İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

COLLISION WARNING AND AVOIDANCE SYSTEM FOR ROAD VEHICLES

M.Sc. Thesis by

Öncü ARARAT

Department: **Mechanical Engineering**

Programme: **System Dynamics and Control**

DECEMBER 2007

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Date of submission : **28 November 2007**

Date of defence examination: **26 December 2007**

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DECEMBER 2007

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

YOL TAŞITLARI İÇİN ÇARPIŞMA UYARICI VE ENGELLEYİCİ SİSTEM

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Tezin Enstitüye Verildiği Tarih : 28 Kasım 2007
Tezin Savunulduğu Tarih : 26 Aralık 2007

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ARALIK 2007

PREFACE

Traffic accidents cause deaths of millions of people every year. Although there are plenty of research studies on active safety systems for road vehicles in different countries, designed systems are immature. Obtained results show that, active safety systems should be more consistent with the human driver to able to show more successful outcomes. This thesis aims at designing Collision Warning System and Collision Avoidance System with regarding characteristics of drivers and complex traffic conditions.

This work was supported by European Union Sixth Framework Project Automotive Control and Mechatronics Research Center (AUTUCOM). The Scientific and Technological Research Council of Turkey (Tübitak) also supported the author by means of Scientist Supporting Programme Scholarship.

I would like to express my sincere thanks to my advisor Assistant Professor Bilin Aksun Güvenç who has supported me by supplying different ideas in my research study. I also thank to all of my instructors and friends working in Mechatronics Research Laboratories. Lastly, I want to express my deep appreciation to my family who has supported me with their lifelong assistance in all of my studies.

December 2007 Öncü ARARAT

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ABBREVIATIONS

ADAS	: Advanced Driving Assistance Systems
AGV	: Automatic Guided Vehicle
AHS	: Autonomous Highway Systems
AHSRA	: Advanced Cruise-Assist Highway Systems Research Association
ASV	: Advanced Safety Vehicle
CA	: Collision Avoidance
CD	: Collision Detection
CNRS	: National Scientific Research Organization
CW	: Collision Warning
DGPS	: Differential Global Positioning System
DOT	: Departments of Transport
EU	: European Union
EUREKA	: Europe-wide Network for Industrial R&D
FHWA	: Federal Highway Administration
FOT	: Field Operational Test
GIS	: Geographical Information System
GPS	: Global Positioning System
HIL	: Hardware-in-the-Loop
INRETS	: National Research Laboratory on Transport and Safety
INRIA	: National Research Laboratory on Informatics and Automation
ITS	: Intelligent Transportation System
IVI	: Intelligent Vehicle Initiative
LCPC	: National Research Laboratory on Road Infrastructures
MITI	: Ministry of International Trade and Industry
MMIC	: Microwave Monolithic Integrated Circuit
MOC	: Ministry of Construction
MOT	: Ministry of Transportation
MOTIV	: Mobility and Transport in Intermodal Traffic
NHTSA	: National Highway Traffic Safety Administration
OCAR	: Office of Crash Avoidance Research
OLS	: Underground Logistical System
PATH	: Partners for Advanced Transit and Highways
RWS	: Rijkswaterstaat
SSVS	: Super-Smart Vehicle System
TAP	: Tunable Avoidance Parameter
TNO	: Netherlands Organization for Applied Scientific Research
TTC	: Time to Collision
VUT	: Vehicle Under Test

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a	: Lateral Offset
b	: Slop Coefficient
c	: Point Where the Lateral Offset Takes Half of Its Final Value
$\mathbf{C_{xf}}$	: Longitudinal Front Tire Force Coefficient
$\mathbf{C_{yf}}$	: Lateral Front Tire Force Coefficient
$\mathbf{C_{xr}}$	: Longitudinal Rear Tire Force Coefficient
$\mathbf{C_{yr}}$	: Lateral Rear Tire Force Coefficient
d	: Present Distance
$\mathbf{d_{at}}$	: Threshold Value for Decision Algorithm
$\mathbf{d_0}$	: Headway Offset
$\mathbf{d_{br}}$	: Braking Distance
$\mathbf{d_{mo}}$	: Maximum Detected Width of the Obstacle
$\mathbf{d_{mv}}$	: Maximum Detected Width of the Host Vehicle
$\mathbf{d_{pt}}$	: Threshold Distance for Path Error
$\mathbf{d_{vt}}$	: Threshold Value for Time Difference
$\mathbf{d_w}$	: Warning Distance
$\mathbf{D_L}$	: Position Change of Leading Vehicle
$\mathbf{D_F}$	: Position Change of Following Vehicle
$\mathbf{f_f}$	: Dugoff Coefficient for Front Tire
$\mathbf{f_r}$	: Dugoff Coefficient for Rear Tire
$\mathbf{F_{ei}}$	: External Force acting on i^{th} node
$\mathbf{F_{ii}}$	: Initial Internal Forces on i^{th} node
$\mathbf{F^*_{ii}}$	: Final Internal Forces on i^{th} node
$\mathbf{F_{tf}}$	: Total Front Tire Force
$\mathbf{F_{tr}}$	: Total Rear Tire Force
$\mathbf{F_x}$	: Total Force on X Axis
$\mathbf{F_y}$	: Total Force on Y Axis
$\mathbf{F_{xf}}$	: X Component of Front Tire Force
$\mathbf{F_{yf}}$	: Y Component of Front Tire Force
$\mathbf{F_{xr}}$	: X Component of Rear Tire Force
$\mathbf{F_{yr}}$	: Y Component of Rear Tire Force
$\mathbf{F_z}$	: Total Load on Both Tires
$\mathbf{I_z}$	: Total Moment of Inertia with Respect to Z Axis
$\mathbf{J_{eq}}$	: Equivalent Moment of Inertia
$\mathbf{k_e}$	: External Force Constant
$\mathbf{k_s}$	: Spring Constant
$\mathbf{l_f}$	: Distance to Front Wheel from Center of Gravity
$\mathbf{l_r}$	: Distance to Rear Wheel from Center of Gravity
m	: Total Mass of the Vehicle
$\mathbf{M_z}$	: Total Moment on Z Axis
$\mathbf{r_0}$	: Threshold Distance for External Force
$\mathbf{r_i}$	: Position Vector Between the Obstacle and the i^{th} node

$\mathbf{R_{eff}}$	: Effective Tire Radius
$\mathbf{s_f}$	: Longitudinal Slip for Front Tire
$\mathbf{s_r}$	: Longitudinal Slip for Rear Tire
$\mathbf{T_e}$	: Engine Torque
$\mathbf{T_{FS}}$	: Stopping Time for Following Vehicle
$\mathbf{T_{LS}}$	: Stopping Time for Leading Vehicle
$\mathbf{T_M}$	: Time for Relative Velocity Reaches Zero
$\mathbf{T_R}$	: Reaction Time
$\mathbf{u_i}$	: Displacement of i^{th} node
$\mathbf{v, v_v}$	: Velocity of the Host Vehicle
$\mathbf{v_{rel}}$	: Relative Velocity
$\mathbf{V}$	: Velocity at Center of Gravity of the Vehicle
$\mathbf{V_f}$	: Velocity at Front Wheel
$\mathbf{V_r}$	: Velocity at Rear Wheel
$\mathbf{V_{fx}}$	: X Component of Velocity at Front Wheel
$\mathbf{V_{fy}}$	: Y Component of Velocity at Front Wheel
$\mathbf{V_{rx}}$	: X Component of Velocity at Rear Wheel
$\mathbf{V_{ry}}$	: Y Component of Velocity at Rear Wheel
$\mathbf{w}$	: Non-Dimensional Warning Value
$\boldsymbol{\alpha}$	: Maximum Deceleration
$\boldsymbol{\alpha_1}$	: Maximum Deceleration of Host Vehicle
$\boldsymbol{\alpha_2}$	: Maximum Deceleration of Leading Vehicle
$\boldsymbol{\alpha_{ACC}}$	: Maximum Deceleration of ACC
$\boldsymbol{\alpha_f}$	: Lateral Angular Slip for Front Tire
$\boldsymbol{\alpha_r}$	: Lateral Angular Slip for Rear Tire
$\boldsymbol{\alpha_{max}}$	: Maximum Deceleration of Following Vehicle
$\boldsymbol{\alpha_{rel}}$	: Relative Deceleration
$\boldsymbol{\alpha_y}$	: Y Component of Acceleration
$\boldsymbol{\beta}$	: Side Slip Angle of the Vehicle
$\boldsymbol{\beta_f}$	: Side Slip Angle at the Front Wheel
$\boldsymbol{\beta_r}$	: Side Slip Angle at the Rear Wheel
$\boldsymbol{\eta}$	: Transmission Ratio
$\boldsymbol{\delta_f}$	: Steering Angle of the Front Wheel
$\boldsymbol{\delta_r}$	: Steering Angle of the Rear Wheel
$\boldsymbol{\tau}$	: Total Delay
$\boldsymbol{\tau_1, \tau_{sys}}$	: System Delay
$\boldsymbol{\tau_2, \tau_{hum}}$	: Driver Delay
$\boldsymbol{\tau_{ACC}}$	: ACC Delay
$\boldsymbol{\psi}$	: Yaw Angle
$\boldsymbol{\omega_f}$	: Angular Velocity of Front Wheel
$\boldsymbol{\omega_r}$	: Angular Velocity of Rear Wheel

YOL TAŞITLARI İÇİN ÇARPIŞMA UYARICI VE ENGELLEYİCİ SİSTEM

ÖZET

Bu tez kapsamında, yol taşıtları için sürücünün çarpışma tehlikesi altındaki davranışları ve olası karmaşık trafik koşulları göz önünde bulundurularak çarpışma tehlikesini önceden belirleyen Çarpışma Uyarıcı Sistem ve bu sistemin verdiği uyarının dikkate alınmadığı ve tehlikenin artarak devam ettiği durumlarda devreye girerek ani manevralar yoluyla olası çarpışmayı engelleyen Çarpışma Engelleyici Sistem geliştirilmiştir. Giriş bölümüyle başlayan tez, Çarpışma Uyarıcı Sistem ve Çarpışma Engelleyici Sistem bölümleriyle devam etmekte ve Sonuç bölümüyle sonlandırılmaktadır.

Giriş bölümü genel olarak, yol taşıtları için geliştirilen güvenlik sistemlerinin farklı ülkelerde geldiği son noktayı özetleyerek bu konudaki mevcut durumu ortaya koymaktadır.

Geliştirilen Çarpışma Uyarıcı Sistem öncekilerin aksine, formülasyonunda sürücünün reaksiyon karakteristiklerini dikkate alan adaptif bir parametre ve aracın Adaptif Seyir Kontrol Sistemi ihtiva ettiği durumları göz önünde bulunduran ek bir kısım barındırmaktadır. Bu şekilde sistemin sürücüyle olan uyumu maksimum düzeye çıkartılmış, yanlış ve eksik uyarı durumları ortadan kaldırılmıştır. Çarpışma Uyarıcı sistem bölümü literatürdeki mevcut durumu ve daha önce geliştirilmiş uyarıcı sistem algoritmalarını özetleyen Literatür Tanıtım kısmı, algoritmanın tasarım aşamalarını ve formülasyonunu veren Geliştirilen Çarpışma Uyarı Algoritması kısmı, geliştirilen araç modelini ve simülasyonların yapıldığı ortamı tanıtan Simülasyon Ortamı kısmı ve farklı durumlar ve farklı senaryolar için yapılmış simülasyonları ve bu simülasyonların sonuçlarını sunan Simülasyon kısmından oluşmaktadır.

Literatürde karmaşık trafik durumlarını göz önünde bulunduran ve olası çarpışmaları ani direksiyon manevralarıyla engellemeye çalışan bir Çarpışma Engelleyici Sistem bulunmamaktadır. Geliştirilen Çarpışma Engelleyici Sistem bu anlamda ileriki çalışmalar için önemli bir adım teşkil etmektedir. Çarpışma Engelleyici Sistem bölümü Literatür Tanıtım kısmıyla başlayıp, geliştirilen algoritmanın temel aldığı elastik bant teorisini tanıtan Elastik Bant Teorisi kısmıyla devam etmektedir. Elastik Bant teorisinin araç tabanlı uygulamalarda karşılaştığı problemler Uyarlama Problemleri başlığı altında verilmiştir. Geliştirilen Çarpışma Engelleyici Algoritma kısmı geliştirilen algoritmanın nasıl çalıştığını özetlemektedir. Karmaşık trafik koşullarını gerçeğe yakın araç modelleriyle beraber sunması sebebiyle algoritmanın test edildiği simülasyon ortamı olarak kullanılan Carsim programı Simülasyon Ortamı kısmında tanıtılmıştır. Simülasyon kısmı farklı durumlar ve senaryolar için gerçekleştirilen simülasyonları ve bu simülasyonlardan elde edilen sonuçları vermektedir.

Sonuç bölümü tezde elde edilen sonuçları alt başlıklarda elde edilen test sonuçlarına bağlı kalarak değerlendirmekte ve daha iyi sonuçlar için ileride gerçekleştirilebilecek çalışmalara dair öneriler sunmaktadır.

COLLISION WARNING AND COLLISION AVOIDANCE SYSTEM FOR ROAD VEHICLES

SUMMARY

In this thesis, Collision Warning System which detects possible collisions and warns drivers regarding the behaviors of drivers under the collision circumstances as well as complex traffic environments and Collision Avoidance System which takes control of the vehicle when drivers give no response to warnings given by warning system and applies emergency maneuver to avoid possible collision risk are designed. Thesis starts with Introduction part, continues with Collision Warning System and Collision Avoidance System parts and finishes with Conclusion part.

Introduction part generally, summarizes the point reached in research on safety systems for road vehicles in different countries and presents state-of-the-art of this area of study.

Contrary to previously designed system, proposed Collision Warning System has adaptive parameter which depends on reaction characteristics of the driver and specific part that is added to consider Adaptive Cruise Control Vehicles. In this way, consistency between human driver and warning system raised its maximum level and missing and wrong warnings are eliminated. Collision Warning System part is composed of Literature Overview section which summarizes the state-of-art and presents previously designed warning algorithms, Developed Collision Warning Algorithm section that gives the design phases of algorithm with its formulation, Simulation Environment section which describes developed vehicle model with introducing simulation environment and Simulation section which gives information about simulations that are done in various different situations with different scenarios and the results that are obtained from these simulations.

There is not any Collision Avoidance System in the literature which considers complex traffic scenarios and tries to avoid possible collisions by applying emergency steering maneuvers. In this sense, developed system acts as an important role in its area considering future studies in same subject. Collision Avoidance System part starts with Literature Overview section and continues with Elastic Band Theory section which is the core method used in designing algorithm. Implementation problems of Elastic Band Theory that are faced in vehicle based applications are given in part with same name. Developed Collision Avoidance Algorithm section summarizes how algorithm works. Carsim program is used to test algorithm for different scenarios and different situations since this program provides complex traffic conditions with high fidelity vehicle models and this program is introduced in Simulation Environment section. Simulation section contains different simulations with their results.

Conclusion part criticizes obtained results with relying on test results of previous sections and gives suggestions about how it can be possible to improve obtained results.

1. INTRODUCTION

Traffic crashes cause deaths of millions of people every year. Researchers tried to overcome this fatal problem by developing passive safety systems like seat belts, air bags and crash zones [1]. Although these passive measures helped a lot; there must be more effective ways of holding accidents at acceptable levels. This goal is closer to realization through advances in preventive and active safety systems [2].

Despite the fact that research on these subjects began with Autonomous Highway Systems (AHS), the auto industry has turned to Advanced Driving Assistance Systems (ADAS) considering the reality that progressions on AHS can only be realized in the long term period [3].

Another reason for the great interest on ADAS is economic. Driving assistance systems increase the efficiency of traffic and reduce fuel consumption [4]. Highway capacity is related to both vehicle speed and inter-vehicle spacing [5]. With more intelligent vehicles, it is possible to realize fast vehicles following each other with small inter-vehicle spaces safely and this leads to increased highway capacity. On the other hand, low velocity changes and the ability of vehicles to communicate with each other will diminish fuel consumption [4].

Collision Warning (CW) and Collision Avoidance (CA) Systems are an important part of ADAS which are composed of systems such as Lane Keeping, Lane Departure Prevention, Driver Condition Monitoring, Night Vision, Adaptive Cruise Control and Stop and Go Assistants [2].

1.1 The State-of-the-Art

Collision Avoidance and Collision Warning Systems have received great attention all over the world. Despite this attention, countries are on different positions on the progression of this technology. USA, Japan and Europe have a leading role on CA/CW System research [2].

Research in USA on CA/CW Systems is executed mainly by the Departments of Transport (DOT) at state and national level despite lack of hierarchy between them.

Beginning with AHS studies in Federal Highway Administration (FHWA), research turned to ADAS in National Highway Traffic Safety Administration-Office of Crash Avoidance Research (NHTSA-OCAR) at the national level. The state level research was started by California DOT. Minnesota, Virginia and Arizona DOT followed California [3].

NHTSA-OCAR keeps on CA/CW Systems research within the Intelligent Vehicle Initiative (IVI) project. Organizations which are composed of universities, industrial and public foundations are responsible for specific subjects of these research efforts. To obtain effective systems, human factors and legal issues were investigated after determining the most common crash types and searching for their causes. Results of studies on forward collision avoidance, rear-end-collision avoidance and intersection collision avoidance systems were tested in Field Operational Tests (FOTs) which were also part of the IVI project [6].

Since its main aim was to develop a reliable system which had market potential and easily adaptable characteristics, an extensive part of the forward collision avoidance system project coordinated by NHTSA-OCAR was allocated to cheap and reliable component development. Cheaper materials for Microwave Monolithic Integrated Circuit (MMIC) and Transferred-Electron (GUNN) receivers were tested. Another related research was carried out for developing cheap laser sensors. The component development phase was followed by an algorithm development phase. The developed system determined the radius of curvature by using yaw, speed and steering sensors. By determining the radius of curvature, it was possible to determine the presence of vehicles traveling on the host vehicle's lane with the aids of radar data. Then relative parameters were calculated and compared with the critical parameter values [1].

The NHTSA-OCAR study on rear-end-collision avoidance system was at the algorithm development level. In this research, kinematical analyses of the selected scenarios were carried out to build an overall algorithm. Critical warning distance was determined according to the appropriate scenario which best represented the present status of the two vehicles [7].

Intersection collision avoidance systems were studied by two groups in NHTSA-OCAR. The first project aimed at overcoming specific intersection collision scenarios. The developed system used both Differential Global Positioning System (DGPS) and Geographical Information System (GIS). The system took vehicle position, velocity and heading information from DGPS. GIS gave intersection point and roadway geometry information. GIS also gave traffic control infrastructure information. If traffic control unit sign and sign phase time allowed the vehicle to pass through the intersection, then whether the vehicle could stop with a maximum deceleration of 0.35g or not was controlled. If it could, then whether there was any collision risk or not with the crossover vehicle was controlled. If there was no risk, the system let the vehicle pass through the intersection. Otherwise, the driver was warned by the system [8].

The second project in intersection collision avoidance aimed at developing a system that worked regardless of the direction of the vehicles. This system did not need any GIS information. All of the information was obtained by vehicular sensors and Inter-Vehicle Communication Systems. Relative position of the vehicles was calculated according to a fixed coordinate system [9].

California DOT carries out research on CA/CW Systems via its Partners for Advanced Transit and Highways (PATH) program. A detailed rear-end collision avoidance system was created within that project [2].

In another research effort, a nonlinear controller for this rear end collision avoidance system was developed by modeling the brake and the vehicle as a whole. The brake system was modeled as second order differential equation. The maximum jerk was held between -10 and 10 m/s^3, the desired acceleration/deceleration profile was selected as a sine function within the start and stop periods. After inserting brake pressure into the vehicle model, a sliding surface for brake pressure was defined and a sliding mode controller was applied [10].

Simulation of this system was done using Hardware-In-the-Loop (HIL) testing. The controller of this system was installed on a DSP chip. Velocity and position information of the leading and following vehicles were taken from a vehicle model. With the calculated values, a DC motor which was installed as hardware controlled the relative distance and velocity. Measured values of relative distance and velocity taken from a radar sensor were fed into the controller [11].

Japan is one of the big actors on ADAS research. Research in Japan is coordinated by the government via three ministries: Ministry of Construction (MOC), Transportation (MOT) and International Trade and Industry (MITI) [3].

MOC supports ADAS research by means of Advanced Cruise-Assist Highway Systems Research Association (AHSRA). AHSRA was set up after two successful projects on ADAS. This association carries out the infrastructure research in Japan. Initial projects were on the development of system components. In the second stage, required services and essential studies for these services were determined. Standards, bases and education for popularization were created for developed projects to provide widespread usage. Last stage composed of verification and demonstration tests of developed systems. The next objective is converting the developed systems to viable and practical applications [12].

Intelligent vehicle research is carried out by Advanced Safety Vehicle (ASV) project which is sponsored by MOT. Success of the first part which was finished in 1996 provided powerful support for the second part. Unlike AHSRA, research in ASV was carried out by industrial organizations individually rather than collective studies. Accident avoidance system for intersection, collision avoidance system by means of inter-vehicle communication and collision avoidance system by means of road-vehicle communication are ongoing projects in ASV. Activities for understanding ASV technologies, studies on telecommunication standards for ASV and standardization of ASV technologies are further issues which are intended to be realized in the short term period [13].

MITI has a smaller workspace on ADAS than the other two ministries. Research on assistance systems was controlled by its Mechanical Engineering Laboratory which is sponsored by the ministry. Research concentrated on ITS and Platoon Systems. The Super-Smart Vehicle System (SSVS) research project dealt with a wide range of topics on ADAS and was coordinated by this laboratory. These systems were based on inter-vehicle communication and GPS [3].

Industrial research organizations had their own projects on ADAS along with supporting projects which were coordinated by the government. Honda and Mazda, for example, developed a kinematical analysis based rear-end collision avoidance algorithm [2].

Research in Europe on ADAS kept on with great success resulting from very well planned projects. There were three ways of research on ADAS in Europe: industrial research, governmental research projects and European Union projects [2].

Governments were influential on solving arising traffic crash problems which caused deaths of millions of people and enormous economic losses each year. France was one of these countries interested in conquering this problem as it had the largest transportation network in Europe and accidents resulting in deaths of 8000 people per year. Research in France was coordinated by four laboratories which were The National Research Laboratory on Transport and Safety (INRETS), The National Research Laboratory on Road Infrastructures (LCPC), The National Research Laboratory on Informatics and Automation (INRIA) and The National Scientific

Research Organization (CNRS). INRETS and LCPC opened a joint research laboratory which was called LIVIC. This laboratory had projects on interactions between road, vehicle and driver. There were also demonstration programs that tested the developed technologies. Another organization studying this subject was LARA which was created by INRETS, LCPC, INRIA, CNRS and top universities of the country. In addition to ADAS projects, there were also research efforts on AHS [3].

Holland is another important country in Europe in ADAS. Rijkswaterstaat (RWS), which is a Directorate of the Ministry of Transport and Public Works in the Holland, had started ADAS and AHS project cooperation with the Netherlands Organization for Applied Scientific Research (TNO) [3].

Simulation results were then controlled in a Hardware-in-the-Loop (HIL) system called VEHIL. VEHIL contained two HIL systems. The first one was used for longitudinal technology testing. The host vehicle was called Vehicle Under Test (VUT) in this system and it had headway sensors and receivers as well as other vehicles which were on the platform simulating the real road in an environment animated by a robot vehicle. Lateral tests were realized using Automatic Guided Vehicle (AGV) which can move in the lateral and longitudinal directions. Underground Logistical System (OLS) vehicle was positioned on the AGV. AGV determined its position by inter-vehicle sensors where OLS determined its position with the magnetic grids. Magnetic grids were formed by Grid Simulator which was composed of three metal shaft and three magnetic disks rotating around this shaft. In this way, simulation of OLS which would be tested in real magnetic environment was realized [14].

European Union’s Framework Programs had been constructed for creating a centralized research organization studying new technologies and their social and legal results. 6th Framework Program which is the latest and continuing one was composed of four areas which are thematic research, strengthening the foundations of ERA, structuring ERA and nuclear energy. There are also cross-cutting research activities consisting of multidisciplinary research. ADAS research is realized in thematic and cross-cutting research activities [15].

Prometheus was the first project on ADAS realized by the EU which started in 1986 and finished with the VITA II demonstration in 1994. Studies on AHS and ADAS were directed by Daimler-Benz. Lane departure warning, lane obstacle warning and adaptive cruise control were three topics of the project which was categorized as a Europe-wide Network for Industrial R&D (EUREKA) project [3].

Mobility and Transport in Intermodal Traffic (MOTIV) was a regional research project supported by the EU Union. This project was composed of two parts which were Mobility in Urban Areas and Safe Roads. Safe Roads was a kind of ADAS project which consisted of turn-off and lane-change assistance, adaptive cruise control, vehicle-vehicle communication, driver assistance strategies and man-machine interaction topics [3].

PREVENT is composed of five parts which are: safe speed and safe following, lateral support, intersection safety and vulnerable road users. Horizontal activities consist of three component improvement projects: RESPONSE 3, MAP&ADAS and Profusion. RESPONSE 3 investigates the legal issues and human factors. Digital maps for ADAS are being studied in MAP&ADAS. Profusion is a sensor improvement project. Safe speed and safe following are projects on longitudinal collision avoidance systems and contain two subprojects: SASPENSE and WILLWARN. SASPENSE aims at avoiding collisions with road condition, traffic density, road geometry, frontal obstacles, potentially dangerous road locations and weather condition information by using vehicular sensors. WILLWARN uses radars as inter-vehicle communication system and GPS data to prevent possible accidents. SAFELANE and LATERAL SAFE form the third part of the project called lateral support. Purpose of SAFELANE is developing a lane departure warning system which uses radar, camera and digital map information. Lane changing assistant system that detects side obstacles and warns driver of blind zone, dangerous lane changing and merging maneuvers is a subject of LATERAL SAFE. Failing to distinguish other drivers' actions, missing road signs or inappropriate maneuvers are the most common sources of intersection collisions. The main aim of INTERSAFE was to remove these sources by fusion of radar-camera sensors and information from traffic signals. Last part of PREVENT is formed for collision mitigation for crashes including vulnerable road users. It consists of two subprograms APALACI and COMPOSE, which use different algorithms for sensor fusion to detect pedestrians and motorcycle drivers [16].

There are also research projects on ADAS in Turkey. European Union Sixth Framework Programme Project Automotive Control and Mechatronics Research Center (AUTUCOM) funded in Mechanical Engineering Department of Istanbul Technical University has many successful projects on ADAS. Collision Warning, Collision Avoidance, Active Steering, Yaw Stability Control, Rollover Avoidance and Adaptive Cruise Control are some subjects that are studied in AUTOCOM. Corporative projects with other universities and industrial organizations also support ADAS research. DRIVESAFE project which is embodying Sabancı and Koç

Universities, Mechatronics Research Laboratories in Istanbul Technical University with Ford Otosan, Tofaş and Renault aims at designing Collision Warning Systems by detecting whether the driver is tired and sleepy or not using facial expressions of driver and brain waves information. Mechatronics Research Center has also individual research projects with Ford Otosan like Active Steering and Yaw Stability System Design projects.

1.2 The Problem Statement and Thesis Organization

The state-of-the-art on Collision Warning and Collision Avoidance Systems clearly exhibits the great attention on these systems allover the world. As is seen from previous paragraphs, there are plenty of projects in different countries whose purposes are reducing traffic accidents. The common point of these projects is creating well-defined systems that can accomplish all of the desired objectives while being in harmony with the human driver. This key idea is crucial since there will always be a human driver who controls the vehicle in short term period and it is not realistic to expect obtaining effective results with such systems that are not coherent with the human driver. The main purpose of this work is to achieve effective active safety systems which are able to reduce traffic accidents.

This thesis is composed of two main parts devoted to the development of two important systems in active safety which are Collision Warning System and Collision Avoidance System. Each part embodies subsections that present the progressive development and testing phases. Conclusion part serves as a discussion environment for obtained results of systems proposed in these parts.

The purpose of the CW System part is a development of a new CW Algorithm which considers various human factors in critical situations as well as critical maneuvers of the Adaptive Cruise Control (ACC) System equipped vehicles in these situations. This part is introduced with the detailed literature overview. Second subsection is devoted to the algorithm development phase. Vehicle model developed in Matlab Simulink environment which is used to test proposed algorithm is presented in the third subsection. The simulation section gives the obtained results for the proposed method with different scenarios by comparing with the previous algorithms.

The purpose of the CA System part is a development of a new CA Algorithm which can avoid most common collision scenarios. After giving literature overview, this part concentrates on Elastic Band Theory which will be the core method on developing avoidance algorithm. Following part contains implementation problems with this method in using vehicle based applications. Fourth section describes the developed avoidance algorithm. Carsim which is used as a simulation environment with Simulink connection is presented in fifth section. Simulation section gives the obtained results with various scenarios and different vehicle configurations.

Conclusion part discusses overall results. Possible works which may improve the proposed methods are also given in this section.

2. COLLISION WARNING SYSTEM

Collision Warning (CW) System is an important jump from passive to active safety systems. CW System tries to detect any collision risk between two vehicles by means of radar and vehicular sensor information. If the system detects collision risk, it will warn the driver so that a possible accident can be avoided [17].

Rear-end collision is the most common traffic accident type encountered in approximately 30 percent of all accidents. According to police records in USA, 1.8 million rear-end collisions occurred in 1996, which resulted in 2000 fatalities and 800,000 injuries [18]. CW Systems available in the literature use kinematical analysis based (e.g. [19], [20], [21]) or experimental analysis based (e.g. [22]) algorithms. These systems use a radar sensor to measure relative parameters between the host vehicle and the leading vehicle and vehicular sensors to measure leading vehicle's parameters such as velocity and acceleration. Since these systems use the same sensors as ACC, they might easily be adapted to vehicles with ACC. However, there must be some modifications made to the algorithms to achieve satisfactory results [17].

Previous algorithms on Collision Warning Systems are introduced in Literature Overview subsection. Human factors, ACC maneuvers during critical situations and the performance of previous systems have key roles on the algorithm modification phase. These considerations are taken into account and a new algorithm is developed in Developed Collision Warning Algorithm subsection. ACC System is also described in this subsection. Derivation of the dynamics of the vehicle in Matlab Simulink Environment is given in Simulation Environment subsection. Simulation subsection presents the obtained results for proposed method with comparison analysis to previous methods.

2.1 Literature Overview

Rear-end collision avoidance system algorithms are based on the tendency of a rear end collision by calculating critical distances between two vehicles following each other and comparing this with the present inter-vehicular separation to apply appropriate actions for different scenarios [2]. The basic geometry of a rear-end collision is displayed in Figure 2.1 where V is the velocity, a is the deceleration and d is the distance between two vehicles.

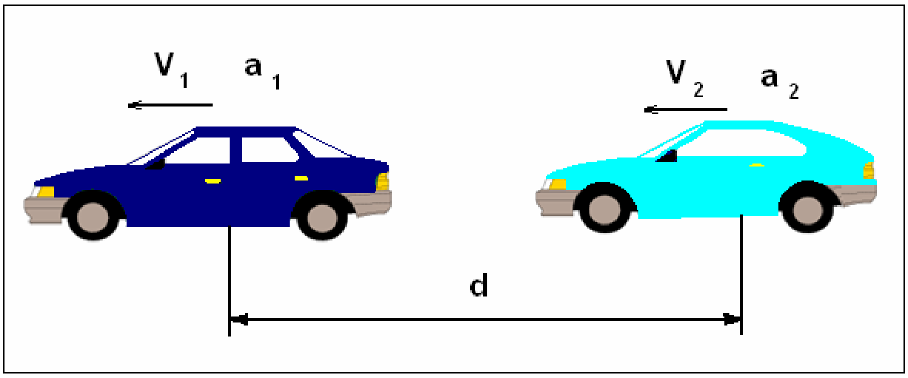

Figure 2.1 **:** Basic Geometry of Rear End Collision

2.1.1 The Mazda Algorithm

This system uses a kinematical analysis based algorithm to determine critical braking distance. However, the calculated distance is too conservative for braking and must be taken as a critical warning distance. The critical warning distance d_w is given by

$$d_w = \frac{1}{2}\left(\frac{v^2}{\alpha_1} - \frac{(v - v_{rel})^2}{\alpha_2}\right) + v\tau_1 + v_{rel}\tau_2 + d_0 \qquad \textbf{(2.1)}$$

where d_0 is the headway offset, v is the velocity of the following vehicle, v_{rel} is the relative velocity between the following and leading vehicles, τ_1 is the system delay, τ_2 is the driver delay and α_1 and α_2 are the maximum decelerations of the following and leading vehicles, respectively.

This algorithm assumes that the leading vehicle begins to brake with maximum deceleration of α_2 and the following vehicle begins to brake with maximum deceleration of α_1 after driver delay of τ_2 and system delay of τ_1. To make the algorithm more conservative, a headway offset of d_0 is added to the critical warning distance [19].

2.1.2 The Honda Algorithm

Honda's system is based on experimental data. The critical warning distance d_w is given by

$$d_w = 2.2v_{rel} + 6.2 \quad \textbf{(2.2)}$$

where v_{rel} is the relative velocity between the following and leading vehicles.

The critical warning distance calculated using equation (2.2) is lower than the average maneuver distance for collision avoidance. Average distance is determined by collision tests for different drivers [22].

2.1.3 The PATH Algorithm

The PATH algorithm is a modified version of Mazda's algorithm [19]. The critical warning distance d_w is given by

$$d_w = \frac{1}{2}\left(\frac{v^2}{\alpha} - \frac{(v - v_{rel})^2}{\alpha}\right) + v\tau + d_0 \quad \textbf{(2.3)}$$

where d_0 is the headway offset, v is the velocity of the following vehicle, v_{rel} is the relative velocity between following and leading vehicle, α is the maximum deceleration of the vehicles and τ is the total delay for the system and driver.

The PATH algorithm aims to obtain a more conservative warning distance than Mazda. However, warning is scaled by a non-dimensional warning value *w* given by

$$w = \frac{d - d_{br}}{d_w - d_{br}} \quad \textbf{(2.4)}$$

where d is the present distance and d_{br} is the critical braking distance which is calculated as

$$d_{br} = v_{rel}\tau + \frac{1}{2}\alpha\tau^2 \quad \textbf{(2.5)}$$

Braking distance shows the distance where there is nothing to do even driver notices the collision risk. This distance is simply calculated by kinematical formulation used for calculating traveled road with initial velocity and constant deceleration rate. Total time which is used in formulation equals to total delay that is sum of driver and system delays. Figure 2.2 shows d, d_w and d_{br} in schematic representation.

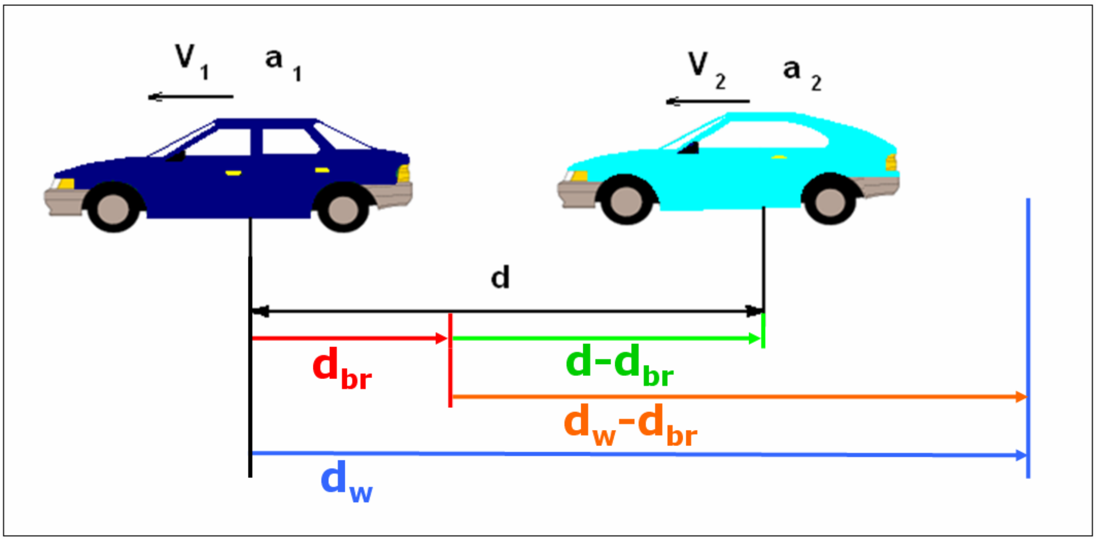

Figure 2.2 : Schematic Representation of d, d_w and d_{br}

This non-dimensional w value is used for grading warnings that are given to the driver. Decreasing w shows increasing collision risk. w>1 means safe driving situation. Warning is given to the driver when w takes value between 0 and 1. PATH uses graduated Light Display to grade warnings with obtained w value. Graduated Light Display Screen shows colored signals changing between green to red where green shows safe driving and red shows last warnings to the collision. When w starts to decrease from 1 to 0, Graduated Light Display turns to yellow and finally red respectively from green gradually. The system applies the brake if w<0 [20].

2.1.4 The NHTSA Algorithm

The NHTSA algorithm is also kinematical analysis based. The NHTSA system uses acceleration information in addition to velocity information. The critical warning distance is calculated using

$$
\begin{aligned}
& d_{w1} = 0.1v + d_0 - \frac{1}{2}(a - a_{\max})(T_R)^2 \\
& + \frac{1}{2}(a - a_{rel})(T_{LS})^2 + (a - a_{\max})T_R T_{FS} - v_{rel} T_{FS} \\
& -(a - a_{rel}) T_{FS} T_{LS} + \frac{1}{2} a_{\max} (T_{FS})^2
\end{aligned} \tag{2.6}
$$

$$d_{w2} = 0.1v + d_0 - v_{rel}T_M - \frac{1}{2}(a - a_{rel} - a_{\max})(T_M)^2$$
$$+(a - a_{\max})T_M T_R - \frac{1}{2}(a - a_{\max})(T_R)^2 \quad \textbf{(2.7)}$$

where d_0 is the headway offset, v is the velocity of following vehicle, v_{rel} is the relative velocity between following and leading vehicles, α is the acceleration of the following vehicle, α_{max} is the maximum deceleration of following vehicle, α_{rel} is the relative acceleration between following and leading vehicles, T_R is the reaction time, T_M is the time for the relative velocity between the two vehicles to reach zero and T_{LS} and T_{FS} are the stopping times of the leading and following vehicles, respectively. T_{LS}, T_{FS} and T_M are calculated by the following formulas.

$$T_{LS} = -\frac{(v - v_{rel})}{(a - a_{rel})} \quad \textbf{(2.8)}$$

$$T_{FS} = T_R - \frac{(v + aT_R)}{a_{\max}} \quad \textbf{(2.9)}$$

$$T_M = \frac{(v_{rel} - a_{rel}T_R)}{(a_{\max} - a + a_{rel})} + T_R \quad \textbf{(2.10)}$$

The algorithm selects the appropriate warning distance according to the values of T_{LS} and T_{FS}. If T_{HS} is greater than T_{LS}, d_{w1} is selected as the critical warning distance. Otherwise, d_{w2} is used. However, if the velocity of the leading vehicle is constant or if the acceleration of the leading vehicle is greater than the -1 m/s^2, the algorithm selects d_{w2} [21].

2.2 Developed Collision Warning Algorithm

2.2.1 Adaptive Cruise Control System

Adaptive Cruise Control (ACC) System is a kind of comfort system which aims at holding velocity at the prescribed level determined by the driver without necessitating any driver input while trying to adapt other vehicles' maneuvers on the road to avoid possible collisions in this period. ACC System is composed of hierarchical control structure. High level controller tries to determine the configuration of the vehicles on the road, and put this configuration into one of the predefined scenarios while low level controller aims at applying command comes from high level controller with throttle and brake inputs [23].

System uses different predefined scenarios in interpreting the configurations of the vehicles. First scenario represents no target vehicle situation. Other scenarios are evaluated after determining target vehicles. Target vehicle existence information is obtained using radar and yaw rate sensor data. Radar azimuth data provides lateral movement information where distance data provides longitudinal movement information. Upper level controller compares lateral movement of the vehicles around the host vehicle obtained by radar azimuth and distance data with the lateral movement of the host vehicle obtained by yaw rate sensor and velocity data to decide on whether investigated vehicle is on the same lane with the host vehicle or not. In this way, it is possible to determine lane changing vehicles with cornering target vehicles. When it is decided that there is a target vehicle on the same lane with the host vehicle, longitudinal movement detection part is initialized. This part tries to determine whether target vehicle is accelerating, decelerating or having constant velocity. Command information is sent to the low level controller according to the decided scenario [23].

Low level controller tries to obtain desired acceleration using throttle and brake input. Desired acceleration is converted to desired longitudinal force using second law of Newton. Then this longitudinal force information converted to desired engine or brake torque. Desired engine torque is converted to desired throttle input using inverse engine model look-up table and engine angular velocity data. Brake model also gives desired braking pedal input [23].

2.2.2 Human Factors

Certainly, human factors are of primary importance in the development of CW algorithms. These factors are crucial for vehicles with an ACC System since the ACC controls the velocity of following vehicle according to the velocity of the leading vehicle when the system is on. If the leading vehicle is braking or has a constant velocity lower than the velocity of following vehicle, ACC starts to decrease the velocity of the following vehicle. Considering ACC's adaptability characteristics, previous algorithms might give a warning to the driver even though there is no such need. These unnecessary warnings desensitize the driver. On the other hand, since ACC is a comfort system, its deceleration is limited to -3 m/s^2. In other words, ACC limits are not sufficient for emergency braking situations. The over relaxed driver must be warned for emergency braking. In summary, warnings must be non-conservative so that the driver knows that a warning means that there is a need for emergency braking.

2.2.3 Algorithm Development

The proposed algorithm is developed using a step by step procedure. Considering the flexibility requirements expected from the algorithm to conditions of ACC and driver aggressiveness, a kinematical analysis based algorithm is used instead of an experimental analysis based algorithm.

According to [24], the NHTSA algorithm is more sensitive to sensor errors since this algorithm measures relative acceleration by taking the derivative of relative velocity. Hence, it is not efficient to use acceleration information in the algorithm considering wrong warnings resulting from numerical derivative errors. The proposed algorithm uses only velocity information.

Graduated light display in the PATH system might be very effective when human factor considerations are taken into account. The proposed algorithm uses a similar display.

The proposed algorithm calculates two critical warning distance values depending on whether ACC is on or off. Critical warning distance is more conservative for the off position of ACC.

Before passing through formulation, simple kinematical formulations will be given first. Traveled road information can be obtained by limited integration of velocity data.

$$d = \int_{t_0}^{t_f} v dt \tag{2.11}$$

where d is the traveled road, v is the velocity and t_0 and t_f are initial and final times respectively. If the vehicle has constant acceleration, velocity information can be obtained as

$$v = v_i + \int_{t_0}^{t_f} adt = a(t_f - t_0) \tag{2.12}$$

where α is the acceleration and v_i is the initial velocity. With 2.12, 2.11 is returned to

$$d = \int_{t_0}^{t_f} (v_i + a(t_f - t_0))dt = v_i(t_f - t_0) + \frac{1}{2}a(t_f - t_0)^2 \tag{2.13}$$

To remove dependence on time we introduce

$$d = \int_{t_0}^{t_f} vdt = \int_{v_0}^{v_f} v\frac{dv}{a} = \frac{1}{a}\int_{v_0}^{v_f} vdv = \frac{1}{2a}v^2\Big|_{v_0}^{v_f} = \frac{(v_f - v_0)^2}{2a} \tag{2.14}$$

With this introduction we can formulate the algorithm.

2.2.3.1 ACC is on

The leading vehicle's position change is with 2.14

$$D_L = \frac{(v_{2i} - v_{2f})^2}{2a_{\max}} = \frac{{v_{2i}}^2}{2a_{\max}} = \frac{(v - v_{rel})^2}{2a_{\max}} \tag{2.15}$$

where v is the velocity of following vehicle, v_2 is the velocity of the leading vehicle, v_{rel} is the relative velocity between the following and leading vehicles, α_{max} is the maximum deceleration of the two vehicles. The following vehicle's position change is calculated by dividing time interval to different periods. In the first period, since ACC does not apply maneuver, vehicle moves with constant velocity for ACC delay time.

$$D_{F1} = v\tau_{ACC} \tag{2.16}$$

where τ_{ACC} is the delay of ACC and D_{F1} is the traveled road in this period. In the second period, ACC starts to apply braking with its maximum limit for the time which is the sum of human and system delay with TAP value. With 2.13

$$D_{F2} = v(TAP + \tau_{sys} + \tau_{hum}) - \frac{1}{2}a_{ACC}(TAP + \tau_{sys} + \tau_{hum})^2 \tag{2.17}$$

where α_{ACC} is the maximum deceleration limit of ACC, τ_{sys} is the system delay, τ_{hum} is the driver delay, TAP is the "Tunable Avoidance Parameter" and D_{F2} is the traveled road in this period.

In the last period driver applies emergency braking to decrease velocity to 0. With 2.14

$$D_{F3} = \frac{(v_i - v_f)^2}{2a_{\max}} = \frac{v_i^2}{2a_{\max}} = \frac{(v - a_{ACC}(TAP + \tau_{sys} + \tau_{hum}))^2}{2a_{\max}} \tag{2.18}$$

with D_{F1}, D_{F2} and D_{F3}, following vehicle's position change is

$$\begin{aligned} &D_F = v\tau_{ACC} + v(TAP + \tau_{sys} + \tau_{hum}) \\ &-\frac{1}{2}a_{ACC}(TAP + \tau_{sys} + \tau_{hum})^2 \\ &+\frac{(v - a_{ACC}(TAP + \tau_{sys} + \tau_{hum}))^2}{2a_{\max}} \end{aligned} \tag{2.19}$$

The warning distance is

$$d_w = D_F - D_L + d_0 \tag{2.20}$$

Or using (2.19) and (2.15)

$$\begin{aligned} &d_w = v(TAP + \tau_{sys} + \tau_{hum} + \tau_{ACC}) - \frac{1}{2}a_{ACC}(TAP + \tau_{sys} + \tau_{hum})^2 \\ &+\frac{(v - a_{ACC}(TAP + \tau_{sys} + \tau_{hum}))^2}{2a_{\max}} - \frac{(v - v_{rel})^2}{2a_{\max}} + d_0 \end{aligned} \tag{2.21}$$

where d_w is the critical warning distance, d_0 is the headway offset.

2.2.3.2 ACC is off

The leading vehicle's position change is

$$D_L = \frac{(v - v_{rel})^2}{2a_{\max}} \tag{2.22}$$

The following vehicle's position change is

$$D_F = v(TAP + \tau_{sys} + \tau_{hum}) + \frac{v^2}{2a_{\max}} \quad \textbf{(2.23)}$$

The warning distance is

$$d_w = D_F - D_L + d_0 \quad \textbf{(2.24)}$$

Or using (2.22) and (2.23)

$$d_w = v(TAP + \tau_{sys} + \tau_{hum}) + \frac{v^2}{2a_{\max}} - \frac{(v - v_{rel})^2}{2a_{\max}} + d_0 \quad \textbf{(2.25)}$$

2.2.4 Tunable Avoidance Parameter (TAP)

Tunable Avoidance Parameter (TAP) is a parameter which is used to modify Collision Warning (CW) Algorithms according to the characteristics of the drivers. By adding this parameter to the formulation, the assumed delay time for the driver is changed with observed reaction times. The purpose of TAP is reducing the number of unnecessary warnings as well as increasing the accuracy of the algorithms by determining all of the situations that require warnings.

Drivers use different techniques while driving and these techniques totally change their reaction times to specific situations. In Rear-End Collisions, which is the subject of proposed Collision Warning (CW) Algorithm, some drivers prefer applying brakes as soon as possible after they are able to be aware of the danger of the situation, while some of them think that it would be better waiting until last second. Some of them even prefer to stop pushing gas pedal before the situation becomes dangerous and not to apply braking. Regarding these characteristics, optimum warning times for specific collision configurations are not the same for all drivers. Using same formulation for all drivers results in desensitization soon. Standard warning time is thought to be very early for drivers who like fast driving. If they think and experience that they can come over the collision risk after system gives warning, they will think that the warning system is unnecessary. On the other hand, cautious drivers consider the standard warning as a late warning. This can make them panic and cause unwanted maneuvers which are resulted in collisions in situations where there is an avoidance chance by just applying emergency braking. In order to obtain a specialized CW Algorithm, proposed method necessitates initialization procedure to observe optimum TAP value. This initialization procedure contains realistic test driving with the subjected driver. Warning Algorithm is evaluated according to obtained numbers of true, missing and unnecessary warnings. These warnings are summarized in Figure 2.3.

TAP value is modified according to the numbers of true, missing and unnecessary warnings. Numbers of true warnings have no effect on TAP value. However, number of missing warnings tends to increase the TAP value. On the other hand, TAP value is decreased with the rise in the number of unnecessary warnings. Figure 2.4 presents the procedure. However, while proposed algorithm was testing in simulation environment, this procedure was not applied since both the simulation environment and the driver characteristics were not realistic. TAP value was determined with trial and error method by using comparison with other methods. Since driver model was a simple model with constant delay, it was easy to determine this value. Since there is a difference in delay values because of the addition of ACC effect, TAP values are different between ACC is on and ACC is off situations. The difference between these two TAP values is equal to ACC contribution for that configuration.

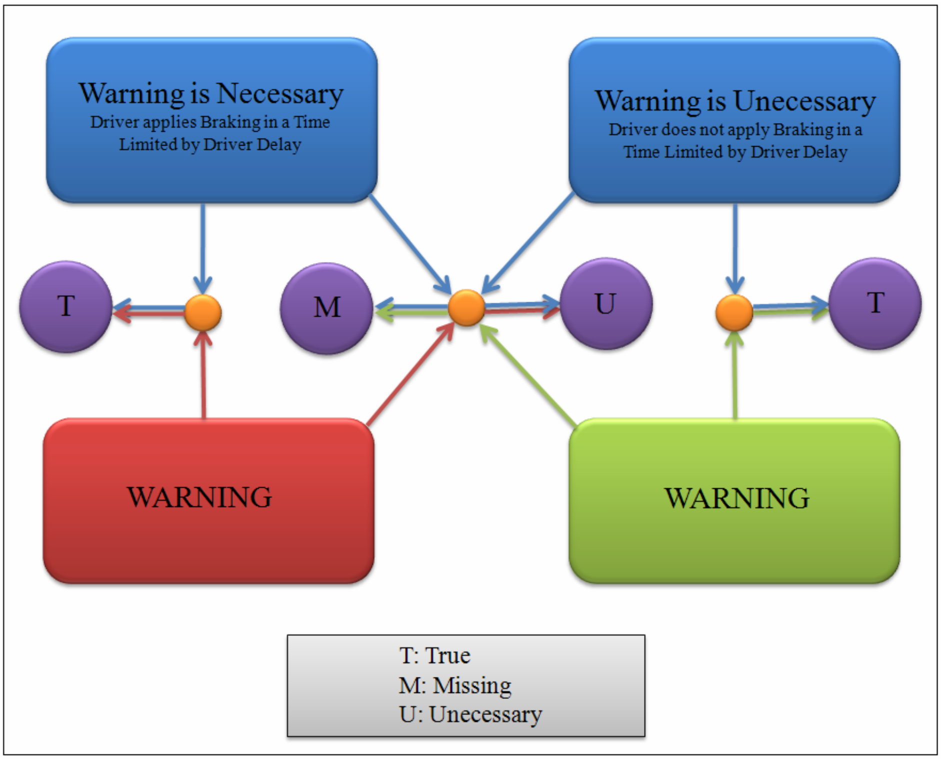

Figure 2.3 : True, Missing and Unnecessary Warnings

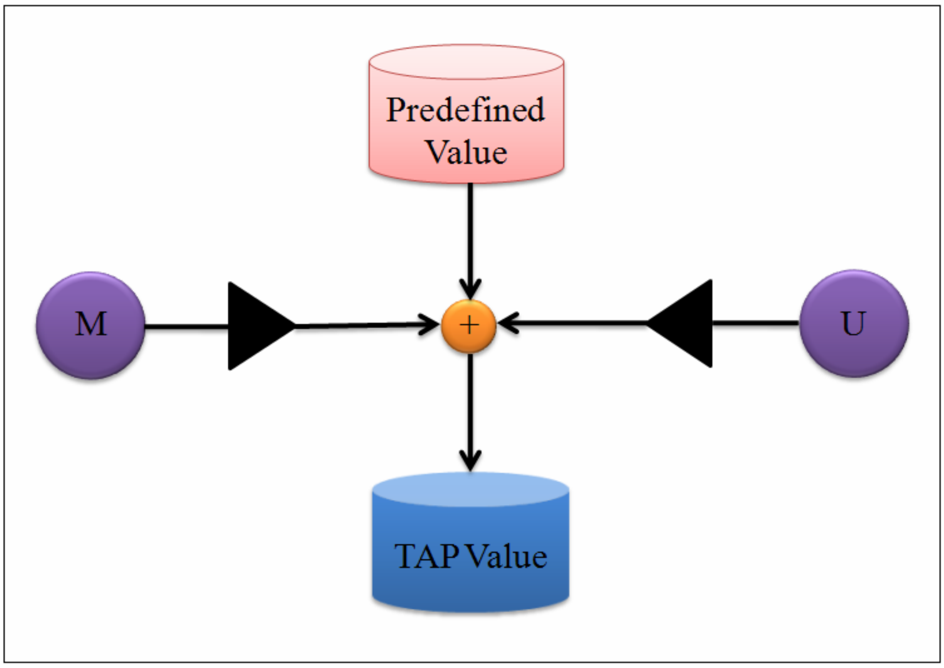

Figure 2.4 : Modification of TAP Value

Figure 2.5 presents the critical warning range according to velocities of the following and leading vehicles for different TAP values.

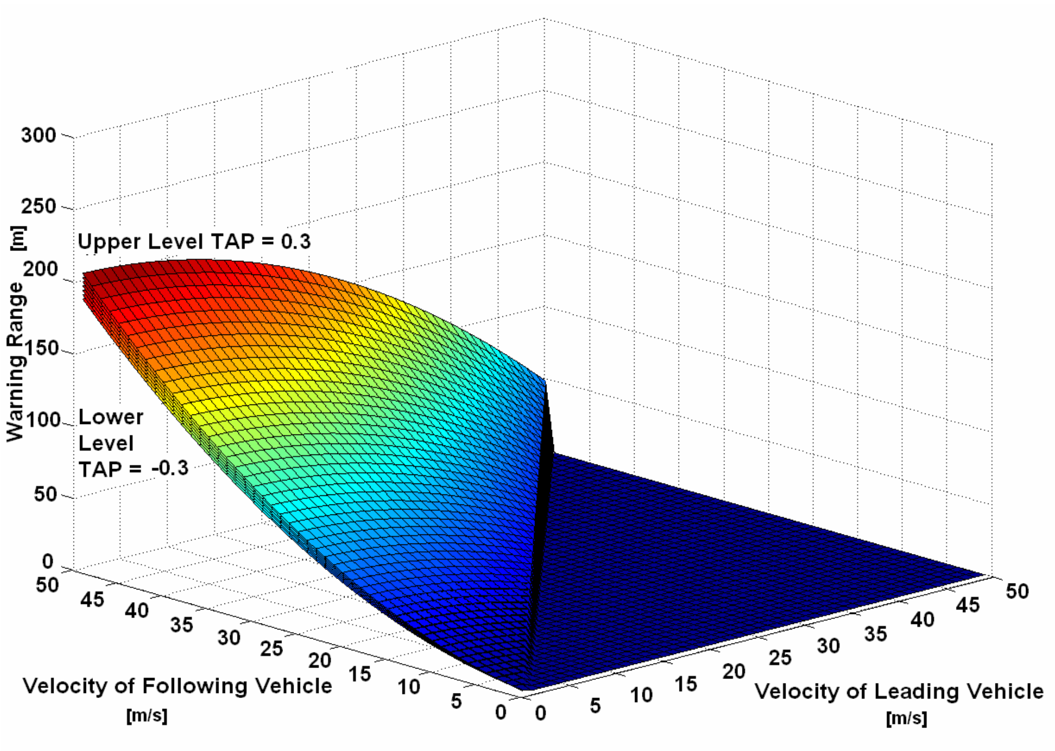

Figure 2.5 : Warning Range for Different TAP Values

2.3 Simulation Environment

High fidelity vehicle model plays crucial role in testing proposed algorithms for CW Systems. Both dynamics of the vehicle and the dynamics of the components of the vehicle have to be considered to be able to obtain vehicle model which shows realistic characteristics in simulation environment. Matlab Simulink program is used to build vehicle model. Following subsections describe the formulation.

2.3.1 Vehicle Dynamics

Vehicle dynamics is modeled by the most common method called Bicycle Model which is obtained by projecting double track vehicle model into single track vehicle model. Schematic representation of the Bicycle Model is given in Figure 2.6. Vehicle dynamics is obtained as formulating force equations for X and Y coordinate and moment equation for Z coordinate. Tire model which will be introduced in the next subsection provides total forces on X and Y axis as well as total moment on Z axis by using tire-road surface contact formulation. By putting these forces and moment into the force and moment equations and integration, it will be possible to reach kinematical parameters of the vehicle for every time instant in simulation [25].

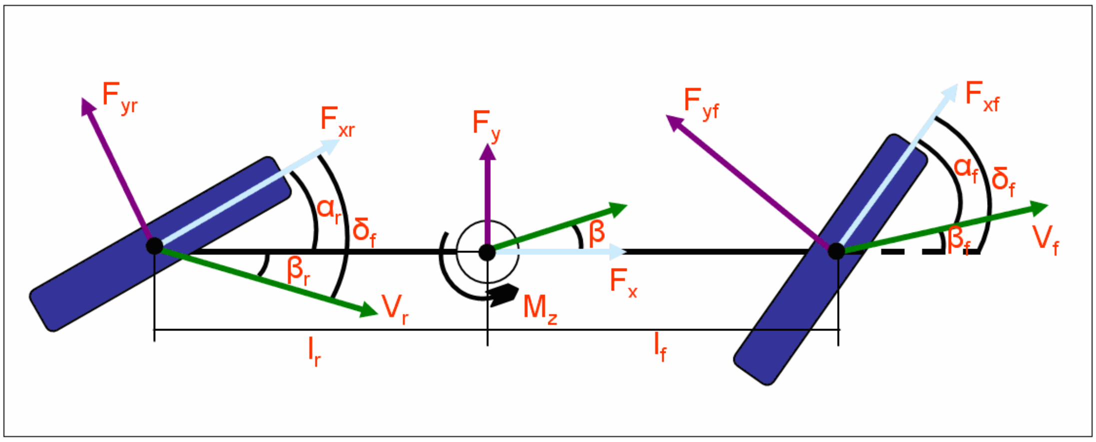

Figure 2.6 : Schematic Representation of the Bicycle Model

As is seen from Figure 2.6, velocity vector for the center of gravity can be written as

$$\vec{V} = V.\cos\beta.\vec{i} + V.\sin\beta.\vec{j} \qquad \textbf{(2.26)}$$

where V is the velocity of the center of gravity and β is the side slip angle of the vehicle. Derivative of this equation is then

$$\vec{a} = \frac{d\vec{V}}{dt} = \left[\dot{V}.(\cos\beta) - V.(\sin\beta).\dot{\beta}\right]\vec{i} + \left[\dot{V}.\sin\beta + V.(\cos\beta).\dot{\beta}\right]\vec{j}$$
$$+V.(\cos\beta)\frac{d\vec{i}}{dt} + V.(\sin\beta)\frac{d\vec{j}}{dt} \tag{2.27}$$

With

$$\frac{d\vec{i}}{dt} = \dot{\psi}.\vec{k}\times\vec{i} = \dot{\psi}.\vec{j} \tag{2.28.a}$$

$$\frac{d\vec{j}}{dt} = \dot{\psi}.\vec{k}\times\vec{j} = -\dot{\psi}.\vec{i} \tag{2.28.b}$$

where α is the acceleration and ψ is the yaw angle with respect to Z axis. (2.27) can be rewritten as

$$\vec{a} = \frac{d\vec{V}}{dt} = \left[\dot{V}.(\cos\beta) - V.(\sin\beta).\dot{\beta}\right]\vec{i} + V.(\cos\beta).\dot{\psi}.\vec{j}$$
$$+\left[\dot{V}.\sin\beta + V.(\cos\beta).\dot{\beta}\right]\vec{j} - V.(\sin\beta).\dot{\psi}.\vec{i} \tag{2.29}$$

$$\vec{a} = \frac{d\vec{V}}{dt} = \left[\dot{V}.(\cos\beta) - V.(\sin\beta).(\dot{\beta}+\dot{\psi})\right]\vec{i}$$
$$+\left[\dot{V}.\sin\beta + V.(\cos\beta).(\dot{\beta}+\dot{\psi})\right]\vec{j} \tag{2.30}$$

Force equations for X and Y coordinate and moment equation for Z coordinate are obtained as

$$\sum F_x = ma_x = m\left[\dot{V}.(\cos\beta) - V.(\sin\beta).(\dot{\beta}+\dot{\psi})\right] \tag{2.31}$$

$$\sum F_y = ma_y = \left[\dot{V}.\sin\beta + V.(\cos\beta).(\dot{\beta} + \dot{\psi}) \right] \quad \textbf{(2.32)}$$

$$\sum M_z = I_z \ddot{\psi} \quad \textbf{(2.33)}$$

where m is the total mass, F_x and F_y are the total tire-road contact forces on X axis and Y axis respectively, a_x and a_y are the acceleration values on X axis and Y axis respectively, M_z total moment on Z axis and I_z is the total moment of inertia for Z axis.

2.3.2 Tire Model

Tire model is one of the most important parts of the vehicle model. Since realistic tire models are too complex for both formulation and computation, generally simple tire models are used in vehicle modeling applications. Dugoff tire model used in this model is a simple and effective way of simulating tire characteristics. This model combines two linear tire models, where longitudinal tire forces are dependent on the longitudinal slips and lateral tire forces are dependent on the lateral angular slips, into one model which also regards interaction between forces on X and Y coordinates.

The Tire model uses both vehicle kinematical parameters come from vehicle dynamics and applied total torque comes from engine model through transmission model which will be described in following subsection to obtain longitudinal and lateral angular slips. Obtained slip values are used to calculate angular velocities of the wheels and tire-road surface contact forces by means of Dugoff Tire Model. Wheel angular velocities are fed into engine model to be able to derive torque value for the next time instant where tire-road surface contact forces are fed into vehicle dynamics.

Velocity values on the rear and front wheels are required to calculate both longitudinal slip and lateral slip angles. Velocities on both tires are obtained by projecting velocity on the center of gravity to rear and front wheels as follows

$$\vec{V_f} = \vec{V} + \dot{\psi}\,\vec{k} \times l_f\,\vec{i} = V.\cos\beta\,\vec{i} + V.\sin\beta\,\vec{j} + \dot{\psi}.l_f\,\vec{j} \quad \textbf{(2.34.a)}$$

$$\vec{V}_r = \vec{V} + \dot{\psi}\,\vec{k} \times (-l_r)\,\vec{i} = V.\cos\beta\,\vec{i} + V.\sin\beta\,\vec{j} - \dot{\psi}.l_r\,\vec{j} \qquad \textbf{(2.34.b)}$$

where V_f and V_r are the velocities on front and rear tires.

These velocity values are enough to derive longitudinal slip for both tires. Longitudinal slip values are derived by following formulation

$$s_{f,r} = \begin{cases} \dfrac{R_{eff}.\omega_{f,r} - V_{f,r}}{R_{eff}.\omega_{f,r}} & R_{eff}.\omega_{f,r} > V_{f,r} \quad (Traction) \\ \dfrac{R_{eff}.\omega_{f,r} - V_{f,r}}{V_{f,r}} & R_{eff}.\omega_{f,r} < V_{f,r} \quad (Braking) \end{cases} \qquad \textbf{(2.35)}$$

where $s_{f,r}$ are the longitudinal slip values for front and rear tire respectively, R_{eff} is the effective radius of the wheel under loaded condition, $\omega_{f,r}$ are the angular velocities of front and rear tire respectively.

Side slip angles on both tires are also required to derive lateral angular slip.

Side slip angles are obtained by following formulation

$$\beta_f = \frac{V_{fy}}{V_{fx}} = \tan^{-1}\left(\frac{V.\sin\beta + \dot{\psi}.l_f}{V.\cos\beta}\right) \qquad \textbf{(2.36.a)}$$

$$\beta_r = \frac{V_{ry}}{V_{rx}} = \tan^{-1}\left(\frac{V.\sin\beta - \dot{\psi}.l_r}{V.\cos\beta}\right) \qquad \textbf{(2.36.b)}$$

where β_f and β_r are side slip angles on front and rear tires respectively, V_{fx} and V_{rx} are X coordinate components of front and rear wheel velocity respectively, V_{fy} and V_{ry} are X coordinate components of front and rear wheel velocity respectively.

Lateral slip angles are then obtained as

$$\alpha_f = \delta_f - \beta_f \qquad \textbf{(2.37.a)}$$

$$\alpha_r = \delta_r - \beta_r \qquad \textbf{(2.37.b)}$$

where α_f and α_r are lateral angular slips on front and rear tires respectively, δ_f and δ_r are steering angle for front and rear tires respectively. Longitudinal and Lateral tire forces are derived by Dugoff Model as follows

$$F_{xf} = f_f C_{xf} s_f \tag{2.38.a}$$

$$F_{xr} = f_r C_{xr} s_r \tag{2.38.b}$$

$$F_{yf} = f_f C_{yf} \alpha_f \tag{2.38.c}$$

$$F_{yr} = f_r C_{yr} \alpha_r \tag{2.38.d}$$

where C_x and C_y longitudinal and lateral force coefficients respectively, f_f and f_r are Dugoff correction coefficients for front and rear tire respectively.

Dugoff correction coefficients are derived with following formulation

$$f_{f,r} = \left\{ \begin{array}{cc} 1 & F_{tf,tr} \le \dfrac{\mu F_z}{2} \\ \left(2 - \dfrac{\mu F_z}{2F_{tf,tr}}\right)\dfrac{\mu F_z}{2F_{tf,tr}} & F_{tf,tr} > \dfrac{\mu F_z}{2} \end{array} \right\} \tag{2.39}$$

with

$$F_{tf,tr} = \sqrt{F_{xf,xr}{}^2 + F_{yf,yr}{}^2} \tag{2.40}$$

$$F_z = \frac{mg}{2} \tag{2.41}$$

where F_z are total load on both tires, $F_{tf,\ tr}$ are total forces on front and rear tires respectively and μ friction coefficient.

2.3.3 Engine and Transmission Model

As is seen from previous subsections, it is required to know angular velocities of wheels in order to obtain tire forces as well as vehicle kinematical parameters. To be able to derive angular velocities of wheels, total torque on wheels is necessary. Total torque is obtained from engine model through transmission model.

Engine model is a kind of look-up table which is embodied by experimental values. This three dimensional look-up table contains throttle, engine angular velocity and engine torque as axis. In this way, it is possible to obtain engine torque by giving throttle and angular velocity at that time instant. Figure 2.7 presents the three dimensional view of this look table.

Transmission is derived by a simple static model. Acquired torque from engine is transmitted through wheels by proportioned with a transmission constant. Since dynamics of the transmission is not considered, it is effect on the dynamics of the vehicle is reflected through as an equivalent moment of inertia at tire equations.

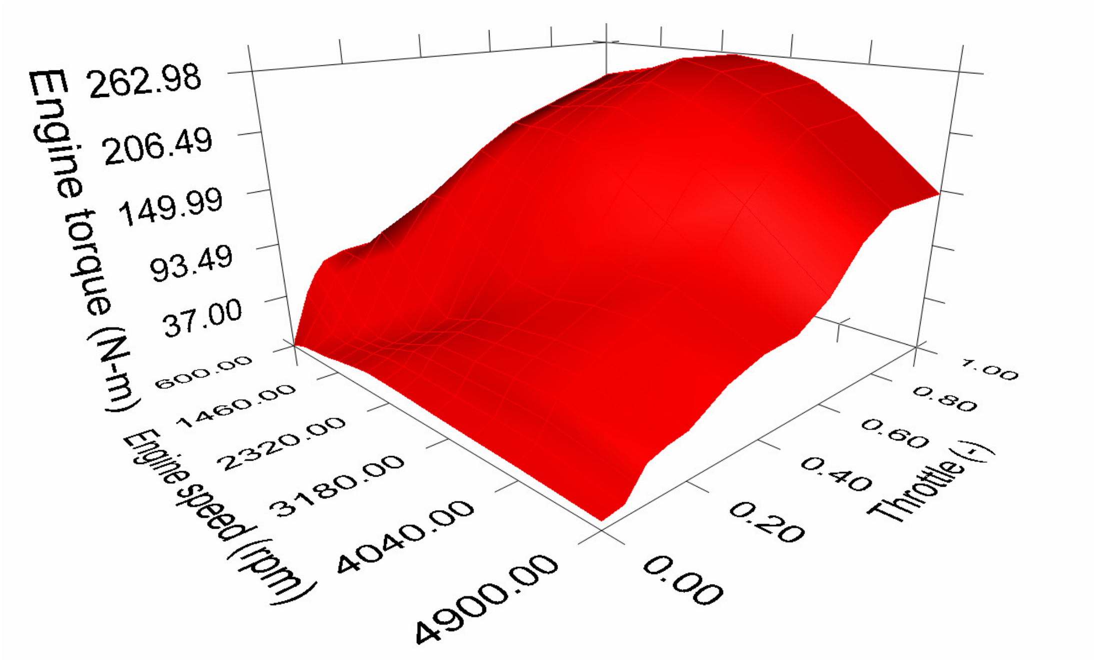

Figure 2.7 : Three Dimensional View of Engine Model Look-Up Table

Angular velocities of wheels with obtained torque values are obtained by following formulation

$$\eta.T_e = J_{eq}.\dot{\omega} + F_x.R_{eff} \qquad \textbf{(2.42)}$$

where η is the transmission ratio, J_{eq} is the equivalent moment of inertia on tires and T_e is the engine torque. Vehicle model is then built in Matlab Simulink by using previous formulations. Figure 2.8 shows the Simulink representation of the vehicle model.

2.4 Simulation

2.4.1 Simulator

The PC based low cost ACC simulator developed in Istanbul Technical University MEKAR Labs was used to obtain performance measurements of different warning algorithms. The simulator includes two 5-DOF vehicle models. The first model is a target vehicle and the other one is the host vehicle with ACC. Models use static drivetrain models and look-up table based engine maps. Communication of computers is supplied by the xPC target option of Matlab Simulink. Rapid controller prototyping is used to create code automatically from Simulink representations. Generated real time code is downloaded to the host PC where the visualization and user inputs are realized by means of game type steering wheels and pedals. Required acceleration and deceleration is provided by low level controllers where high level controllers identify the scenarios such as cut-in and lane changing. Figure 2.9 presents the MEKAR-ACC Simulator [23].

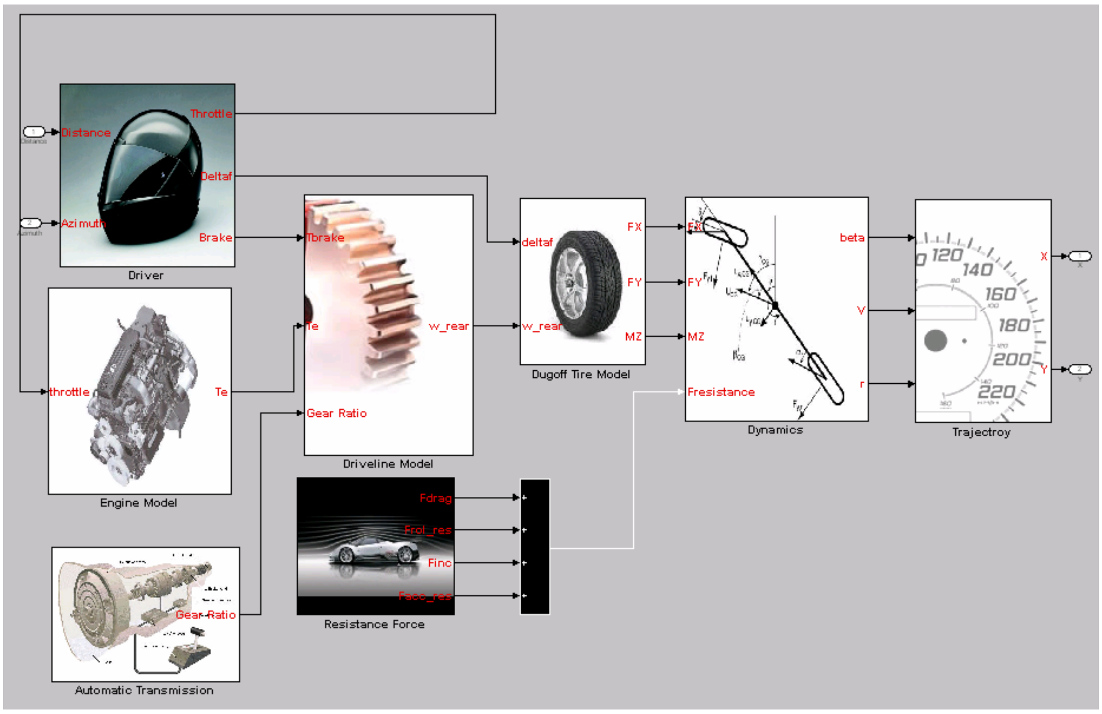

Figure 2.8 : Simulink Representation of the Vehicle Model

The following parameter values are used for related algorithms same as the original papers;

Mazda: τ_1=0.1 s, τ_2=0.6 s, α_1=6 m/s^2, α_1=8 m/s^2 and d_0=5m.

Honda: No parameter value for warning.

PATH: α=6 m/s^2, d_0=5 m, τ=1.2 s and audio warning value a = 0.2.

NHTSA: d_0=2.5 m, T_R=1.5 s and α_{max}=5.5 m/s^2.

Modified New: α_{max}=8 m/s^2, α_{ACC}=3 m/s^2, τ_{ACC}=0.2 s, τ_{sys}=0.1 s, τ_{hum}=0.8 s, d_0=2 m and TAP value for audio warning is -0.3 with ACC on and -0.1 with ACC off.

All the parameters of the previous algorithms have specified values as in their original papers. Parameter values for ACC taken in proposed algorithm are standard values for commercial ACC Systems. Other parameters have average values encountered in the literature. Dimensionless warning value increment is 0.2 for the proposed and the PATH algorithms. Warning is identified by 1 and braking is identified by 2 in the simulations. TAP value is determined with trial and error method for different scenarios to obtain optimum results for all simulations. The difference between TAP values in ACC on and off scenarios are resulted from ACC's initial maneuver.

Figure 2.9 : Mekar ACC Simulator

2.4.2 Simulation Results

Three different scenarios were simulated with the ACC on and one scenario was simulated with ACC off.

2.4.2.1 ACC on Scenarios

In the first scenario, the host vehicle and target vehicle have velocities of 30 m/s and the target vehicle applies emergency braking. Initial distance between the two vehicles is 30 m (1 second time gap). Simulation results are shown in Figure 2.10 and Table 2.1.

First figure in Figure 2.10 shows Range vs. Time Data. Range decreases from initial 30 m value to final value assuming the only maneuver is applied only by ACC without any emergency brake. Second figure in Figure 2.10 represents Velocity vs. Time data for two vehicles. Initially, two vehicles have same velocity of 30 m/s. As is seen from the figure leading vehicle applies emergency braking while host vehicle has ACC's limited deceleration rate. Last figure in Figure 2.10 gives the warning times of the algorithms. In this figure 1 represents warning while 2 represents braking. Since some algorithms have emergency braking option, this option is also considered in simulations. Stair like signals for proposed and PATH algorithm result from non-dimensional warning value which is used for grading warning level. Although Mazda's algorithm gives 2 value which represents braking, this signal is assumed to be warning signal since it is too conservative for braking option.

In the second scenario, the host vehicle comes close to the target vehicle whose velocity is approximately zero. Initial distance between the two vehicles is 120 m (approximate radar range). Simulation results are shown in Figure 2.11 and Table 2.2.

Respective tables give precise warning times with final range and velocity at collision information. It can be easily seen that given warnings are too early for these scenarios which may cause the driver to be desensitized to the Warning Systems. If we assume that driver will apply emergency braking with prescribed delay after warning, final range also can be used to compare different algorithms. Proposed algorithm gives nearly optimum final range values for both scenarios where the results of other algorithms are too conservative.

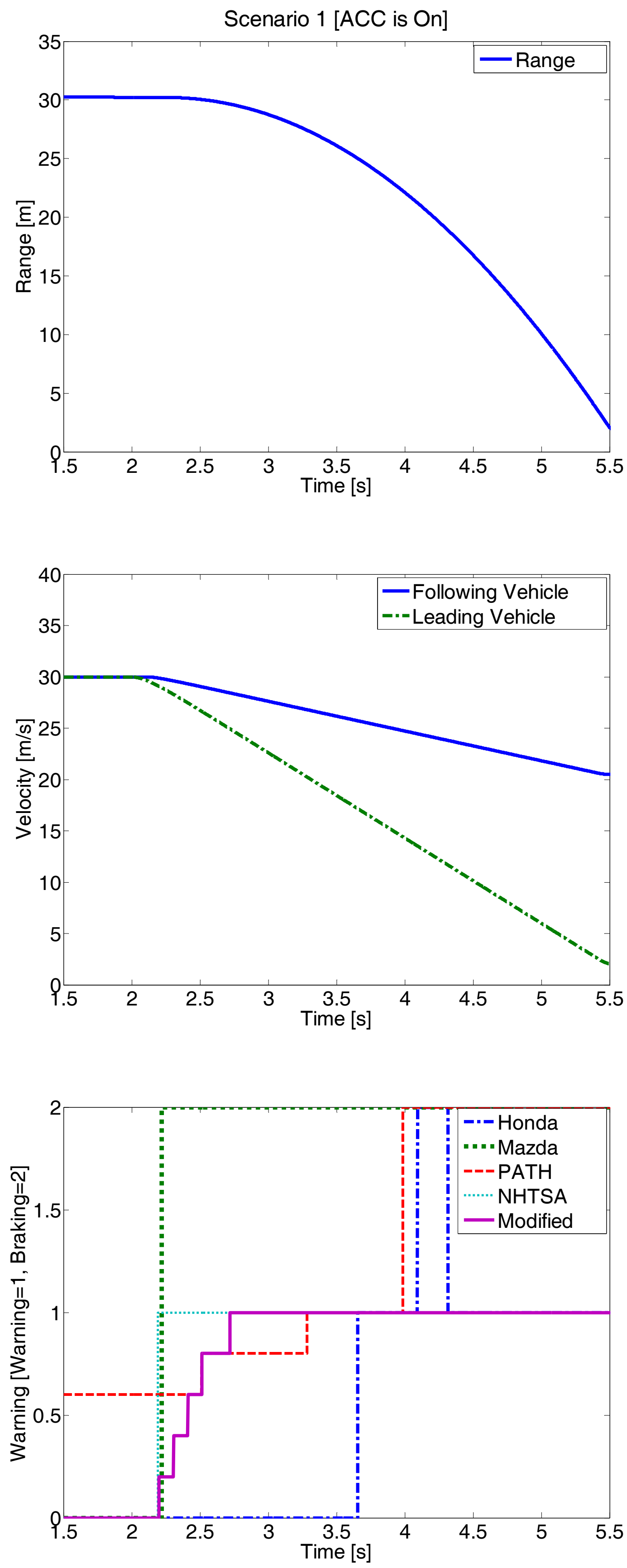

Figure 2.10 : Simulation Results for ACC on Scenario 1

Table 2.1 : Simulation Results for ACC on Scenario 1

Simulation Results for ACC on Scenario 1

Algorithms	Warning Time [s]	Warning Range [m]	Final Range [m]	Velocity at Collision [m/s]
Mazda	2.219	29.96	10.872	-
Honda	3.657	25.01	-11.6389	18.552
PATH	2.512	29.92	6.2266	-
NHTSA	2.191	29.98	11.1527	-
Modified	2.718	29.65	2.7662	-

Simulation Results for ACC on Scenario 2

Algorithms	Warning Time [s]	Warning Range [m]	Final Range [m]	Velocity at Collision [m/s]
Mazda	2.331	66.27	24.0823	-
Honda	3.203	48.07	13.6323	-
PATH	2.998	52.15	16.0141	-
NHTSA	3.175	48.62	14.0055	-
Modified	3.919	34.77	6.1014	-

Table 2.2 : Simulation Results for ACC on Scenario 2

In the third scenario, ACC identifies the target vehicle with a velocity of 20 m/s where the host vehicle's velocity is 30 m/s. Then, the system applies brake to decrease the vehicle's velocity to 20 m/s. However, the target vehicle applies its brake while the host vehicle is trying to decrease its velocity. Initial distance between the two vehicles is 120 m (approximate radar range). Simulation results are shown in Figure 2.12 and Table 2.3.

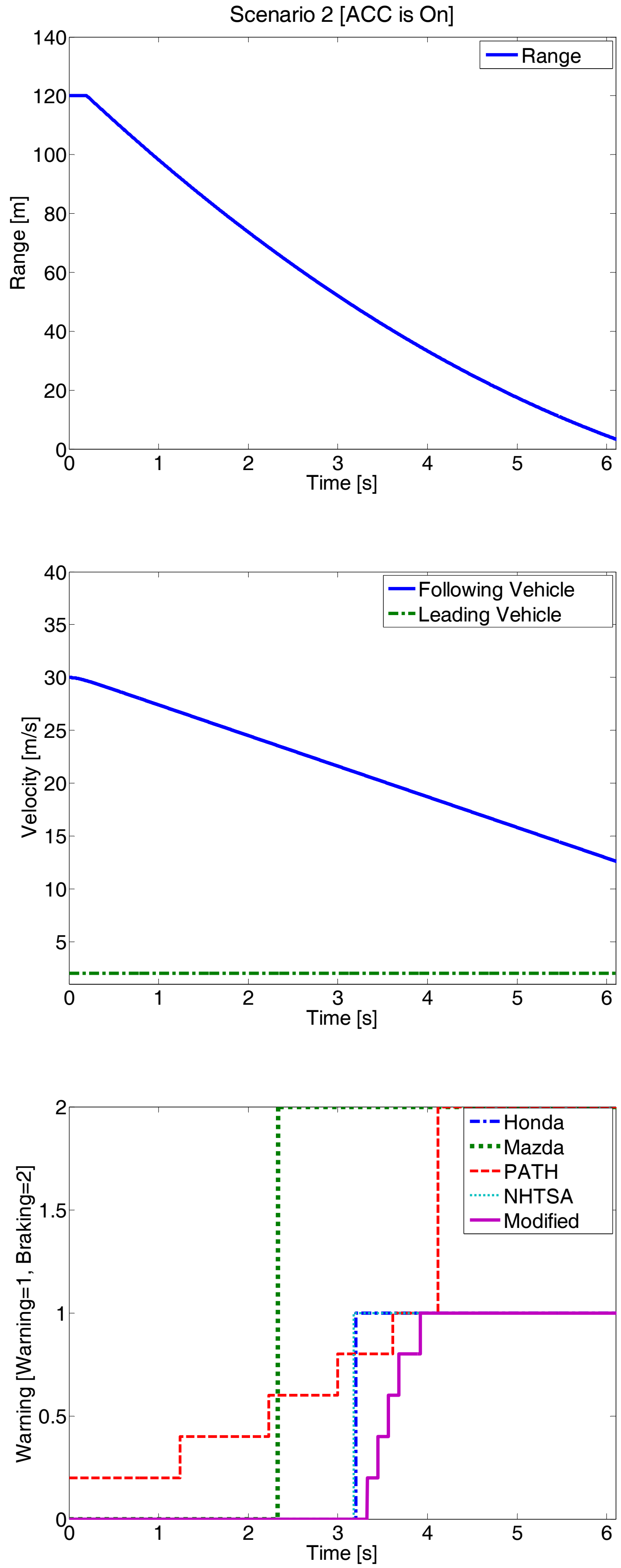

Figure 2.11 : Simulation Results for ACC on Scenario 2

In this scenario, ACC is capable of avoiding possible collision. Hence, there is no need for warning. Actually giving a warning in this case distracts the driver and may cause unnecessary driver maneuvers which may result in a collision. However, velocity information based algorithms other than the proposed algorithm give wrong warnings.

Table 2.3 : Simulation Results for ACC on Scenario 3

Simulation Results for ACC on Scenario 3

Algorithms	Warning Time [s]	Warning Range [m]	Final Range [m]	Velocity at Collision [m/s]
Mazda	22.646	-	-	-
Honda	13.917	-	-	-
PATH	14.198	-	-	-
NHTSA	No Warning	-	-	-
Modified	No Warning	-	-	-

2.4.2.2 ACC off Scenarios

In this scenario, the host and target vehicles both have a velocity of 30 m/s and the target vehicle applies emergency braking.

Table 2.4 : Simulation Results for ACC off Scenario 1

Simulation Results for ACC off Scenario 1

Algorithms	Warning Time [s]	Warning Range [m]	Final Range [m]	Velocity at Collision [m/s]
Mazda	2.958	48.19	2.8548	-
Honda	4.034	37.62	-30.244	23.296
PATH	3.311	45.77	-8.0494	14.5464
NHTSA	2.217	49.97	22.8576	-
Modified	3.085	47.44	-1.0884	4.6272

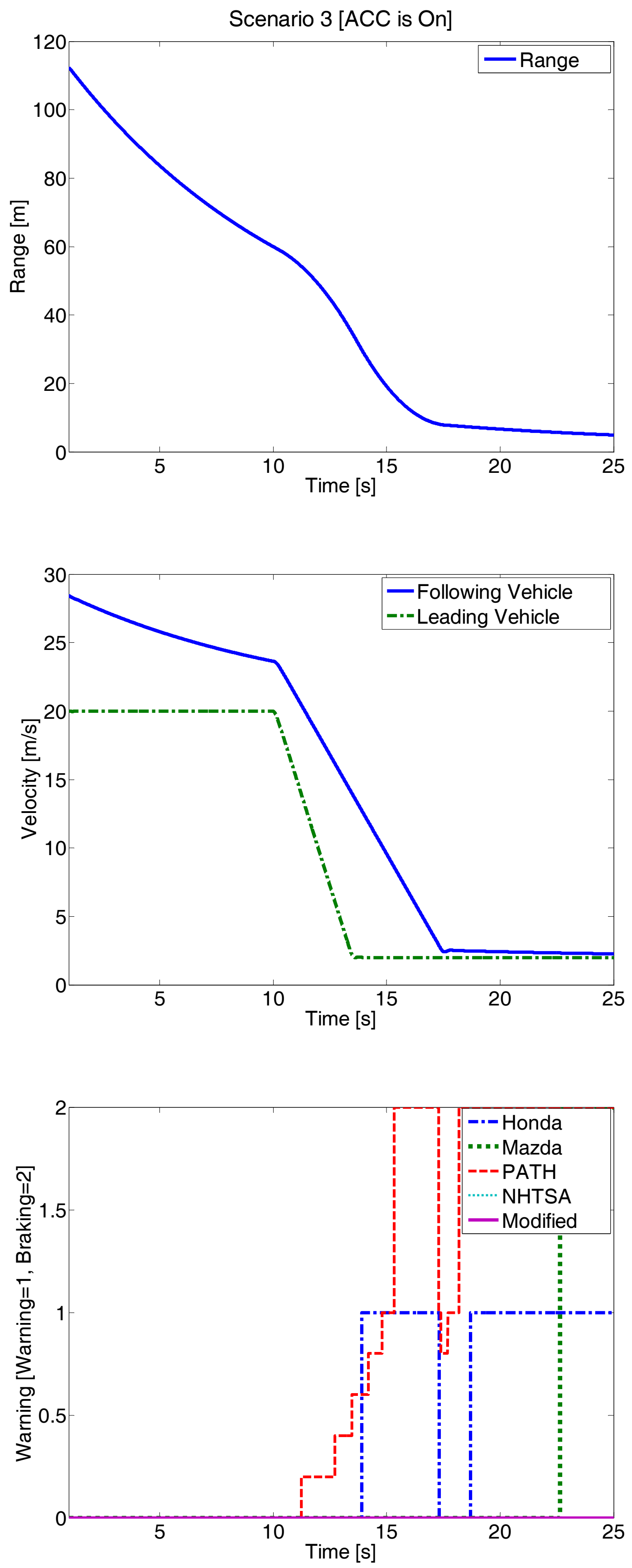

Figure 2.12 : Simulation Results for ACC on Scenario 3

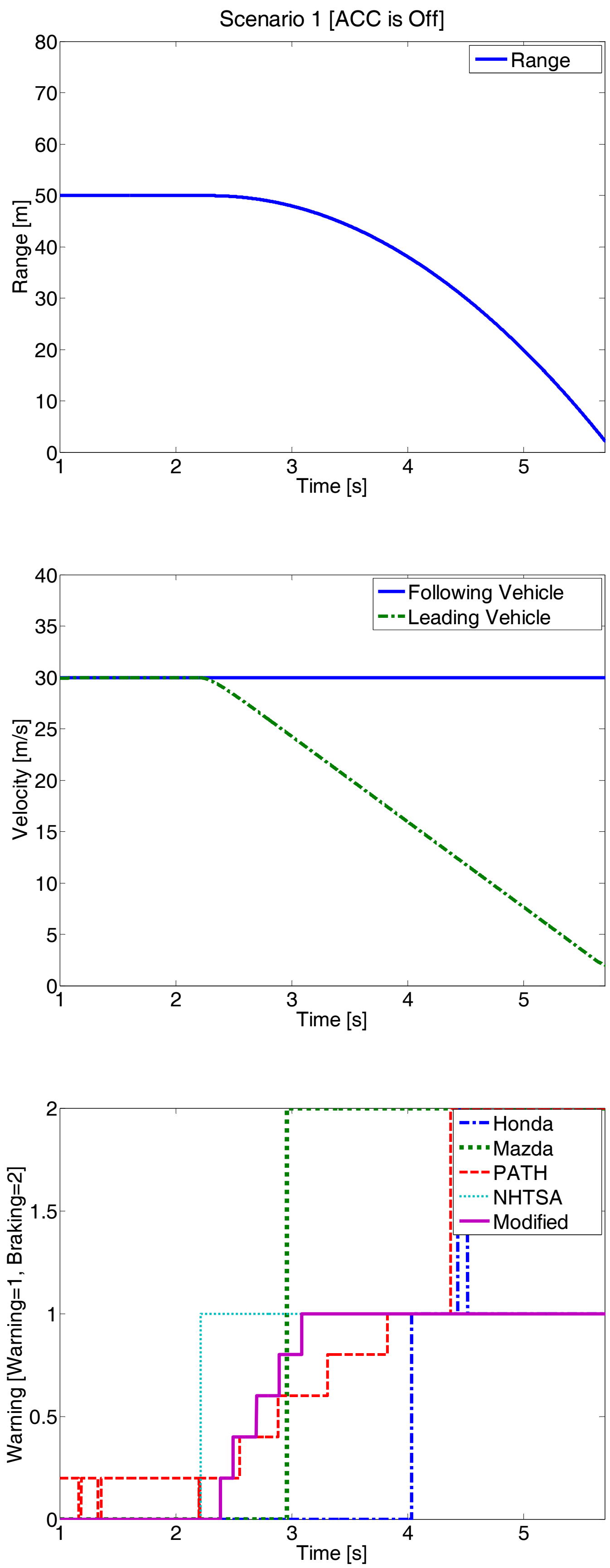

Figure 2.13 : Simulation Results for ACC off Scenario 1

Initial distance between the two vehicles is 50 m. Simulation results are shown in Figure 2.13 and Table 2.4.

Since the final velocities of the vehicles are taken as 2 m/s, Modified algorithm's warning can not avoid the collision in this scenario. However, final velocity of the following vehicle shows that final energy of the vehicle decreases acceptable levels. It is also possible to tune the TAP value for audio warning.

Simulation results show that Modified New algorithm and the ideal NHTSA algorithm follow each other with approximately 0.6 s time delays which result from the assumed total delay. NHTSA uses a total time delay of 1.5 s while the modified algorithm uses 0.9 s. However, it is not easy to obtain the same results with the NHTSA algorithm for these scenarios because of problem with numerical derivatives of relative velocity. On the other hand, since the modified algorithm does not require relative acceleration, such problems do not occur.

3. COLLISION AVOIDANCE SYSTEM

Although a CW System is an efficient way of avoiding possible accidents, these systems become useless when the driver gives no response to the warnings. Collision Avoidance (CA) System takes action and applies emergency maneuver in these kinds of situations [26].

Collision Avoidance is a highly difficult task regarding both complex traffic conditions and a human driver who controls the vehicle and has variety of characteristic behaviors. First idea which comes to one's mind is applying brake when it is detected that there is a collision risk. However, this idea is immature since it does not consider the behaviors of the driver and legal issues. First of all, it is illegal to take control of the vehicle when there is still time for human driver to make a maneuver. This means that system has to check the driver for possible maneuver attempts to avoid collision risk and it has to give the control to driver when he/she starts to make maneuver. On the other hand, human driver may get panic when the system starts to make maneuver, and he/she may try to apply his/her own decision. Decisions have been made under these circumstances generally are unreasonable and may result in more severe collisions.

There is only one solution which avoids previously mentioned possible results which is taking control of the vehicle when driver has nothing to do. Although it seems that this idea can solve the problem, it is highly difficult to achieve successful applications relying on this principle. Firstly, available time is consisting of sum of the delays of the driver and the system and it is very short compare to maneuver which has to be applied. Emergency braking maneuver applied through in this time interval is not enough to avoid collision. Emergency steering maneuver is the zero option. However, to be able to apply steering maneuver, complex traffic condition has to be analyzed first to be able to detect if there is any possible steering maneuver which can avoid collision as well as will not cause any other collision among the maneuver time. It should be also very sharp maneuver considering the available maneuver time. Controlling the vehicle dynamics might be very hard task in these sharp maneuvers.

This part of the thesis aims at designing a Collision Avoidance Algorithm which can solve all of the above mentioned problems and avoid all of the possible collisions. Following subsection of this part is devoted to the Literature Overview of CA systems. Elastic Band Theory which is the core method used in the algorithm is described in Elastic Band Theory subsection. Implementation issues of Elastic Band Theory for vehicle based applications are listed in Implementation Issues subsection. Algorithm is developed in Algorithm subsection. Carsim which is used as simulation environment is presented in Simulation Environment subsection. Simulation subsection gives information about the simulations and their results.

3.1 Literature Overview

The first exported obstacle avoidance method from robotics to vehicle based applications is *Artificial Potential Field* Method which was proposed by Khatib [27]. This method appoints an artificial potential field to all the obstacles in the environment. Goal point which is the point where the robot wants to reach applies negative force to the robot where the obstacles in the environment apply positive forces that point the robot to the goal point. Reichardt et. al. ([28]), Schiller et al. ([29]) and Gerdes et al. ([30]) used potential field method in vehicle based applications. Although this method gives adequate results, final configuration of the vehicle with applied potential forces is unpredictable which may lead to hazardous situations. Another drawback of this method is kinematical constraints. Since the dynamics of the vehicle has constraints, it is not possible to point vehicle to any desired direction.

Elastic Band method uses physical analogy similar to the potential field method to deform the predefined global path which is called *Elastic Band* ([31]). Since the elastic band method does not only use the physical analogy resulting from the potential field but also the command information from the deformed path, it is called a hybrid method. In this way, it is possible to obtain collision free path using Potential Field Method like physical analogy as well as movement guarantee in deseried direction with achieved specific path. Elastic Band Method was applied to the vehicle based applications by Hilgert et al. ([32]). However, that application did not consider implementation issue for vehicle based applications. Moreover, since this paper only considers the automated vehicle, it may be defined as a lane change assistance system for automated vehicles.

3.2 Elastic Band Theory

Elastic Band is a kind of obstacle avoidance method used in robotics which was first proposed by Quinlan and Khatib ([31]). A deformable predefined path is modified by internal and external forces acting on the band. Internal forces are like spring forces which hold the band together while external forces are like artificial potential forces which keep the band away from obstacles. Figure 3.1 presents the schematic representation of the elastic band with internal and external forces acting on the band.

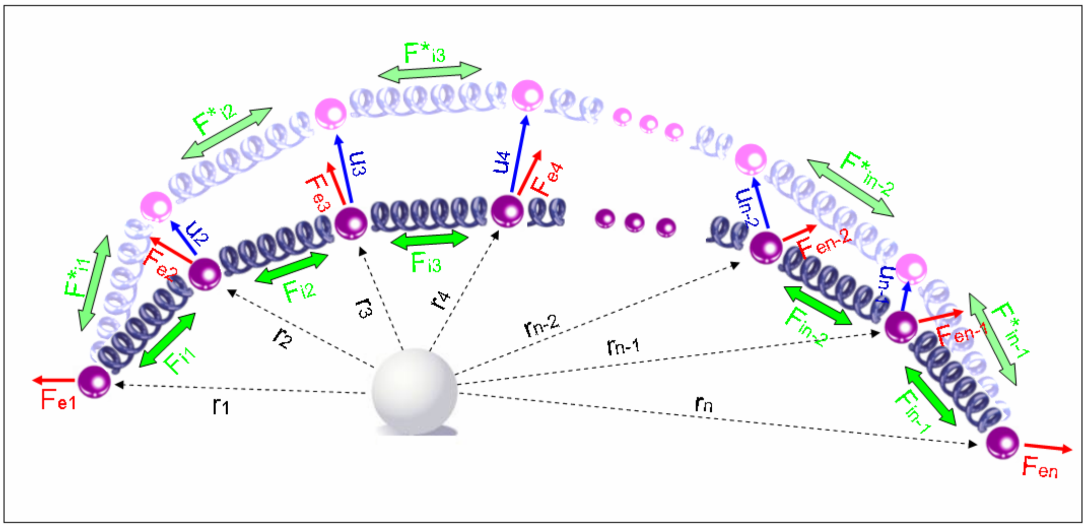

Figure 3.1 : Schematic Representation of the Elastic Band

If we ignore the dynamics of the system, variation of the internal forces can be modeled as follows

$$\vec{F}^{*}_{ii} - \vec{F}_{ii} = k_s(\vec{u}_{i+1} - \vec{u}_i) \quad \textbf{(3.1)}$$

where F^*_{ii} and F_{ii} are final and initial internal forces in the i^{th} spring part, u_i is a displacement of the i^{th} knot and k_s is a spring constant. The force balance equation for each knot can be defined as

$$\vec{F}_{ei} = -[k_s(\vec{u}_{i+1} - \vec{u}_i) + k_s(\vec{u}_{i-1} - \vec{u}_i)] \quad \textbf{(3.2)}$$

where F_{ei} is an external force acting on the i_{th} knot. If we divide the terms into their components we obtain the simplest elastic band model as follows

$$F_{ex,ey} = k_s K u_{x,y} \tag{3.3}$$

where

$$K = \begin{bmatrix} -1 & 2 & -1 & 0 & 0 & \dots & 0 \\ 0 & -1 & 2 & -1 & 0 & \cdots & 0 \\ \vdots & & \ddots & \ddots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & & -1 & 2 & -1 \end{bmatrix}, \; u_{x,y} = \begin{bmatrix} u_{x1,y1} \\ u_{x2,y2} \\ \vdots \\ u_{xn,yn} \end{bmatrix}, \; F_{ex,ey} = \begin{bmatrix} F_{ex1,ey1} \\ F_{ex2,ey2} \\ \vdots \\ F_{exn,eyn} \end{bmatrix}$$

Since the band has to be held on the predefined global path, the first and the last knot are static and the model is transformed to

$$k_s \begin{bmatrix} 2 & -1 & 0 & & \dots & 0 \\ -1 & 2 & -1 & & \cdots & 0 \\ & \ddots & \ddots & \ddots & & \\ 0 & \cdots & & & -1 & 2 \end{bmatrix} \begin{bmatrix} u_{x2,y2} \\ u_{x3,y3} \\ \vdots \\ u_{xn-1,yn-1} \end{bmatrix} = \begin{bmatrix} F_{ex2,ey2} \\ F_{ex3,ey3} \\ \vdots \\ F_{exn-1,eyn-1} \end{bmatrix} \tag{3.4}$$

where

$$u_{x1,y1} = [0,0] \quad and \quad u_{xn,yn} = [0,0]$$

External forces acting on the band can be written as

$$F_e = \begin{cases} -k_e(\|r_i\| - r_0)\dfrac{r_i}{\|r_i\|} & ; \quad (\|r_i\| - r_0) \le 0 \\ 0 & ; \quad (\|r_i\| - r_0) > 0 \end{cases} \tag{3.5}$$

where r_i is the position vector between the obstacle and the i^{th} knot, r_0 is the threshold distance and k_e is the external force constant.

This simple model neglects the dynamics of the band. However, since the band takes its final form in second or third iteration, this assumption gives adequate results which are very close to exact band model. Moreover, since the band model is transformed into a matrix inverse operation and both stiffness matrix and the external force vector are sparse (Several knot points satisfy threshold distance), this model is not a time consuming model which requires heavy computations.

3.3 Implementation Issues

Elastic Band Theory introduced in previous section has very successful applications in mobile robot platforms. However, the method has to be modified for vehicle based applications that are realized in highly dynamic environments with different road conditions. Following subsections present these modifications.

3.3.1 Modifying Repulsive Force

Repulsive force formulation described in (3.5) does not give uniform results in the vicinity of the obstacle. Formulation is modified for close distance to the obstacle. Figure 3.2 gives the comparison of two formulations.

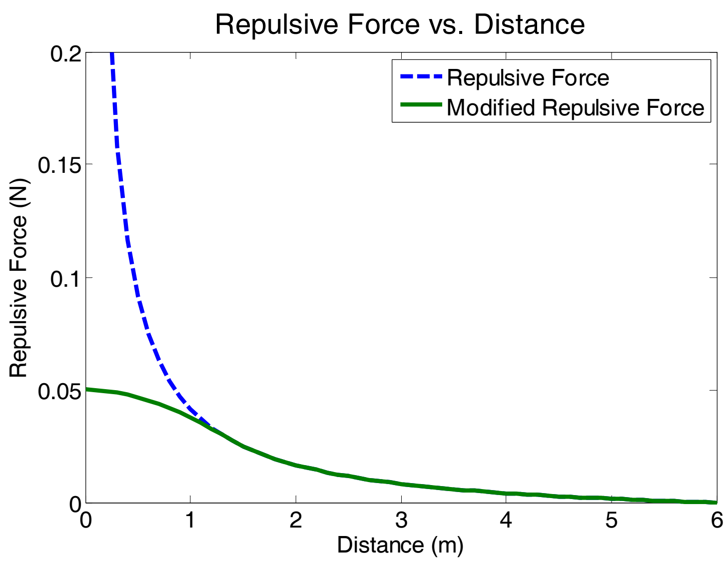

Figure 3.2 : Variation of Repulsive Force with Distance

Second issue about the repulsive force is continuity and smoothness. Since the host vehicle and the other road users move with high velocities, elastic band has to be moved and modified. To be able to obtain continuous path and smooth trajectories, the band has to show harmonic characteristics. Figure 3.3 shows one of the unintended behaviors of the band. When the obstacle approaches the band too much, repulsive forces acting on the band show non-uniform distribution. Method is modified for this kind of situations. If the obstacle is too close to the band, algorithm searches for the parts that have similar kind of properties. Parts that have similar characteristics are grouped together. Forces acting on the groups are modified according to the characteristics of the group.

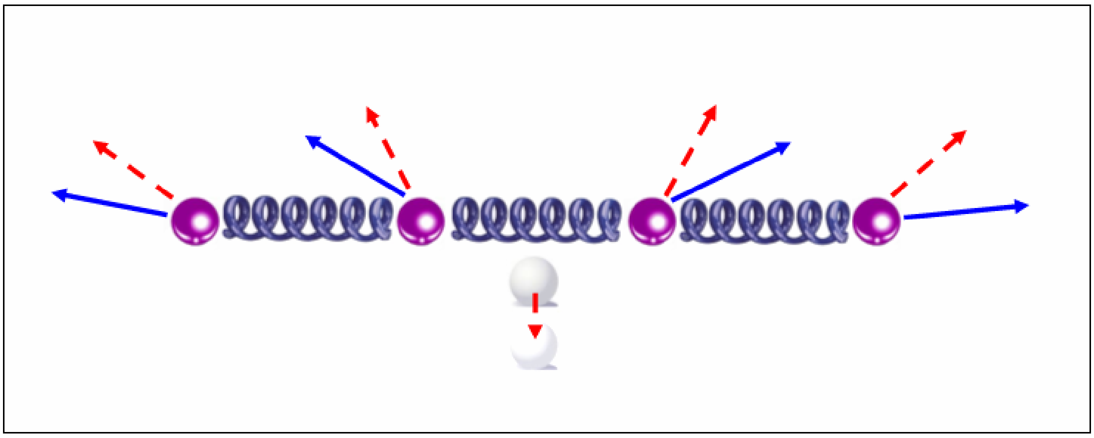

Figure 3.3 **:** Non-Uniform Repulsive Force Distribution in the Vicinity of Band

3.3.2 Modifying Predefined Path

In vehicle based applications, predefined global path is the road data for the middle of the lane. However, since vehicles do not follow the lane exactly, elastic band can be modified for the wrong direction that may drag the host vehicle to the outside of the road. To solve this problem, the algorithm defines two alternative paths for right and left lane directions. Connections to the alternative paths are made with cycloids

$$y = \frac{a}{1 + e^{-b(x-c)}} \tag{3.6}$$

where a describes the desired lateral offset and c describes the longitudinal point where the lateral offset takes half of its final value. b is used to change the slope. Figure 3.4 shows the right alternative path that the algorithm creates

3.3.3 Corrupting Elastic Band

Collision Avoidance Algorithm needs error detection subsystems that control possible errors with road limits and other road users. Following subsections describe these subsystems.

3.3.3.1 Path Error Detection

The bubble concept in robotics is relatively much more time consuming for vehicle based applications than for mobile robot platforms. It is also much simpler to track defined trajectory for mobile robots than for vehicles. Hence, the bubble which is defined for vehicle based applications should be larger than the bubble defined in robotics. Instead of defining bubbles around the vehicle, the algorithm uses distances to the obstacles to determine any path error. Distance threshold for the path error

$$d_{pt} = d_{mo} + d_{mv} + 0.5 \tag{3.7}$$

where d_{pt} is the threshold distance, d_{mo} is the maximum detected width of the obstacle, d_{mv} is the maximum width of the host vehicle. Figure 3.5 shows an example situation for the path error.

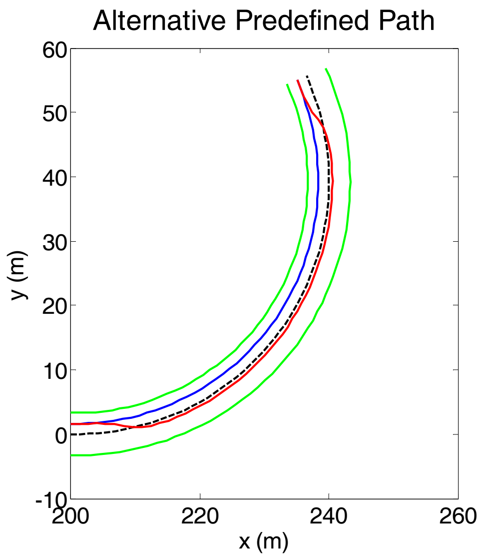

Figure 3.4 : Alternative Predefined Path

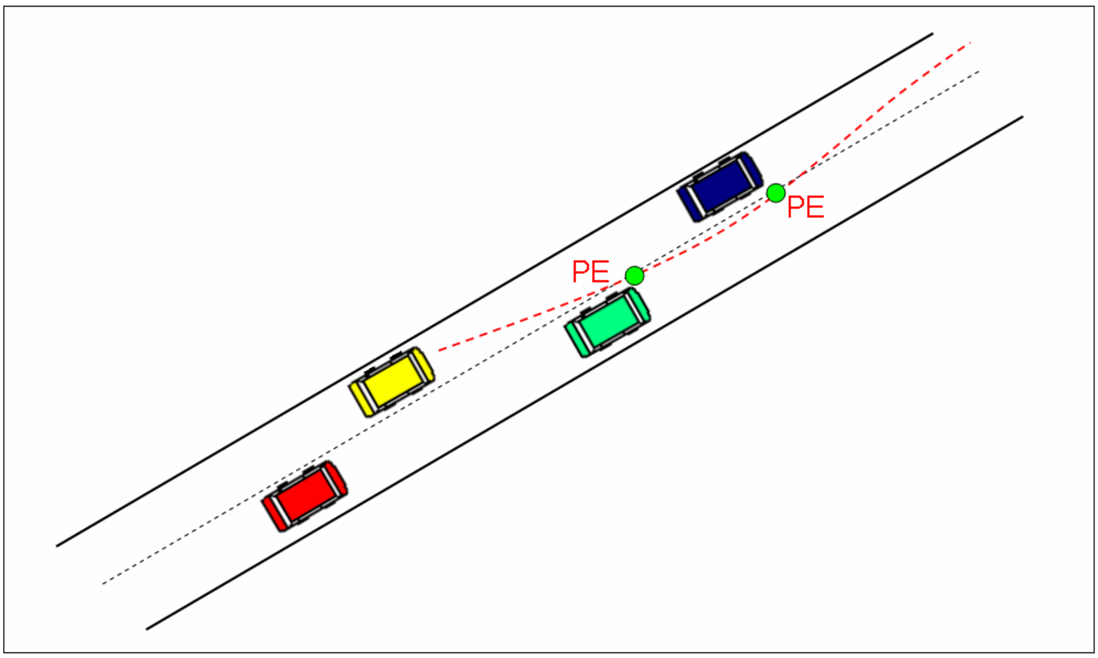

Figure 3.5 : Example Situation for Path Error

3.3.3.2 Road Error Detection

Algorithm also has to detect any road error of the band. For this purpose, road data is divided into parts. These parts are grouped together and parts satisfy predefined threshold linked together linearly. Global points that represent the knot positions are compared with these linked parts. Elastic Band is corrupted at the point where the knot and road limit intersect. Figure 3.6 shows an example situation for the road error

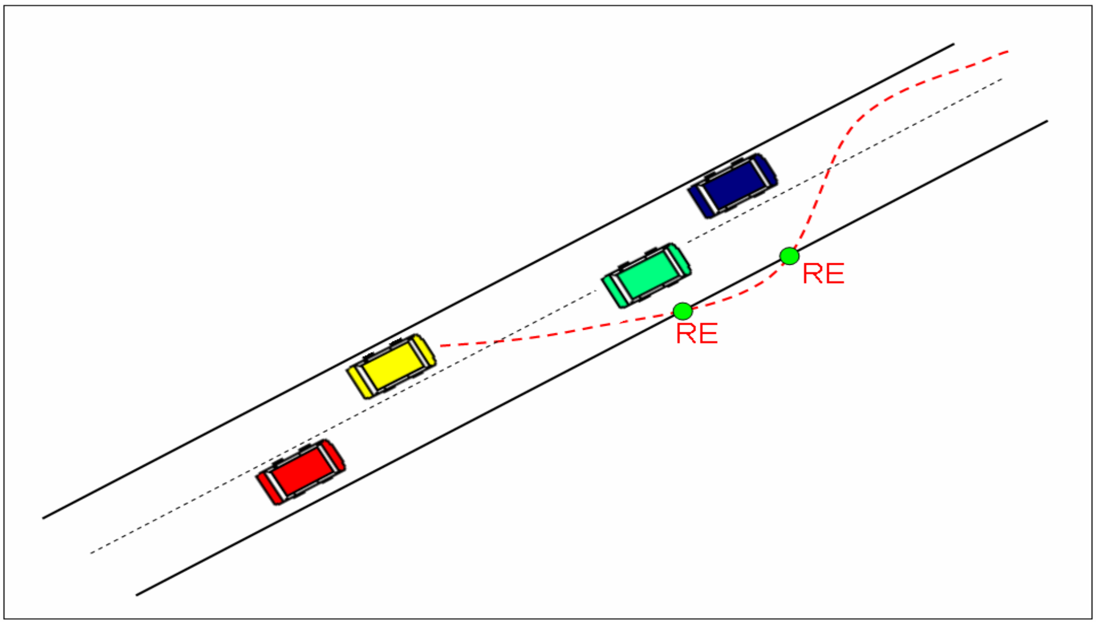

Figure 3.6 : Example Situation for Road Error

3.3.3.3 Route Error Detection

Algorithm needs an extra error detection subsystem for intersection points and lane change maneuvers. Lateral movements in an application area constitute important problems if the velocity of the object is high. Modifying repulsive forces might solve the problem. Objects having lateral movements might apply repulsive forces proportional to their velocities. However this solution destroys the uniformity of the band. Another solution is an error detection subsystem. Time to collision is calculated for the obstacles that cut the band and compared with the arrival time of the host vehicle to the cutting point. If the time difference is less than the predefined threshold value than route error detection subsystem gives an error for that point. Figure 3.7 shows an illustrative figure for that subsystem.

Threshold value for the time difference can be calculated with the following formulation

$$d_{vt} = \frac{v_v}{\sqrt{2}} \quad (3.8)$$

where d_{vt} is the threshold value for the time difference, v_v is the velocity of the host vehicle.

Route error detection subsystem works both in the algorithm and in the collision detection system. This subsystem detects error with predefined path and the obstacles in the collision detection system while it detects error with modified path and the obstacles in the algorithm. This system detects error in lane change maneuvers of the obstacles as well as detecting error with intersection points.

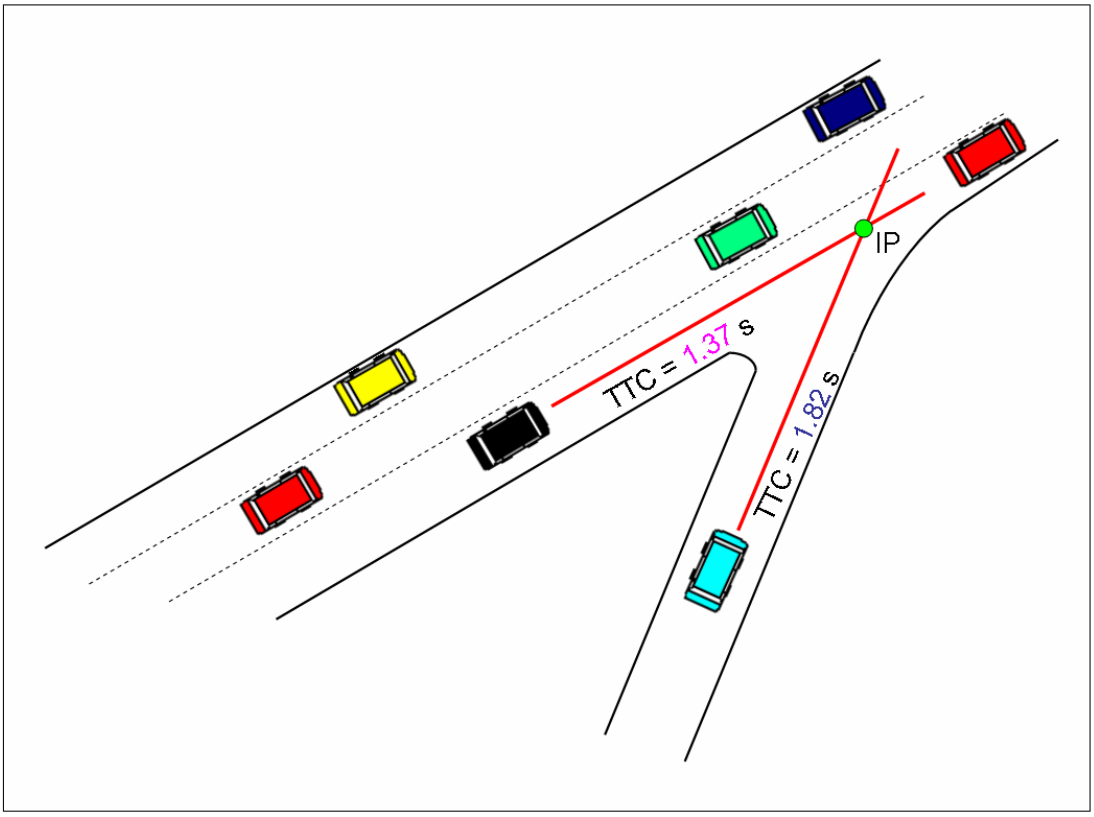

Figure 3.7 : Example Situation for Route Error

3.4 Developed Collision Avoidance Algorithm

Collision Avoidance (CA) Algorithm is composed of main algorithm, error detection subsystem and the decision algorithm. Algorithm uses laser, digital map and driver as an input source. Laser data gives obstacle data where digital map satisfies the predefined path. Algorithm uses driver data in decision part. Collision Detection

(CD) Algorithm which is introduced in ([2]) is a kind of kinematical analysis based algorithm that provides Time to Collision (TTC) information.

Algorithm is initialized with the collision risk data which comes from CD Algorithm. CD Algorithm calculates TTC with the preceding vehicle via kinematical analysis based algorithm and with the intersection object via route error detection subsystem. If TTC is lower than the total delay time which means there is nothing to do even if driver becomes aware of the crash possibility, CA Algorithm is initialized.

Algorithm first defines the alternative right and left paths. Firstly, left alternative path is sent to the deformation process. If the deformation process gives error with this path, algorithm passes through the right alternative path. If this path also is not an adequate path, algorithm gives an error at a point which is the minimum value of the errors for left and right path given by error detection subsystems.

Deformation process is composed of modification of the elastic band with the repulsive and external forces resulting from objects around the vehicle and the spring forces. Deformed path is sent to the error detection subsystems. These systems which are defined in previous sections detect path, road and route errors and send the minimum value of knot number which gives error.

Decision Algorithm is the last part of the algorithm. Algorithm first searches for an alternative modified path without any error. If algorithm finds a path, it assigns this path as a maneuver path and puts a trajectory on this path. If driver gives no response, final velocity is defined as zero. If algorithm can not find any modified path without error, it searches for the path with maximum of the minimum of knot points which gives error. If obtained value is higher than the predefined threshold, algorithm selects this path and assigns the trajectory to be followed as this path whose velocity values at the error knots is zero. In this way, it is possible to search for an alternative path at the next time step. Threshold value is

$$d_{at} = \frac{v_v}{\sqrt{2}/2} \tag{3.9}$$

where d_{at} is the threshold value for the decision algorithm, v_v is the velocity of the host vehicle.

Since it is not possible to avoid collision with the emergency braking because of the inadequate time, emergency braking is the last choice for the algorithm. If decision algorithm can not find a path without error or a path which gives error before the predefined threshold, algorithm decides on emergency braking. Figure 3.8 shows the flowchart of the algorithm.

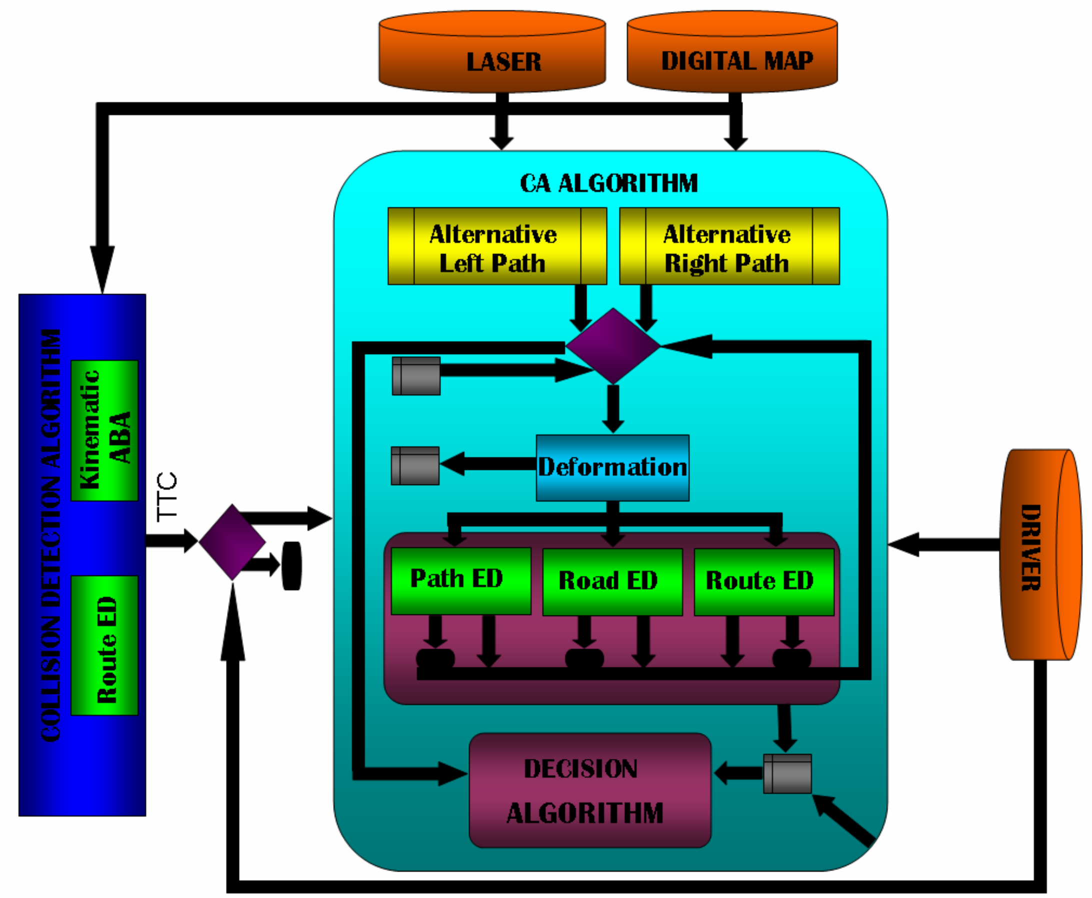

Figure 3.8 : Schematic Representation of the Developed Algorithm

3.5 Simulation Environment

Since proposed algorithm is designed for solving problems mentioned in the introduction of this part, it should be tested in a realistic environment which may result in these problems. First of all, simulation environment has to have highly complex traffic which can test the ability of algorithm to adapt difficult scenarios. Secondly, it might also be very difficult to realize given maneuver data from CA Algorithm which avoids the collision since real vehicles have highly nonlinear dynamics that is very hard to control. It means that used vehicle model in simulation environment has to have dynamics which is very close to that of real vehicles.

Carsim program can provide all of the desired characteristics described above. Carsim uses highly nonlinear mathematical vehicle model which can be modified with changing parameters given in graphical user interface.

It is possible to use different vehicle models in your simulation. It is allowed to change graphical view of the vehicle as well as dynamics of it. Carsim uses complex transmission and suspension models which can also be changed with the given choices and parameters in user interface. It uses experimental engine data based look-up table to model engine characteristics in simulation.

Carsim also gives power to user to change road data. In this way it is possible to create your own road by just entering road data to tabular data section in road information section. .Road surface data can be modified according to testing purposes by changing friction data or road elevation data.

Carsim lets user run multiple vehicle models in one simulation. It provides user to create complex traffic. All of the used vehicle models have realistic dynamics and none of them is kinematical. In this way all of the maneuvers in simulation close to real not just that of host vehicle. It is also possible to test designed controller by means of Matlab Simulink connection in Carsim. Figure 3.9 gives the representation of how Carsim works. Figure 3.10 gives the Matlab Simulink connection which is used to test CA Algorithm.

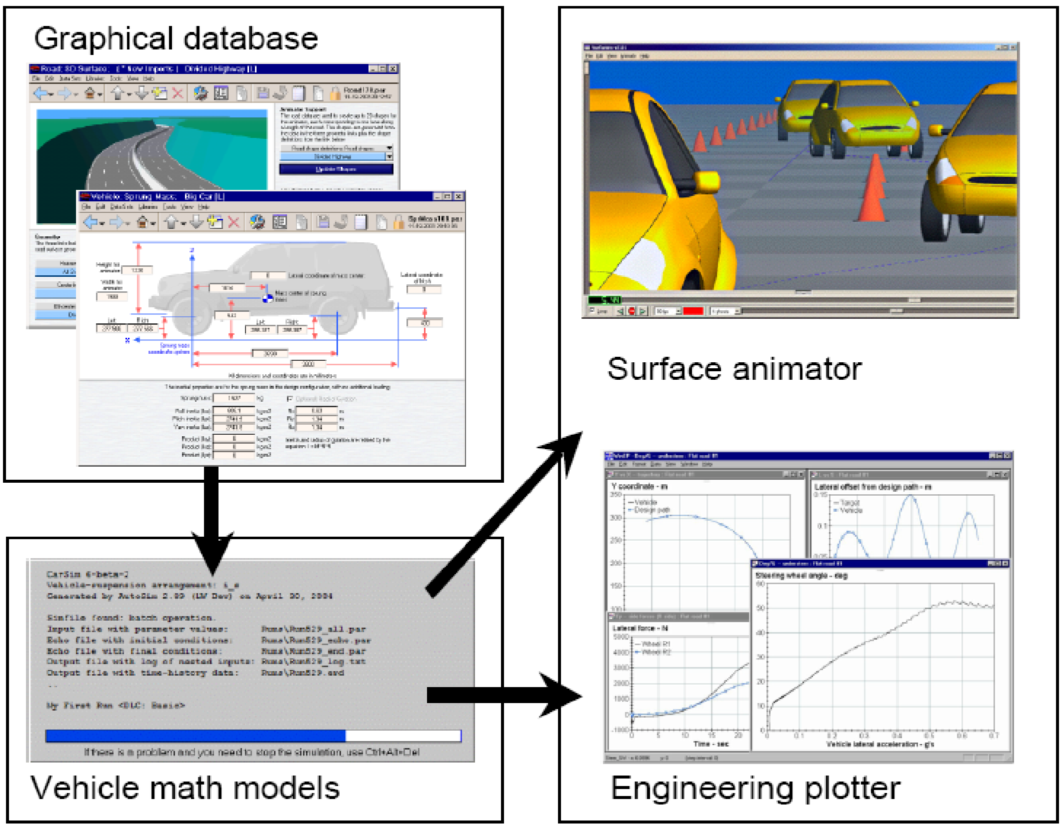

Figure 3.9 : Representation of How Carsim Works (taken from [31])

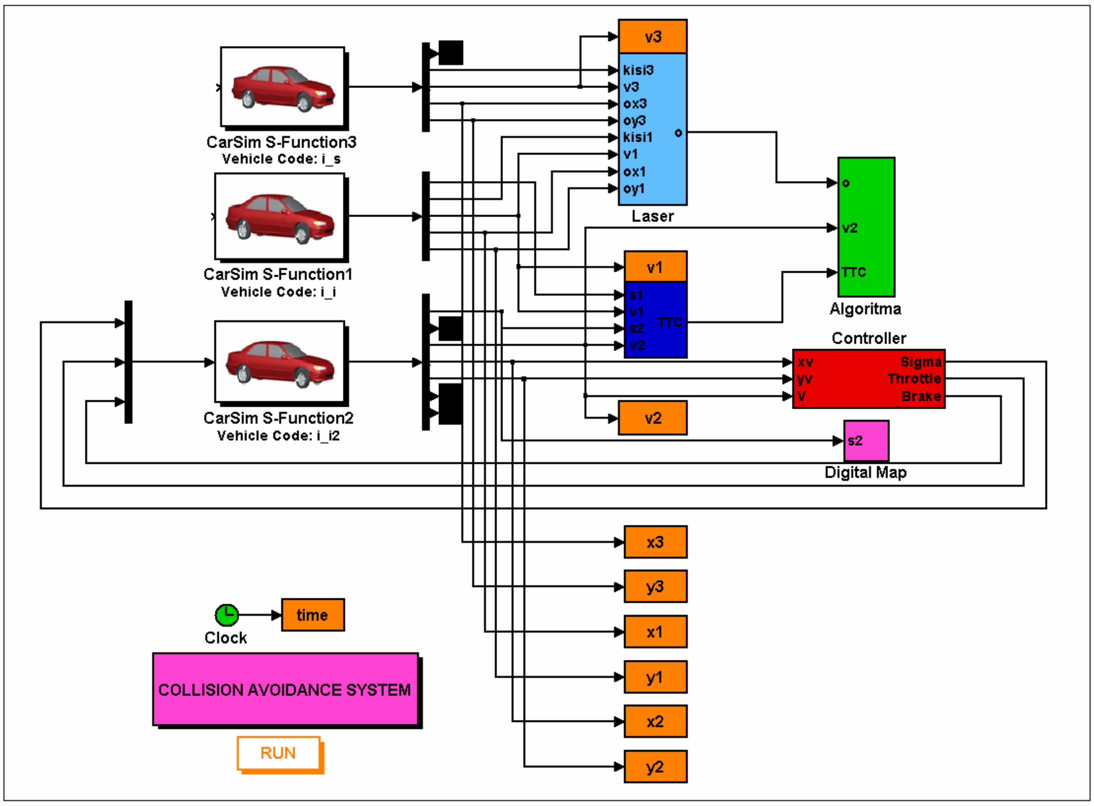

Figure 3.10 : Created Simulink Representation Which Tests Algorithm in Carsim

3.6 Simulation

Conventional controllers are used at the first step for trajectory tracking. Three different configurations with different scenarios are tested with developed algorithm. Following subsections give detailed results of the algorithm for these configurations.

3.6.1 Rear End Collision

In this configuration, host vehicle approaches preceding vehicle too much which will resulted in a rear-end collision. For this configuration, algorithm is tested for different positions of the vehicle driving in the next lane.

In the first simulation, preceding vehicle applies emergency braking at 4 s and the vehicle which is coming from the next lane does not let the host vehicle make an emergency maneuver for first few seconds. Host vehicle applies emergency braking first. When the vehicle coming from opposite direction moves away, host vehicle starts emergency maneuver. Figure 3.11 gives the emergency braking maneuver as a first action. Figure 3.12 shows the stroboscopic view of the emergency steering maneuver which is applied after vehicle coming from opposite site moves away.

Figure 3.13 shows velocity vs. time data for three vehicles and Figure 3.14 presents X vs. Y data for three vehicles.

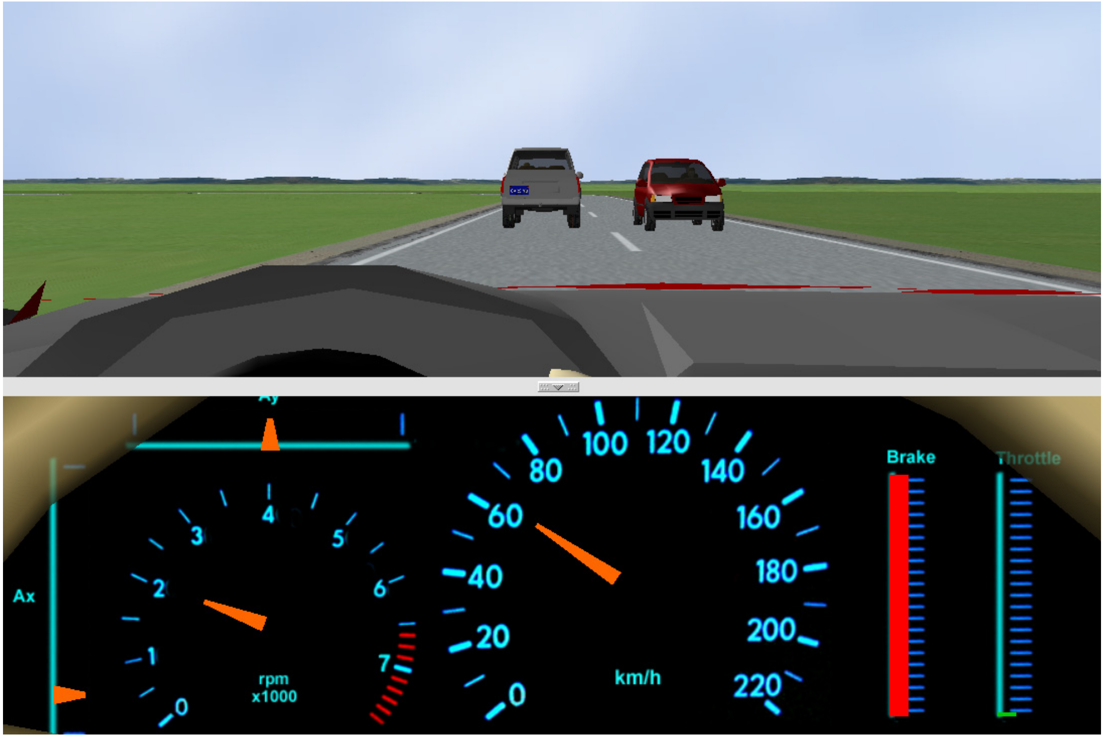

Figure 3.11 : Rear End Scenario 1: Emergency Braking Maneuver: First Action

Figure 3.12 : Rear End Scenario 1: Stroboscopic View: Steering Maneuver

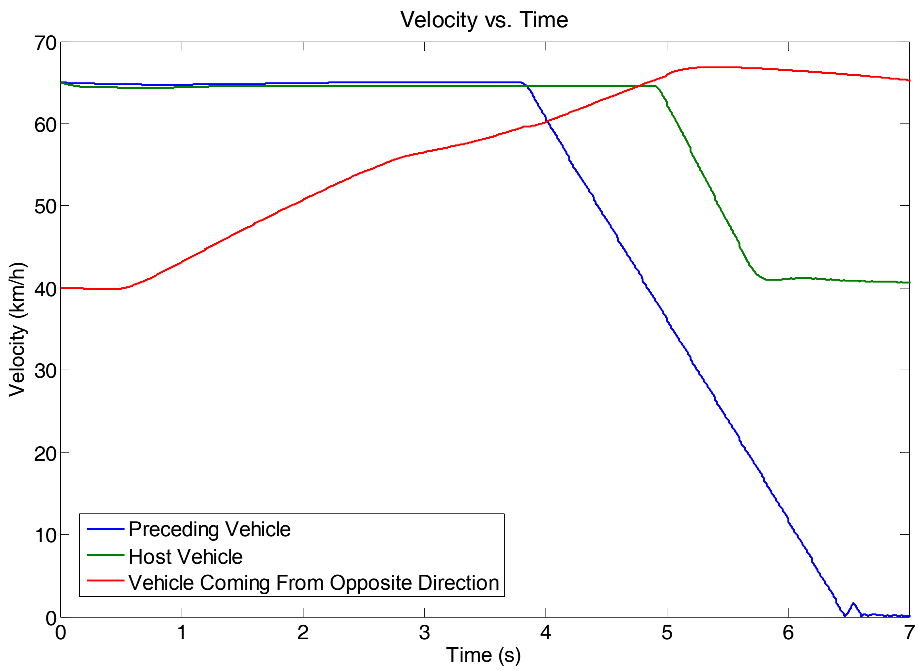

Figure 3.13 : Rear End Scenario 1: Velocity vs. Time Data for Three Vehicles

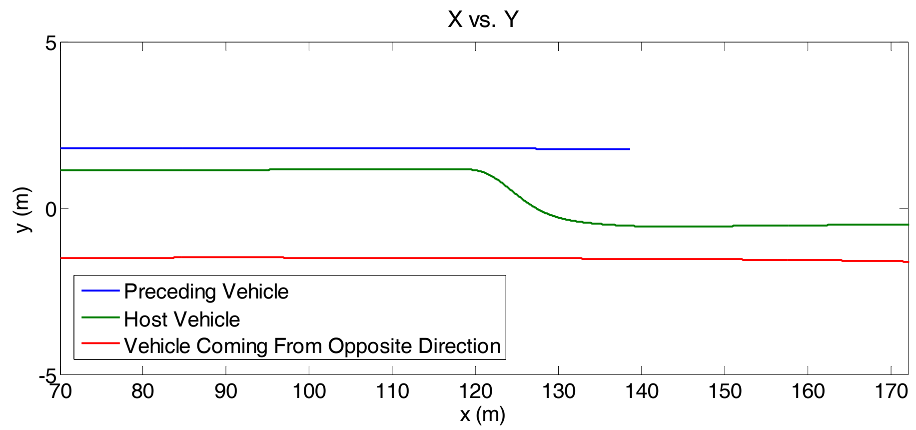

Figure 3.14 : Rear End Scenario 1: X vs. Y Data for Three Vehicles

Second simulation is done for the same configuration except that vehicle coming from opposite site is far away from the host vehicle and lets host vehicle make an emergency maneuver. Figure 3.15 shows the stroboscopic view of the emergency steering maneuver. Figure 3.16 shows velocity vs. time data for three vehicles and Figure 3.17 presents X vs. Y data for three vehicles.

Figure 3.15 : Rear End Scenario 2: Stroboscopic View: Steering Maneuver

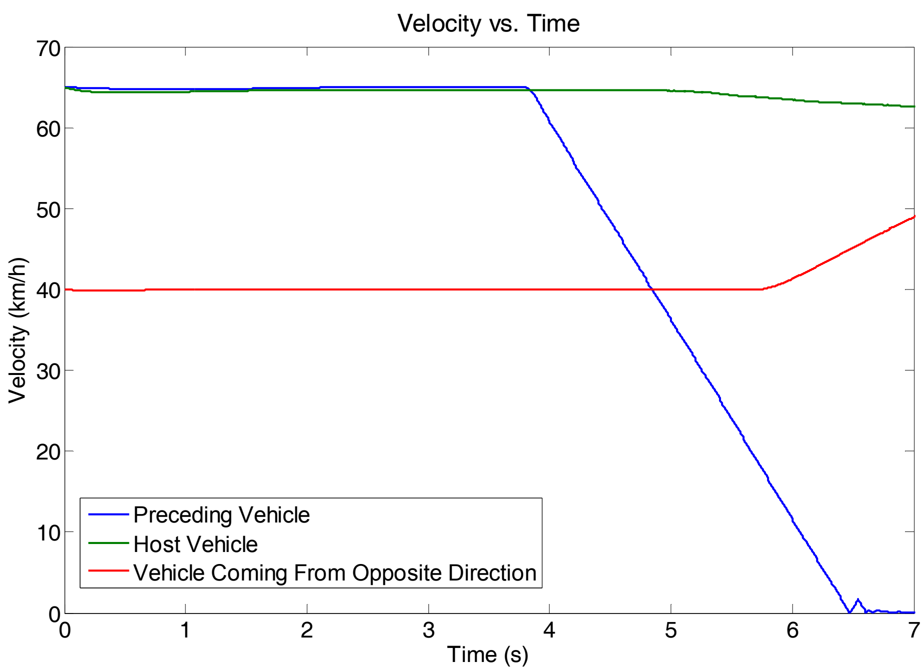

Figure 3.16 : Rear End Scenario 2: Velocity vs. Time Data for Three Vehicles

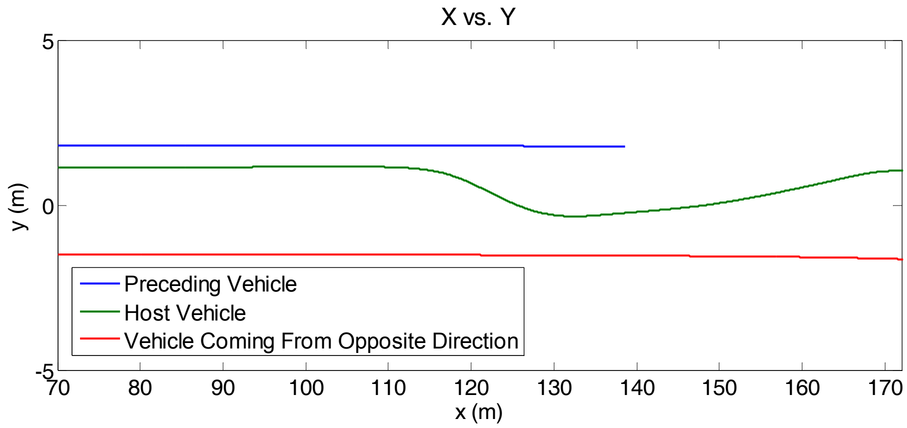

Figure 3.17 : Rear End Scenario 2: X vs. Y Data for Three Vehicles

3.6.2 Lane Change Collision

In this configuration, vehicle driving in the next lane does not recognize the host vehicle and starts to change its lane. Algorithm detects the collision risk and applies emergency braking first. Since emergency braking can not avoid collision alone, algorithm applies emergency maneuver after vehicle changing its lane comes closer to host vehicle's lane. Figure 3.18 gives the emergency braking maneuver as a first action. Figure 3.19 shows velocity vs. time data for three vehicles and Figure 3.20 presents X vs. Y data for three vehicles.

Figure 3.18 : Lane Change: Emergency Braking Maneuver: First Action

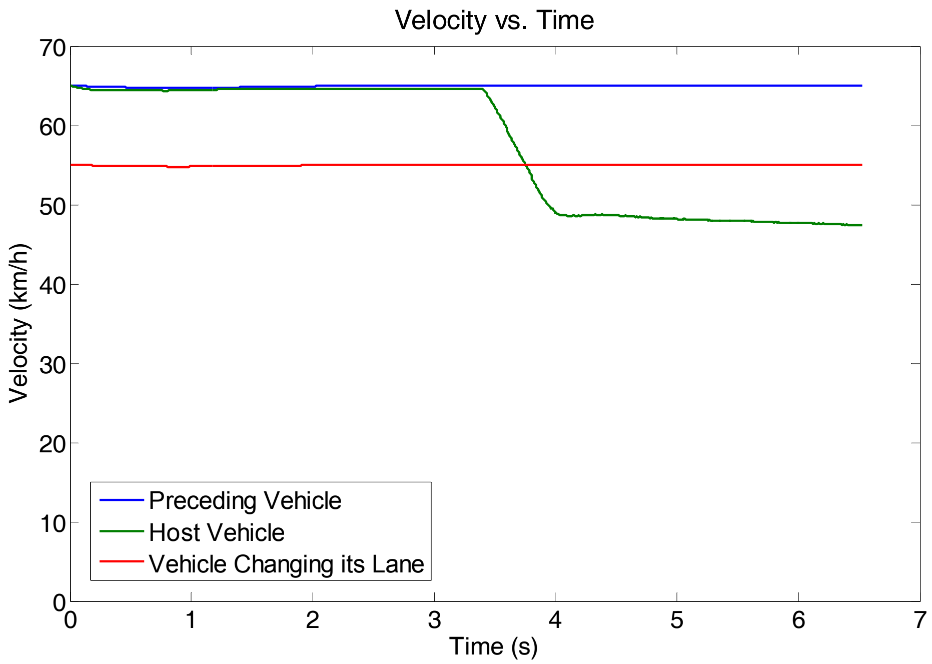

Figure 3.19 : Lane Change: Velocity vs. Time Data for Three Vehicles

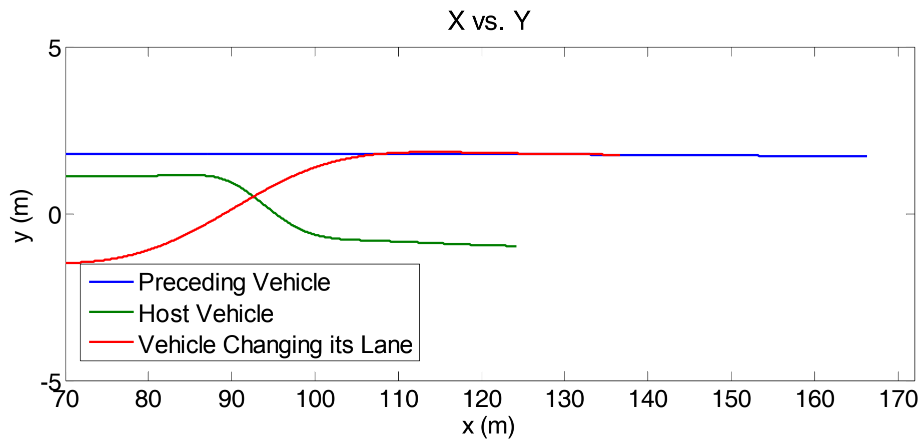

Figure 3.20 : Lane Change: X vs. Y Data for Three Vehicles

3.6.3 Intersection Point Collision

In this configuration, all three vehicles are approaching intersection point. Preceding vehicle stops at stop sign where host vehicle do not notice the sign and causes a possible collision risk. Algorithm detects available maneuver for the host vehicle. However, available maneuver causes a possible collision risk with the third vehicle. Algorithm chooses first applying emergency braking to avoid collision with third vehicle and applying emergency maneuver when it finds collision free emergency maneuver. Figure 3.21 gives the emergency braking maneuver as a first action.

Figure 3.22 shows the stroboscopic view of the emergency steering maneuver which is applied after vehicle coming from opposite site moves away.

Figure 3.21 : Intersection Point: Emergency Braking Maneuver: First Action

Figure 3.22 : Intersection Point: Stroboscopic View: Steering Maneuver

Figure 3.23 shows velocity vs. time data for three vehicles and Figure 3.24 presents X vs. Y data for three vehicles.

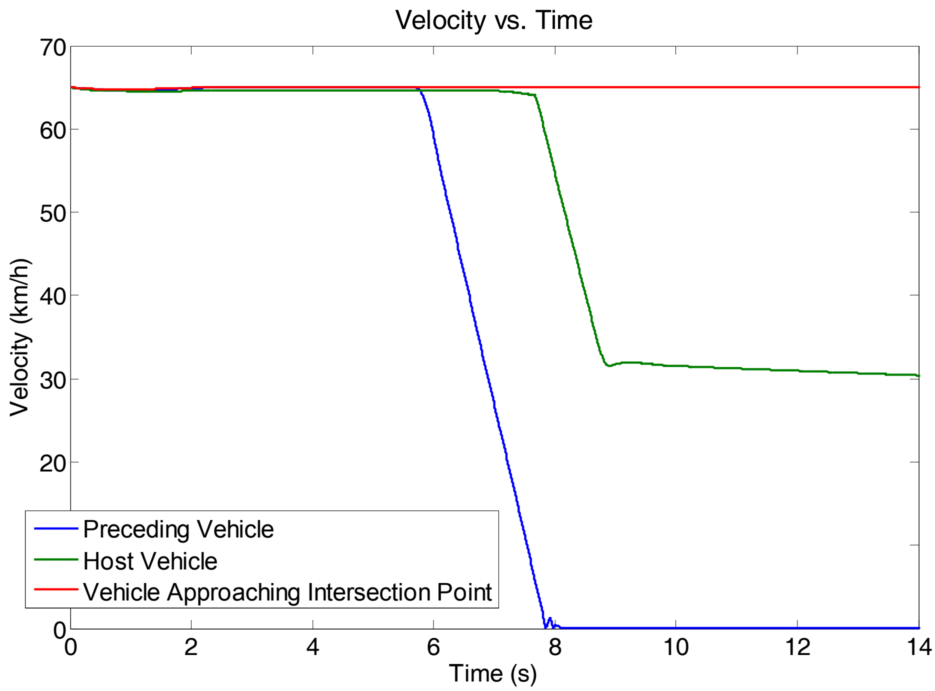

Figure 3.23 : Intersection Point: Velocity vs. Time Data for Three Vehicles

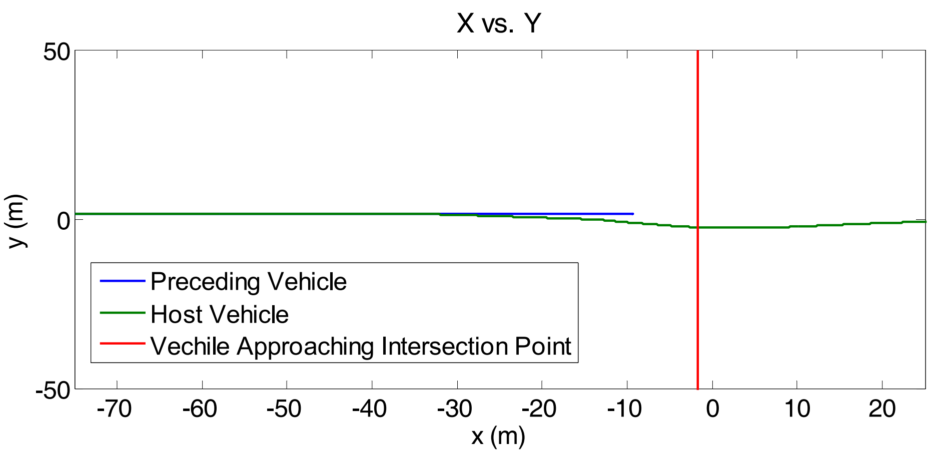

Figure 3.24 : Intersection Point: X vs. Y Data for Three Vehicles

4. CONCLUSION

In this thesis, Collision Warning System which detects possible collisions and warns drivers regarding the behaviors of drivers under the collision circumstances as well as complex traffic environments and Collision Avoidance System which takes control of the vehicle when drivers give no response to warnings given by warning system and applies emergency maneuver to avoid possible collision risk were designed.

Contrary to previously designed system, proposed Collision Warning System has adaptive parameter which depends on reaction characteristics of the driver and specific part that is added to consider Adaptive Cruise Control Vehicles. In this way, consistency between human driver and warning system raised its maximum level and missing and wrong warnings are eliminated. In Collision Warning Part; previous algorithms were firstly investigated and these algorithms were evaluated according to expected performance criteria. Then, considering ACC capabilities, these algorithms were modified to obtain a more powerful CW algorithm. To make the algorithm more flexible, a “Tunable Avoidance Parameter” (TAP) was identified and accommodated into formulation. The proposed algorithm was tested using the MEKAR-ACC Simulator along with the other algorithms for specified scenarios. The proposed algorithm gave more realistic warnings than the other velocity information based warning algorithms as well as velocity and acceleration based algorithm which was affected numerical differentiation tremendously.

Elastic Band is a strong method which combines the simplicity of the potential field method with the accuracy of the trajectory generation based methods. This strong method was modified for vehicle based applications. Reactive forces that push the vehicle away from the other objects in an environment was first modified. Uniformity of the band was satisfied by changing the method for the situation which has objects in the vicinity of the band. Alternative paths were developed considering the restrictions of the vehicle dynamics. Error detection subsystems were developed for searching available modified alternative paths. Proposed algorithm was tested with Carsim 6.05 for different scenarios and different configurations. Algorithm gave acceptable results for Rear-End, Lane Change and Intersection Point Collisions.

Although conventional controllers gave acceptable results, performance of the algorithm might be increased with much more advanced trajectory following controllers. In the next stages of this work, different trajectory controllers will be tested with the proposed algorithm.

Vehicle to vehicle communication has great attention allover the world from the Active Safety Systems Research Society. Vehicle to vehicle communication provides infrastructure-free communication and can be used on all roads without any additional operation. The ad hoc network which is a wireless and decentralized network type supports the necessities of vehicle to vehicle communication. It is possible to apply unicast, multicast and broadcast to an ad hoc network. This technology decreases the dependence to inter vehicular sensors such as radar and laser sensor to minimum levels. Moreover, accuracy in obtained data is much higher than the obtained data from radar and laser sensor.

It is certain that this coming technology will greatly influence Collision Avoidance System which is dependent to inter vehicular sensor information. First of all, it will be much easier to detect and follow the other vehicles and other road users in close environment using inter vehicle communication. In this way, Avoidance System gets this required information faster and this provides system more time in deciding following maneuver. Secondly, obtained information is more precise which yields avoiding possible wrong decisions resulting from error in acquired information. Finally, vehicle to vehicle communication will remove the line of sight problem of inter vehicular sensor. In this way, it will be possible to design more effective Intersection Collision Avoidance Systems. On the other hand, this technology has still many problems waiting for solution.

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