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AUTOMOTIVE MECHATRONICS AND INTELLIGENT VEHICLES

MODELING AND EXPERIMENTAL STUDY OF ADAPTIVE CRUISE CONTROL SYSTEM

MASTER OF SCIENCE

submitted by

RECEPŞAN GÜNAY

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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Program: Automotive Mechatronics and Intelligent Vehicles

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THESIS

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SUPERVISOR: PROF. DR. R. NEJAT TUNCAY

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ABSTRACT

MODELING AND EXPERIMENTAL STUDY OF ADAPTIVE CRUISE CONTROL SYSTEM

The cruise control system is used frequently in today's vehicles and it is a system that allows the vehicles to move at a desired velocity. The adaptive cruise control, in addition to the cruise control system, is a system that senses other vehicles around, measures the relative distance and velocity continuously, adjusts the vehicle velocity according to the safe driving distance and brakes if necessary. In addition to reducing driver faults, this system also reduces fatigue and increases driving motivation, especially by long road drivers. This system improves the safety in driving conditions that need to be reacted briefly in all kinds of situations such as when another vehicle gets ahead and wild animals suddenly comes to the road. Today, this system, which can be purchased as an option, will bring down the driver errors to zero and will provide safe transportation to us by adding equipment that will enable the vehicles to communicate with each other in the future. In this thesis, the control dynamics of the cruise control and the adaptive cruise control systems are simulated and the performance of the controller is simulated by creating the scenarios. These scenarios have been performed with a vehicle which has an adaptive cruise control system in practice. The measurement data from the electronic control unit of this vehicle were compared with the predicted data and it was seen that the measurement results supported each other.

Keywords: Cruise Control, Adaptive Cruise System, Electronic Control Unit, Modeling, Advanced Driver Assistance System

KISA ÖZET

ADAPTİF SEYİR SİSTEMİ TASARIMI VE DENEYSEL OLARAK İNCELENMESİ

Günümüz araçlarında sıklıkla kullanılmakta olan seyir kontrol sistemi, araçların istenilen bir hızda ilerlemesine olanak sağlamaktadır. Adaptif seyir kontrol sistemi ise seyir kontrol sistemine ek olarak, etrafta bulunan diğer araçları algılayan, göreceli mesafeyi ve hızı sürekli ölçerek, araç hızını güvenli sürüş mesafesine göre ayarlayan ve gerektiğinde aracın frenlemesini sağlayan bir sistemdir. Bu sistem sürücü hatalarını azaltmanın yanı sıra, yorgunluğu da azaltarak özellikle uzun yol sürücülerinin sürüş motivasyonunu arttırmaktadır. Bu sistem, başka bir aracın aniden öne geçmesi ve yabani hayvanların yola fırlaması gibi durumlarda, kısaca ani tepki verilmesi gereken sürüş koşullarında güvenliği artıran bir sistemdir. Günümüzde opsiyonel olarak satın alınabilen bu sistem, gelecekte araçların birbirleriyle haberleşmesini sağlayan donanımların da eklenmesiyle sürücü hatalarını sıfıra indirecek ve güvenli ulaşımı bizlere sunacaktır. Bu tez çalışmasında seyir kontrol sistemi ve adaptif seyir kontrol sistemi üzerine kontrol tasarımı yapılmış ve araç dinamiğiyle kontrolcünün performansı senaryolar oluşturularak simule edilmiştir. Bu senaryolar adaptif seyir kontrol sisteminin bulunduğu bir araçla pratikte de uygulanmıştır. Bu aracın elektronik kontrol ünitesinden alınan ölçüm verileri teorik olarak öngörülen veriler ile karşılaştırılmış ve ölçüm sonuçlarının birbirlerini desteklediği görülmüştür.

Anahtar Kelimeler: Seyir Sistemi, Adaptif Seyir Sistemi, Elektronik Kontrol Ünitesi, Modelleme, Gelişmiş Sürücü Sistemleri

To My Family

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SYMBOLS

a	Acceleration
D_{safe}	Safe distance
D_{act}	Actual distance to the target vehicle
$D_L(s)$	Load disturbance signal
$D_S(s)$	Supply disturbance signal
e	Controller input (system error)
$e(t)$	Time domain controller input
$E(s)$	Laplace domain controller input
$E(s)$	Process error input to process
F_{xf}	Front tire force
F_{xr}	Rear tire force
F_{aero}	The aerodynamic resistance
$G_c(s)$	The controller unit
g	Gravitational acceleration
$G(s)$	The process model
$G_A(s)$	The actuator unit model
$H(s)$	The measurement process model
k_p	Proportional gain
k_I	Integral gain
k_D	Derivative gain
m	The mass of the vehicle

$N(s)$	Measurement noise
R_{xf}	Front tire rolling resistance
R_{xr}	Rear tire rolling resistance
$R(s)$	Setpoint or reference signal
$u_c(t)$	Time domain PID control signal
$u_c(s)$	Laplace domain PID control signal
$U_c(s)$	Controller output
$U(s)$	Actuator output to process
u_c	PID control signal
v	Velocity
v_r	Relative velocity between the vehicles
v_{set}	The driver-set velocity
v_h	Velocity of the host vehicle
v_t	Velocity of the target vehicle
x	The longitudinal position
x_r	Relative distance between vehicles
$Y_m(s)$	Measured process output
$Y(s)$	Process output
ϕ	The roll angle
θ	The pitch angle
α	The slope angle of road
Ψ	The yaw angle

ACRONYMS

ABS	Antilock Braking System
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
ALVINN	Autonomous Land Vehicle in a Neural Network
CAN	Controller Area Network
CC	Cruise Control
DARPA	Defence Advanced Research Projects Agency
DAS	Driver Assistance System
ECU	Electronic Control Unit
EGM	General Directorate of Public Securıty
EUREKA	EUropean REsearch Coordination Agency
EVSC	External Vehicle Speed Control
GPS	Global Positioning System
HDC	Hill Descent Control
ISA	Intelligent Speed Adaptation
JGnK	General Command of Gendarmerie
LDW	Lane Departure Warning
MPC	Model Predictive Control
NAVLAB	The Carnegie Mellon University Navigation Laboratory
NMPC	Nonlinear Model Predictive Control
PID	Proportional Integral Derivative
PMD	Photonıc Mixer Device

PROMETHEUS	PROgraM for European Traffic with Highest Efficiency and Unprecedented Safety
RHC	Receding Horizon Control
TCS	Traction Control System
TÜİK	Turkish Statistical Institute

I. INTRODUCTION

The content of the thesis is organised as follows.

Chapter 1 provides an introduction to advanced driver assistance systems (ADASs) of describing the practical issues that will be analysed in the following chapters. It is pointed out that this is indeed an important issue for the safety. In particular, the importance, a brief history and current state, the future, potential benefits and costs of ADAS technology actions are described. Chapter 2 describes the equipment used to accommodate ADAS. Also, in this context, various types of ADAS technologies, which are common recently in the automotive industry are explained. In Chapter 3, the design of the main task of the adaptive cruise control system’s (performance features, vehicle model, procedure and control methods) is discussed and adaptive cruise control strategy is described. In Chapter 4, a large number of simulation are made to analyse the cruise control system and the adaptive cruise control system and they are compared to the practice. The developed cruise control and adaptive cruise control strategies are described in detail. Finally in Chapter 5, the last of this thesis looks at concludes and summarizes the whole research and also defines the possibilities of extension according to future demands in this research.

1.1. What are Advanced Driver Assistance Systems?

An Advanced Driver Assistance Systems (ADASs) are equipped with vehicle control systems which use sensors (e.g. radar, LIDAR, ultrasonic, photonic mixer device (PMD), camera, nightvision device) to improve the safety of traffic and reducing the workload on the driver. Modern automobiles which are equipped with ADAS functions can help to assists the driver in recognizing and reacts to potentially dangerous traffic situations.

1.2. The Importance of Advanced Driver Assistance Technology

According to the Data on Highway Traffic Accident Statistics that are compiled from the administrative records of the General Directorate of Public Security (EGM) and General Command of Gendarmerie (JGnK) and published annually by the Turkish Statistical Institute (TÜİK) under the Official Statistics Program (RİP), 1 202 716 traffic accidents occurred in total during year 2017 in Turkey (Table 1.1.).

Table 1.1. Number of accidents, people killed and injured between 2002 – 2017 years in Turkey [1]

Year	Total number of accidents	Accidents involving material loss only	Accidents involving death and personal injury	Killed persons			Number of persons injured
				Total	At accident scene	Accident follow-up	
2002	439 777	374 029	65 748	4 093	4 093	-	116 412
2003	455 637	388 606	67 031	3 946	3 946	-	118 214
2004	537 352	460 344	77 008	4 427	4 427	-	136 437
2005	620 789	533 516	87 273	4 505	4 505	-	154 086
2006	728 755	632 627	96 128	4 633	4 633	-	169 080
2007	825 561	718 567	106 994	5 007	5 007	-	189 057
2008	950 120	845 908	104 212	4 236	4 236	-	184 468
2009	1 053 346	942 225	111 121	4 324	4 324	-	201 380
2010	1 106 201	989 397	116 804	4 045	4 045	-	211 496
2011	1 228 928	1 097 083	131 845	3 835	3 835	-	238 074
2012	1 296 634	1 143 082	153 552	3 750	3 750	-	268 079
2013	1 207 354	1 046 048	161 306	3 685	3 685	-	274 829
2014	1 199 010	1 030 498	168 512	3 524	3 524	-	285 059
2015	1 313 359	1 130 348	183 011	7 530	3 831	3 699	304 421
2016	1 182 491	997 363	185 128	7 300	3 493	3 807	303 812
2017	1 202 716	1 020 047	182 669	7 427	3 534	3 893	300 383

1 020 047 of these accidents are financially damaged. 74.4% of the traffic accidents occurred in the settlement and 25.6% occurred outside the settlement. Looking at the 182 669 accidents involving death or injury occurred, roughly seven thousand people are killed and more than three thousand injured in crashes. As a result of 213 325 total faults causing accidents involving death or injury, it was observed that 89.9% of faults were driver faults – such as driving too fast and misjudging other drivers' behaviors, as well as alcohol impairment, distraction, and fatigue, 8.5% were pedestrian faults, 0.7% were road faults, 0.5% were vehicle faults and 0.4% were passenger faults. And concerning the 294 515 road motor vehicles involved in accidents with death or injury was cars 52.7%, motorcycles 15.2%, small trucks 15.7%, minibuses 3.1%, trucks 2.9%, buses 2.2%, trailers 2.6%, tractors 1.1% and the other vehicles 4.5% [1].

The use of ADAS technologies have the potential to considerably decrease a life-threatening situations by eliminating the human drivers' mistakes that the primary cause of road accidents. The hope is that lives can be saved through improving vehicle driver assistance system technologies.

1.3. A Brief History and Current State of Advanced Driver Assistance Systems

With the help of ADAS applications, a great deal of traffic problems will be avoided, allowing vehicles to use roads more efficiently and thus save space and time. In particular, switching to an automatic transport structure will greatly prevent many problems caused by traffic. The research shows that with the integration of autonomous instruments, traffic models will be more predictable and less problematic.

The first valuable initiative to build an autonomous vehicle was carried out by the Tsukuba Mechanical Engineering Laboratory in Japan in 1977. The car worked by following the white street markers and reached a speed of up to 30 km/h for up to 50 m on a special test course.

The research programme launched by the European Automotive Industry on 1 October 1986, PROMETHEUS (PROgraM for European Traffic with Highest Efficiency and Unprecedented Safety), is one of the first research actions supporting driving safer, more economical, environmentally acceptable, efficient and comfortable in Europe. Companies, universities and research institutions from 11 European countries participated in this research project, which lasted eight years between 1987 and 1995. Being initiated by Daimler-Benz, PROMETHEUS has contributed greatly to the development of radar technology. This project, which laid the foundations for many work in the area is originated from the EUREKA project (EUropean REsearch Coordination Agency, an open framework for cooperation between European industry and research industries) [2]. Ernst Dickmanns joined the European project PROMETHEUS in the late 80s, and the project produced vehicles that could be driven on highways at 80 km/h in busy traffic by the mid-90s [3]. They developed other techniques such as automatic tracking of other vehicles, convoy driving, and lane changes with autonomous transition of other cars.

Another important milestone in the history of autonomous vehicles was ALVINN (Autonomous Land Vehicle in a Neural Network) which developed by Dean Pomerleau in the early 90s [4]. ALVINN is an artificial neural network designed to control the

NAVLAB (the Carnegie Mellon University Navigation Laboratory, Carnegie Mellon) autonomous navigation test vehicle.

Before 2000, most automobile manufacturers seemed unconcerned to build an autonomous vehicle because the projects were taking too long. All major autonomous vehicle projects in the 1980s and 1990s were financed by the governments of the technologically leading countries such as the USA, Germany and Japan. Nowadays, almost every automobile manufacturer has an autonomous vehicle project or sponsors external projects. Today, the number of projects in this area is so high that the best example is the increase in the number of teams participating in the DARPA (Defence Advanced Research Projects Agency) Challenge.

DARPA awarded a $1 million prize for the first autonomous vehicle competition on a 142 mile (228 kilometers) course beginning in Barstow, California; ending in Primm, Nevada in 2004. None of the robot vehicles finished the route, only the vehicle of Carnegie Mellon University's Red Team traveled the longest distance (7.4 mile of the course) [5]. The next year, when DARPA reorganized the competition, this time the results were very different. Five vehicles successfully completed the 132 mile (212 kilometers) course. Influenced by this success, DARPA launched a new challenge in 2007, known as the Urban Challenge. In this competition, the desert environment was transformed to the urban area. The course included a 60 mile (96 kilometres) route that would be completed in less than 6 hours, requiring autonomous vehicles to comply with traffic rules such as following the superiority of crossing at intersections, controlling the opposite lane and back side during overtaking, maintaining safe tracking distance.

The Urban Challenge and subsequent competitions have been a powerful driving force in the development of autonomous vehicles. While advances in GPS and LIDAR technologies are progressing, limitations still remain. Further developments are required in these technologies. Other challenges remain, such as questions of responsibility and how to adequately prove safety, even if technical difficulties are solved.

II. ADVANCED DRIVER ASSISTANCE SYSTEMS' FEATURES

2.1. The Core Elements

It is important to learn about the continuous state of the target vehicle in ADASs, which are systems developed for automating/adapting/developing vehicle systems for safety and better driving, and this requires additional hardware (Figure 2.1). The most common method of obtaining this information is to mount Radar or Radar-like sensors (microwave and Doppler radar units as well as light-based LiDAR) in front of the vehicle.

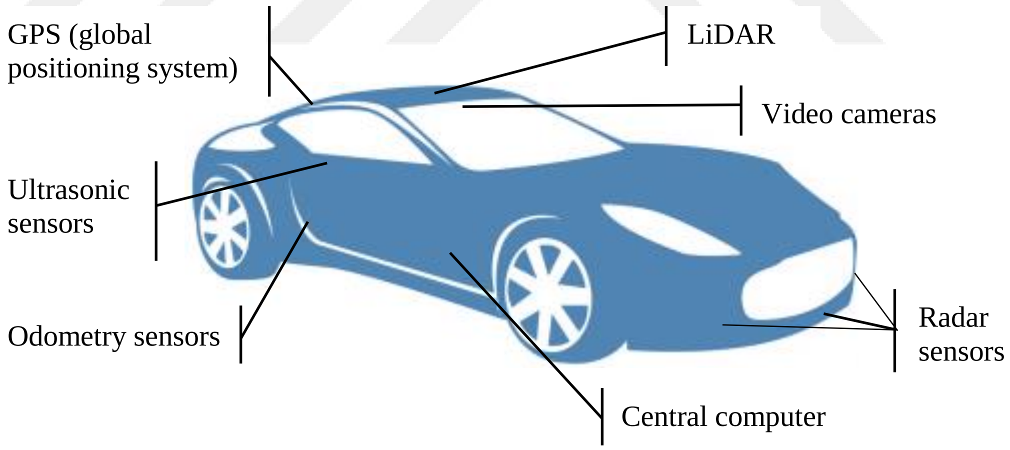


Fig. 2.1. Sensors for ADAS

2.1.1. Radar

The radar (radio detection and ranging) is a sensor that radially emits a laser and predicts the depth through reflected time. It reflects every point in 3D space to get 3D spatial information about the vehicle and in this way; stereoscopic spatial information that is not related to the light source can be obtained at the same time.

2.1.2. LiDAR

LiDAR systems which means Light Detection and Ranging are laser based systems that operate on principles similar to radar or sonar (sound navigation and ranging) [6]. LiDAR (Light + Radar) is an optical remote sensing technology that uses near infrared light laser pulses to take measurements the distance and velocity difference with the predecessor. This system emits light pulses and measures the time required for the pulse to return from a distant surface. Since the light moves at a constant velocity, the LiDAR unit can accurately calculate the distance between itself and the target.

2.2. Applications

Recently, one of the most important aims in the automotive industry is improve ADASs that present passengers the highest level of safety, comfort, and efficiency, partially or totally removing the assignments of the drivers. There are various types of ADASs that work for the user to provide a different feature (a critical safeguard for the driver's safety, convenience to help the driver avoid small accidents). As ADAS can even intervene autonomously, a vehicle equipped with ADAS is called by the popularly as an "intelligent vehicle". The following types of ADASs can be distinguished:

2.2.1. Cruise control

Ralph Teetor (1890 – 1982) was a blind engineer who invented the first viable Cruise Control (CC) device for vehicles in 1945. The idea behind a CC, which is a common and well known Driver Assistance System (DAS), is that the driver adjusts a reference velocity and the throttle is controlled to keep this reference velocity under the influence of external loads such as wind, road slope or varying vehicle parameters. The driver can turn CC on, allowing the vehicle to control the same rate of velocity and thus focus on driving.

2.2.2. Adaptive cruise control

The purpose of the Adaptive Cruise Control (ACC) also named autonomous cruise control or radar cruise control system is to maintain an appropriate relative distance between target vehicle and also to adjust the velocity required by the driver if there is no target vehicle or the target vehicle is faster than the desired velocity. It should also react softly if the target vehicle is cut out from the vehicle or a new vehicle is cut from a side lane. Such systems that take account of traffic in front of the vehicle, support the driver in the driving process, and enhance target, driving comfort and traffic safety are often known as ADAS.

2.2.3. Adaptive light control

The adaptive light control systems also called active headlights or adaptive front-lighting systems are an ADAS technology projected to assist drivers see better and further in the night driving. The system optimizes the light distribution of the headlights to improve the driver's field of visibility at the curves and intersections (Figure 2.2).

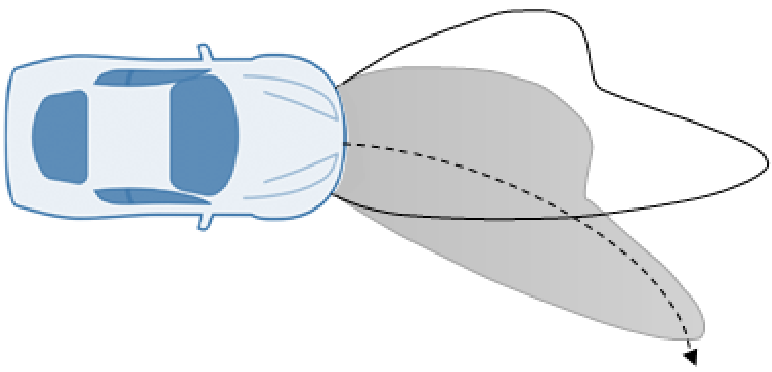


Fig. 2.2. Adaptive Light Control: The headlights are directed into the bend ahead

2.2.4. Automatic braking

Automatic braking is a safety technology that associates sensors and brake controls to assist avoid high velocity collisions in case of a stumble into driver attention. Although some systems can indeed prevent collisions, it usually means that the vehicle slows down to the point where less damage occurs and deaths are not possible. Some of these systems provide the driver with brake assistance, while some advanced systems take over and stop the vehicle entirely before a collision occurs.

2.2.5. Automatic park assistant

Some of the automatic parking systems can actually do all the work automatically, and others only recommend that the driver know when to turn the steering wheel and when to turn it off. These systems, which are probably the most commonly used and demanded ADAS today, are always monitored by the driver and can be overridden by pressing accelerator pedal or brake pedal by the driver. These systems, which most of them are designed to assist drivers in parallel parking, use lateral and longitudinal controllers simultaneously.

2.2.6. Blind spot detection

Blind spot detection systems prevent possible dangerous situations in the lane changing process, alert the driver if they detect the presence of an object within the blind spot (Figure 2.3). Blind spot detection systems often use a variety of sensors located on the sides of the vehicle near the external rear view mirrors or near the rear bumpers.

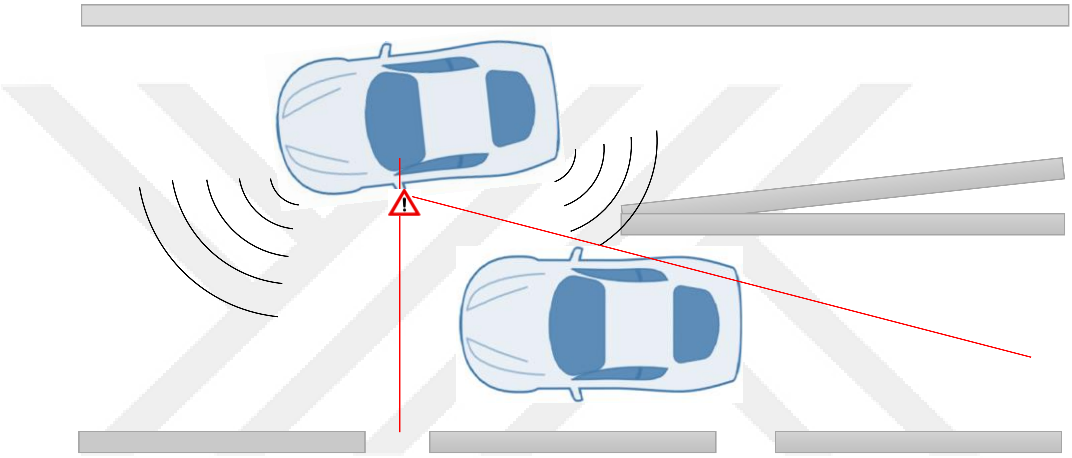


Fig. 2.3. Blind spot assistant sensors for safe lane changes

2.2.7. Collision avoidance systems

Collision avoidance systems warn the driver when the vehicle is in danger of colliding with other vehicles, pedestrians, animals and various road obstacles contain a collision danger. These systems, which use various sensors, help the driver to be more careful on the road and react early to dangerous situations, especially at high velocities.

2.2.8. Driver drowsiness detection

Developed for monitoring the driver's drowsiness techniques can be generally classified into three main categories [7]. The first category includes methods based on biomedical signals such as brain waves, muscle, pulse, respiration, heart rate [8, 9]. These techniques, which usually require electrodes connected to the driver’s body, are often uncomfortable to the driver, and their ability to monitor accurately is diminished by sweating on long-running driving.

The second category includes methods of predicting driver fatigue by monitoring signals recorded by Controller Area Network (CAN) in driving behaviors such as the use of a gas pedal, brake pedal, steering wheel movement, vehicle velocity, lateral acceleration, lateral displacement and distance to the vehicle in front [10-13].

In the third category, the computer vision uses techniques that efficiently measure the physical changes of the driver such as the driver's sagging position, head tilting, and the open/closed states of the eyes, from the images taken by the cameras placed in front of the driver. In the literature, different types of cameras and analysis algorithms have been reported for this approach for instance methods based on stereo camera, visible spectrum camera [14, 15] and Infra-red (IR) camera [7, 16-18].

2.2.9. Global position system navigations

The in-vehicle navigation system relies on the Global Positioning System (GPS) to define the location of the vehicle according to a desired location and to provide visual direction and vocal direction (which saves the driver from looking at the screen) in real time. Some of the GPS navigation systems that take paper maps in place effectively provide live traffic data by listening to news radio stations previously. According to Bryden *et.al.*, in-vehicle navigation techniques have the potential to simplify the driving task, especially by reducing the need for drivers to navigate in unfamiliar environments [19]. At present, many vehicles are delivered with a GPS based in-vehicle navigation system from the factory, and owners of used vehicles can buy portable satellite navigation systems to their vehicles.

Nowadays, the positioning accuracy of the navigation technology is provided using expensive sensors, while in 2013 a laser navigation system was used for autonomous flight by Huh *et.al*. [20]. But this system’s cost is very high to implement in mass-produced vehicles.

2.2.10. Hill descent control systems

Hill descent control (HDC) system is an ADAS that facilitates descend steep inclines on all wheel drive off-road vehicles such as SUVs. This system which operating in conjunction with the same basic mechanism as technologies like ABS (Antilock Braking System), TCS (Traction Control System), works by activating the brakes to slow down the vehicle automatically. HDC tracks the velocity of each wheel individually by removing the possibility of locking the wheel thanks to the vehicle's ability to work in harmony with the ABS. Some of the modern HDC systems allow velocity limit to be changed over the CC function. The HDC system, which can usually be overridden by pressing the brake or accelerator pedal, is useful when traveling on loose and slippery roads, especially snow or gravel roads.

2.2.11. Intelligent velocity adaptation

According to the results of a "The effects of drivers’ velocity on the frequency of road accidents" research carried out by the Transport Research Laboratory, the accidents frequency increases with increases in velocity [21]. Accidents and casualties related to velocity are a clear problem in many countries. Although some car manufacturers have developed a velocity limiting system that will be manually adjusted, this system is cumbersome because it requires manual adjustment of every velocity limit change.

Intelligent Speed Adaptation (ISA), also know as External Vehicle Speed Control (EVSC) system automatically adjusts the velocity when the velocity of a vehicle exceeds the velocity limit while continuously monitoring the velocity of a vehicle. The standard system uses an in-vehicle route map consisting of the current velocity limit information for each road section with a GPS receiver that determines the location of the vehicle. Thus, the in-vehicle system knows the position on the road network and the prevailing velocity limit, and even about future changes depending on the current network conditions (weather, traffic intensity, etc.). The ISA system gives tactile feedback by the driver, with a vibration motor attached to the gas pedal when the gas demand exceeds 40% of the current velocity limit [22].

2.2.12. Lane departure warning systems

Lane departure warning (LDW) system is a system that uses a variety of sensors to track the location of the vehicle relative to the lane and warns if the vehicle is leaving the lane. The LDW is designed to reduce the risk of accidents by stimulating the driver with acoustic or tactile stimuli while the driver is about to leave the lane (Figure 2.4). The system deliberately detects the maneuver and does not trigger an alarm when the lane change is accompanied by signal rotation or acceleration.

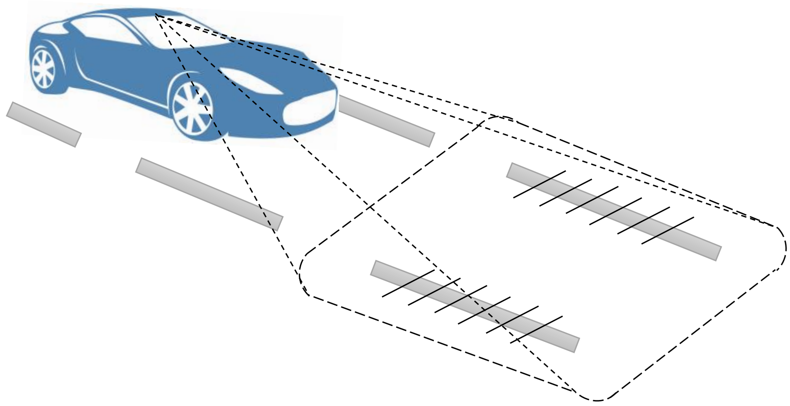


Fig. 2.4. A LDW system based on lane markings

III. ADAPTIVE CRUISE CONTROL

3.1. Performance Features

ACC system is one of the first commercial applications of ADASs for passenger vehicles and today, it is made available in various vehicles by many automobile manufacturers around the world. The main task of the ACC system is to ensure safe distance to the target vehicle and if there is no target vehicle, it is to maintain the velocity set by the driver. It is important that distance and velocity control work together properly and steadily. The transition performance should be stable and straight when the control is passed from one to the other control. The control in the ACC system, which allows the driver to personalize the control system for comfort and safety, is only based on sensor information from the on-board sensors.

3.1.1. Distance and velocity control

The ordinary CC (velocity control) mode works when the distance between vehicles is greater than the safety distance or the target vehicle's velocity is higher than the cruising velocity set by the driver. The adaptive (space control) part of the ACC works when the host vehicle approaches the target vehicle (slower) and maintains the safety distance between vehicles. The design of a controller for this system requires the specification of a safety distance policy. In the literature, there are various distance control policies [23-26] whether collision can be prevented and various velocity and deceleration profiles [27, 28] to protect the inter-vehicles distance.

3.1.2. Stability and string stability

Stability in ACC systems means that the velocity of the host vehicle and the relative distance to the target vehicle approach the desired values. In addition to the stability of a single vehicle, the controllers for a platoon of vehicles should be designed to provide string stability to avoid collisions in the platoon, i.e., spacing errors must not be raised as they advance toward the tail of the string [29].

3.1.3. Safety

Studies have shown that ADASs such as (A)CC in the automotive market can increase safety by reducing the number of traffic accidents [30]. Although the comfort of passengers is important, safety is the highest priority in an emergency case. For instance, the host vehicle must decelerate quickly to reduce the stopping distance in the case of an emergency stop and the host vehicle must be slowly decelerated so that the passengers do not feel uncomfortable in the case of non-emergency stop. That is, the optimal acceleration and deceleration profile should be determined according to the situation.

3.1.4. Comfort and confidence

In the ACC system, acceleration and deceleration are inevitable during the operation. Acceleration and deceleration of the ACC system are important parameters to provide the comfort of passengers. Excessive acceleration or deceleration makes the passengers feel uncomfortable and restless, and also if the acceleration or deceleration of the host vehicle is exactly the opposite of the driver's expectation, the driver's confidence in the

ACC system is reduced [31]. For this reason, an ACC system should be implemented to maintain acceleration and deceleration within a certain range.

3.2. Vehicle Model

3.2.1. Vehicle body dynamics

Nowadays ISO coordinate system (ISO8855) is the predominant coordinate system used [32]. From the frame of coordinates, the vehicle motion is composed of two types of displacements: translations along the (x, y, z) axes and rotations around these same axes. Figure 3.1 indicates the vehicle's coordinate system (3 main geometrical planes) and the degrees of freedom. The motion in the ground plane is often treated as the primary motion that's why the longitudinal, lateral, and yaw are referred to as ground plane degrees of freedom and the other degrees of freedom are called the out of groud plane.

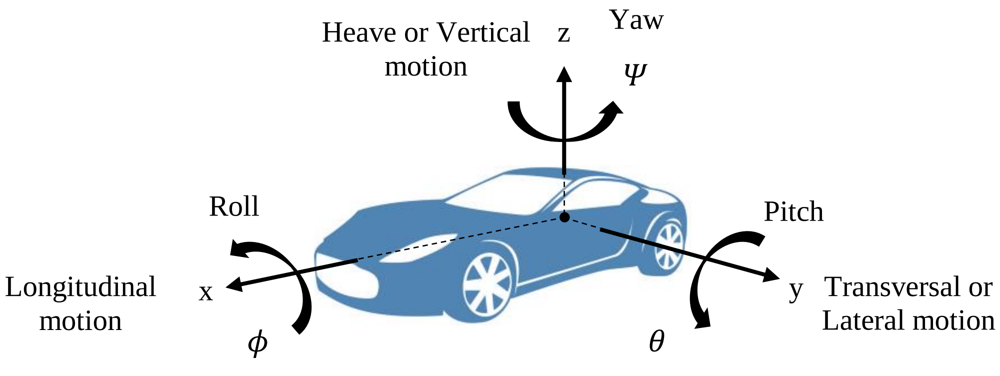


Fig. 3.1. Degrees of freedom of a vehicle and coordinate system

According to this coordinate system, the forward direction or the longitudinal direction of the vehicle is described in the positive x-axis, the lateral direction is described by the y-axis, is positive when oriented to the left from the driver's viewpoint, the vertical movement is represented in the z-axis and this axis points to the ground satisfying the right hand rule. The z-axis is perpendicular to the ground, against to the gravitational acceleration (g), when the vehicle is parked on a straight horizontal road.

Rotations around the x, y, z axes of the vehicle cabin are also included in this system of coordinates. To describe this rotation, three angles are defined about the axes of the rotating vehicle frame. In honour of Leonhard Euler (1720 – 1723), who proves that an arbitrary three-dimensional rotation can be achieved with three individual rotations around the axes, these angles referred to as Euler angles. The roll (the roll angle is the ϕ), pitch (the pitch angle is the θ) and yaw (the yaw angle is the Ψ) rotations are defined around the (x, y, z) axes, respectively.

3.2.2. Longitudinal vehicle body dynamics

CC controls the longitudinal dynamics of the host vehicle and ACC extends this system by detecting the presence of a target vehicle and adjusting the velocity of the vehicle.

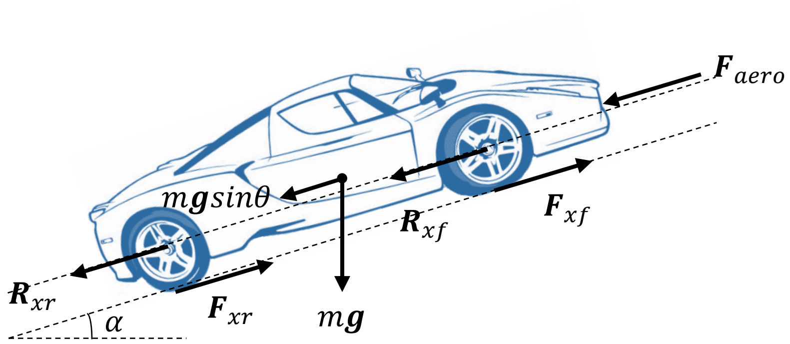


Fig. 3.2. Free body diagram of the longitudinal vehicle model

The sign of gravitational force depends on whether the vehicle is going uphill or downhill. The governing equation for the longitudinal vehicle model is given as (referring to Figure 3.2):

$$m\ddot{x} = F_{xf} + F_{xr} - F_{aero} - R_{xf} - R_{xr} - mgsin\alpha \tag{3.1}$$

where m is the mass of the vehicle, x is the longitudinal position of the vehicle, F_{xf} and F_{xr} are the tire forces at front and rear tires, F_{aero} is the aerodynamic resistance, R_{xf} and R_{xr} are the rolling resistances at front and rear tires, and α is the slope angle of the road.

3.3. The Adaptive Cruise Control Task

Main variables of an ACC system is shown in Figure 3.3. The left vehicle is the host (following) vehicle that equipped with an ACC system, the right vehicle is the target (lead) vehicle.

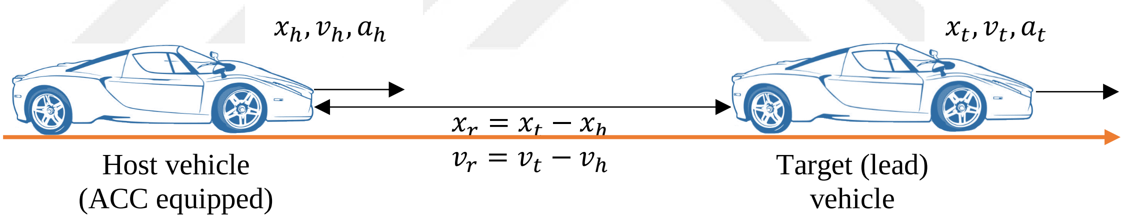


Fig. 3.3. Main variables of an ACC system

x, v and a represents the position, velocity and acceleration, respectively. The subscript h and t indicating the host vehicle and the target vehicle. x_r and v_r are the relative distance and relative velocity between the vehicles.

The relative distance x_r between the target vehicle and the host vehicle is formulated as

$$x_r = x_t - x_h \tag{3.2}$$

$$v_r = v_t - v_h \tag{3.3}$$

3.4. Control Methods

3.4.1. A proportional integral derivative

A Proportional Integral Derivative (PID) control is a standard three-term controller that refers to the first letters of the names of the individual terms P (the proportional term), I (the integral term) and D (the derivative term) in the controller. With a long history in the field of automatic control from the beginning of the last century, PID controller has become the standard controller in industrial settings, thanks to its intuition and relative simplicity [33]. PID controllers, the most common way of using feedback in natural and man-made systems, are widely used in the industry.

The typical industrial control system is represented in Figure 3.4. According to the loop operations, the main components can be divided into process, actuation, measurement, control, and communications [34].

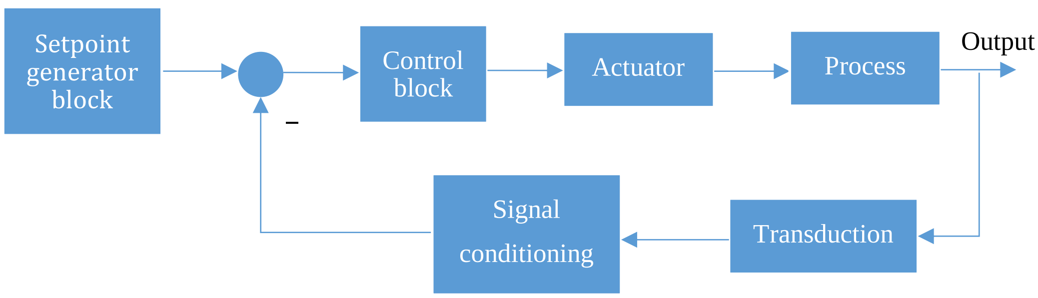
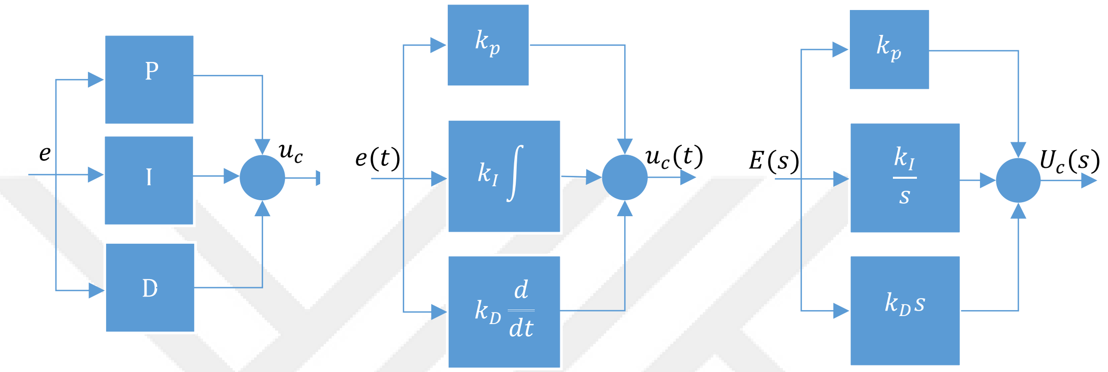


Fig. 3.4. Typical components of the typical control loop

The theoretical basis for analyzing the performance of PID control helps to simplify the simple representation of the Integrator with the Laplace transform $\left[\frac{1}{s}\right]$ and a

Differentiator using $[s]$ [34]. The PID control architecture can be given the following equivalent time-domain and Laplace s-domain mathematical representations (Table 3.1).

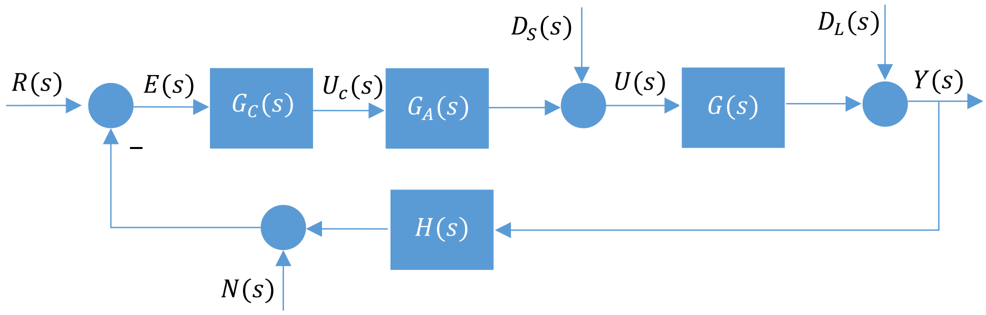
Table 3.1. PID controller representations



Symbolic representation		Time domain operator form		Laplace transform version	
e	: Controller input (system error)	$e(t)$	: Time domain controller input	$E(s)$	: Laplace domain controller input
u_c	: PID control signal	$u_c(t)$	: Time domain PID control signal	$u_c(s)$	: Laplace domain PID control signal
k_P	: Proportional gain	k_I	: Integral gain	k_D	: Derivative gain

The block diagram of Table 3.2 is considered, where $G(s)$ is the process model, $H(s)$ is the measurement process model, $G_c(s)$ is the controller unit and $G_A(s)$ is the actuator unit model.

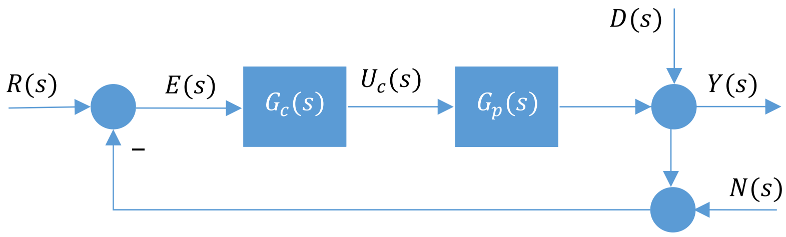
Table 3.2. Schematic block diagram of a control loop using Laplace transform terms



Components		Loop signals	
$G(s)$	: Process model	$Y(s)$	: Process output
		$D_L(s)$	: Load disturbance signal
$H(s)$	: Measurement process model	$N(s)$	: Measurement noise
$G_C(s)$	: Controller unit	$R(s)$	: Setpoint or reference signal
		$E(s)$	: Process error input to process
		$U_c(s)$	: Controller output
$G_A(s)$	: Actuator unit model	$U(s)$	: Actuator output to process
		$D_S(s)$	: Supply disturbance signal

The typical control system is represented in Table 3.3.

Table 3.3. Block diagram of a typical control system



Components		Loop signals	
$G_P(s)$	: Composite process model	$R(s)$	: Reference signal
$G_C(s)$	: Controller unit	$N(s)$	: Noise signal
$D(s)$	: Disturbance signal		

Implementation of a PID control law consists in properly applying the sum of the three types of control actions: a proportional action, an integrative action, and a derivative. Figure 3.5 shows the signal frame of the inputs and outputs for the PID controller.

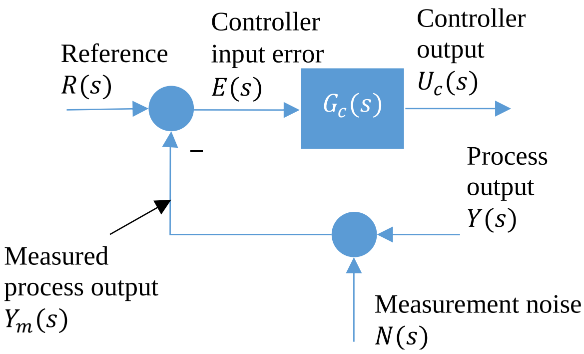


Fig. 3.5. Inputs and outputs of the three-term controller

The time and Laplace domain formulae for proportional action, integral control and derivative control are shown in Table 3.4. While the proportional action relies on the present value of the control error and the integral action relies on the past values of the control error, the derivative action relies on the estimated future values of the control error.

Table 3.4. The time and Laplace domain represantations for PID control

Three-Term Control	Time Domain Formula	Laplace Domain Formula
Proportional Control	$u_c(t) = k_p e(t) = k_p(r(t) - y_m(t))$	$U_c(s) = k_p E(s)$
Integral Control	$u_c(t) = k_I \int^t e(\tau)d\tau$	$U_c(s) = \left[\frac{k_I}{s}\right] E(s)$
Derivative Control	$u_c(t) = k_D \frac{de}{dt}$	$U_c(s) = [k_D s]E(s)$

The time and Laplace domain representations for PID control are given in Table 3.5.

Table 3.5. The time and Laplace block diagrams for PID control

	Block Diagrams	
Three-Term Control	Time Domain	Laplace Domain
Proportional Control	$e(t) \rightarrow \boxed{k_p} \rightarrow u_c(t)$	$E(s) \rightarrow \boxed{k_p} \rightarrow U_c(s)$
Integral Control	$e(t) \rightarrow \boxed{k_I \int} \rightarrow u_c(t)$	$E(s) \rightarrow \boxed{\frac{k_I}{s}} \rightarrow U_c(s)$
Derivative Control	$e(t) \rightarrow \boxed{k_D \frac{d}{dt}} \rightarrow u_c(t)$	$E(s) \rightarrow \boxed{k_D s} \rightarrow U_c(s)$

The combination of the proportional, integral, and derivative actions can be made in different ways to meet specific performance requirements.

3.4.2. Parallel and time constant forms of the PID controller

The parallel form is the most common of the PID forms, because it permits complete closure of the integral action by fixing $k_I = 0$ (in other cases the value of the integral time constant must tend to infinity). The industrial displays of the PID controller generally use a time constant form for the PID parameters instead of the decoupled form.

The time and Laplace s-domain formulae for parallel and the industrial time constant form for the PID control are shown in Table 3.6.

Table 3.6. The formulae and architecture for basic parallel and the time constant forms of the PID controller

	Time domain	Laplace s-domain
Parallel	$u_c(t) = k_p e(t) + k_I \int^t e(\tau)d\tau + k_D \frac{de}{dt}$	$U_c(s) = \left[k_p + k_I \frac{1}{s} + k_D s\right] E(s)$
Time constant	$u_c(t) = k_p \left(e(t) + \frac{1}{\tau_i} \int^t e(\tau)d\tau + \tau_D \frac{de}{dt} \right)$	$U_c(s) = k_p \left[1 + \frac{1}{\tau_i s} + \tau_D s\right] E(s)$

3.4.3. Model predictive control

Model Predictive Control (MPC) is a control strategy that offers attractive solutions for the regulation of constrained linear or nonlinear systems that is also referred to as Nonlinear Model Predictive Control (NMPC) for nonlinear systems and Receding Horizon Control (RHC). MPC, which has been used in the process industries such as chemical plants and oil refineries since the 1980s, is an important advanced control technique for difficult multivariable control systems. Due to the complexity of its calculations, MPC was first applied to chemical process control, where plant dynamics were slow and the real-time calculation requirement was not so strict. With the computer becoming cheaper and more powerful, it has expanded its applications to other areas such as vehicle control and has been used to develop ACC systems.

The overall objectives of MPC, which had a major impact on industrial practice, are summarized by Qin and Badgwell in 2003 [35]:

- Prevent violation of input and output constraints.
- Bring some output variables to their optimum set points while maintaining other outputs at certain ranges.

- Prevent excessive movement of input variables.
- When there is no sensor or actuator available, control as many process variables as possible.

The MPC calculations are based on a history of past control moves, current measurements and predictions of the future values of the outputs. While PID controllers are not capable of predicting future events, the MPC is capable of this prediction and can perform control actions accordingly. A block diagram of MPC system is shown in Figure 3.6.

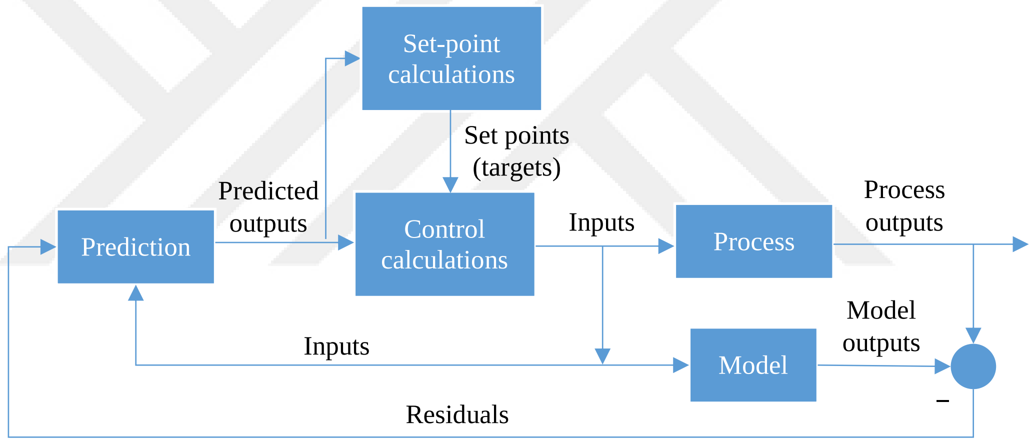


Fig. 3.6. Block diagram for MPC

The procedure is measuring the current state of the system, estimating the behavior of the system based on the model and calculating the optimal control sequence by calculating the optimal control problem, applying the first element of the control sequence to the system and moving the horizon forward in time.

IV. CASE STUDY

4.1. Simulation Setup

Matlab/Simulink is the commonly used industrial tool in the automotive sector which performs system-level design, simulation [36], automatic code generation, testing, and verification of embedded systems. In this thesis, ACC system is designed and simulated by the help of Matlab/Simulink environment.

4.2. Parameters to be Tuned

The vehicle model is constructed by using Matlab/Simulink, for the purpose of developing an ACC system which is controls only the longitudinal behavior of the vehicle. The objective of ACC is either to run at a desired CC velocity if there is no vehicle in front or to ensure following of a target vehicle in safe clearance when a target vehicle at slower velocity is detected. In addition, ACC system controls only the longitudinal behavior of the vehicle.

The throttle and brake system are controlled to maintain the inter-vehicle distance which is set by the control system and therefore, the ACC system operates in two separate performance specifications: velocity and safe distance control modes.

According to based on real-time radar measurements, the host vehicle (an ACC equipped vehicle) travels at a driver-set velocity in velocity control and maintains a safe distance from the target vehicle in spacing control (Figure 4.1 – 4.2).

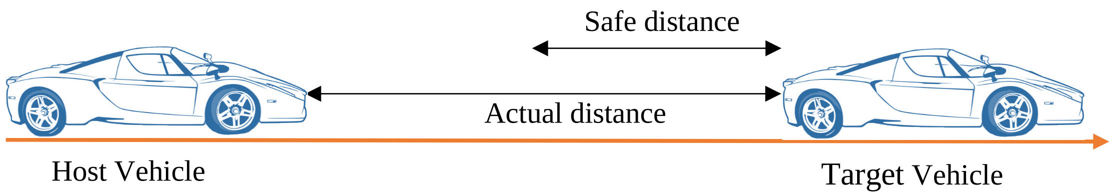


Fig. 4.1. Velocity control mode

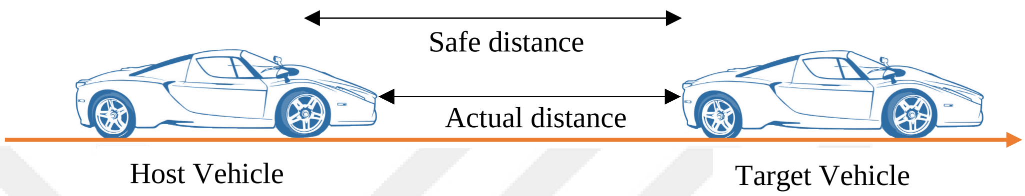


Fig. 4.2. Spacing control mode

The inputs of the system are characterized by the driver-set velocity (v_{set}), velocity of the host vehicle (v_h), actual distance to the target vehicle (D_{act}), velocity of the target vehicle (v_t). Acceleration of the host vehicle is investigated through simulation. Vehicle dynamics model has been experimentally performed and it has been shown to work according to selected parameters.

The relation between acceleration and velocity are determined by the following formula which approximates the dynamics of the throttle body and vehicle inertia:

$$\frac{1}{s(0.5s+1)} \tag{4.1}$$

The safe distance between the target vehicle and the host vehicle is a function of the velocity of the host vehicle, (v_h) is expressed as follows:

$$D_{safe} = 10 + 1.4 \times (v_h) \tag{4.2}$$

where 10 (m) is the standstill distance and 1.4 (sec) is the time gap.

If there is no vehicle in front of the host vehicle within the radar sensor range, the host vehicle is under velocity control only ($v_t = \text{constant}$).

In the case of velocity control mode ($D_{act} \geq D_{safe}$), while the following mode continues, if the target vehicle begins to velocity up, the velocity of the host vehicle also increases until the host vehicle's velocity reaches that of the target vehicle. The control target is to track the driver-set velocity (v_{set}).

In the case of spacing control mode ($D_{act} < D_{safe}$), a slower vehicle is detected by the radar as the target vehicle, the host vehicle velocity is reduced to that of the target vehicle and the distance between the vehicles is controlled until the two vehicles travel at the same velocity and the safe distance. The control target is to maintain the safe distance (D_{safe}).

4.3. Evaluation of Designed Controllers

Various test scenarios are used to examine longitudinal controller performance in different driving situations. The simulations consist of two vehicles, a target vehicle and a host vehicle which is refer to the ACC-equipped vehicle. Six different scenarios are foreseen for the ACC driving and are explained in detail below.

4.3.1. Scenario 1: CC

Scenario 1 represents the situation where there is no target vehicle (Figure 4.3). In this scenario, it is desirable for the vehicle to travel at a constant velocity determined by the driver. In fact, in this scenario, the CC system is active and there is no effect of the ACC system. In the stateflow diagrams, the velocity of the vehicle is set to $v_h = 30$ km/h with the CC operating with subsystems activated during simulation. Another application in this scenario is to enter a variable reference velocity profile instead of constant velocity. It is expected that the reference velocity value entering the controller will change with time and the vehicle velocity will follow this profile.

Fig. 4.3. Scenario 1

4.3.2. Scenario 2: ACC

In this scenario, while the vehicle is traveling at constant velocity with the velocity controller, that is, when Scenario 1 is active, a target vehicle arises to the sensor field of view at a velocity lower than host vehicle's velocity and from the same lane (Figure 4.4).

In this case, when the ACC system is turned on, the inputs related to the required velocity and distance control are transmitted to the vehicle model. In Scenario 2, an important issue is that the velocity of the target vehicle is constant or close to constant. The profile of the target vehicle velocity has been changed in other scenarios.

In scenario 2, while the target vehicle is steered at v_t = 20 km/h, the fixed velocity value of the host vehicle is v_h = 30 km/h. The distance between the vehicles is 180 m when t = 0 second. The radar range is 150 m and the time gap value is set to 2 s. The host vehicle trains at the velocity of the target vehicle and follows the target vehicle at this velocity.

The desired distance between vehicles is 40 meters. This value is obtained by multiplying the follow-up time (2 s) with the target vehicle's velocity (20 km/h).

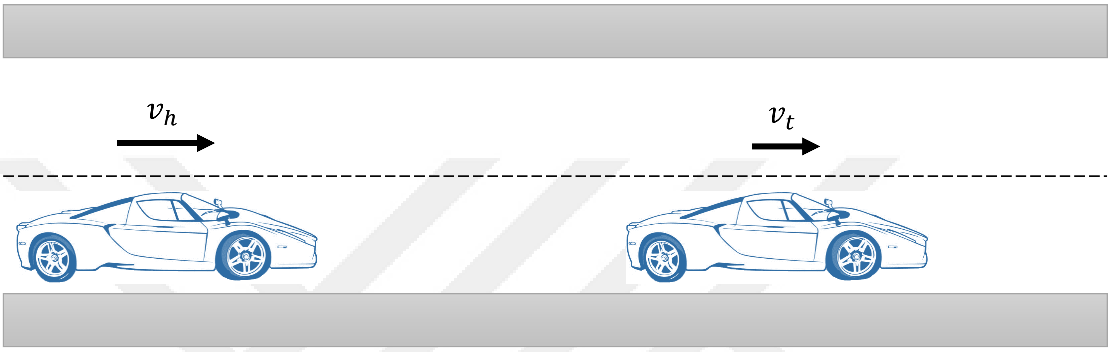


Fig. 4.4. Scenario 2

4.3.3. Scenario 3

This scenario is the continuation of Scenario 2. Once the vehicle has been trained, that is, when the second scenario occurs, the acceleration of the target vehicle is provided and Scenario 3 is obtained. What is wanted to try with this scenario is how the performance of the system will change if the target vehicle travels at a non-constant velocity. During acceleration of the target vehicle, the system will adjust velocity and distance. However, if the velocity of the target vehicle exceeds the velocity that the ACC tool uses in Scenario 1, then the follow-up will be terminated and driving at cruising velocity will continue. Figure 4.5 shows an illustration of the Scenario 3.

In Scenario 3, Scenario 1 and Scenario 2 were first created, and then the target vehicle was accelerated to start Scenario 3. At t = 12 s, the reference value of the target vehicle velocity controller has been increased from 20 km/h to 24 km/h. In response to acceleration of the target vehicle, the host vehicle increases its velocity and catches the front vehicle. In this case, the tracking distance has reached 48 meters with a target vehicle velocity of 24 km/h.

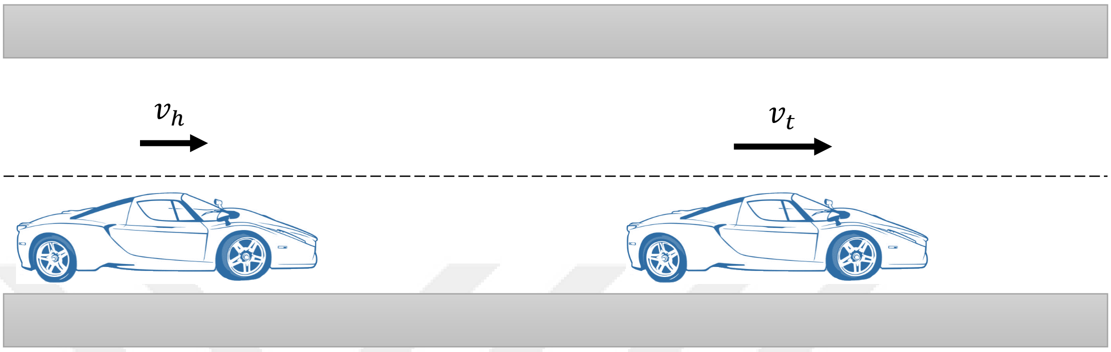


Fig. 4.5. Scenario 3

4.3.4. Scenario 4

This scenario is also the continuation of Scenario 2. As in Scenario 3, Scenario 4 is performed as soon as Scenario 2 is supplied or completed, and the velocity of the target vehicle is reduced when the velocity is constant (Figure 4.6).

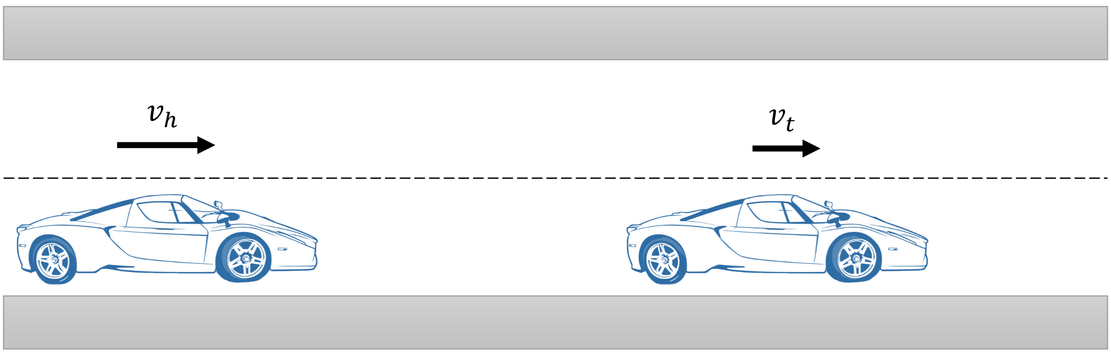


Fig. 4.6. Scenario 4

This scenario can be performed behind Scenario 3. In other words, the target vehicle accelerates and then starts to slow down. In Scenario 4 unlike Scenario 3, the target vehicle is slowed down, the new velocity of the target vehicle is brought to $v_t = 15$ km/h. Another application in this scenario is that the target vehicle advancing suddenly stops moving.

4.3.5. Scenario 5

In this scenario, the lane change of the target vehicle during the follow-up is simulated. Similarly, the lane change of the host vehicle should also be considered in the framework of this scenario. Accordingly, there is no target left in front of the host vehicle after any vehicle changes lane and Scenario 1 is activated again. In this way, when the front vehicle is somehow removed from the target vehicle during tracking, the host vehicle automatically increases its velocity to a predetermined constant value. In Scenario 5, the target vehicle is allowed to change lanes and it has been ensured not to be a target vehicle (Figure 4.7). The host vehicle is expected to accelerate after the target is lost and increase its velocity to the specified value.

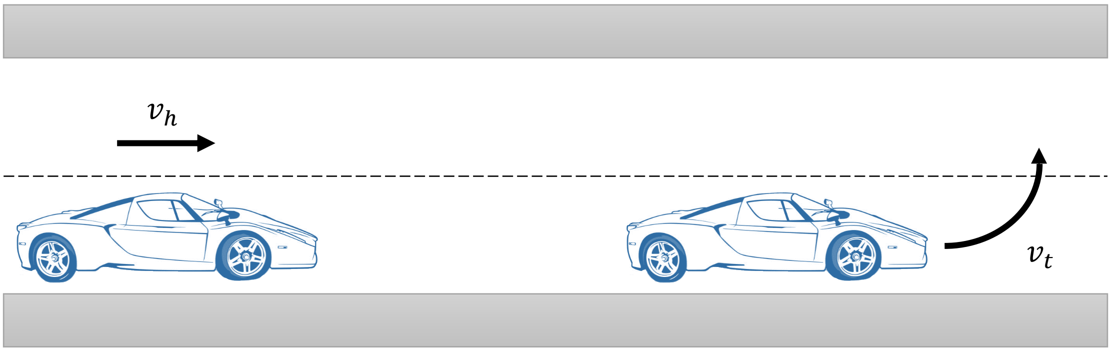


Fig. 4.7. Scenario 5

4.3.6. Scenario 6: Limited accelaration

In this Scenario, the minimum longitudinal acceleration is limited to – 4 m/s^2 and the maximum longitudinal acceleration is limited to 4 m/s^2, taking into account the physical limitations of the vehicle dynamics. The initial velocity of the host vehicle is 20 m/s and then set to 30 m/s by increasing. A target vehicle whose initial velocity of 25 m/s and then its velocity is changed between 25 and 30 m/s, appears in the field of view of the host vehicle. An important consideration in Scenario 6 is that the velocity of the target vehicle is changing wavily. The host vehicle moves at the velocity of the target vehicle and follows the target vehicle at this velocity.The distance between vehicles is 180 m when t = 0 second. The safe distance between the target vehicle and the host vehicle is obtained from equation 4.2. Accordingly, the time gap between the vehicles is 1.4 seconds and the standstill default spacing is 10 meters.

4.4. Simulation Results

In this chapter, vehicle dynamic conditions and ACC function with PID controller is modeled were done using Matlab/Simulink tool. The main blocks in these simulations can be seen from Figures 4.8 – 4.27.

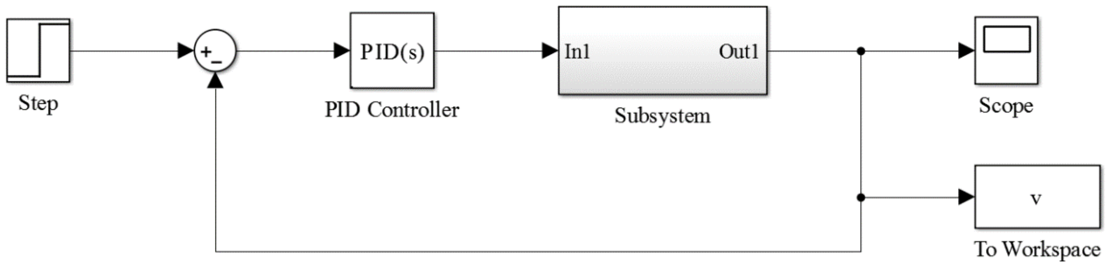


Fig. 4.8. Matlab/Simulink main block diagram of the Scenario 1.a

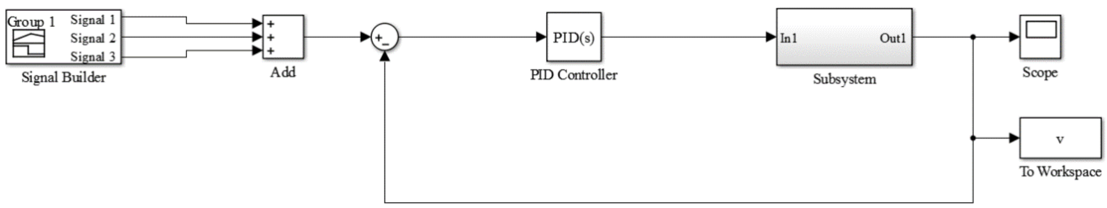


Fig. 4.9. Matlab/Simulink main block diagram of the Scenario 1.b

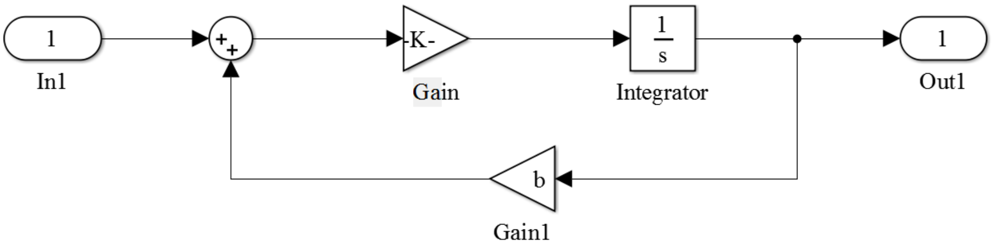


Fig. 4.10. Matlab/Simulink block diagram of the subsystem in the Scenario 1.a and 1.b

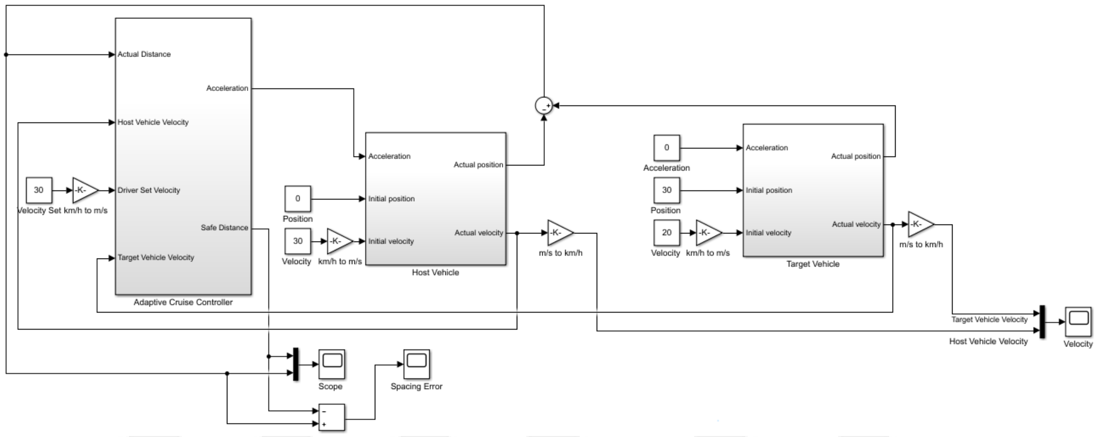


Fig. 4.11. Matlab/Simulink main block diagram of the Scenario 2

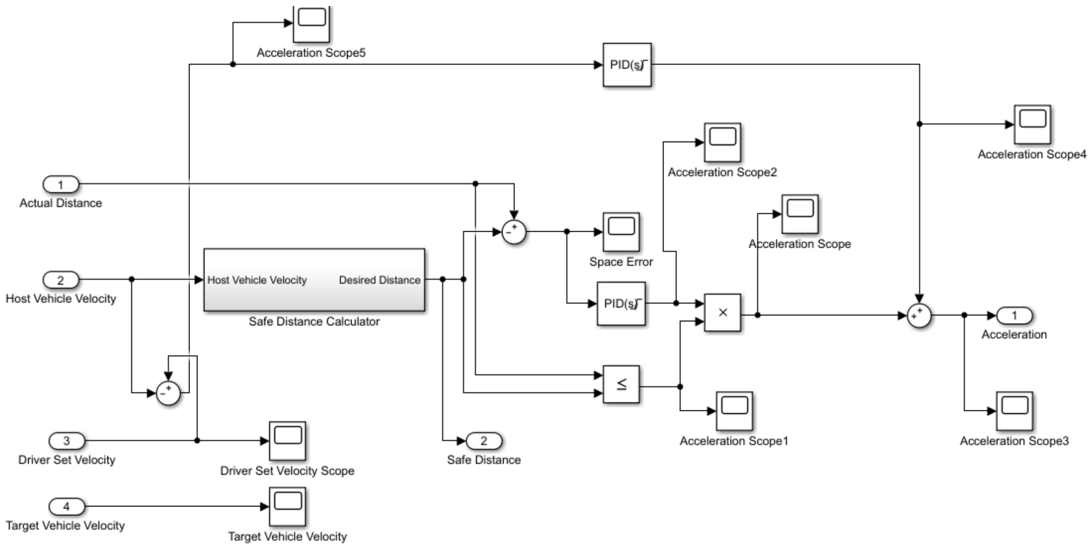


Fig. 4.12. Matlab/Simulink block diagram of the controller in the Scenario 2

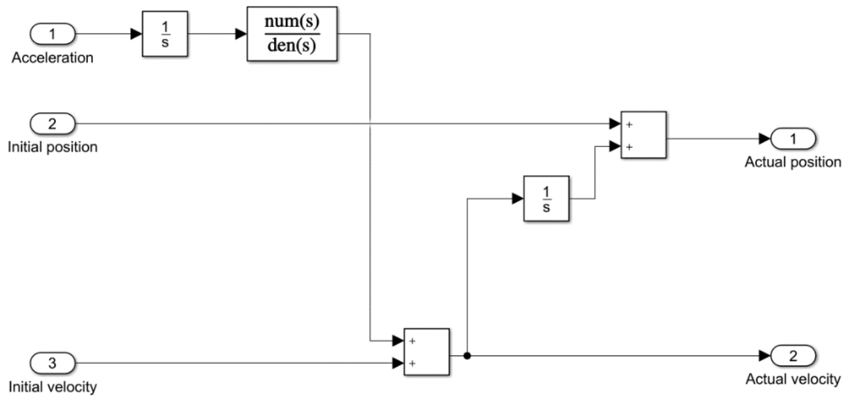


Fig. 4.13. Matlab/Simulink block diagram of the target and host vehicles in the Scenario 2

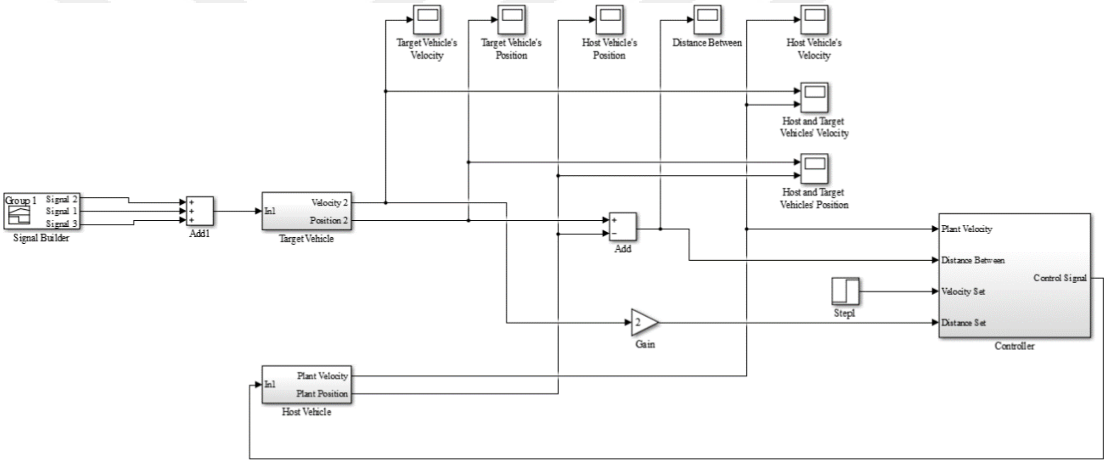


Fig. 4.14. Matlab/Simulink main block diagram of the Scenario 3

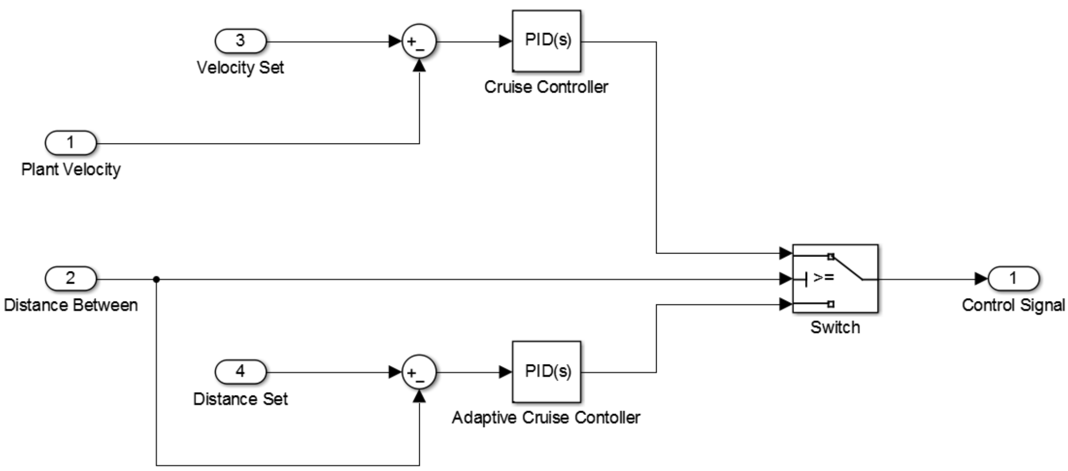


Fig. 4.15. Matlab/Simulink block diagram of the controller in the Scenario 3

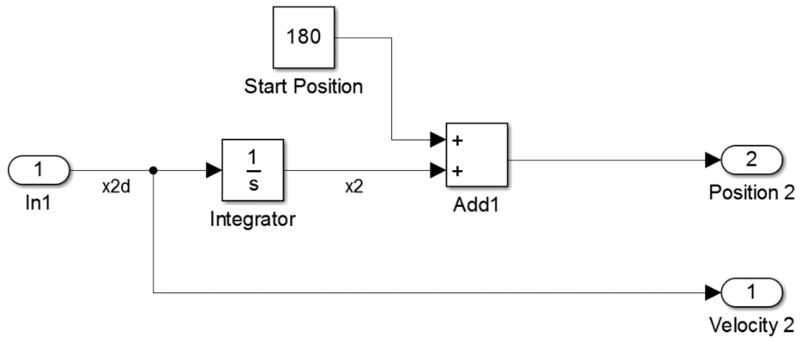


Fig. 4.16. Matlab/Simulink block diagram of the target vehicle in the Scenario 3

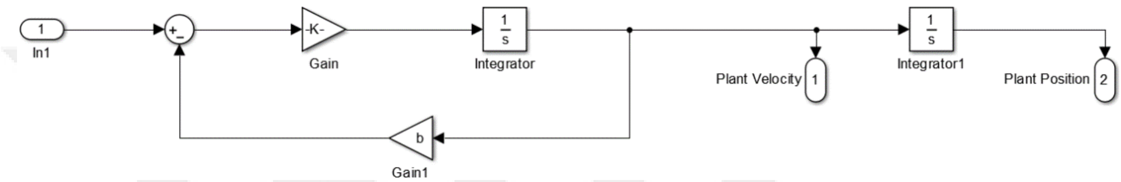


Fig. 4.17. Matlab/Simulink block diagram of the host vehicle in the Scenario 3

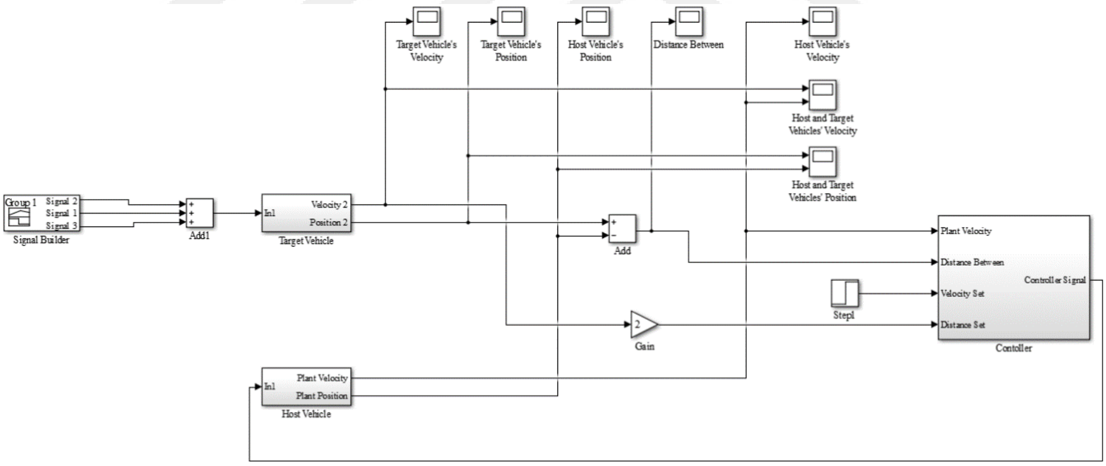


Fig. 4.18. Matlab/Simulink main block diagram of the Scenario 4

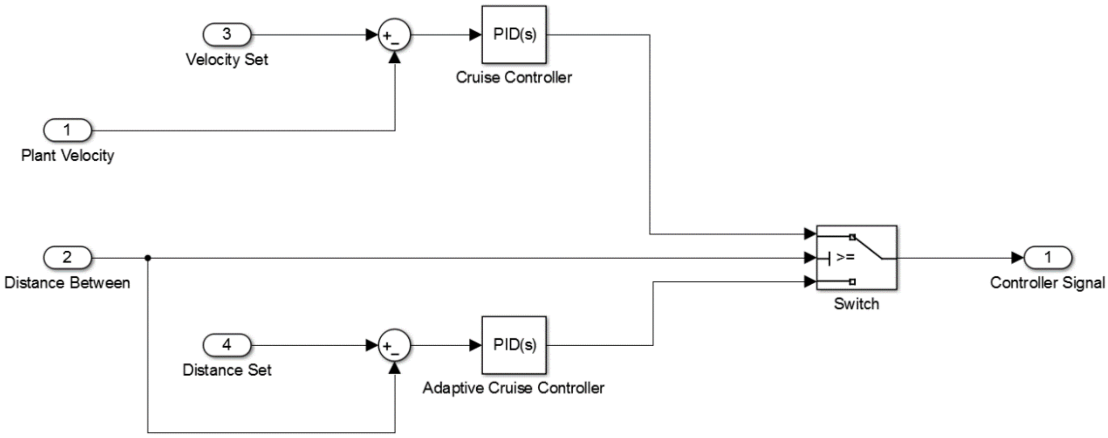


Fig. 4.19. Matlab/Simulink block diagram of the controller in the Scenario 4

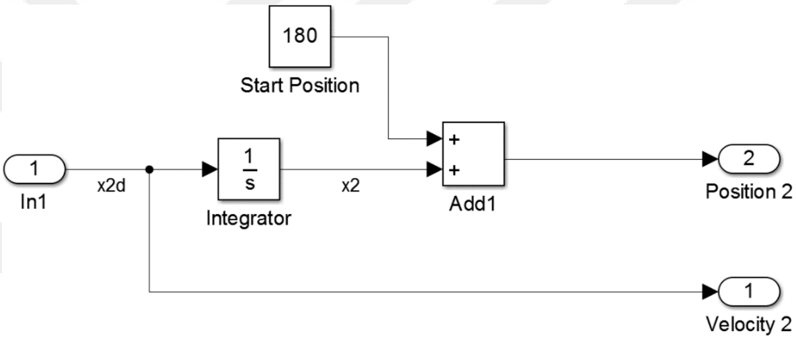


Fig. 4.20. Matlab/Simulink block diagram of the target vehicle in the Scenario 4

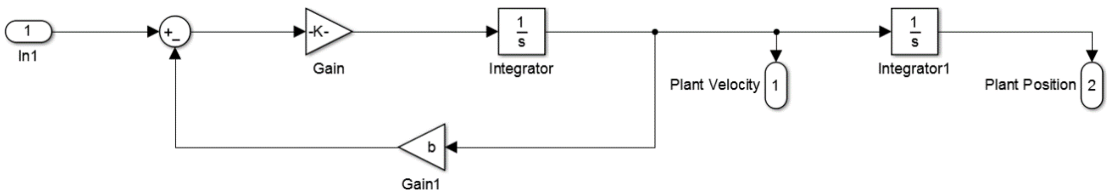


Fig. 4.21. Matlab/Simulink block diagram of the host vehicle in the Scenario 4

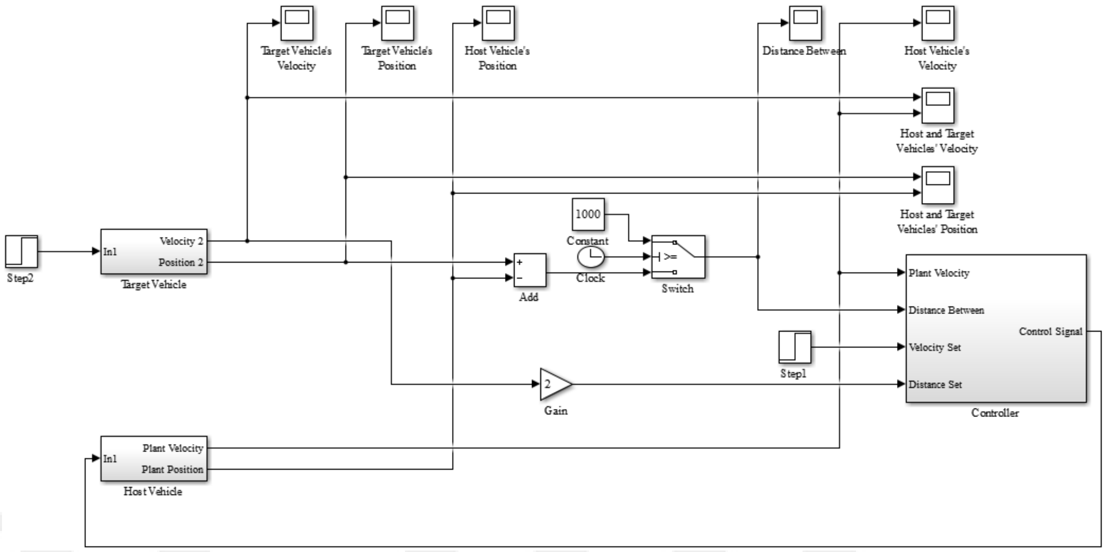


Fig. 4.22. Matlab/Simulink main block diagram of the Scenario 5

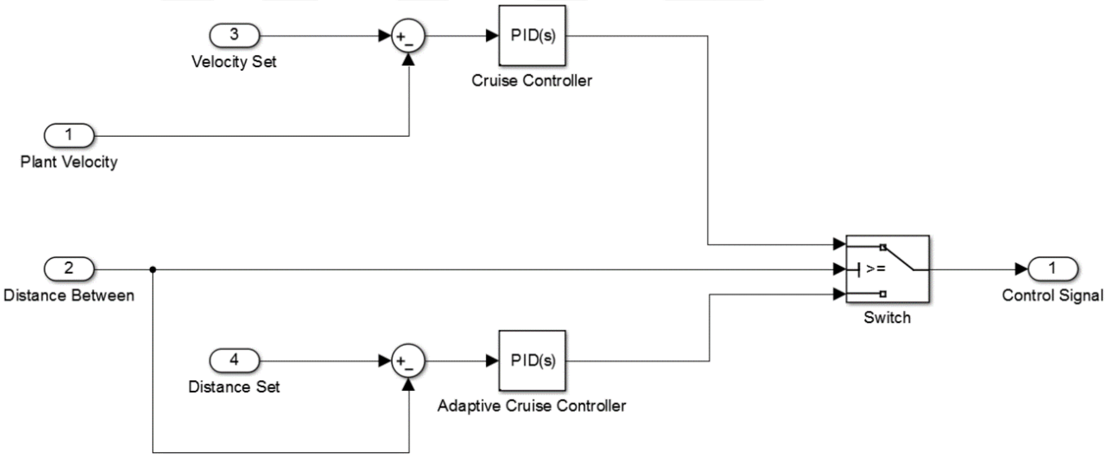


Fig. 4.23. Matlab/Simulink block diagram of the controller in the Scenario 5

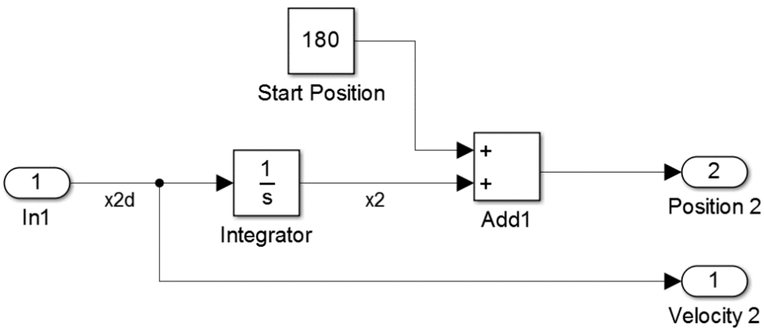


Fig. 4.24. Matlab/Simulink block diagram of the target vehicle in the Scenario 5

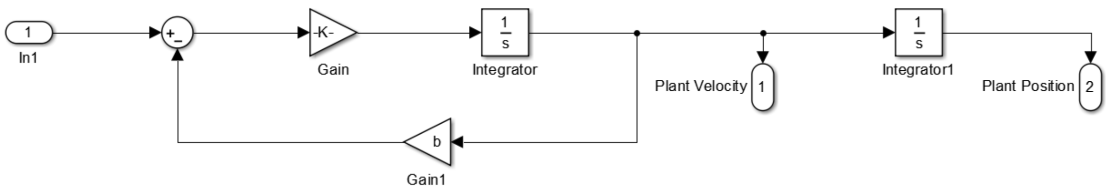


Fig. 4.25. Matlab/Simulink block diagram of the host vehicle in the Scenario 5

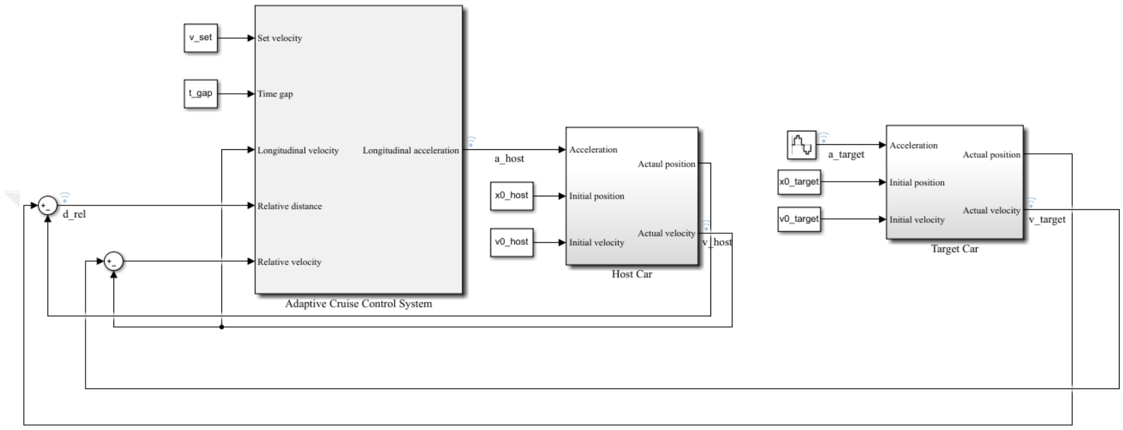


Fig. 4.26. Matlab/Simulink main block diagram of the Scenario 6

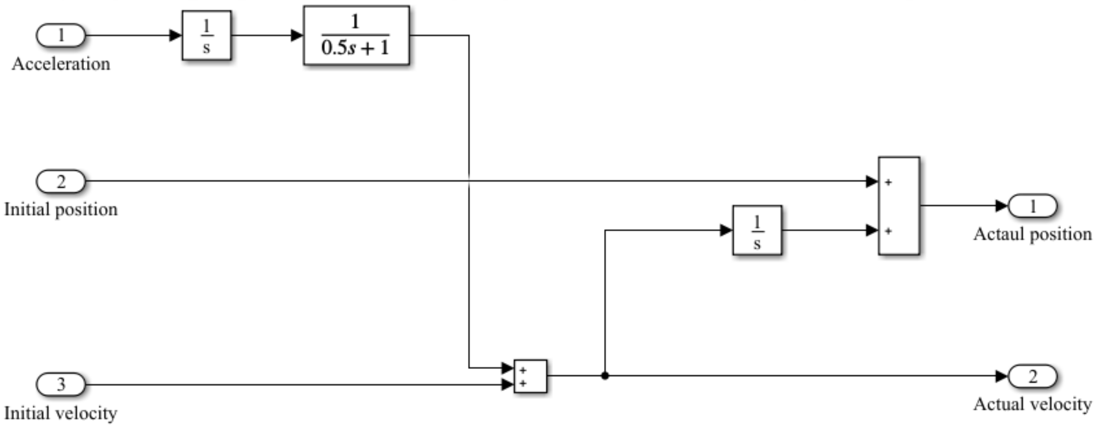


Fig. 4.27. Matlab/Simulink block diagram of the target and host vehicles in the Scenario 6

4.4.1. Position performance

In this section, the trajectories of the host and target vehicles are seen in Figures 4.28 – 4.32.

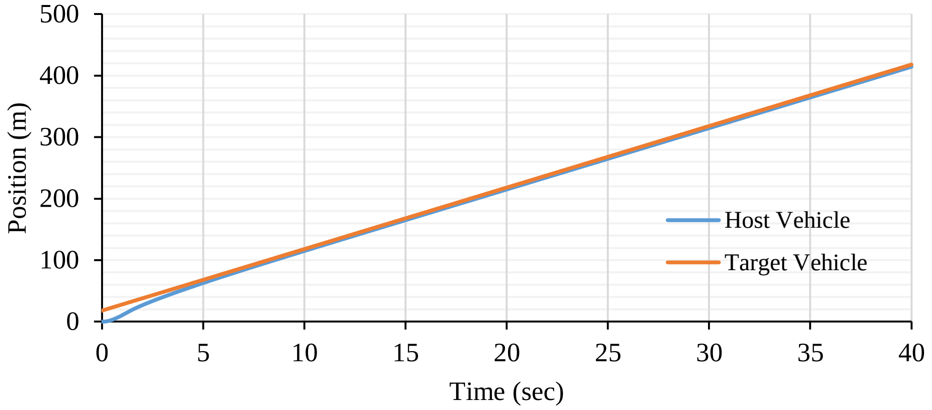


Fig. 4.28. Host and target vehicles' position-time graph in Scenario 2

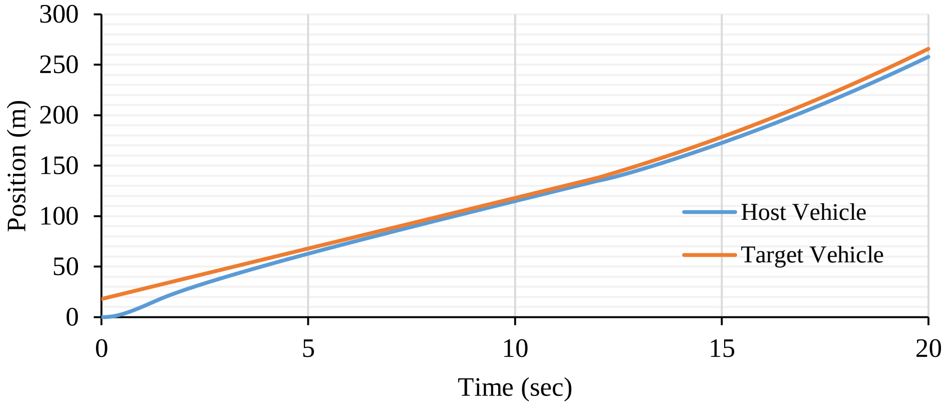


Fig. 4.29. Host and target vehicles' position-time graph in Scenario 3

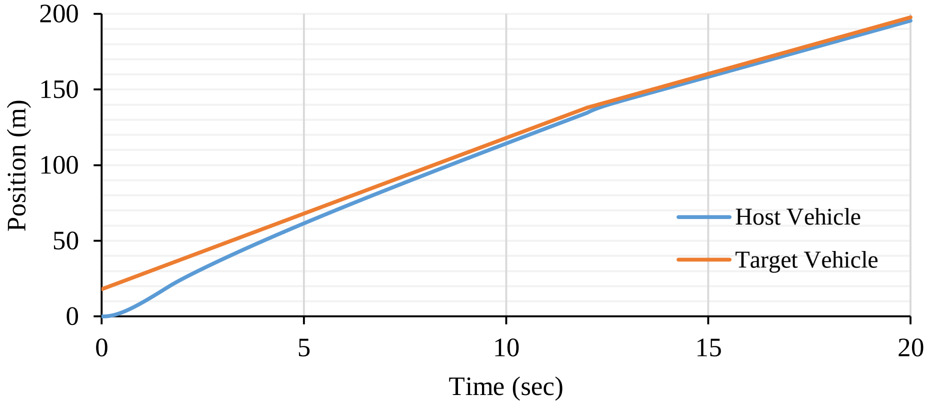


Fig. 4.30. Host and target vehicles' position-time graph in Scenario 4.a

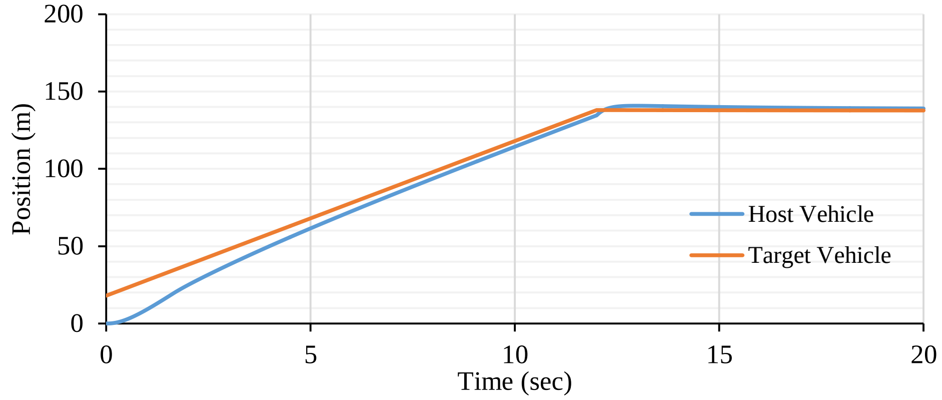


Fig. 4.31. Host and target vehicles' position-time graph in Scenario 4.b

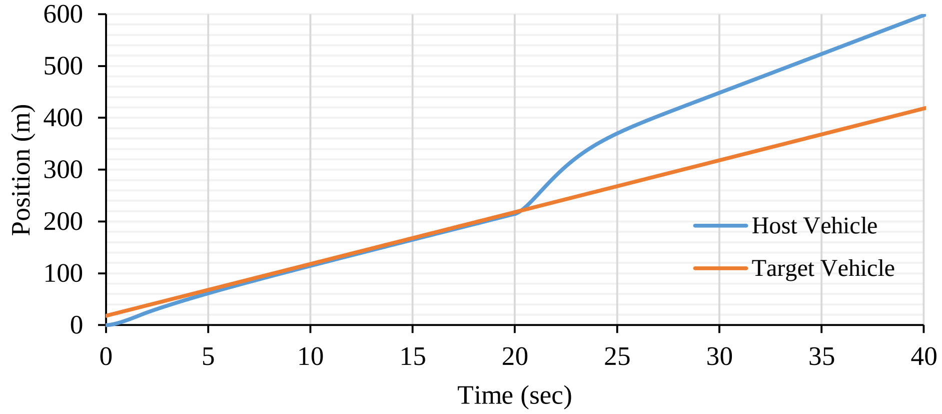


Fig. 4.32. Host and target vehicles' position-time graph in Scenario 5

4.4.2. Velocity performance

With the activation of the CC system, vehicle velocity is shown in Figure 4.33 for Scenario 1.a. The desired velocity is set to v_h = 30 km/h in this simulation. The host vehicle accelerated to 30 km/h velocity for approximately 4 seconds and it takes approximately 24 seconds to stabilize.

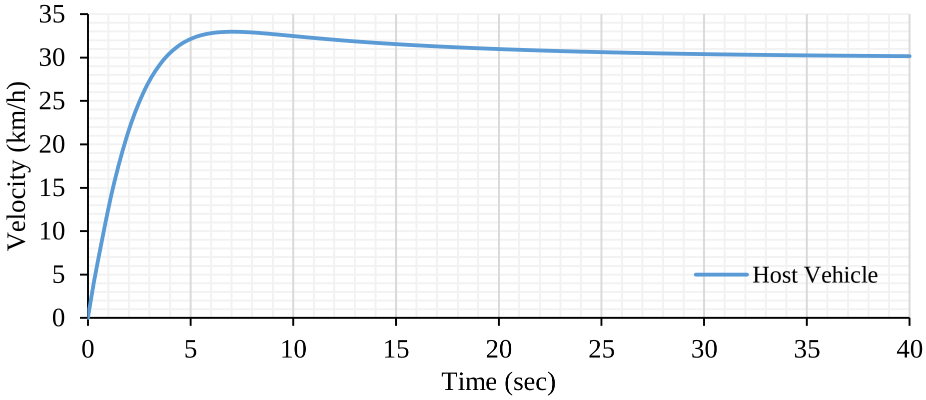


Fig. 4.33. Fixed vehicle velocity (Scenario 1.a)

In Scenario 1.b, three variable velocities are applied to the host vehicle at certain times for 40 seconds. In the first variable, the vehicle accelerates for 12 seconds to reach a 30 km/h velocity. It is seen that the vehicle reaches the target velocity of 20 km/h from 12th second to 24th second. After 24th second the vehicle reaches a velocity of 40 km/h (Figure 4.34).

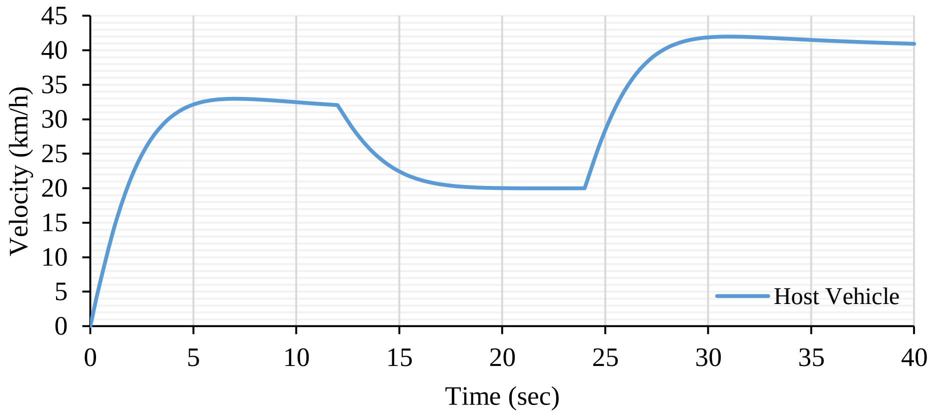


Fig. 4.34. Variable vehicle velocity (Scenario 1.b)

Figure 4.35 shows the velocity of the host and target vehicles. The velocity of two vehicles is equal to approximately 18th second.

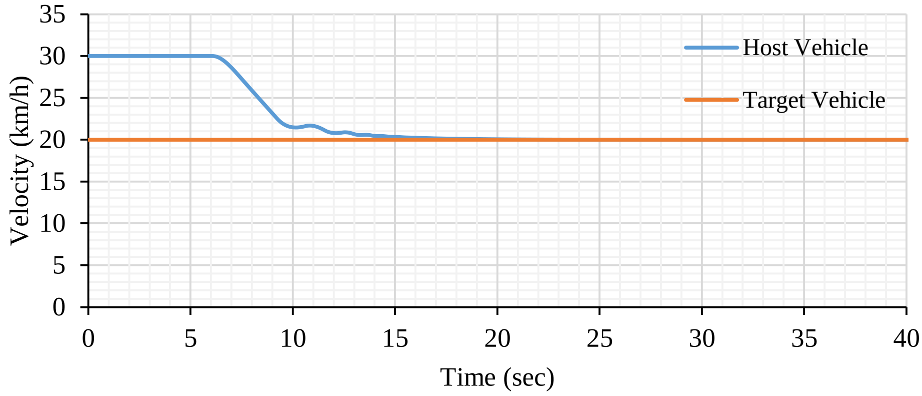


Fig. 4.35. Velocities of the vehicles in Scenario 2

According to Scenario 3, the velocity graph of the host and target vehicles is shown in Figure 4.36. After the velocity of the vehicles is equal in the 12th second, the velocity of the target vehicle increases to 24 km/h and then increases linearly. During this time, the host reduced the vehicle velocity and provided a safe driving distance. The host vehicle then followed the target vehicle within the safe tracking distance.

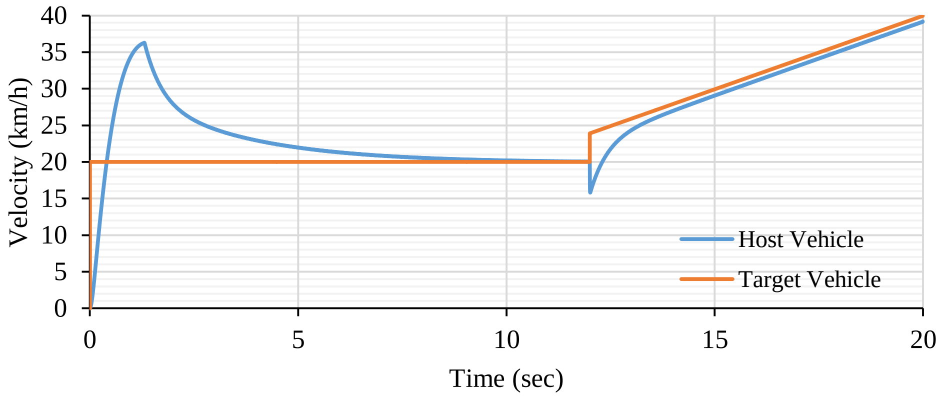


Fig. 4.36. Velocities of the vehicles in Scenario 3

According to Scenario 4.a and 4.b, the velocity graph of the host and target vehicles are shown in Figure 4.37 and 4.38. It is seen that the velocity of the vehicles is equalized in the 12th second and the velocity of the target vehicle decreases from 20 km/h to 15 km/h after the 12th second. The host vehicle accelerates to close the distance and follows the target vehicle in the safe distance limits by reaching the same velocity. Accordingly, it is seen that the host vehicle accelerates to close the distance and follows the target vehicle within the safe distance limits by reaching the same velocity.

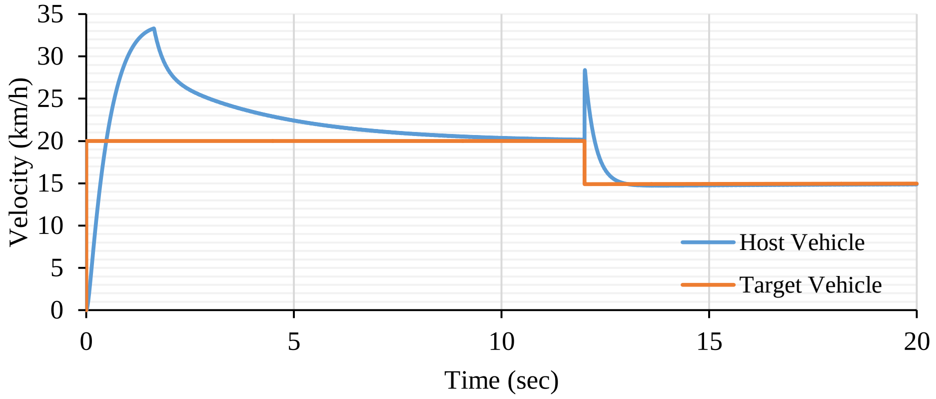


Fig. 4.37. Velocities of the vehicles in Scenario 4.a

According to Scenario 4.b, it is seen that the velocity of the vehicles is equalized in the 12th second and the velocity of the target vehicle decreases from 20 km/h to 0 km/h after the 12th second.

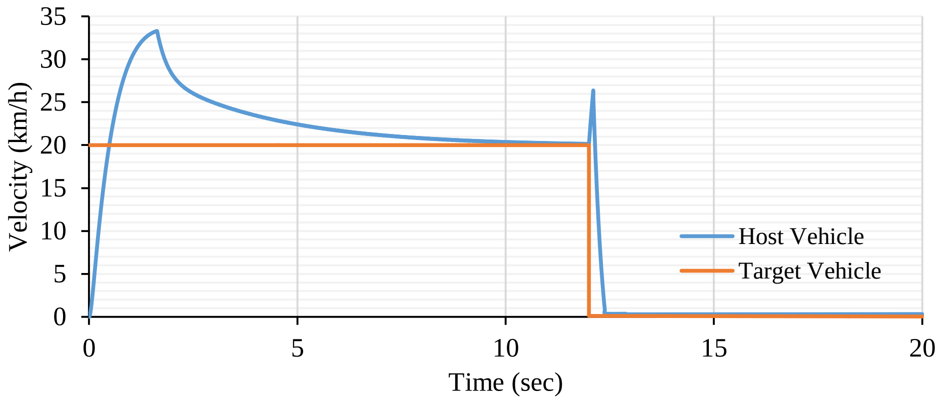


Fig. 4.38. Velocities of the vehicles in Scenario 4.b

The host and target vehicles' velocity-time graph is shown in Figure 4.39 for Scenario 5. In this simulation, which the vehicle velocities are equalized in 12th second, the target vehicle changes the lane without changing its velocity in 20 seconds. Since there is no vehicle in front of the host vehicle, it is seen that it accelerates after 20 seconds and continues at a velocity of 30 km/h from 28th second.

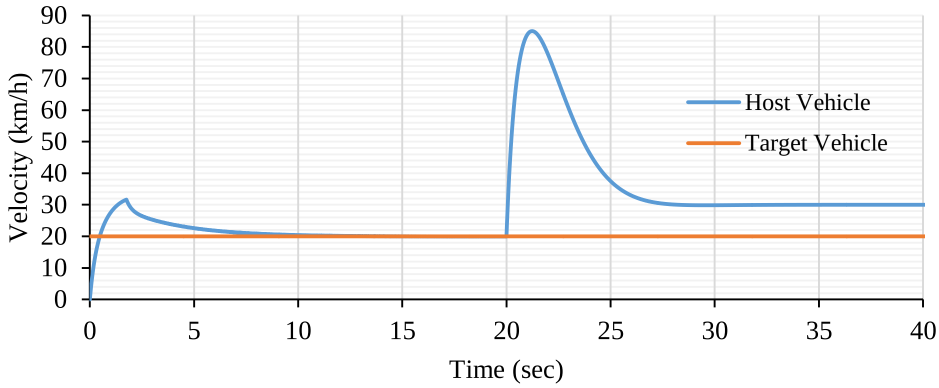


Fig. 4.39. Velocities of the vehicles in Scenario 5

According to Scenario 6, in the first 6 seconds, the host car accelerates at full throttle to reach the velocity set by the driver, and reaches 30 m/s velocity. At 65th second, the host vehicle detects the target vehicle in the same lane and starts to slow down to maintain safe distance. The host vehicle accelerates with a slow rate because the target vehicle slowly accelerates from 63 to 80 seconds. Between 77 and 87 seconds, the host vehicle maintains the velocity set by the driver as shown in Figure 4.40. After 86th second, the target vehicle slows down and the host vehicle adjusts the velocity to provide a safe distance to the target vehicle. After 95th second, the deceleration/acceleration sequence in 15 seconds interval is repeated.

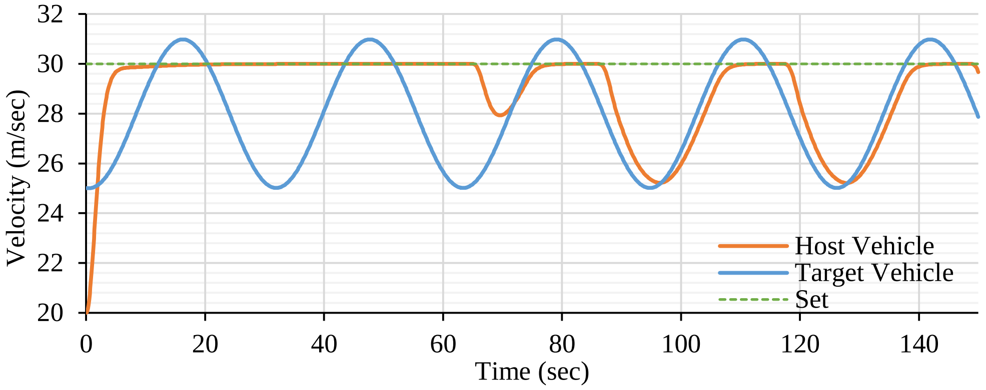


Fig. 4.40. Velocities of the vehicles in Scenario 6

4.4.3. Relative distance between the vehicles

The distance between the two vehicles is 180 m at the beginning and it falls to 40 m in 10th second. As the target vehicle travels at 20 km/h, the host vehicle tries to keep its safe driving distance at 40 m (Figure 4.41).

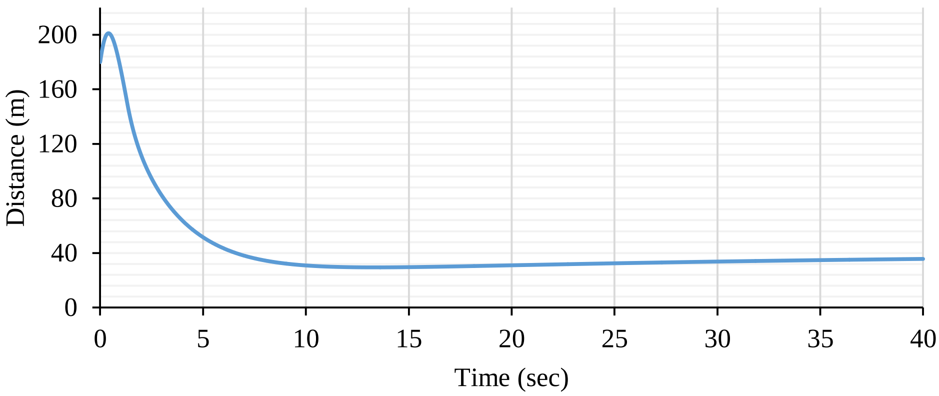


Fig. 4.41. The relative distance between the vehicles in Scenario 2

In Scenario 3, the distance between the two vehicles, which was initially 180 m, fell to 40 m in 10 seconds and increased from 12th second (Figure 4.42).

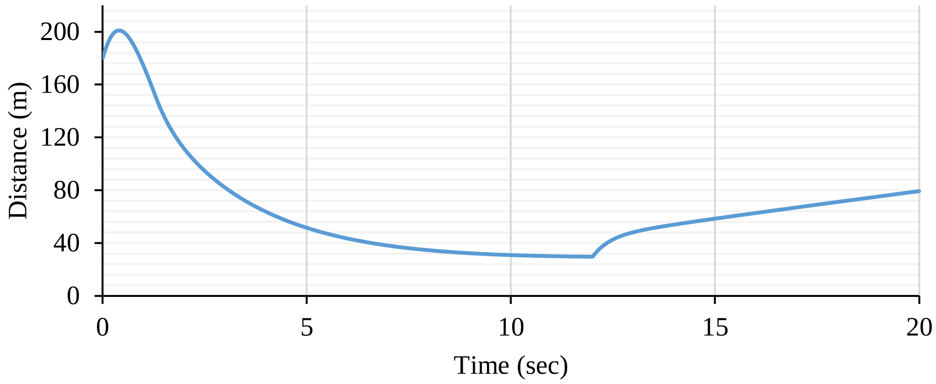


Fig. 4.42. The relative distance between the vehicles in Scenario 3

According to Figure 4.43, initially between the two vehicles are 180 m distance and this distance falls to 40 m in the tenth second and then continues linearly in Scenario 3. The target vehicle speed is 15 km/h from the twelfth second, therefore, the distance between vehicles is reduced to a safe driving distance of approximately 30 m.

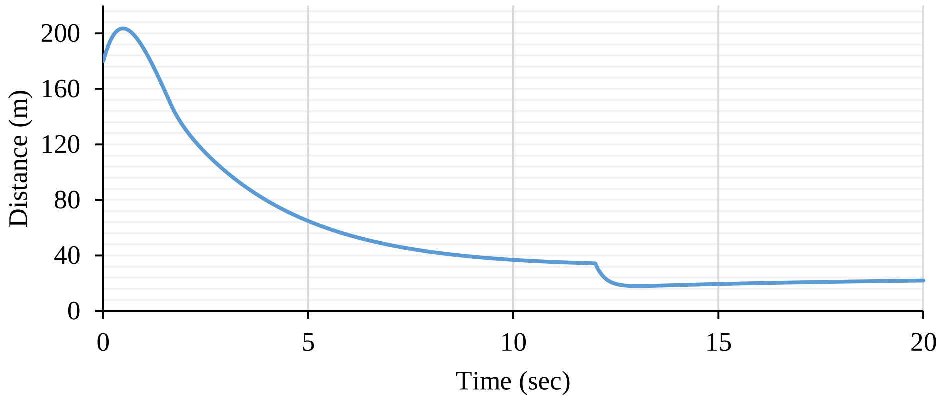


Fig. 4.43. The relative distance between the vehicles in Scenario 4.a

According to Figure 4.44, the target vehicle's velocity is 0 km/h at twelfth seconds, therefore, the host vehicle has stopped at safe driving distance in Scenario 4.a.

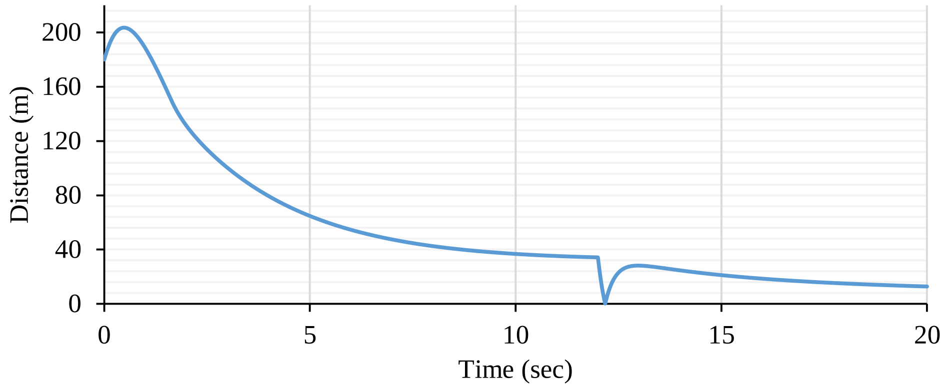


Fig. 4.44. The relative distance between the vehicles in Scenario 4.b

In Scenario 4.b, it is observed that the distance between two vehicles is 180 m at the beginning and it falls to 40 m in 10 seconds. After 20 seconds the target vehicle changed the lane (Figure 4.45).

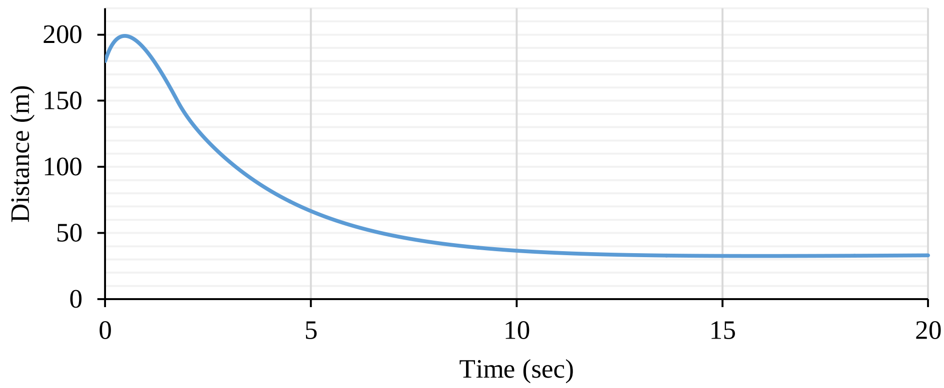


Fig. 4.45. The relative distance between the vehicles in Scenario 5

In Scenario 6, the distance between the two vehicles is 180 m at the beginning and in 73^{th} seconds the host vehicle reaches the target vehicle and tries to keep its safe driving distance as shown in the distance plot (Figure 4.46).

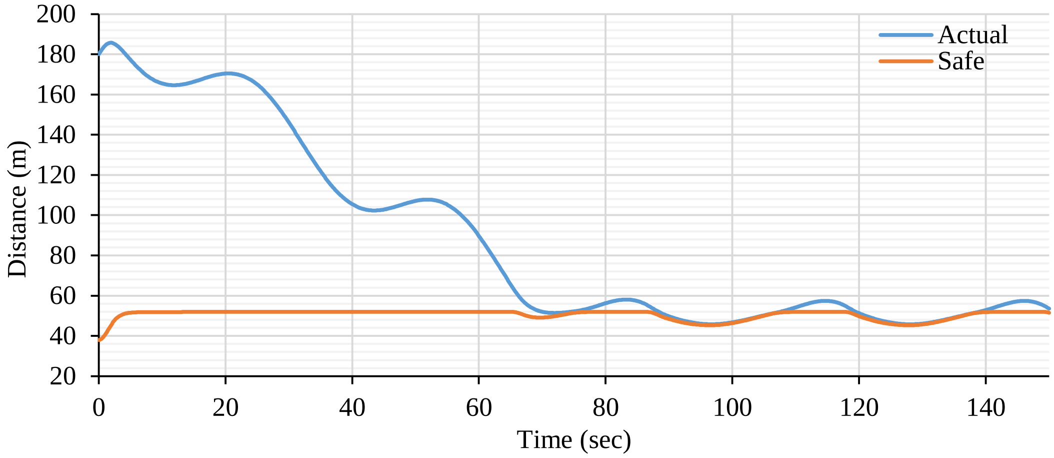


Fig. 4.46. The relative distance between the vehicles in Scenario 6

4.4.4. Acceleration performance

In Scenario 6, in order to determine a real driving environment, the acceleration of the target vehicle has been changed according to the sinus wave during the simulation (Figure 4.47). The ACC system block outputs an acceleration control signal for the host vehicle.

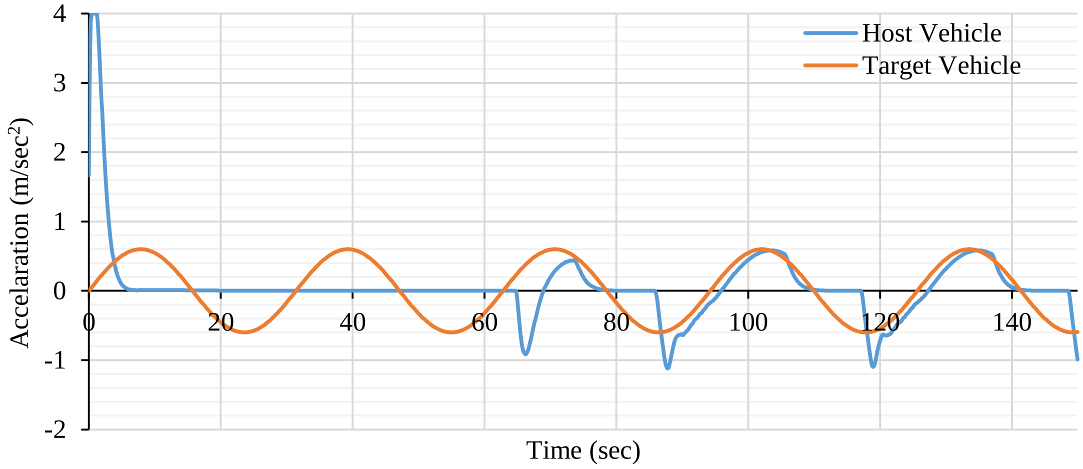


Fig. 4.47. Accelaration changes of the vehicles in Scenario 6

4.5. Experimental Results

The results obtained from the scenarios created in the ACC and the data obtained from the application are presented here together. The Vgate iCar OBD II adapter which is developed by the HK Vgate Technology Co., Ltd. was used to measure engine speed. This product that a powerful vehicle diagnostic tool for communication with vehicle, was connected to our pad with a wireless connection and enabled us to see all measurements (Figure 4.41). The overview of Vgate iCar OBD II interface is provided in Appendix.

Fig. 4.48. OBD II diagnostic interface

After the OBD II diagnostic interface was placed on the vehicle, measurements for Scenario 1.a and Scenario 2 were taken (Figure 4.49).

Fig. 4.49. A photograph from the experimental measurements

According to simulated and experimental results, Figures 4.50 – 4.52 show the velocity-time graphs for Scenario 1.a, 2 and 4.b.

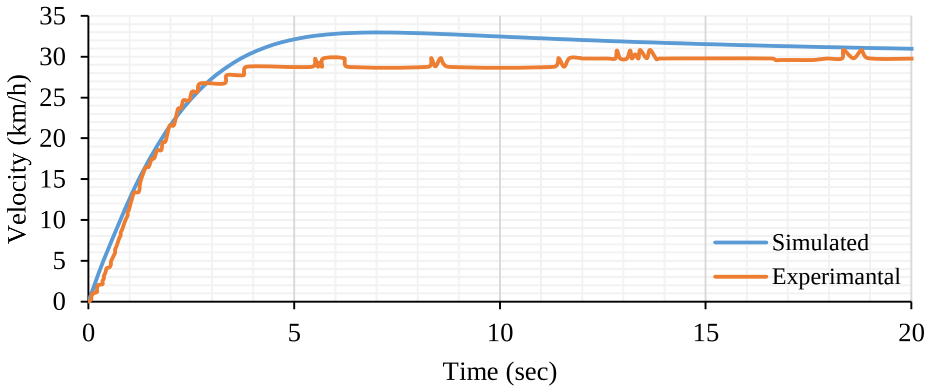


Fig. 4.50. Simulated and experimental host vehicle's velocities in Scenario 1.a

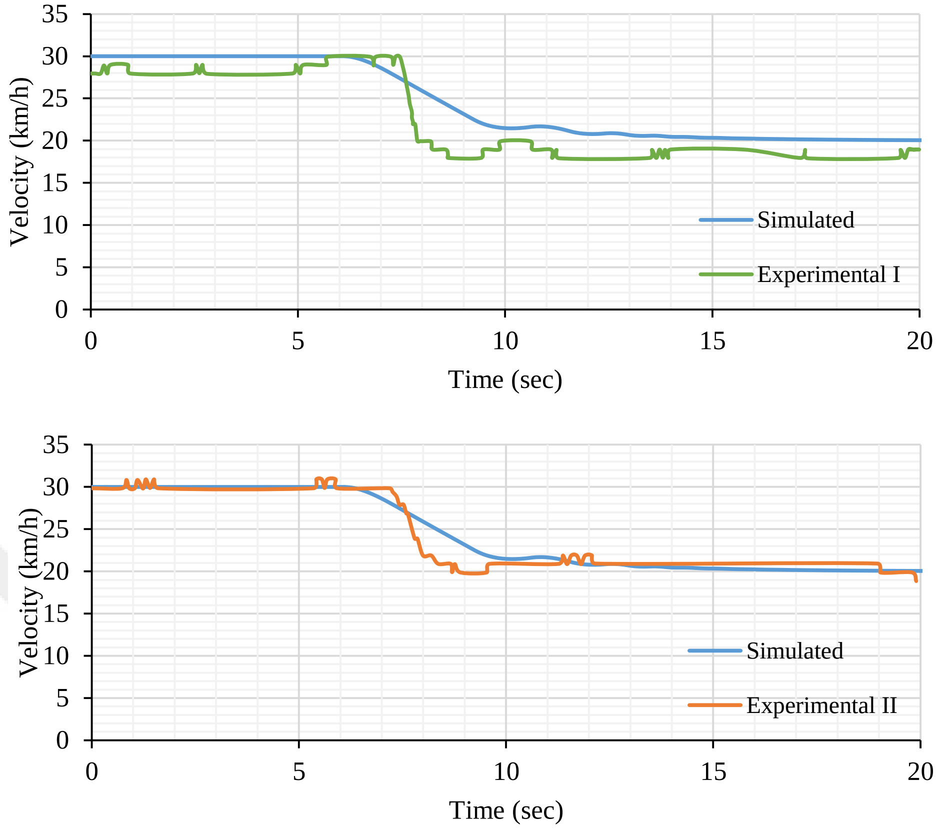


Fig. 4.51. Simulated and experimental host vehicle’s velocities in Scenario 2

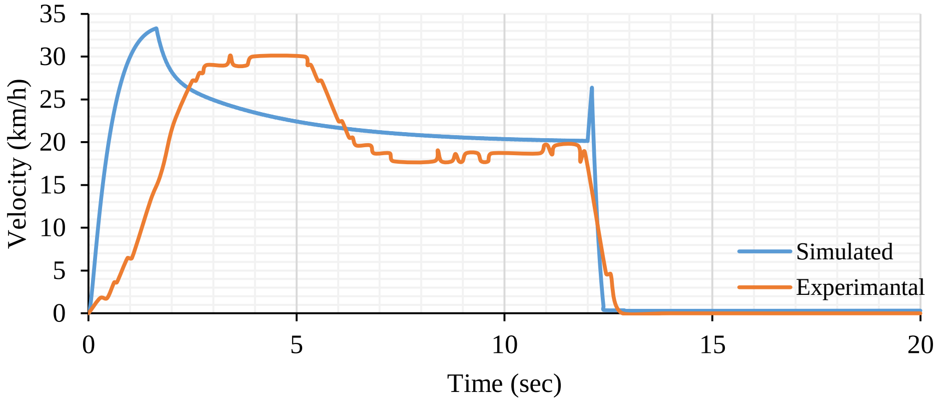


Fig. 4.52. Simulated and experimental host vehicle’s velocities in Scenario 4.b

V. CONCLUSION AND FUTURE WORK

In this thesis, Simulink control design was applied on the CC and ACC systems and the performance of the controller with the dynamics of the vehicle was simulated by creating scenarios. These scenarios were also applied in practice with an ACC system and the measurement data obtained by connecting to the Electronic Control Unit (ECU) of this vehicle were compared with the predicted data.

All software is created in Matlab/Simulink environment and it is suitable for development because of its modular structure. This simulation was developed in detail to examine how the control system reacts in daily life. In this context, this control system is experimentally examined with a vehicle that has ACC system. The actual values and the control system's values are compared. The coherence of experimental and simulation results suggests that it may pioneer future studies.

The controller in the simulation works with the target detection method. When the traffic is in the driving state, there are many target vehicles around. Therefore, these objectives should be included in the infrastructure of the controller in future studies. In the future, these navigation systems will become a system that will be used not only by detecting targets but also by communicating with other vehicles around. As a continuation of this work, studies should be carried out on how these systems can be optimized in order to investigate the effects of this communication system on traffic or to increase the capacity of the traffic.

In addition, by using these systems, convoy system can be formed in traffic and it can be investigated how the effect of communication of these vehicles with each other. One of the benefits of the convoy system is that it allows us to keep track of the vehicles with a shorter distance and contribute positively to the traffic density. In fact, the effect of this short-distance tracking on the reduction of the friction resistance of the wind can be examined and fuel savings can be achieved. By improving sensor, radar and camera structures and adding image processing systems, enrichment of the control structure of the system can be investigated.

Finally, by adding GPS to the control structure, the traffic situation can be reached and alternative routes can be found for the route the vehicle will be following. Thus, very useful simulators can be created.

REFERENCES

[1] The Turkish Statistical Institute (TÜİK), 13 September 2018. Available: http://www.tuik.gov.tr.

[2] M. Williams, "PROMETHEUS-The European research programme for optimising the road transport system in Europe", IEE Colloquium on Driver Information, London, UK, December 1, 1988.

[3] E. D. Dickmanns, R. Behringer, D. Dickmanns, T. Hildebrandt, M. Maurer, F. Thomanek, J. Schiehlen, "The seeing passenger car 'VaMoRs-P'", Proceedings of the Intelligent Vehicles '94 Symposium, Paris, France, 24-26 October 1994.

[4] D. A. Pomerleau , "ALVINN: An Autonomous Land Vehicle in a Neural Network", Advances in Neural Information Processing Systems, San Mateo, CA, Morgan Kaufmann Publishers Inc., pp. 305-313, 1989.

[5] DARPA, "Grand Challenge 2004 Final Report", Defense Advanced Research Projects Agency, Arlington, VA, 2004.

[6] V. A. Kovalev, W. E. Eichinger, "Elastic Lidar: Theory, practice, and analysis methods", New Jersey: John Wiley & Sons, Inc., 2004.

[7] L. M. Bergasa, J. Nuevo, M. A. Sotelo, R. Barea, E. Lopez, "Real-time system for monitoring driver vigilance", IEEE Transactions on Intelligent Transportation Systems, vol. 7(1), pp. 63-77, 2006.

[8] C. Papadelis, Z. Chen, C. Kourtidou-Papadeli, P. D. Bamidis, I. Chouvarda, E. Bekiaris, N. Maglaveras, "Monitoring sleepiness with on-board

electrophysiological recordings for preventing sleep-deprived traffic accidents", Clinical Neurophysiology, vol. 118(9), pp. 1906-1922, 2007.

[9] C. T. Lin, C. J. Chang, B. S. Lin, S. H. Hung, C. F. Chao, I. J. Wang, "A real-time wireless brain-computer interface system for drowsiness detection", IEEE Transactions on Biomedical Circuits and Systems, vol. 4(4), pp. 214-222, 2010.

[10] Y. Takei, Y. Furukawa, "Estimate of driver's fatigue through steering motion", IEEE International Conference on Systems, Man and Cybernetics, Waikoloa, HI, USA, 10-12 October 2005.

[11] T. Wakita, K. Ozawa, C. Miyajima, K. Igarashi, K. Itou, K. Takeda, F. Itakura, "Driver identification using driving behavior signals", IEICE Transactions on Information and Systems, vol. E89-D(3), pp. 1188-1194, 2006.

[12] J. C. McCall, D. P. Wipf, M. M. Trivedi, B. D. Rao, "Lane change intent analysis using robust operators and sparse bayesian learning", IEEE Transactions on Intelligent Transportation Systems, vol. 8(3), pp. 431-440, 2007.

[13] T. H. Chang, C. S. Hsu, C. Wang, L. K. Yang, "Onboard measurement and warning module for irregular vehicle behavior", IEEE Transactions on Intelligent Transportation Systems, vol. 9(3), pp. 501-513, 2008.

[14] M. Suzuki, N. Yamamoto, O. Yamamoto, T. Nakano, S. Yamamoto, "Measurement of driver’s consciousness by image processing – a method for presuming driver’s drowsiness by eye-blinks coping with individual differences", IEEE International Conference on Systems, Man and Cybernetics, Taipei, Taiwan, 8-11 October 2006.

[15] T. D'Orazio, M. Leo, C. Guaragnella, A. Distante, "A visual approach for driver inattention detection", Pattern Recognition, vol. 40(8), pp. 2341-2355, 2007.

[16] Q. Ji, X. Yang, "Real-time eye, gaze, and face pose tracking for monitoring driver vigilance", Real-Time Imaging, vol. 8(5), pp. 357-377, 2002.

[17] L. Bretzner, M. Krantz, "Towards low-cost systems for measuring visual cues of driver fatigue and inattention in automotive applications", IEEE International Conference on Vehicular Electronics and Safety, Shaan'xi, China, 14-16 October 2005.

[18] J. Heinzmann, D. R. D. Tate, R. Scott, "Using technology to eliminate drowsy driving", SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production, Nice, France, 15-17 April 2008.

[19] K. J. Bryden, J. L. Charlton, J. A. Oxley, G. J. Lowndes, "Acceptance of navigation systems by older drivers", Gerontechnology, vol. 13(1), pp. 21-28, 2014.

[20] S. Huh, D. H. Shim, J. Kim, "Integrated navigation system using camera and gimbaled laser scanner for indoor and outdoor autonomous flight of UAVs", IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Tokyo, Japan, 03-07 November 2013.

[21] M. C. Taylor, D. A. Lynam, A. Baruya, "The effects of drivers' speed on the frequency of road accidents", TRL Report 421, Crowthorne, Berkshire, 2000.

[22] O. Carsten, M. Fowkes, F. Lai, K. Chorlton, S. Jamson, F. Tate, B. Simpkin, "ISA - UK intelligent speed adaptation", The University of Leeds and MIRA Ltd., June 2008.

[23] D. Swaroop, J. K. Hedrick, C. C. Chien, P. Ioannou, "A comparison of spacing and headway control laws for automatically controlled vehicles", Vehicle System Dynamics, vol. 23(8), pp. 597-625, 1994.

[24] D. Yanakiev, I. Kanellakopoulos, "Nonlinear spacing policies for automated heavy-duty vehicles", IEEE Transactions on Vehicular Technology, vol. 47(4), pp. 1365-1377, 1998.

[25] K. Santhanakrishnan, R. Rajamani, "On spacing policies for highway vehicle automation", IEEE Transactions on Intelligent Transportation Systems, vol. 4(4), pp. 198-204, 2003.

[26] J. Marzbanrad, N. Karimian, "Space control law design in adaptive cruise control vehicles using model predictive control", Journal of Automobile Engineering, vol. 225(7), pp. 870-884, 2011.

[27] B. H. Wilson , "How soon to brake and how hard to brake: Unified analysis of the envelope of opportunity for rear-end collsion warnings", 17th International Technical Conference on the Enhanced Safety of Vehicles, Amsterdam, Holland, 4-7 June 2001.

[28] B. Németh, P. Gáspár, "Design of low conflict cruise control for safety critical vehicle interactions", IFAC-PapersOnLine, vol. 48(21), pp. 1186-1191, 2015.

[29] S. Darbha, "String stability of interconnected systems: an application to platooning in automated highway systems", Ph. D. Thesis in Mechanical Engineering, University of California, Berkeley, April 1997.

[30] R. Gerhard, J. Scheef, H. Becker, M. Stanzel, R. Zobel, "Active safety systems change accident environment of vehicles significantly - A challange for vehicle

design", The 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Washington, DC., 6-9 June 2005.

[31] Y. Takae, M. Iwai, M. Kubota, T. Watanabe, "A study of drivers’ trust in a low-speed following system", SAE World Congress & Exhibition, Detroit, Michigan, USA, 21-23 April 2005.

[32] ISO 8855 - Road vehicle - Vehicle dynamics and road holding ability, International Organization for Standardization, Genève, Switzerland, 15 December 2011.

[33] A. Visioli, "Practical PID Control", London: Springer-Verlag London Limited, 2006.

[34] M. A. Johnson, M. H. Moradi, "PID Control New Identification and Design Methods", London: Springer-Verlag London Limited, 2005.

[35] S. J. Qin, T. A. Badgwell, "A survey of industrial model predictive control technology", Control Engineering Practice, vol. 11(7), pp. 733-764, 2003.

[36] R. Günay, A. Köse, R. N. Tuncay, “Adaptif Seyir Kontrol Sistemi Simülasyonu”, Elektrik Elektronik Mühendisliği Kongresi (EEMKON 2017) Elektrik ve Kontrol Mühendisliği Sempozyumu, İstanbul, Turkey, 16-18 December 2017.

APPENDIX

Table A.1. Electrical specification of Vgate iCar Pro OBD II adapter

Supply Voltage	: 11.5 V – 15 V
Supply Current	: < 200 mA
Standby Current	: < 30 mA (iCar Pro =<3 mA)
Operating Temperature	: – 40℃ – 85℃
Operating Humidity	: 5% – 95%RH Non-Dewfall

Table A.2. Protocols supported by Vgate iCar OBD II adapter

SAE J1850 PWM(41.6 Kbaud)	ISO15765-4 CAN(29bit ID,500 Kbaud)
SAE J1850 VPW(10.4 Kbaud)	ISO15765-4 CAN(11bit ID,250 Kbaud)
ISO9141-2(5 baud init,10.4 Kbaud)	ISO15765-4 CAN(29bit ID,250 Kbaud)
ISO14230-4 KWP(5 baud init,10.4 Kbaud)	SAE J1939 CAN(29bit ID,250* Kbaud)
ISO14230-4 KWP(fast init,10.4 Kbaud)	USER1 CAN(11*bit ID,125* Kbaud)
ISO15765-4 CAN(11bit ID,500 Kbaud)	USER2 CAN(11*bit ID,50* kbaud)

Table A.3. Some features available in the Vgate iCar OBD II database

Clear trouble codes and turn off the MIL ("Check Engine" light)	Oxygen sensor voltages/associated short term fuel trims
Engine RPM	Timing Advance
Calculated Load Value	Intake Air Temperature
Coolant Temperature	Air Flow Rate
Fuel System Status	Absolute Throttle Position
Vehicle Speed	Fuel System status
Short Term Fuel Trim	Fuel Pressure
Long Term Fuel Trim	Many others…
Intake Manifold Pressure	

VITA

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