acceleration and in the end apply brakes and stops at stop line. If the target vehicle had not applied brakes, it would have collided with the ego vehicle. Target vehicle start at some distance from negative y-direction (x-axis) and stop at stop line (y = -2). Radial velocity is negative because the rate of change of distance is decreasing (target vehicle is moving towards ego vehicle). The radial velocity is decreasing constantly in the beginning because the rate of change of distance is decreasing with constant increasing rate and when target vehicle start applying brakes to stop at stop line, the radial velocity graph starts increasing at that point, and
going towards zero because the target vehicle is going to stop at stop line. The radial velocity in Figure 20 has not completely drops to zero because at this point in time, ego vehicle has reached road junction while the target vehicle is still slowing down and has some speed which will eventually drops to zero later on, and thus equals to the speed of target vehicle. If the target vehicle applies soft brakes, the radial velocity graph will start increasing slowly and this change in curve will shift towards left. If it applies hard brakes, the radial velocity graph will increase very abruptly and this change in curve will shift towards right.

The behavior of radial velocity ($v_{rad}$) of target vehicle in a Target Brake scenario when it is moving initially with constant deceleration of $0.2 \text{m/s}^2$ before applying brakes can be seen in the Figure 21.

![Radial Velocity Behavior](image)

Figure 21: $v_{rad}$ Behavior in Target Brake Scenario with Target Deceleration

Figure 21 shows the results of radial velocity of target vehicle, when it is moving on a collision course with constant deceleration and in the end apply brakes and stops at stop line. If the target vehicle had not applied brakes, it would have collided with the ego vehicle. Target vehicle start at some distance from negative y-direction (x-axis) and stop at stop line ($y = -2$). Radial velocity is negative because the rate of change of distance is decreasing (target vehicle is moving towards ego vehicle). The radial velocity is increasing constantly in the beginning because the rate of change of distance is decreasing with constant decreasing rate and when target vehicle start applying brakes to stop at stop line, the radial velocity graph starts increasing at that point, and
going towards zero because the target vehicle is going to stop at stop line. The radial velocity in Figure 21 has not completely drops to zero because at this point in time, ego vehicle has reached road junction while the target vehicle is still slowing down and has some speed which will eventually drops to zero later on, and thus equals to the speed of target vehicle. If the target vehicle applies soft brakes, the radial velocity graph will start increasing slowly and this change in curve will shift towards left. If it applies hard brakes, the radial velocity graph will increase very abruptly and this change in curve will shift towards right.

c. **Target Pass By**

Let’s say there is another non-collision scenario as shown in Figure 22 in which ego vehicle (yellow car) is moving in x-direction with constant speed of 10m/s while target vehicle (red car) is moving in y-direction with initial speed of 10m/s and has a constant acceleration and deceleration of 0.2m/s² for 20s. Ego vehicle reaches the road junction position in 20s while target vehicle passes the ego vehicle at the road junction for about 2s earlier. The starting positions of ego vehicle \((x_{ego},y_{ego})\) and target vehicle \((x,y)\) can be calculated from the following equation of motion,

\[
s = vt + \frac{1}{2}at^2
\]

\[\text{(32)}\]

**Figure 22**: Target Pass By Scenario with Accelerated Motion
The radial velocity of the target vehicle in Target Pass By Scenario with Accelerated Motion can be calculated from the following equation which is modified from Equation 13 as,

\[ v_{rad} = (v_x \cos \theta + v_y \sin \theta) - v_{ego} \cos \theta \]  

(33)

Here ‘v\text{ego}’ is the velocity of ego vehicle (observer) and is already known, theta (\theta) is the azimuth angle between ego vehicle and target vehicle and can be determined from the current positions of vehicles as,

\[ \theta = \tan^{-1}\left(\frac{y - y_{ego}}{x - x_{ego}}\right) \]  

(34)

Velocity ‘v’ of the target vehicle and orientation angle ‘\alpha’ at which the target vehicle is moving on the reference frame is already known beforehand. Hence ‘v_x’ and ‘v_y’ can be calculated from Equation 15 and Equation 16 respectively. So all parameter values are known, the behavior of radial velocity (v_{rad}) of target vehicle in a Pass By scenario when it is moving with constant acceleration of 0.2m/s^2 can be seen in the Figure 23.

![Radial Velocity Behavior](image)

**Figure 23:** V_{rad} Behavior in Target Pass By Scenario with Target Acceleration

Figure 23 shows the results of radial velocity of target vehicle, when it is passing by ego vehicle on a cross road and it is plotted against its distance along y-axis. Target vehicle start at some distance from negative y-direction (x-axis) and pass by ego vehicle at distance ‘y’ equals to zero (road junction) few seconds earlier. Radial
velocity is negative because the rate of change of distance is decreasing (target vehicle is moving towards ego vehicle). The radial velocity graph is almost constantly decreasing in the beginning because the rate of change of distance is decreasing with almost increasing rate, but rapidly start increasing in the end when target vehicle is about to cross the ego vehicle path at road junction. The radial velocity is not remaining constant because one of the parameter in the Equation 30 is changing throughout the course now, which is azimuth angle ($\theta$). The azimuth angle ($\theta$) is changing in this scenario because of the difference of the rate of change of distance of each vehicle to the junction point. The radial velocity at road junction ($y=0$) is equal to the velocity of reference frame (ego vehicle) and it is negative because it is moving towards the target vehicle.

The behavior of radial velocity ($v_{rad}$) of target vehicle in a Pass By scenario when it is moving with constant deceleration of 0.2m/s$^2$ can be seen in the Figure 24.

![Radial Velocity Behavior](image)

**Figure 24:** $v_{rad}$ Behavior in Target Pass By Scenario with Target Deceleration

Figure 24 shows the results of radial velocity of target vehicle, when it is passing by ego vehicle on a cross road and it is plotted against its distance along y-axis. Target vehicle start at some distance from negative y-direction (x-axis) and pass by ego vehicle at distance ‘y’ equals to zero (road junction) few seconds earlier. Radial velocity is negative because the rate of change of distance is decreasing (target vehicle is moving towards ego vehicle). The radial velocity graph is almost constantly increasing in the beginning because the rate of change of distance is decreasing with
almost decreasing rate, but rapidly start increasing in the end when target vehicle is about to cross the ego vehicle path at road junction. The radial velocity is not remaining constant because one of the parameter in the Equation 30 is changing throughout the course now, which is azimuth angle (θ). The azimuth angle (θ) is changing in this scenario because of the difference of the rate of change of distance of each vehicle to the junction point. The radial velocity at road junction (y=0) is equal to the velocity of reference frame (ego vehicle) and it is negative because it is moving towards the target vehicle.

Figure 25 shows the combined results of radial velocity behavior of target vehicle for all the three scenarios which have been described above for accelerated motion (constant acceleration) of target vehicle. The plot shows the results of radial velocity until both or any one of the vehicle has reached the road junction. The change in radial velocity behavior is again quite evident for the non-collision scenarios (Target Pass By, Target Brake) and radial velocity in a collision course constantly decreased until the collision happened at road junction and it is interesting to know the behavior of radial velocity just before the ego or target vehicles reach the road junction (0,0).

![Radial Velocity Behavior](image)

**Figure 25:** Combined Radial Velocity Results with Target Acceleration

Hence the collision and non-collision cases can be differentiated from the behavior of radial velocity if target vehicle is moving with constant acceleration. For collision case, it constantly decreases; while for non-collision cases, it starts increasing rapidly when the target applies brakes or passes by.
Figure 26 shows the combined results of radial velocity behavior of target vehicle for all the three scenarios which have been described above for accelerated motion (constant deceleration) of target vehicle. The plot shows the results of radial velocity until both or any one of the vehicle has reached the road junction. The change in radial velocity behavior is again quite evident for the non-collision scenarios (Target Pass By, Target Brake) while the radial velocity in a collision course constantly increased until the collision happened at road junction and it is interesting to know the behavior of radial velocity just before the ego or target vehicle reaches the road junction (0,0). Hence the collision and non-collision cases can be differentiated from the behavior of radial velocity if target vehicle is moving with constant deceleration. For collision case, it constantly increases; while for non-collision cases, it starts increasing rapidly when the target applies brakes or passes by.

So if the change in radial velocity behavior is accurately and timely detected, Crossing EBA will not give any false alarms.
3.4 Summary

In this chapter, first of all the main problem area of Crossing EBA system is addressed. Then it describes the method which is already existed but not able to reduce the false alarm rate for non-colliding objects. Then it explained in detail the new radar based method which has been adopted to reduce the false alarm rate of Crossing EBA system. In this new method, the behavior of radial velocity of target vehicle is examined and categorized into three different crossing scenarios (Collision, Target Brake, and Target Pass By). The behavior of the radial velocity is examined by considering the accelerated and non-accelerated motion of target vehicle.
4 Implementation

This Chapter describes the developed algorithm in detail. The algorithm is developed especially to detect the maneuvering of target vehicle in order to reduce the false alarm rate of Crossing EBA system.

To differentiate between collision and non-collision (target braking or passing by) scenarios, it is extremely important to detect the change in radial velocity behavior of moving target vehicle with respect to ego vehicle. If radial velocity starts increasing from its normal behavior then it means either target vehicle is applying brakes or is going to pass by ego vehicle without having a collision. To detect this change in radial velocity behavior, following steps have been taken.

4.1 Block Diagram

The block diagram of Crossing EBA function is shown in Figure 27. This function has three modules or sub-functions. Maneuver Detection module, Time to Collision module and Decision module. The main focus of this thesis work is on Maneuver Detection function only. Time to Collision function estimates the time of expected collision between Ego vehicle and Target vehicle. Decision function makes the final decision after getting the TTC and Collision State values, either to send a warning signal or apply emergency braking etc.

![Figure 27: Block Diagram of Crossing EBA Function](image)

Maneuver Detection function extracts the radar measurement parameter values of the target object in every cycle and decides on the behavior of the radial velocity and ego
kinematic that either there will be a collision or not. The block diagram of this function is shown in Figure 28.

![Figure 28: Block Diagram of Maneuver Detection Function](image)

The flow diagram of Maneuver detection function is shown in Figure 33.

### 4.2 Detection Method

First of all, it is important to know the nature of the data in order to extract the information from it. As it is known that the radial velocity measurement data generally possesses a linear pattern in crossing scenarios. Hence linear trendline method as explained in Chapter 2 can be used to detect the behavior of radial velocity measurement data coming from radar sensor. The slope of straight line will determine either the trend in the data is increasing, decreasing or constant. To calculate a best fit straight line (trendline), at least two consecutive values of radial velocity are necessary. Due to available memory it is possible to store the last five measurement values in the history and trendline can be calculated by using sliding window of up to these last five samples. One thing should be noted here, the slope of trendline could be very fluctuating if the slope of the sliding window of less number of data samples is taken, and could be very lagging behind or not very sensitive towards change if more number of data samples are used.
The cycle time of radar sensor is 66.7ms; hence an estimated time taken by the number of samples to calculate the slope or to see the trend in the data can be seen in the Table 1. Full available memory is used to save the measurement data and then by using a sliding window of 5 data samples as shown in Figure 29, the slope is calculated. Sliding window of 5 samples takes approximately one third of a second to see the trend in the data, which is not much time consuming.

<table>
<thead>
<tr>
<th>No. of Samples</th>
<th>Time (s) Approx.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.13</td>
</tr>
<tr>
<td>5</td>
<td>0.33</td>
</tr>
<tr>
<td>8</td>
<td>0.53</td>
</tr>
<tr>
<td>16</td>
<td>1.06</td>
</tr>
</tbody>
</table>

Table 1: Estimated Time Duration
4.3 Adaptive Threshold

After calculating the slope of the sliding window of data samples, the next step is to decide from the slope or pattern of the data either there is a probability of collision or not between ego vehicle and target vehicle. When there is not a collision, then the slope will start rising at some point in time, hence there should be a threshold value of slope to decide between collision and non-collision cases. Ideally when both ego and target vehicles are moving with constant speed on a collision course, the slope will remain zero because of constant radial velocity over the period of time. Hence if the slope is slightly above zero, it means the target is braking or passing by. So the threshold value to detect the non-collision scenarios in an ideal case when both vehicles are moving with constant velocity would be,

$$\text{Threshold} = 0$$ \hspace{1cm} (35)

But if the ego vehicle is moving constantly and target vehicle is moving with constant acceleration then the radial velocity does not remain constant but will increase or decrease with constant factor hence the slope of radial velocity will have a positive or negative offset depending on whether target is moving with constant acceleration or deceleration. Hence if the slope is slightly above this offset afterwards, it means the target is braking or passing by. So the threshold value to detect the non-collision scenarios in an ideal case when ego is moving with constant speed and target vehicle is moving with constant acceleration would be,

$$\text{Threshold} = \text{Offset}$$ \hspace{1cm} (36)

In reality, every system has a noise associated with it. Radial velocity measurement from radar also contains system and environmental noises. Hence in real cases, this noise factor should also be considered along with offset value to calculate threshold value. Therefore the above threshold Equation 36 in real cases will become as,

$$\text{Threshold} = \text{Offset} + \text{NoiseLevel}$$ \hspace{1cm} (37)

Where offset and noise level values are calculated from the initial measurement values. Offset is calculated from the slope and noise level is calculated from the variance of radial velocity values from its mean. Once these values are calculated and threshold
value is set, and the slope of radial velocity increases from this threshold value then it means either the target vehicle is braking or passing by ego vehicle.

4.4 Ego Compensation

Until now, it has been assumed that the ego vehicle is moving with constant speed in all the crossing scenarios and checked the radial velocity behavior of target vehicle but in reality ego vehicle is not always moving with constant speed. Hence to check the radial velocity behavior of target vehicle in real scenarios it is important that it should be checked from the reference of constant ego vehicle speed. It means while calculating the slope of sliding window of 5 radial velocity data samples, each measurement value should be considered with the same constant ego vehicle speed. It can be done, if we fix the first radial velocity data as a reference in a sliding window and compensate the remaining radial velocity data samples with the change in ego vehicle speed as compared to the ego vehicle speed in the reference sample. The system gets the actual speed of ego vehicle during each time cycle. Hence the ego compensation is done as shown in Figure 30,

\[ V_{rad} \]

\[ \Delta V_{ego \, \text{Comp}} \]

Figure 30: Ego Compensation

4.5 Curve Smoothing

If the signal is highly polluted with noise in real cases, then it is very difficult to extract the required information in time. Curve smoothing is an additional parameter which can be applied to radial velocity measurement values to smooth the signal values. There are several ways by which the signal values can be refined as explained in Chapter 2. Simple Moving Average method has been used in an algorithm to smooth the sliding
window of 5 measurement values and saving the results in the last slot. The reason why this method have been chosen can be seen in Figure 31 and Figure 32.

![Figure 31: Moving Average Curves](image)

Figure 31 shows the results of a simple crossing scenario in which the radial velocity is changing over time. Black color signal is the original radial velocity signal which is noisy. To smooth this noisy signal different methods have been tried and their results are displayed with different colors. Cumulated moving average method is not very responsive to the change in the signal while Exponential Moving Average method is very sensitive to the fluctuations in the signal as shown in Figure 32.
The method which is not too sensitive to the fluctuations in the signal as well as not too irresponsive is Simple Moving Average as shown in Figure 32 which comes in the middle of all the signals after the change occurred in the radial velocity signal.

### 4.6 Flow Diagram

The algorithm first collects the radar measurement parameters (Radial Velocity, Azimuth Angle and Range) of the Target object and the Ego kinematics. It saves these values into the memory. When the memory is full it computes the Ego compensation on the bases of Ego kinematics value and Noise Level in the signal from the Radial velocity parameter values. In the next step, compensated radial velocity is calculated by subtracting the Ego compensation value from original radial velocity value. The signal is then get smoothed by using the Simple Moving Average technique and then the slope of the sliding window of 5 data samples is calculated. In the next step offset of the signal is measured from the initial slope of the data samples, which then help in calculating the adapting threshold value for the current target. Offset tells about how much target vehicle is accelerating or decelerating. Once the adaptive threshold is calculated, it will be fixed for the rest of the course. The calculated slope is then checked against this adaptive threshold value which then tells about the confidence of having a collision or not. The flow diagram can also be seen in Figure 33.
The level of the confidence can be set in between 0 to 100 to decide between collision and non-collision scenarios.

4.7 Summary

In this chapter the detailed implementation of the proposed algorithm is described. First it contained he block diagram, then the description of different steps which have been taken for the implementation and concluded with the flow diagram of the algorithm.
5 Results and Evaluation

This chapter contains the Results and Evaluation of all the tests conducted. The first section of this chapter comprises of all the theoretical results, then moving on to the real results in the second section and finally evaluates the results of both real and theoretical data.

5.1 Theoretical Results

First of all, the radial velocity of target vehicle is generated theoretically by creating different artificial scenarios in Matlab. These artificial scenarios include collision (Collision) and non-collision (Target Pass By, Target Brake) scenarios. In real life, there could be infinite number of cases for the crossing scenarios, but theoretically only some cases have been created by varying different parameter values. The behavior of the generated radial velocity in each case is then checked by an algorithm to classify it into one of the above mentioned three categories of crossing scenario. Finally the distance and time for an ego vehicle to reach junction point have is calculated when the algorithm detect the change in radial velocity behavior to classify the scenario into collision (Collision) or non-collision (Target Pass By, Target Brake) for Crossing EBA to take further action.

5.1.1 Set of Parameters

The parameters whose values have been varied are as follows.

**Crossing Angle**

This is the angle at which the target vehicle is crossing the path of ego vehicle. For simplicity, it is assumed that the ego and target vehicles are moving on the roads which are at an angle of 90° to each other in all the assumed crossing cases.

**Ego Velocity** ($V_{ego}$)

The velocity of ego vehicle is set 5m/s, 10m/s and 15m/s.

**Target Velocity** ($V_{tar}$)

The velocity of target vehicle is set 5m/s, 10m/s and 15m/s.

**Target Braking Acceleration** (accel)
When the target vehicle is braking to stop at a stop line, different cases have been assumed when it is applying soft brakes (-1.5m/s\(^2\)), normal brakes (-3.0m/s\(^2\)), hard brakes (-6.0m/s\(^2\)) and very hard brakes (-9.0m/s\(^2\)).

**Noise**

Normally the accuracy of radial velocity parameter is ±0.1m/s. But the noise is varied also till ±0.5m/s in a step of 0.1 to check the behavior of the algorithm.

**Collision State**

This is the output of the maneuver detection function, which gives the information to Crossing EBA about the crossing scenario on the basis of momentary Radar measurements signals and Ego kinematics. The output will be either there might be a collision (1) or there is not a collision (0). When there might be a collision, Crossing EBA will continuously calculate the time-to-collision of the target vehicle and send warning signal or intervene if the critical time reaches. When there is not a collision, it means either the target vehicle has stopped at a stop line before reaching the road junction or the target vehicle has passed by ego vehicle path at road junction.

<table>
<thead>
<tr>
<th>Collision State</th>
<th>What Does It Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>There might be a Collision. Crossing EBA should take</td>
</tr>
<tr>
<td></td>
<td>appropriate measures at critical times</td>
</tr>
<tr>
<td>0</td>
<td>There will be No Collision. Target vehicle has applied</td>
</tr>
<tr>
<td></td>
<td>Brakes or Passed By road junction</td>
</tr>
</tbody>
</table>

**Table 2: Description of Collision State for Artificial Scenarios**

### 5.1.2 Results

The results of artificially generated scenarios have been recorded in the following tables. As an example, the results of one case from each three scenarios have been plotted here. The parameter values of the plotted results of artificially generated scenarios have been selected according to the parameter values of the real results which have been plotted in the next section.

**a) Collision**

An artificial collision scenario has been created in Matlab in which the ego vehicle is moving constantly with a speed of 8m/s and target vehicle is moving constantly with a speed of 6m/s at an angle of 90°. The vehicles get collided after some time and the
results are shown in the Figure 34 when there is no noise in the system and the Figure 35 shows results when there is a variance of 0.1 m/s in the radial velocity parameter.

![Graph showing theoretical results of collision scenario without noise](image)

**Figure 34:** Theoretical Results of Collision Scenario without Noise

The upper plot in Figure 34 shows the generated radial velocity ($V_{rad}$) of target vehicle against its distance along y-axis when it is moving on a collision course. The distance is negative because it is crossing ego vehicle at an angle of 90°, hence it has started from some negative position on a reference frame. The radial velocity remained constant throughout the collision course and became zero when the collision occurred at the road junction ($Y = 0$). The lower plot in Figure 34 is the output of an algorithm which took the generated radial velocity (shown in upper plot) as an input parameter and classified it into collision scenario because the change in slope of radial velocity was not detected more than threshold value (0.1) with certainty until the collision had happened at road junction. The values of parameters like Ego Distance to Junction (Ego DTJ) and Ego Time to reach Junction (Ego TTJ) also become zero as shown in figure because the ego vehicle has reached the road junction when this collision happened.
The upper plot in Figure 35 shows the generated radial velocity \( (V_{rad}) \) of target vehicle with noise against its distance along y-axis when it is moving on a collision course. The distance is negative because it is crossing ego vehicle at an angle of 90°, hence it has started from some negative position on a reference frame. The radial velocity had some variations but almost remained constant throughout the collision course and became zero when the collision occurred at the road junction \( (Y = 0) \). The lower plot in Figure 35 is the output of an algorithm which took the generated radial velocity with noise (shown in upper plot) as an input parameter and classified it into collision scenario because the change in slope of radial velocity was not detected more than threshold value \( (0.4) \) with certainty until the collision had happened at road junction. The value of adaptive threshold \( (THRESH) \) is greater here than the adaptive threshold value in an ideal case \((\text{Noise} = 0)\) because of the noise present in the system. The values of parameters like Ego Distance to Junction \( (\text{Ego DTJ}) \) and Ego Time to reach Junction \( (\text{Ego TTJ}) \) also become zero as shown in figure because the ego vehicle has reached the road junction when this collision happened.
b) Target Brake

An artificial scenario has been created in Matlab in which ego and target vehicles are initially moving on a collision course at an angle of 90° but target vehicle apply soft brakes (-3.0m/s²) later on and stop at stop line. In this scenario ego vehicle is moving constantly with a speed of 14m/s and target vehicle is moving constantly with a speed of 8m/s before it apply brakes. The results are shown in the Figure 36 when there is no noise in the system and the Figure 37 shows results when there is a variance of 0.1 m/s in the radial velocity parameter.

![Figure 36: Theoretical Results of Target Brake Scenario without Noise](image)

The upper plot in Figure 36 shows the generated radial velocity ($V_{rad}$) of target vehicle against its distance along y-axis when it is moving on a collision course but apply brakes to stop at stop line (non-collision scenario). The distance is negative because it is crossing ego vehicle at an angle of 90°, hence it has started from some negative position on a reference frame. The radial velocity remained constant until the target vehicle started applying brakes (at $Y = -22m$) and then it started increasing afterwards. The lower plot in Figure 36 is the output of an algorithm which took the radial velocity (shown in upper plot) as an input parameter and classified it into a non-collision...
scenario because the increase in the slope of radial velocity has detected more than threshold value (0.1) with certainty and collision state value has dropped to zero (at $Y = -18m$). This change in radial velocity behavior is detected around 2.1 seconds earlier the ego vehicle reaches road junction and it is also displayed on the lower plot.

Figure 37: Theoretical Results of Target Brake Scenario with Noise

The upper plot in Figure 37 shows the generated radial velocity ($V_{\text{rad}}$) of target vehicle with noise against its distance along $y$-axis when it is moving on a collision course but apply brakes to stop at stop line (non-collision scenario). The distance is negative because it is crossing ego vehicle at an angle of 90°, hence it has started from some negative position on a reference frame. The radial velocity remained almost constant until the target vehicle started applying brakes (at $Y = -22m$) and then it started increasing afterwards. The lower plot in Figure 37 is the output of an algorithm which took the radial velocity with noise (shown in upper plot) as an input parameter and classified it into a non-collision scenario because the increase in the slope of radial velocity has detected more than threshold value (0.3) with certainty and collision state value has dropped to zero (at $Y = -17m$). This change in radial velocity behavior is detected around 1.9 seconds earlier the ego vehicle reaches road junction and it is also
displayed on the lower plot. Here the change in radial velocity behavior is detected a bit late than ideal case because of the noise present in the radial velocity.

The following Table 3 shows the results of different artificial crossing scenarios generated in Matlab when ego and target vehicles are moving on a collision course but target vehicle apply soft brakes (acc = -1.5m/s²) and stop at stop line. Distance (Ego DTJ) and time (Ego TTJ) for an ego vehicle to reach junction point is calculated when the maneuver detection function detect the change in radial velocity behavior due to target braking. The results are calculated against different noise present in the radar measurement parameter (Radial Velocity $V_{rad}$).

<table>
<thead>
<tr>
<th>Crossing Angle = 90°</th>
<th>$V_{ego} / V_{tar}$ (m/s)</th>
<th>Param.</th>
<th>$V_{rad}$ Noise (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>5 / 5</td>
<td>Ego DTJ</td>
<td>6.33m</td>
<td>6.0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>1.26s</td>
<td>1.2s</td>
</tr>
<tr>
<td>5 / 10</td>
<td>Ego DTJ</td>
<td>13.67m</td>
<td>13.34m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>2.73s</td>
<td>2.66s</td>
</tr>
<tr>
<td>5 / 15</td>
<td>Ego DTJ</td>
<td>21.67m</td>
<td>21.34m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>4.33s</td>
<td>4.26s</td>
</tr>
<tr>
<td>10 / 5</td>
<td>Ego DTJ</td>
<td>12.0m</td>
<td>11.3m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>1.2s</td>
<td>1.13s</td>
</tr>
<tr>
<td>10 / 10</td>
<td>Ego DTJ</td>
<td>27.34m</td>
<td>27.24m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>2.73s</td>
<td>2.72s</td>
</tr>
<tr>
<td>10 / 15</td>
<td>Ego DTJ</td>
<td>43.35m</td>
<td>42.6m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>4.33s</td>
<td>4.26s</td>
</tr>
<tr>
<td>15 / 5</td>
<td>Ego DTJ</td>
<td>18.0m</td>
<td>16.0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>1.2s</td>
<td>1.06s</td>
</tr>
<tr>
<td>15 / 10</td>
<td>Ego DTJ</td>
<td>41.02m</td>
<td>39.0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>2.73s</td>
<td>2.6s</td>
</tr>
<tr>
<td>15 / 15</td>
<td>Ego DTJ</td>
<td>65.02m</td>
<td>63.0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>4.33s</td>
<td>4.2s</td>
</tr>
</tbody>
</table>

Table 3: Complete Theoretical Results of Target Brake Scenario 1
The following Table 4 shows the results of different artificial crossing scenarios generated in Matlab when ego and target vehicles are moving on a collision course but target vehicle apply normal brakes (acc = -3.0 m/s²) and stop at stop line. Distance (Ego DTJ) and time (Ego TTJ) for an ego vehicle to reach junction point is calculated when the maneuver detection function detect the change in radial velocity behavior due to target braking. The results are calculated against different noise present in the radar measurement parameter (Radial Velocity V_rad).

<table>
<thead>
<tr>
<th>Coordination Angle = 90°</th>
<th>Target Brake (acc = -3.0 m/s²)</th>
<th>V_rad Noise (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ego DTJ</td>
<td>0.0</td>
</tr>
<tr>
<td>5 / 5</td>
<td>2.33m</td>
<td>2.0m</td>
</tr>
<tr>
<td></td>
<td>0.46s</td>
<td>0.4s</td>
</tr>
<tr>
<td>5 / 10</td>
<td>5.66m</td>
<td>5.01m</td>
</tr>
<tr>
<td></td>
<td>1.13s</td>
<td>1.0s</td>
</tr>
<tr>
<td>5 / 15</td>
<td>9.67m</td>
<td>9.0m</td>
</tr>
<tr>
<td></td>
<td>1.93s</td>
<td>1.8s</td>
</tr>
<tr>
<td>10 / 5</td>
<td>4.66m</td>
<td>4.0m</td>
</tr>
<tr>
<td></td>
<td>0.46s</td>
<td>0.40s</td>
</tr>
<tr>
<td>10 / 10</td>
<td>10.67m</td>
<td>10.0m</td>
</tr>
<tr>
<td></td>
<td>1.06s</td>
<td>1.0s</td>
</tr>
<tr>
<td>10 / 15</td>
<td>18.67m</td>
<td>18.0m</td>
</tr>
<tr>
<td></td>
<td>1.86s</td>
<td>1.8s</td>
</tr>
<tr>
<td>15 / 5</td>
<td>7.0m</td>
<td>5.0m</td>
</tr>
<tr>
<td></td>
<td>0.46s</td>
<td>0.33s</td>
</tr>
<tr>
<td>15 / 10</td>
<td>16.0m</td>
<td>14.0m</td>
</tr>
<tr>
<td></td>
<td>1.06s</td>
<td>0.93s</td>
</tr>
<tr>
<td>15 / 15</td>
<td>28.01m</td>
<td>28.01m</td>
</tr>
<tr>
<td></td>
<td>1.86s</td>
<td>1.86s</td>
</tr>
</tbody>
</table>

*Table 4: Complete Theoretical Results of Target Brake Scenario 2*
The following Table 5 shows the results of different artificial crossing scenarios generated in Matlab when ego and target vehicles are moving on a collision course but target vehicle apply hard brakes (acc = -6.0m/s²) and stop at stop line. Distance (Ego DTJ) and time (Ego TTJ) for an ego vehicle to reach junction point is calculated when the maneuver detection function detect the change in radial velocity behavior due to target braking. The results are calculated against different noise present in the radar measurement parameter (Radial Velocity V_rad).

<table>
<thead>
<tr>
<th>V_ego / V_tar (m/s)</th>
<th>Param.</th>
<th>V_rad Noise (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>5 / 5</td>
<td>Ego DTJ</td>
<td>0.66m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.13s</td>
</tr>
<tr>
<td>5 / 10</td>
<td>Ego DTJ</td>
<td>1.66m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.33s</td>
</tr>
<tr>
<td>5 / 15</td>
<td>Ego DTJ</td>
<td>3.33m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.66s</td>
</tr>
<tr>
<td>10 / 5</td>
<td>Ego DTJ</td>
<td>1.33m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.13s</td>
</tr>
<tr>
<td>10 / 10</td>
<td>Ego DTJ</td>
<td>3.33m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.33s</td>
</tr>
<tr>
<td>10 / 15</td>
<td>Ego DTJ</td>
<td>6.67m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.66s</td>
</tr>
<tr>
<td>15 / 5</td>
<td>Ego DTJ</td>
<td>1.0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.06s</td>
</tr>
<tr>
<td>15 / 10</td>
<td>Ego DTJ</td>
<td>5.0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.33s</td>
</tr>
<tr>
<td>15 / 15</td>
<td>Ego DTJ</td>
<td>10.0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.66s</td>
</tr>
</tbody>
</table>

Table 5: Complete Theoretical Results of Target Brake Scenario 3
The following Table 6 shows the results of different artificial crossing scenarios generated in Matlab when ego and target vehicles are moving on a collision course but target vehicle apply very hard brakes (acc = -9.0 m/s²) and stop at stop line. Distance (Ego DTJ) and time (Ego TTJ) for an ego vehicle to reach junction point is calculated when the maneuver detection function detect the change in radial velocity behavior due to target braking. The results are calculated against different noise present in the radar measurement parameter (Radial Velocity \( V_{\text{rad}} \)).

<table>
<thead>
<tr>
<th>( V_{\text{ego}} / V_{\text{tar}} ) (m/s)</th>
<th>Param.</th>
<th>( V_{\text{rad}} ) Noise (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>5 / 5</td>
<td>Ego DTJ</td>
<td>0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0s</td>
</tr>
<tr>
<td>5 / 10</td>
<td>Ego DTJ</td>
<td>0.33m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.06s</td>
</tr>
<tr>
<td>5 / 15</td>
<td>Ego DTJ</td>
<td>1.33m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.26s</td>
</tr>
<tr>
<td>10 / 5</td>
<td>Ego DTJ</td>
<td>0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0s</td>
</tr>
<tr>
<td>10 / 10</td>
<td>Ego DTJ</td>
<td>0.66m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.06s</td>
</tr>
<tr>
<td>10 / 15</td>
<td>Ego DTJ</td>
<td>2.66m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.26s</td>
</tr>
<tr>
<td>15 / 5</td>
<td>Ego DTJ</td>
<td>0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0s</td>
</tr>
<tr>
<td>15 / 10</td>
<td>Ego DTJ</td>
<td>1.0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.06s</td>
</tr>
<tr>
<td>15 / 15</td>
<td>Ego DTJ</td>
<td>4.0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.26s</td>
</tr>
</tbody>
</table>

**Table 6:** Complete Theoretical Results of Target Brake Scenario 4
c) Target Pass By

An artificial crossing scenario has been created in Matlab in which the ego vehicle is moving constantly with a speed of 8m/s and target vehicle is moving constantly with a speed of 13m/s at an angle of 90°. The target vehicle passes by the ego vehicle at road junction around 1 second earlier without having a collision. The results are shown in the Figure 38 when there is no noise in the system and the Figure 39 shows results when there is a variance of 0.1 m/s in the radial velocity parameter.

The upper plot in Figure 38 shows the generated radial velocity ($V_{rad}$) of target vehicle against its distance along y-axis when it passed by ego vehicle at road junction around 1 second earlier (non-collision scenario). The distance is negative because it is crossing ego vehicle at an angle of 90°, hence it has started from some negative position on a reference frame. The radial velocity graph is gradually increasing in the beginning but rapidly increased in the end when target vehicle is about to cross the ego vehicle path (road junction). The lower plot in Figure 38 is the output of an algorithm which took the radial velocity (shown in upper plot) as an input parameter and classified it into a
non-collision scenario because the increase in the slope of radial velocity has detected more than threshold value (0.1) with certainty and collision state value has dropped to zero (at \( Y = -32m \)). This change in radial velocity behavior is detected around 3.7 seconds earlier the ego vehicle reaches road junction and it is also displayed on the lower plot.

![Theoretical Results of Target Pass By Scenario with Noise](image)

**Figure 39**: Theoretical Results of Target Pass By Scenario with Noise

The upper plot in Figure 39 shows the generated radial velocity (\( V_{\text{rad}} \)) of target vehicle with noise against its distance along y-axis when it passed by ego vehicle at road junction around 1 second earlier (non-collision scenario). The distance is negative because it is crossing ego vehicle at an angle of 90°, hence it has started from some negative position on a reference frame. The radial velocity graph is gradually increasing in the beginning but rapidly increased in the end when target vehicle is about to cross the ego vehicle path (road junction). The lower plot in Figure 39 is the output of an algorithm which took the radial velocity (shown in upper plot) as an input parameter and classified it into a non-collision scenario because the increase in the slope of radial velocity has detected more than threshold value (0.1) with certainty and collision state
value has dropped to zero (at Y = -9m). This change in radial velocity behavior is detected around 2 seconds earlier the ego vehicle reaches road junction and it is also displayed on the lower plot.

<table>
<thead>
<tr>
<th>$V_{\text{ego}} / V_{\text{tar}}$ (m/s)</th>
<th>Param.</th>
<th>$V_{\text{rad}}$ Noise (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>5 / 5</td>
<td>Ego DTJ</td>
<td>20.67</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>4.13</td>
</tr>
<tr>
<td>5 / 10</td>
<td>Ego DTJ</td>
<td>24.00</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>4.80</td>
</tr>
<tr>
<td>5 / 15</td>
<td>Ego DTJ</td>
<td>23.67</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>4.73</td>
</tr>
<tr>
<td>10 / 5</td>
<td>Ego DTJ</td>
<td>36.00</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>3.60</td>
</tr>
<tr>
<td>10 / 10</td>
<td>Ego DTJ</td>
<td>52.02</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>5.20</td>
</tr>
<tr>
<td>10 / 15</td>
<td>Ego DTJ</td>
<td>57.36</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>5.73</td>
</tr>
<tr>
<td>15 / 5</td>
<td>Ego DTJ</td>
<td>47.02</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>3.13</td>
</tr>
<tr>
<td>15 / 10</td>
<td>Ego DTJ</td>
<td>75.03</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>5.00</td>
</tr>
<tr>
<td>15 / 15</td>
<td>Ego DTJ</td>
<td>90.00</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>6.00</td>
</tr>
</tbody>
</table>

Table 7: Complete Theoretical Results of Target Pass By Scenario

The Table 7 shows the results of different artificial crossing scenarios generated in Matlab when target vehicle passes by ego vehicle at road junction 2 seconds earlier. Distance (Ego DTJ) and time (Ego TTJ) for an ego vehicle to reach junction point is calculated when the maneuver detection function detect the change in radial velocity behavior due to target passing by. The results are calculated against different noise present in the radar measurement parameter (Radial Velocity $V_{\text{rad}}$).
5.2 Real Results

Real measurements have been taken on test tracks by creating different crossing scenarios with ego vehicle (real vehicle) and target vehicle (dummy vehicle). The desired parameter (e.g. $V_{\text{rad}}$) values are extracted from these real measurements for each crossing scenario and given as an input to the algorithm to detect the maneuvering of the target vehicle.

5.2.1 Set of Parameters

An algorithm is a step by step operation to be performed in order to accomplish some task. It takes some input, performs calculations and provides output. The algorithm which has been developed to detect the lateral maneuvers of target vehicle in order to differentiate between collision and non-collision cases has the following input and output parameters.

Radial Velocity ($V_{\text{rad}}$)

Radial velocity is the main input parameter of an algorithm which is coming from radar sensor. The algorithm analyzed the behavior of this parameter in order to differentiate between collision and non-collision scenarios. The unit of radial velocity is m/s.

Azimuth Angle (Azi)

Azimuth angle is another input parameter of an algorithm which is coming from radar sensor. Its unit is degree and is used during ego compensation.

Ego Velocity ($V_{\text{ego}}$)

Ego velocity is an input parameter of an algorithm which is the actual speed of the host vehicle. Its unit is m/s and this parameter provides the reference to examine the behavior of radial velocity of target vehicle during every cycle.

Collision State

This is the output of the maneuver detection function, which gives the information to Crossing EBA about the crossing scenario on the basis of momentary Radar measurements signals and Ego kinematics. The output will be either there might be a collision (1) or there is not a collision (0). When there might be a collision, Crossing EBA will continuously calculate the time-to-collision of the target vehicle and send warning signal or intervene if the critical time reaches. When there is not a collision, it
means either the target vehicle has stopped at a stop line before reaching the road junction or the target vehicle has passed by ego vehicle path at road junction.

<table>
<thead>
<tr>
<th>Collision State</th>
<th>What Does It Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>There might be a Collision. Crossing EBA should take appropriate measures at critical times</td>
</tr>
<tr>
<td>0</td>
<td>There will be No Collision. Target vehicle has applied Brakes or Passed By road junction</td>
</tr>
</tbody>
</table>

Table 8: Description of Collision State for Real Scenarios

5.2.2 Results

The results from real scenarios have been plotted here.

a) Collision

A collision scenario has been created on a real test track in which the ego vehicle is moving almost constantly with a speed of 8m/s and target vehicle (dummy vehicle) is moving almost constantly with a speed of 6m/s as shown in Figure 40. The target vehicle is crossing ego vehicle at an angle of 90°. The vehicles get collided after some time and the results of an algorithm are shown in the Figure 41.

![Figure 40: Velocity of Vehicles during Real Collision Scenario](image)

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Methods for Improving Radar Maneuver Detection for Tangentially Moving Targets
In Figure 40, the upper plot shows the ego vehicle speed during the collision course which tried to remain constant around 8m/s, and the lower plot shows the speed of target vehicle during the collision course which tried to remain constant around 6m/s.

The upper plot in Figure 41 shows the radial velocity ($V_{\text{rad}}$) of target vehicle against its distance along y-axis when it is moving on a collision course. The distance is negative because it is crossing ego vehicle at an angle of 90°, hence it has started from some negative position on a reference frame. The radial velocity is almost remained constant throughout the collision course but not completely constant because of small variations in ego and target vehicle velocities. When the collision happened at the road junction ($Y = 0$) the radial velocity had not completely become zero because in reality the vehicles do not stop on the spot when a collision occurred, that’s why some radial velocity still can be seen at that point. The lower plot in Figure 41 is the output of an algorithm which took the radial velocity (shown in upper plot) as an input parameter and classified it into collision scenario because the change in slope of radial velocity was not detected more than threshold value (0.3) with certainty until the collision had happened at road junction. The values of parameters like Ego Distance to Junction (Ego
DTC) and Ego Time to reach Junction (Ego TTJ) also become zero as shown in lower plot because the ego vehicle has reached the road junction when this collision happened. Two other examples of real Collision scenario have been plotted in Appendix A.

b) Target Brake

A non-collision crossing scenario has been created on a real test track in which ego and target vehicles are initially moving with almost constant speed on a collision course but target vehicle apply soft brakes (-1.5m/s²) later on and stop at stop line. The ego vehicle is moving almost constantly with a speed of 14m/s and target vehicle (dummy vehicle) is moving almost constantly with a speed of 8m/s as shown in Figure 42. The target vehicle is crossing ego vehicle at an angle of 90°. The results of an algorithm in this non-collision scenario are shown in the Figure 43.

![Figure 42: Velocity of Vehicles during Real Target Brake Scenario](image)

In Figure 42, the upper plot shows the ego vehicle speed during the non-collision scenario which tried to remain constant around 14m/s, and the lower plot shows the speed of target vehicle which tried to remain constant around 8m/s before it started applying brakes (at Y = -10m ) to stop at stop line.
Figure 43: Results of Real Target Brake Scenario

The upper plot in Figure 43 shows the radial velocity ($V_{rad}$) behavior of target vehicle against its distance along $y$-axis when it is moving on a collision course but apply brakes to stop at stop line (non-collision scenario). The distance is negative because it is crossing ego vehicle at an angle of 90°, hence it has started from some negative position on a reference frame. The radial velocity remained constant until the target vehicle started applying brakes (at $Y = -22m$) and then it started increasing afterwards. The lower plot in Figure 43 is the output of an algorithm which took the radial velocity (shown in upper plot) as an input parameter and classified it into a non-collision scenario because the increase in the slope of radial velocity has detected more than threshold value (0.2) with certainty and collision state value has dropped to zero (at $Y = -11m$). This change in radial velocity behavior is detected around 1.7 seconds earlier the ego vehicle reaches road junction and it is also displayed on the lower plot. Two other examples of real Target Brake scenario have been plotted in Appendix B.
c) Target Pass By

A non-collision crossing scenario has been created on a real test track in which the ego vehicle is almost moving with a constant speed of 8m/s and target vehicle is almost moving with a constant speed of 13m/s as shown in Figure 44. Ego and target vehicles are moving towards each other at an angle of 90°. The target vehicle passes by the ego vehicle at road junction around 1 second earlier without having a collision.

![Figure 44: Velocity of Vehicles during Real Target Pass By Scenario](image)

In Figure 44, the upper plot shows the ego vehicle speed during the non-collision scenario which tried to remain constant around 8m/s and the lower plot shows the speed of target vehicle which tried to remain constant around 13m/s before it crosses the road junction (Y = 0).
The upper plot in Figure 45 shows the radial velocity ($V_{rad}$) of target vehicle with real noise against its distance along y-axis when it passed by ego vehicle at road junction around 1 second earlier (non-collision scenario). The distance is negative because it is crossing ego vehicle at an angle of 90°, hence it has started from some negative position on a reference frame. The radial velocity graph is gradually increasing in the beginning when the target vehicle was at some far distance but rapidly increased in the end when target vehicle was about to cross the ego vehicle path (road junction). The lower plot in Figure 45 is the output of an algorithm which took the radial velocity (shown in upper plot) as an input parameter and classified it into a non-collision scenario because the increase in the slope of radial velocity has detected more than threshold value (0.6) with certainty and collision state value has dropped to zero (at $Y = -9m$). This change in radial velocity behavior is detected around 1.87 seconds earlier the ego vehicle reaches road junction and it is also displayed on the lower plot.
5.3 Evaluation of Results

In this section, the comparison of the theoretical results with respect to the corresponding real results for the three assumed categories of crossing scenarios has been conducted.

a) Collision

A collision scenario has been virtually created in Matlab environment and on a real test track in which Ego vehicle was moving with 8m/s and target vehicle was moving with 6m/s throughout the collision course. Target vehicle was crossing Ego vehicle at an angle of 90°. In this crossing scenario, the radial velocity almost remained constant in real case as was theoretically calculated and plotted. The algorithm also behaved correctly and did not give any false output even in the present of noise in the system. The output of the algorithm (Collision State = 1) is monitored by Crossing EBA in every cycle, and it will take appropriate actions to prepare for the emergency braking when the critical time reaches in order to avoid collision.

b) Target Brake

A crossing scenario has been created virtually in Matlab environment and on a real test track in which Ego vehicle was moving with almost 14m/s and target vehicle was moving with almost 8m/s initially and then applied brakes (-1.5m/s²) to stop at stop line. Target vehicle was crossing Ego vehicle at an angle of 90°. Ego vehicle was able to detect this target maneuvering reliably. The time and distance when Ego vehicle detect this braking maneuver reliably before reaching the road junction are mentioned in the Table 9.

<table>
<thead>
<tr>
<th>Detection of Target Braking (-1.5m/s²)</th>
<th>Theoretical Results</th>
<th>Real Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Noise</td>
<td>With Noise (0.1)</td>
</tr>
<tr>
<td>Ego Distance To Junction (DTJ)</td>
<td>29.88 m</td>
<td>27.08 m</td>
</tr>
<tr>
<td>Ego Time To Junction (TTJ)</td>
<td>2.13 s</td>
<td>1.93 s</td>
</tr>
</tbody>
</table>

Table 9: Comparison of Results in Target Brake Scenario

Normally the Crossing EBA requires 10-15 system cycles (0.7-1s) to prepare for the emergency braking. According to the results mentioned in Table 9, the proposed algorithm was able to detect the braking maneuver of target vehicle way too early. The algorithm detected the change in radial velocity behavior in an ideal case around 1.13
seconds earlier, with some noise in radial velocity around 0.93 seconds earlier and in real case around 0.73 seconds earlier the Crossing EBA makes any decision.

According to the theoretically calculated results of Target Brake scenario, it is easier to detect the target braking (before 1 second) if target applies soft brakes (-1.5m/s²) on a collision course. If the noise is high and the Target vehicle speed is lower than the Ego vehicle speed then it would be difficult to detect the target soft braking. When both Ego and Target vehicles are moving at low speeds then theoretically it is not possible to detect the target soft braking 1 second earlier. The red values in Table 10 show the cases where Crossing EBA is unable to detect the target soft braking before 1 second.

<table>
<thead>
<tr>
<th>V_{ego} / V_{tar} (m/s)</th>
<th>Param.</th>
<th>V_{rad} Noise (m/s)</th>
<th>Target Brake (acc=-1.5 m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 / 5</td>
<td>Ego DTJ</td>
<td>6.33m 6.0m 5.6m 4.66m 4.33m 3.66m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>1.26s 1.2s 1.13s 0.93s 0.86s 0.73s</td>
<td></td>
</tr>
<tr>
<td>5 / 10</td>
<td>Ego DTJ</td>
<td>13.67m 13.34m 13.0m 13.34m 12.33m 9.0m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>2.73s 2.66s 2.6s 2.66s 2.46s 1.8s</td>
<td></td>
</tr>
<tr>
<td>5 / 15</td>
<td>Ego DTJ</td>
<td>21.67m 21.34m 21.01m 20.34m 19.34m 20.34m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>4.33s 4.26s 4.20s 4.06s 3.86s 4.06s</td>
<td></td>
</tr>
<tr>
<td>10 / 5</td>
<td>Ego DTJ</td>
<td>12.0m 11.3m 10.6m 8.0m 7.3m 5.33m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>1.2s 1.13s 1.06s 0.8s 0.73s 0.53s</td>
<td></td>
</tr>
<tr>
<td>10 / 10</td>
<td>Ego DTJ</td>
<td>27.34m 27.24m 26.58m 26.58m 20.57m 13.24m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>2.73s 2.72s 2.65s 2.65s 2.05s 1.32s</td>
<td></td>
</tr>
<tr>
<td>10 / 15</td>
<td>Ego DTJ</td>
<td>43.35m 42.6m 41.3m 42.5m 40.6m 33.3m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>4.33s 4.26s 4.13s 4.25s 4.06s 3.33s</td>
<td></td>
</tr>
<tr>
<td>15 / 5</td>
<td>Ego DTJ</td>
<td>18.0m 16.0m 10.0m 8.0m 4.0m 1.0m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>1.2s 1.06s 0.66s 0.53s 0.26s 0.06s</td>
<td></td>
</tr>
<tr>
<td>15 / 10</td>
<td>Ego DTJ</td>
<td>41.02m 39.0m 38.0m 34.0m 18.0m 10.0m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>2.73s 2.6s 2.53s 2.26s 1.2s 0.66s</td>
<td></td>
</tr>
<tr>
<td>15 / 15</td>
<td>Ego DTJ</td>
<td>65.02m 63.0m 62.0m 58.0m 59.0m 57.0m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>4.33s 4.2s 4.13s 3.86s 3.93s 3.8s</td>
<td></td>
</tr>
</tbody>
</table>

Table 10: Evaluation of Target Brake Theoretical Results 1
The below Table 11 shows the theoretically calculated results of Target Brake scenario, when it is moving on a collision course but apply normal brakes (-3.0m/s²) and stop at stop line. From the results it can be seen that it is easier to detect the target braking (before 1 second) if target applies normal brakes (-3.0m/s²) on a collision course and its speed is not too less than the Ego speed. If the noise is high and the Target vehicle speed is equal or lower than the Ego vehicle speed then it would be difficult to detect the target normal braking. If both Ego and Target vehicles are moving at high speeds then it is very easier to detect the target normal braking. The red values in Table 10 show the cases where Crossing EBA is unable to detect the Target normal braking before 1 second.

<table>
<thead>
<tr>
<th>Vego / Vtar (m/s)</th>
<th>Param.</th>
<th>Vrad Noise (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>5 / 5</td>
<td>Ego DTJ</td>
<td>2.33m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.46s</td>
</tr>
<tr>
<td>5 / 10</td>
<td>Ego DTJ</td>
<td>5.66m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>1.13s</td>
</tr>
<tr>
<td>5 / 15</td>
<td>Ego DTJ</td>
<td>9.67m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>1.93s</td>
</tr>
<tr>
<td>10 / 5</td>
<td>Ego DTJ</td>
<td>4.66m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.46s</td>
</tr>
<tr>
<td>10 / 10</td>
<td>Ego DTJ</td>
<td>10.67m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>1.06s</td>
</tr>
<tr>
<td>10 / 15</td>
<td>Ego DTJ</td>
<td>18.67m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>1.86s</td>
</tr>
<tr>
<td>15 / 5</td>
<td>Ego DTJ</td>
<td>7.0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.46s</td>
</tr>
<tr>
<td>15 / 10</td>
<td>Ego DTJ</td>
<td>16.0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>1.06s</td>
</tr>
<tr>
<td>15 / 15</td>
<td>Ego DTJ</td>
<td>28.01m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>1.86s</td>
</tr>
</tbody>
</table>

Table 11: Evaluation of Target Brake Theoretical Results 2
The below Table 11 shows the theoretically calculated results of Target Brake scenario, when it is moving on a collision course but apply hard brakes (-6.0m/s²) and stop at stop line. From the results it can be seen that it is not easier to detect the target braking when it applies hard brakes. Practically it is true as well because the reaction time to stop is small hence Target vehicle apply hard brakes when it has almost reached stop line. If the noise is high and the Target vehicle speed is equal or lower than the Ego vehicle speed then it would be even more difficult to detect the target hard braking. The red values in Table 12 show the cases where Crossing EBA is unable to detect the Target hard braking before 1 second.

<table>
<thead>
<tr>
<th>Crossing Angle = 90°</th>
<th>Vego / Vtar (m/s)</th>
<th>Param.</th>
<th>Vrad Noise (m/s)</th>
<th>0.0</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 / 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego DTJ</td>
<td>0.66m</td>
<td>0.33m</td>
<td>0.33m</td>
<td>0m</td>
<td>0m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.13s</td>
<td>0.06s</td>
<td>0.06s</td>
<td>0s</td>
<td>0s</td>
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<tr>
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<td>1.66m</td>
<td>1.33m</td>
<td>1.0m</td>
<td>0.33m</td>
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<tr>
<td></td>
<td>Ego TTJ</td>
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<td>0.26s</td>
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<td>0.06s</td>
<td>0s</td>
<td></td>
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<td>2.33m</td>
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<tr>
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<td>Ego TTJ</td>
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<td>0.6s</td>
<td>0.53s</td>
<td>0.53s</td>
<td>0.46s</td>
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<tr>
<td></td>
<td>Ego DTJ</td>
<td>1.33m</td>
<td>1.33m</td>
<td>0.66m</td>
<td>0.66m</td>
<td>0m</td>
<td>0m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.13s</td>
<td>0.13s</td>
<td>0.06s</td>
<td>0.06s</td>
<td>0s</td>
<td>0s</td>
<td></td>
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<td>2.66m</td>
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<td>1.33m</td>
<td>0.66m</td>
<td>1.33m</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.33s</td>
<td>0.26s</td>
<td>0.26s</td>
<td>0.13s</td>
<td>0.06s</td>
<td>0.13s</td>
<td></td>
<td></td>
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<td>10 / 15</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego DTJ</td>
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<td>5.33m</td>
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<td>4.66m</td>
<td>4.0m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.66s</td>
<td>0.6s</td>
<td>0.53s</td>
<td>0.46s</td>
<td>0.46s</td>
<td>0.4s</td>
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<td>15 / 5</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Ego DTJ</td>
<td>1.0m</td>
<td>1.0m</td>
<td>0m</td>
<td>0m</td>
<td>0m</td>
<td>0m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.06s</td>
<td>0.06s</td>
<td>0s</td>
<td>0s</td>
<td>0s</td>
<td>0s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15 / 10</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego DTJ</td>
<td>5.0m</td>
<td>3.0m</td>
<td>3.0m</td>
<td>3.0m</td>
<td>3.0m</td>
<td>1.0m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.33s</td>
<td>0.2s</td>
<td>0.2s</td>
<td>0.2s</td>
<td>0.2s</td>
<td>0.06s</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego DTJ</td>
<td>10.0m</td>
<td>9.0m</td>
<td>9.0m</td>
<td>8.0m</td>
<td>7.0m</td>
<td>8.0m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.66s</td>
<td>0.60s</td>
<td>0.60s</td>
<td>0.53s</td>
<td>0.46s</td>
<td>0.53s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 12: Evaluation of Target Brake Theoretical Results 3
The below Table 11 shows the theoretically calculated results of Target Brake scenario, when it is moving on a collision course but apply very hard brakes (-6.0m/s²) and stop at stop line. From the results it can be seen that it is not easier to detect the target braking when it applies very hard brakes. Practically it is true as well because the reaction time to stop is small hence Target vehicle apply very hard brakes when it has already reached stop line. If the noise is high and the Target vehicle speed is equal or lower than the Ego vehicle speed then it would be even more impossible to detect the target very hard braking. The red values in Table 12 show the cases where Crossing EBA is unable to detect the Target very hard braking before 1 second.

<table>
<thead>
<tr>
<th>V_{ego} / V_{tar} (m/s)</th>
<th>Param.</th>
<th>V_{rad}</th>
<th>Noise (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>5 / 5</td>
<td>Ego DTJ</td>
<td>0m</td>
<td>0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0s</td>
<td>0s</td>
</tr>
<tr>
<td>5 / 10</td>
<td>Ego DTJ</td>
<td>0.33m</td>
<td>0.33m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.06s</td>
<td>0.06s</td>
</tr>
<tr>
<td>5 / 15</td>
<td>Ego DTJ</td>
<td>1.33m</td>
<td>1.0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.26s</td>
<td>0.2s</td>
</tr>
<tr>
<td>10 / 5</td>
<td>Ego DTJ</td>
<td>0m</td>
<td>0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0s</td>
<td>0s</td>
</tr>
<tr>
<td>10 / 10</td>
<td>Ego DTJ</td>
<td>0.66m</td>
<td>0.66m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.06s</td>
<td>0.06s</td>
</tr>
<tr>
<td>10 / 15</td>
<td>Ego DTJ</td>
<td>2.66m</td>
<td>2.0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.26s</td>
<td>0.2s</td>
</tr>
<tr>
<td>15 / 5</td>
<td>Ego DTJ</td>
<td>0m</td>
<td>0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0s</td>
<td>0s</td>
</tr>
<tr>
<td>15 / 10</td>
<td>Ego DTJ</td>
<td>1.0m</td>
<td>1.0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.06s</td>
<td>0.06s</td>
</tr>
<tr>
<td>15 / 15</td>
<td>Ego DTJ</td>
<td>4.0m</td>
<td>3.0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>0.26s</td>
<td>0.2s</td>
</tr>
</tbody>
</table>

Table 13: Evaluation of Target Brake Theoretical Results 4
c) **Target Pass By**

A non-collision crossing scenario has been created virtually in Matlab environment and on a real test track in which Ego vehicle was moving with almost 8m/s and target vehicle was moving with almost 13m/s. Target vehicle was crossing Ego vehicle at an angle of 90°. The target vehicle passed by the ego vehicle at road junction around 1 second earlier without having a collision. Ego vehicle was able to detect this non-collision scenario reliably. The time and distance when Ego vehicle detect this non-collision scenario reliably before reaching the road junction are mentioned in the Table 14.

<table>
<thead>
<tr>
<th>Detection of Target Pass By</th>
<th>Theoretical Results</th>
<th>Real Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Noise</td>
<td>With Noise (0.1)</td>
</tr>
<tr>
<td>Ego Distance To Junction (DTJ)</td>
<td>29.88 m</td>
<td>16.0 m</td>
</tr>
<tr>
<td>Ego Time To Junction (TTJ)</td>
<td>3.73 s</td>
<td>2.0 s</td>
</tr>
</tbody>
</table>

*Table 14: Comparison of Results in Target Pass By Scenario*

Normally the Crossing EBA requires 10-15 system cycles (0.7-1s) to prepare for the emergency braking. According to the results mentioned in Table 14, the proposed algorithm was able to detect the braking maneuver of target vehicle way too early. The algorithm detected the change in radial velocity behavior in an ideal case around 2.73 seconds earlier, with some noise in radial velocity around 1 second earlier and in real case around 0.87 seconds earlier the Crossing EBA makes any decision.

Secondly, from the theoretically calculated results for target Pass By scenario in Table 7, it can be seen that it is easier to detect the Passing By target vehicle (before 1 second) if target vehicle passes by ego vehicle 2 seconds earlier, but it is very difficult to detect the Passing By target vehicle (before 1 second) if target vehicle passes by ego vehicle just few moments before. The red values in Table 7 shows the cases when Crossing EBA is unable to detect the target pass by before 1 second. One more thing should be noticed here, if the ego vehicle speed is comparatively lower or equal to the target vehicle then it is easier to detect the target passing by.
The below Table 15 shows the theoretically calculated results of Target Pass By scenario, when it is moving on a crossing path and Pass By ego vehicle at road junction about 2 seconds earlier. From the results it can be seen that it is very easier to detect the target Pass By in most of the cases even if the system has high noise. If the Target vehicle speed is low and the difference is comparatively higher with Ego speed then at high noise the algorithm would not be able to detect the change in radial velocity behavior 1 second earlier. The red values in Table 15 show the cases where Crossing EBA is unable to detect the Target Pass By before 1 second.

<table>
<thead>
<tr>
<th>$\frac{V_{ego}}{V_{tar}}$ (m/s)</th>
<th>Param.</th>
<th>$V_{rad}$ Noise (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>5 / 5</td>
<td>Ego DTJ</td>
<td>20.67m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>4.13s</td>
</tr>
<tr>
<td>5 / 10</td>
<td>Ego DTJ</td>
<td>24.0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>4.8s</td>
</tr>
<tr>
<td>5 / 15</td>
<td>Ego DTJ</td>
<td>23.67m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>4.73s</td>
</tr>
<tr>
<td>10 / 5</td>
<td>Ego DTJ</td>
<td>36.0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>3.6s</td>
</tr>
<tr>
<td>10 / 10</td>
<td>Ego DTJ</td>
<td>52.02m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>5.2s</td>
</tr>
<tr>
<td>10 / 15</td>
<td>Ego DTJ</td>
<td>57.36m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>5.73s</td>
</tr>
<tr>
<td>15 / 5</td>
<td>Ego DTJ</td>
<td>47.02m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>3.13s</td>
</tr>
<tr>
<td>15 / 10</td>
<td>Ego DTJ</td>
<td>75.03m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>5.0s</td>
</tr>
<tr>
<td>15 / 15</td>
<td>Ego DTJ</td>
<td>90.0m</td>
</tr>
<tr>
<td></td>
<td>Ego TTJ</td>
<td>6.0s</td>
</tr>
</tbody>
</table>

Table 15: Evaluation of Target Pass By Theoretical Results
The proposed algorithm is therefore able to detect the non-collision scenarios (Target Braking, Target Pass By) in normal cases; hence it can be used to reduce the false alarm rate significantly.

5.4 Summary

In this chapter, first the theoretical results for the three assumed categories of crossing scenarios (Collision, Target Brake, and Target Pass By) have been presented which are taken in Matlab. For this different parameter values have been defined to take the measurements. Similarly it contained the real results in which the data was taken from measurement recordings. In the end comparison of the theoretical and real results has been made.
6 Conclusions and Recommendations

A Maneuver Detection function for Crossing EBA has been developed by using radar sensor to assist the crossing objects at road junction. The focus was to improve the Detection Rate (Use Case) while keeping the False Alarm Rate (Misuse Case) of the system extremely low. There were two ways by which the false alarm rate could have been reduced, either to improve the performance of available system or to try a new idea. Due to radar system limitations, the performance of the system could not have been improved in short time; hence the second approach have been chosen. Crossing scenarios have been divided into three categories (Collision, Target Brake and Target Pass By). An algorithm has been developed to detect the maneuvering of target vehicles by using one of the sensor measurement parameters called Radial Velocity ($V_{\text{rad}}$) because of its high accuracy. The behavior of the radial velocity of target vehicle helped in determining either there is going to be a collision (Collision) or not collision (Target Brake and Target Pass By). In case of collision, Crossing EBA function estimates the Time to Collision (ttc) and takes appropriate measures (Warning or Emergency Braking) when the critical time reaches. Algorithm is quite efficient in determining the collision cases even if the system has high noise. The algorithm is also efficient in determining the non-collision cases like Target Pass By and Target Brake (when Target applies Soft or Normal Brakes). Hence the overall Detection Rate has been improved and False Alarm Rate has been reduced significantly.

Recommendations for future work

There is a good possibility of further improving or enhancing this Maneuver Detection function for Crossing EBA. At the moment this function has been developed for point targets only. This function can further be extended by considering the effects of real objects. By this it means; there could be many reflection points of the target object, hence one can compensate the $V_{\text{rad}}$ spread and handle reflection point shift. One can also consider the Azimuth profile (radar parameter) in determining or validating the maneuvering of target objects when these are moving tangential to Ego vehicle. The performance of Maneuver Detection function can be increased further by tuning the Adaptive Threshold calculation which would help in determining the non-collision scenarios quite early.
When I first started working on this thesis and begin my research, there was only a little research already being conducted on this particular topic. But now as I am coming to an end of my thesis I have realized that every big name in automotive is working on improvising the Cross Traffic Assist function for their customers. There is a lot of scope and tremendous new possibilities and innovations waiting to be explored in this field.

There is a huge boom in IOT (Internet of Things) industry in this present era. And the collaboration of IOT in automotive field is the next big thing in automotive industry and is termed as Advance Mobility. The Connected vehicles and intelligent automotive systems are going to be new advancement for Automotive OEM’s. DSRC (Direct Short Range Communication) is a wireless communication system that allows two way short-to-medium-range communications and can help in active safety applications. It’s a globally accepted standard and supports both V2V and V2I communications. It is the key technology to provide non-line-of-sight communication in next generation ADAS and can help to avoid severe collisions by providing real-time traffic information (cf. [23]). So there is a great possibility to conduct useful research on this topic using IOT and DSRC to enhance the performance of Cross Traffic Assist systems.
Appendixes

Appendix A

Collision Example 1

Figure 46: Velocity of Vehicles during Real Collision Scenario Example 1

Figure 47: Results of Real Collision Scenario Example 1
Collision Example 2

![Graphs showing velocity and collision state during real collision scenario example 2.](image)

**Figure 48:** Velocity of Vehicles during Real Collision Scenario Example 2

**Figure 49:** Results of Real Collision Scenario Example 2
Appendix B

Target Brake Example 1

Figure 50: Velocity of Vehicles during Real Target Brake Scenario Example 1

Figure 51: Results of Real Target Brake Scenario Example 1
Target Brake Example 2

Figure 52: Velocity of Vehicles during Real Target Brake Scenario Example 2

Figure 53: Results of Real Target Brake Scenario Example 2
Bibliography


[22] Crossing Kinematic (Kalman) Tracker, Continental Internal Document.

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