MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES IN PURE AND APPLIED SCIENCES

Control System Architecture Design for Safety in Intelligent Adaptive Cruise Control (IACC): Model-Based Approach

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MASTER THESIS

Department of Electrical and Electronics Engineering

Thesis Supervisor

Assoc. Prof. Onur CIHAN

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To my family,

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ÖZET

AKILLI HIZ KONTROL SİSTEMİNDE GÜVENLİK İÇİN KONTROL SİSTEM MİMARİ TASARIMI: MODEL TABANLI YAKLAŞIM

Bu yüksek lisans tezi, otonom araçlarda yaygın olan endüstriyel ve güvenlik standartlarını dikkate alan Akıllı Adaptif Hız Kontrolü için bir kontrol sistem mimarisinin tasarımını ortaya koymakta ve uygulamaktadır. Temel hedef, Akıllı Adaptif Hız Kontrolü özelliğini otonom araçlara entegre etmek için kontrol sistem mimarisini oluşturmaktı. Tez, bilimsel, ekonomik ve sosyal boyutlarda önemli katkılara sahiptir. Bu tasarımda kullanılan temel bileşenler, Trafik Hız Sınırı Tanıma özelliği ve küresel konumlandırma sistemi verilerini içermektedir. Bu özelliklerin entegrasyonunun sürücülere gelişmiş ve daha güvenli bir sürüş deneyimi sunması beklenmektedir. Temel odak, özellikle güvenli sürüş uygulamalarına katkı sağlayan yeni destekleyici özellikleri içeren bir kontrol sistem mimarisi tasarlamaya yöneliktir. Bu mimari çerçeve, Akıllı Adaptif Hız Kontrolü'ndeki güvenlik yönlerini detaylı bir şekilde incelemek için kapsamlı bir şekilde incelenmiştir. Bu tezin ana katkıları şu şekilde özetlenebilir: Virajlı yollarda güvenliğin artırılması: Tez, GPS verilerinden yararlanarak virajlı yollarda güvenlik risklerinin azaltılmasına katkıda bulunacak, böylece hayati bir ADAS özelliği olan mevcut ACC'yi geliştirecektir. Güvenlik için veri entegrasyonu: Güvenlik amacıyla, IACC'nin, sağlandığında başka bir ADAS özelliğinden gelen trafik hız sınırı verilerini aktif olarak paylaşarak ve işleyerek genel güvenlik önlemlerini güçlendirmesi bekleniyor. Mimari gelişmeler: Bu çalışma, mimarisinde daha önce bahsedilen özellikleri destekleyerek yeni bir ACC konseptinin oluşmasına katkı sağlayacaktır. Bu, uyarlanabilir hız sabitleyici işlevselliğini geliştirmeye yönelik bütünsel bir yaklaşımı temsil eder.

ABSTRACT

CONTROL SYSTEM ARCHITECTURE DESIGN FOR SAFETY IN INTELLIGENT ADAPTIVE CRUISE CONTROL (IACC)

This master's thesis delineates and implements the design of a control system architecture for Intelligent Adaptive Cruise Control, aligning with industrial and safety standards prevalent in autonomous vehicles. The primary objective was to formulate the control system architecture for integrating the Intelligent Adaptive Cruise Control feature into autonomous vehicles. The thesis holds noteworthy contributions in scientific, economic, and social dimensions. The foundational components utilized in this design encompass the Traffic Speed Limit Recognition feature and global positioning system data. The integration of these features is anticipated to furnish drivers with an enhanced and safer driving experience. The primary focus was directed towards designing the control system architecture, specifically incorporating novel supportive features conducive to safe driving practices. This architectural framework was extensively examined to scrutinize the safety aspects inherent in Intelligent Adaptive Cruise Control. The main contributions of this thesis can be summarized as follows: Enhancing safety on curved roads: The thesis will contribute to reducing safety risks on curved roads by leveraging GPS data, thus improving the existing ACC, a vital ADAS feature. Data integration for security: For security purposes, IACC is expected to strengthen overall security measures by actively sharing and processing traffic speed limit data from another ADAS feature when provided. Architectural advancements: This study will contribute to the formation of a novel ACC concept by supporting the previously mentioned features in its architecture. This represents a holistic approach to improving adaptive cruise control functionality.

SYMBOLS

c : Clearance

kph : Kilometer per hour

N : Number of Active Rule

t : Time

$\boldsymbol{\tau_{gap}}$: Time Gap

v : Velocity

$\boldsymbol{v_{set}}$: Set Velocity

ABBREVIATIONS

ABS : Anti-Lock Braking

ACC : Adaptive Cruise Control

ADAS : Advanced Driving Assistance System

AEB : Automatic Emergency Braking

ASIL : Automative Safety Integrated Level

CACC : Cooperative Adaptive Cruise Control

ESC : Electronic Stability Control

EuroNCAP : The European New Car Assessment Programme

HARA : Hazard Analysis and Risk Assessment

KPI : Key Performance Indicators

LCA : Lane Centering Assistance

LKA : Lane Keep Assistance

LRR : Long Range Radar

IACC : Intelligent Adaptive Cruise Control

ISO : International Organization for Standardization

GPS : Global Positioning System

NA : Not Applicable

NTHSA : National Highway Traffic Safety Administration

MBSE : Model-Based System Engineering

OEM : Original Equipment Manufacturer

SAE : Society of Automobile Engineers

SysML : System Modelling Language

S&G : Stop&Go

TSLR : Traffic Speed Limit Recognition

TTC : Time-to-Collision

UML : Unified Modelling Language

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1. INTRODUCTION

The planned creation of the Intelligent Adaptive Cruise Control (IACC) system architecture design serves as the focal point of this thesis. A model-based system approach will be employed, encompassing a comprehensive standard and regulatory scan, safety evaluation of the vehicle, and the subsequent determination of IACC system requirements. The ensuing system-level architecture will align meticulously with these defined requirements. Drawing insights from literature studies and industry standards, the architecture will be meticulously crafted using the Enterprise Architect modeling tool. Control and system-level flow and status diagrams will be generated, utilizing MATLAB & SIMULINK's State flow program.

In this study, outputs related to the modeling and design phases will be presented and scrutinized for practical applicability. During the formulation of the thesis topic and scope, an exhaustive examination of preceding thesis studies was conducted. The current state of sectoral studies influenced the decision-making process, leading to the selection of a thesis topic that addresses pertinent gaps or unresolved issues.

1.1. What is the ADAS?

Road traffic accidents pose a significant global challenge, with an estimated 1.3 million lives lost annually, according to the World Health Organization (WHO) [1]. Additionally, 20 to 50 million people suffer non-fatal injuries, frequently leading to disabilities [7]. Traffic, being an intricate interplay between people, vehicles, and road infrastructure, is susceptible to human error, accounting for nearly all accidents.

Measures to mitigate traffic accidents fall into three categories: altering human behavior, vehicle-related enhancements, and infrastructure-related modifications. Car-related measures encompass both passive (e.g., vehicle structures, seatbelts, airbags) and active components, including Electronic Stability Control (ESC), Anti-Lock Braking (ABS), and Advanced Driver Assistance System (ADAS) features. The ADAS not only aims to enhance safety but also focuses on improving efficieny [2]. Safety-oriented ADAS features encompass speed assistance, navigation, collision avoidance, intersection support, and lane-keeping. The ADAS features impact safety and accident avoidance, classifying these systems as real-time systems [3].

The capabilities of Advanced Driving Assistance Systems continue to expand [4]. Numerous commercially available advanced driving assistance systems hold the potential to enhance both safety and comfort of the driving experience [5]. Various ADAS functionalities utilize a range of driver alerts, employing visual, audio, and vibrational cues to deliver numerous safety warnings to the driver [6]. ADAS relies on a combination of supportive elements, such as Lidar, RADAR, cameras, and sensors, to fulfill its purpose. The incorporation of cameras into vehicles leverages sensor fusion, emulating the cognitive processes of the human brain. This cutting-edge technology, powered by image recognition software, ultrasound sensors, LiDAR, and radar, enables swift physical responses that surpass human capabilities. It operates by analyzing real-time streaming video, identifying depicted objects, and determining appropriate reactions.

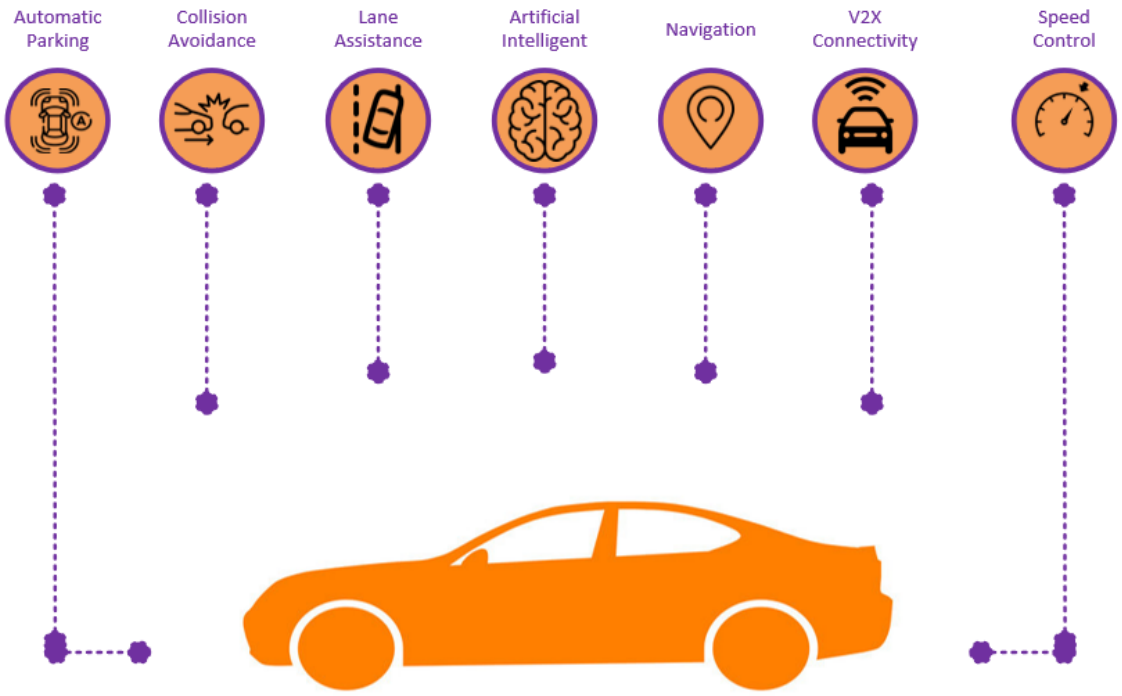

Figure 1.1. Some ADAS Features and Capabilities

Sensor fusion, akin to the information processing mechanism of the human brain, amalgamates vast datasets utilizing image recognition software, ultrasound sensors, LiDAR, and radar. This advanced technology possesses the capability to deliver physical responses at a speed surpassing that of a human driver. It can swiftly analyze real-time streaming video, discern the content of the video, and determine the appropriate reaction.

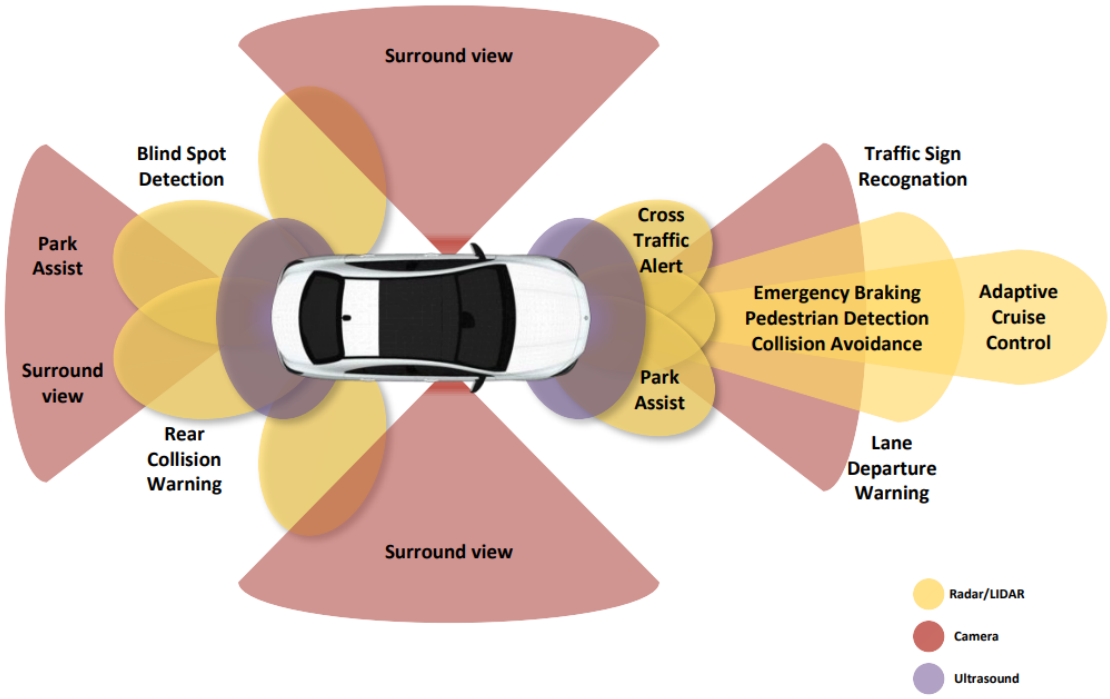

Figure 1.2. The common ADAS Features Valid Ranges

This thesis delves into the technical intricacies of the IACC and TSR/TSLR (traffic speed and/or limit recognition) features.

1.2. Background

In previous thesis studies, adaptive speed control systems have been meticulously crafted using a variety of control algorithms. These controllers predominantly include PID, Stanley, Pure Pursuit, Linear Quadratic Regulator (LQR), Linear Model Predictive (LMP), and Fuzzy Logic Controller. The model predictive algorithm, employed in previous studies, predicts vehicle acceleration and deceleration and, subsequently generates the necessary control inputs [7]. An in-depth analysis is conducted to compare the performance of these control algorithms. In terms of autonomous intervention in an adaptive cruise control system, a mathematical model centered on safety-critical distance was suggested and experimentally validated across diverse environmental conditions [8].

In summary, the Pure Pursuit controller exhibits sensitivity to short-distance areas, while the following controller, although less precise, demonstrates increased stability. The Stanley controller excels in precise following on smooth paths, but experiences challenges

on curved roads, resulting in more following errors. The linear quadratic regulator control provides a linear solution. Model Predictive Control, while proactive in its behaviors, comes with a higher computational burden, but its advantages include a reduced following error compared to other controllers [9].

One of the previous, primary objectives of the ACC study is to formulate model equations and, consequently, to develop a suitable objective function based on system logins and states [10]. The longitudinal vehicle control system is typically designed to be hierarchical, consisting of an upper-level controller and a lower-level controller [11].

The CACC system represents a more complicated form of cruise control, with an architecture that orchestrates motion and navigation capabilities within the cars [12]. The CACC concept differs slightly from IACC, with its primary focus on time-gap. A CACC vehicle is recognized as a CACC sequence follower when it meets all three conditions:

(1) the automation system is activated, and the CACC vehicle is in CACC operation;

(2) the tool is in space editing mode;

(3) the tool maintains the intra-sequence spacing as the desired time interval rather than the inter-sequence spacing [13].

Low-level studies in the field of ACC have been discussed. These studies cover aspects such as the control system, the time-gap status of the system, or enhancements to sensor details. It is noticeable that the security aspect is not extensively addressed. It can be inferred that the system architectural design is not approached using a model-based method, and adherence to standards is not emphasized. Creating an ACC system that caters to multiple objectives becomes a challenging task, especially when the system model incorporates uncertainty [14].

In the context of these comparisons, close attention was paid to vehicle following distance, speed control outputs, stability, and error. Error analysis studies were also conducted to enhance collision avoidance capabilities with this Advanced Driver Assistance System (ADAS) feature.

1.3 Motivation of The Thesis

The primary motivation behind this thesis stems from extensive experience in the automotive industry and specialized knowledge of Advanced Driver Assistance System (ADAS) features. Contributing to the automotive sector through a synthesis of system engineering expertise, We aimed to enhance the existing Intelligent Adaptive Cruise Control (IACC) concept—a subsystem designed to enable vehicles to maintain a constant speed based on the driver's decision, providing fatigue-free long-distance driving. The study delves into the improvement possibilities for the current IACC concept, driven by automotive industry background and the desire to contribute to driving safety and human life preservation. Notably, the integration of Traffic Speed and/or Limit Recognition (TSLR), a feature reading traffic speed limit signs using GPS data, adds a novel dimension to the study, allowing an analysis of its impact on driving safety.

Within this thesis, two key concepts were explored integral to Intelligent Adaptive Cruise Control. The first concept involves Traffic Speed Limit Recognition as a crucial Advanced Driver Assistance System (ADAS) feature. This functionality allows us to retrieve speed limit data from external sources for interpreting traffic signs on the road. Its primary purpose is to proactively prevent the target speed from exceeding the preset value. A comparative analysis is conducted between these two-speed values to ascertain compliance with the stipulated speed limit. Complementing this, we delve into the utilization of global positioning system (GPS) data as an additional supporting element. The incorporation of GPS data is instrumental in identifying the lead vehicle, especially in scenarios involving non-linear road configurations such as curves. This capability becomes particularly beneficial for drivers navigating curved roads. Consequently, the IACC feature emerges as a more reliable and safety-oriented solution, distinguished by its heightened sensitivity in comparison to other adaptive cruise control concepts.

1.4 Organization of the Thesis

The thesis is structured to showcase the control system architecture of the Intelligent Adaptive Cruise Control (IACC) features using a model-based approach. The introduction provides a comprehensive overview of the thesis, defining its main elements. The second chapter details the IACC's control system architecture, featuring system-level and control

system-level diagrams, including context, use case, logical block, activity, and user state diagrams. It also explores the relationships with other supporting ADAS features. The third chapter presents simulations of IACC driving scenarios, focusing on key performance indicators (KPIs) such as Free Lane and Follow the Target metrics, as well as vehicle safety behavior. The fourth chapter engages in a discussion of results and provides simulation tool outputs, evaluating the methods used. The final chapter encapsulates the thesis with a conclusion, summarizing the study's main purpose and results.

1.5 Summary of The Thesis

This thesis centers on the system architecture design of an Intelligent Adaptive Cruise Control (IACC) system, employing model-based system engineering for enhanced safety. It elucidates the safety implications of this novel ADAS feature and outlines the methodologies employed during the IACC development survey. The study particularly scrutinizes the effects of newly incorporated elements.

2 CONTROL SYSTEM ARCHITECTURE OF THE IACC

As widely acknowledged, Adaptive Cruise Control (ACC) is a prominent Advanced Driver Assistance System (ADAS) feature, existing in various forms such as active cruise control, dynamic cruise control, radar cruise control, automatic cruise control, and intelligent cruise control. This thesis delves into the Intelligent Adaptive Cruise Control (IACC) concept, a feature that not only manages the vehicle's speed for enhanced safety but also incorporates compatibility with additional features, distinguishing it from conventional ACC systems.

This study entails the design of the ACC system, utilizing data sourced from both Global Positioning System (GPS) and Traffic Speed and/or Limit Recognition (TSLR), another crucial ADAS feature. The overarching aim is to proactively prevent accidents on curved roads, leveraging the capabilities of GPS data in conjunction with TSLR [15].

Even if the speed data entered by the driver does not align with the road's speed limit, a preventive control mechanism is in place to avert accidents. This mechanism involves an algorithm that compares data from the Traffic Speed and/or Limit Recognition (TSLR) feature with the input speed information. Through this approach, a safety-centric driving

system has been crafted, enhancing speed control sensitivity on both straight and curved roads.

2.1 Intelligent Adaptive Cruise Control

Adaptive Cruise Control (ACC) typically employs advanced radar technology. Its primary objective is to uphold a secure following distance by gauging the speed and position of the vehicle ahead. Drivers can adjust their desired speed and following distance using the steering wheel control buttons. Post adjustment, the adaptive cruise control system autonomously regulates the vehicle's speed and generates control signals, encompassing gas and brake requests, to maintain a safe driving distance. Upon scrutiny of these explanations, it is evident that the adaptive cruise control system models various components, including the vehicle itself, the speed data of the lead vehicle, and the road, contingent on the prevailing conditions. This section underscores the development of mathematical models for these components, which directly influence system performance.

2.1.1 The IACC – Speed Control

This subsection elucidates the cruise control behavior of the Intelligent Adaptive Cruise Control (IACC) system. In the IACC system, the vehicle's speed to be controlled is determined by the driver-entered value, representing the targeted speed information specified by the driver.

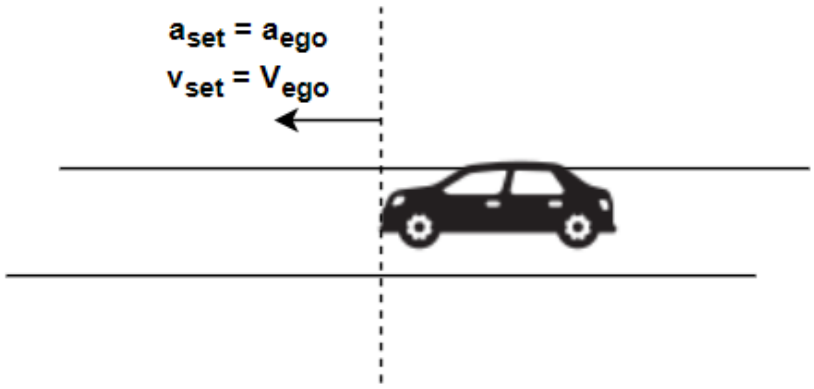

Figure 2.1. The IACC Feature-Speed Control State

The vehicle attains the speed specified by the entered speed value, regardless of the presence of the target vehicle. In instances where the target vehicle is absent, the driver adjusts the speed input to reflect the ego vehicle's speed. In Figure 2.1, v_{ego} represents the

current vehicle speed value, while the desired IACC speed value set by the driver is denoted as v_{set}.

2.1.2 The IACC – Following Control

Within the IACC tracking control algorithm, the ego vehicle maintains a distance from the leading vehicle. The decision to transition to the following control algorithm hinges on the availability of the target vehicle. If IACC identifies a vehicle within the set following clearance (c), the system switches from adaptive cruise control to the following control mode. The velocity of the tracked vehicle is represented as v_{target}, and its acceleration is a_{target}, as illustrated in Figure 2.2.

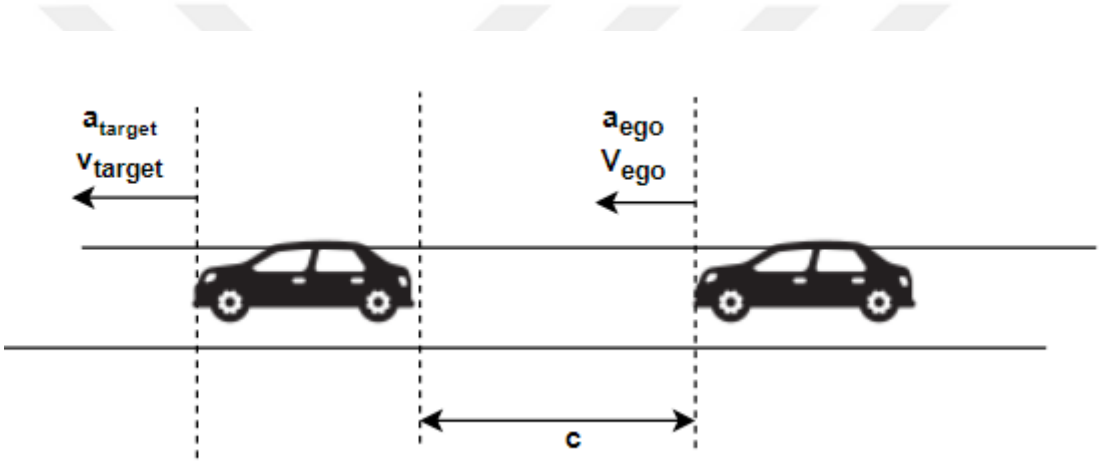

Figure 2.2. The IACC Feature - Following Control State

2.1.2.1 Clearance

Clearance is defined as the distance from the leading surface of the ego vehicle to the trailing surface of the lead vehicle.

2.1.2.2 Time gap

The time gap (τ_{gap}) is calculated in Equation (2.1) as clearance (c) divided by the ego vehicle speed (v_{ego}).

$$\tau = \frac{c}{v} \tag{2.1}$$

2.1.2.3 Safe Distance

The safe distance is calculated in Equation (2.2):

$$d_{safe} = d_{default} + \tau \, x \, v_{ego} \tag{2.2}$$

2.2 The IACC Components

IACC systems are constructed using shared electronic control units (ECUs) to form distributed systems. Standard ECUs such as engine, brake, and transmission control modules are utilized. The ECU also referred to as the IACC control module, incorporates both an IACC controller and a distance sensor, including components like the light detection and ranging sensor (Lidar) and the long-range radar (LRR) sensor in the first generation.

The next generation of IACC systems will integrate additional sensors such as thermal radiation sensors, video cameras, and mid to short-range sensitive radar to enhance safety and usage rates. Current studies focus on the human-machine interface (HMI), including displays, warning devices, operational switches, acceleration, and brake pedals, to improve user acceptance of ACC systems. The HMI aims to convey to the user that they are in full control of the vehicle with system support. Various sensors, including speed sensors and corner sensors, are employed to aid IACC operations. These modules are typically interconnected via LINBUS or CANBUS to optimize communication and coordination [16].

2.3 The IACC: Model Based System Architecture

Model-based system architecture is an outcome of model-based systems engineering (MBSE), progressively emerging as a predominant approach in systems engineering practices. The primary emphasis in systems engineering lies in identifying and addressing communication gaps between sub-systems and systems. MBSE brings a methodical and enlightening process to the study of systems engineering, manifesting in various methods employed within MBSE. In essence, these methods involve crafting architectures through models, establishing decisions regarding architecture, performing analyses to bolster architectural decisions, and delineating novel decisions for subsequent stages of the architectural process [17].

Two fundamental modeling languages are employed in the modeling process: SysML (Systems Modeling Language) and UML (Unified Modeling Language). SysML, designed for system modeling with an emphasis on requirements creation, offers fewer diagrams compared to the more technically detailed UML, which contains software or hardware technical information. Both languages, at the system level, encompass three distinct diagram groups, namely requirements, behavior, and structure diagrams. Common diagrams shared between the two languages include use case, activity, block definition, package, and state machine diagrams.

2.3.1 How to Create System Model Organization of the IACC using MBSE?

This section provides insights into the model-based system engineering (MBSE) approach. When considering the IACC system as a separate project, the initial steps involve addressing customer requirements if available, benchmarking the system, defining the system's scope, and determining activity areas. The IACC concept, evolving with added supporting elements, progresses from the Adaptive Cruise Control (ACC). After defining the scope, consulting relevant standards and regulations, creating necessary arguments, and generating supporting documentation are essential. This documentation aids in the creation of the system model. Subsequently, a system package is established in the system modeling application/toolbox.

2.3.2 The IACC System Package Diagram

The system package serves as a top-level structure, ensuring logical integrity and enhancing the model's readability and comprehensibility during the creation phase, as illustrated in Figure 2.3. The package structure can be seen as a kind of containment tree [18]. System packages are categorized into verification, diagrams, requirements, logical diagrams, resources, and behavior analysis, as illustrated in Figure 2.3. These diagrams are generated during the initial stages of the project's architectural design, providing valuable assistance throughout the design process.

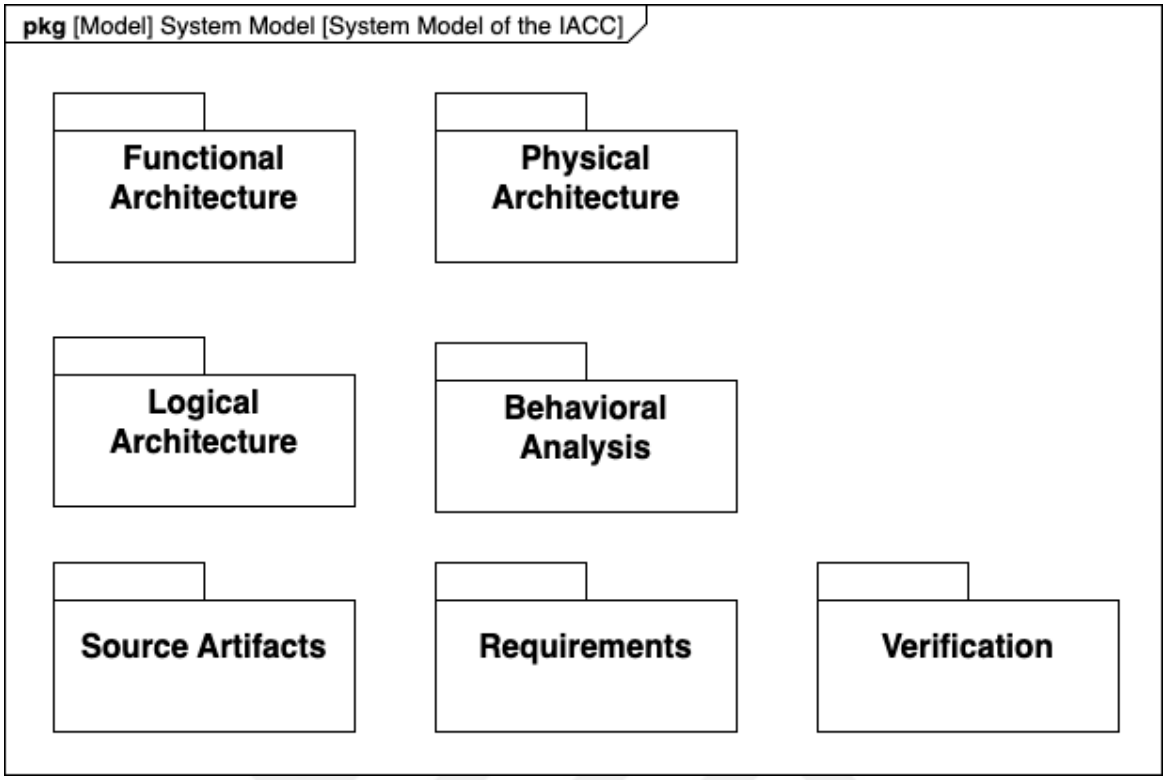

Figure 2.3. System Package Diagram

2.3.2 The IACC Functional Overview

A longitudinal control strategy is implemented based on the received information. Specific commands are relayed to the actuators, and real-time status information is communicated to the driver, who retains the option to select speed suggestions. Broadly, the iACC concept focuses on controlling vehicle speed in the longitudinal plane. This speed control strategy incorporates factors such as the presence of the leading vehicle and its distance from the ego vehicle, driver-entered commands, and the ego vehicle's movement information [19]. Notably, the operational minimum speed limit is set at 5 km/h.

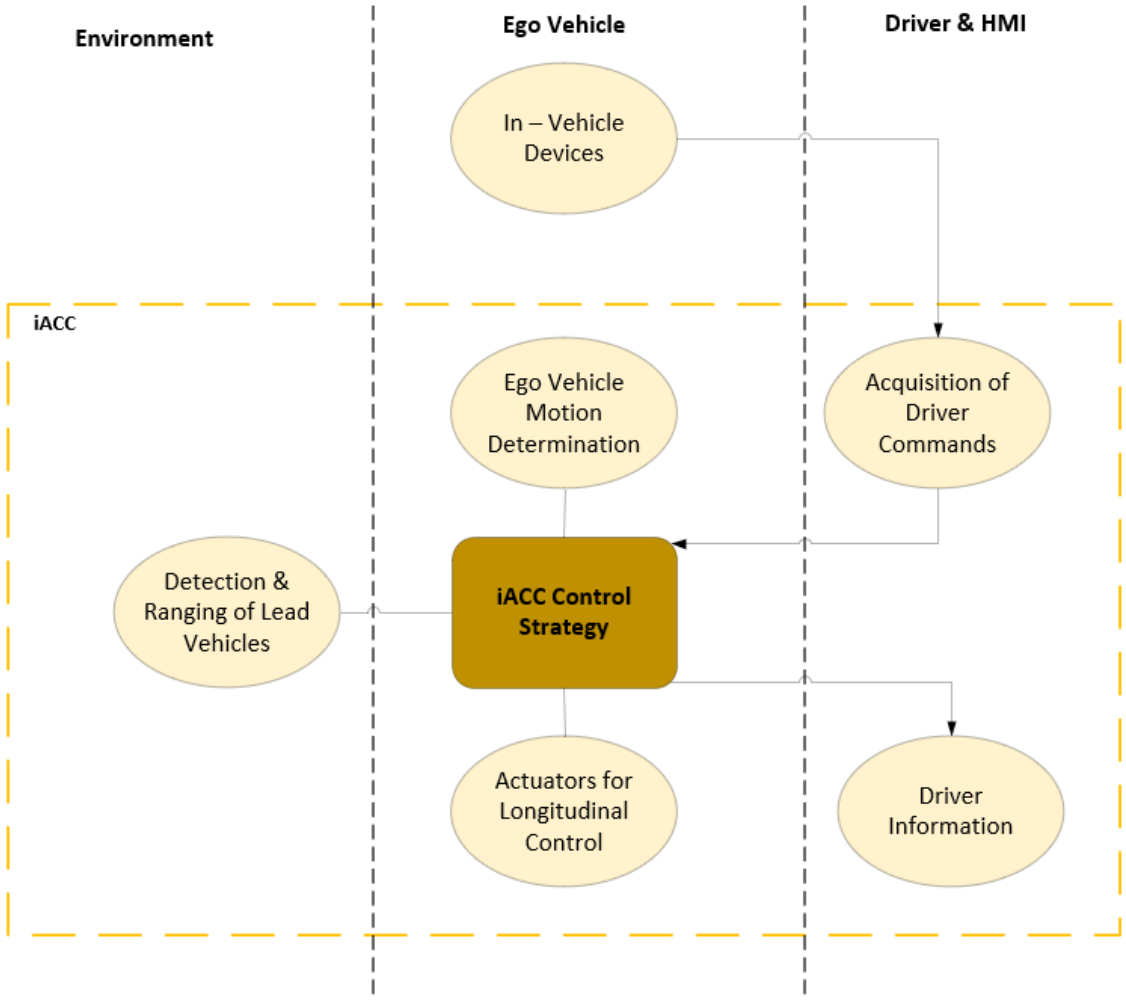

Figure 2.4. Functional iACC Elements

2.3.1.1 In-Vehicle Device

The in-vehicle device means that OEMs (original equipment manufacturers) provide the ACC-set speed value without any active communication with the external environment.

2.3.3 The IACC Use Case Diagram

While use case diagrams predominantly feature Actors, Systems, and usage patterns, their primary objective is to depict the entire scenario comprehensively. Consequently, additional components in use case diagrams, such as include and extend, are incorporated to illustrate the system's operation based on the specific situation and scenario requirements. For the IACC use case diagram, details regarding these components are elucidated in Figure 2.5. Use case scenarios are crafted to delineate situations in which communication transpires between the driver and the vehicle as illustrated in Figure 2.5.

The primary use cases of IACC are explicitly outlined. It is imperative to provide detailed descriptions that delve into a lower level when juxtaposed with block diagrams.

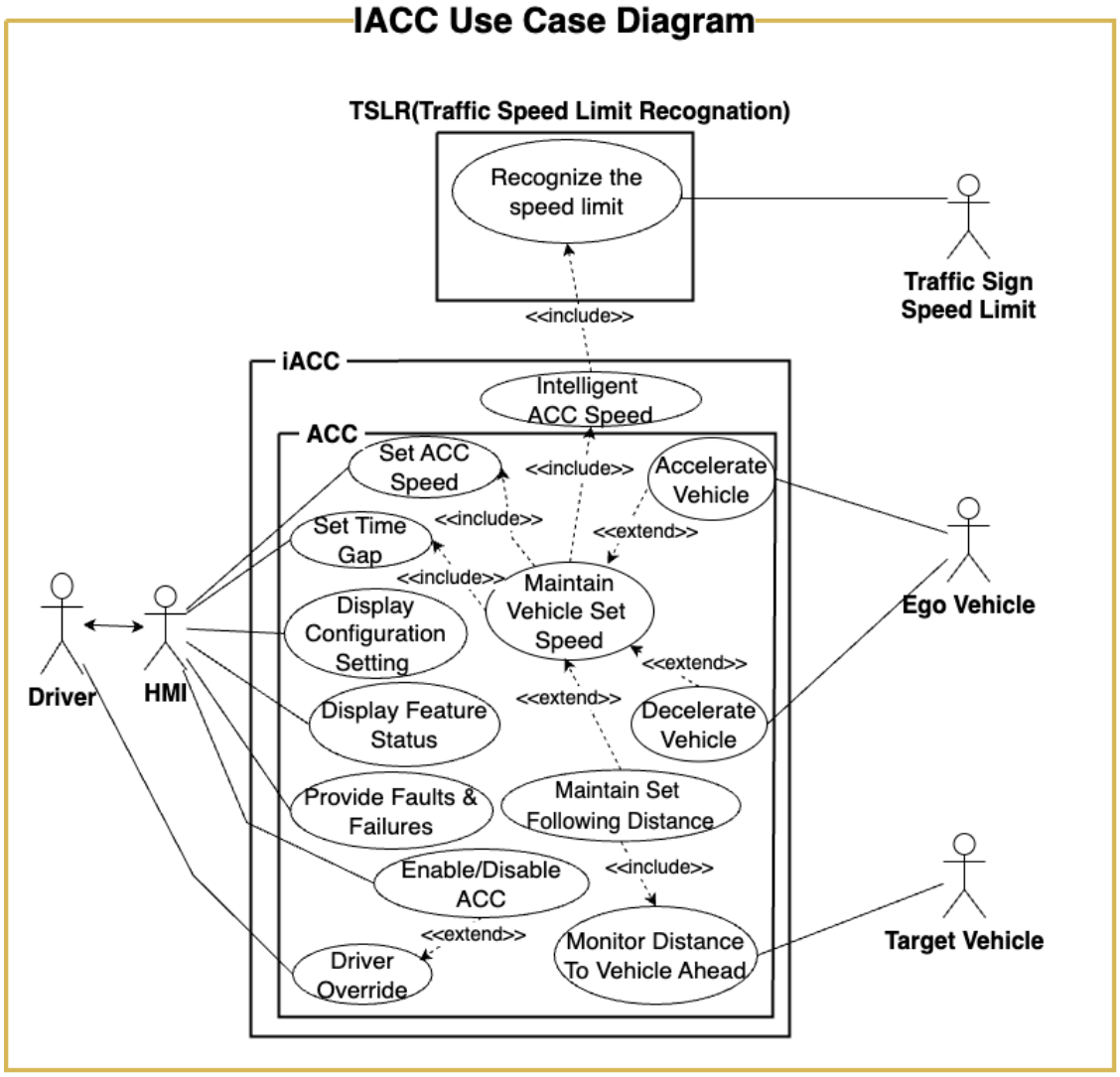

Figure 2.5. The IACC Use Case Diagram

Include: This scenario group, found in many scenario groups, is employed when there are two or more recurring steps within the inclusion relationship scenario(s). In such cases, the duplicated portions are separated into distinct use cases, and the inclusion relationship is utilized. It can be likened to branching out into a sub-program from within a script and subsequently returning.

Extend: The extend relationship comes into play when there is a possibility that the scope of one use case may be extended by another use case. If we consider a use case and a series of steps comprising its scope, there might be a point in the process where it becomes

feasible to introduce novel steps and expand the existing ones by incorporating the steps from another use case [3].

Five distinct actors have been delineated in the use-case diagram: the driver, HMI (Human-Machine Interface), target vehicle, ego vehicle, and TSLR from ADAS features. These actors are identified due to their role in providing external input to the IACC feature, each associated with different feature environments, namely ACC and TSLR. The ACC feature, which serves as the foundational feature, has been designed and is intended to be further developed in this study.

2.3.4 The IACC Feature Interface Diagram

The IACC feature engages with various vehicle subsystems and the environment, establishing interactions that involve the receipt of inputs and transmission of outputs to the relevant subsystems. These interactions occur through interfaces. During the creation of the system architecture, the interactions between this feature and other subsystems were delineated, and interfaces were identified. These interfaces specify the data transmitted and received. This aspect was documented using feature interface diagrams, showcasing interactions with the driver, ego vehicle, environment, and the traffic speed limit recognition ADAS feature, as illustrated in Figure 2.6. The IACC interface diagram illustrates the interactions of the IACC feature with other environments, as depicted in Figure 2.6. The directions of the arrows are assigned based on the unit to which they convey information. In this context, the ego vehicle and the driver are treated as distinct environments, and IACC, the ego vehicle's internal unit, and external factors are represented within the diagram. The primary information flow is delineated through this diagram.

This diagram illustrates the interfaces both within and outside the vehicle. The vehicle receives gas and brake input from the driver, generating images based on the speed or time interval information provided. The driver can view configurations, errors, and warnings, while entering requests such as speed adjustments, safe distances, ACC enable/disable, and stop/hold commands. These inputs are processed within the ACC feature. The vehicle then transmits data, including throttle pedal position, brake pedal position, ego speed, ego gear, and ignition status, to the ACC feature for further processing.

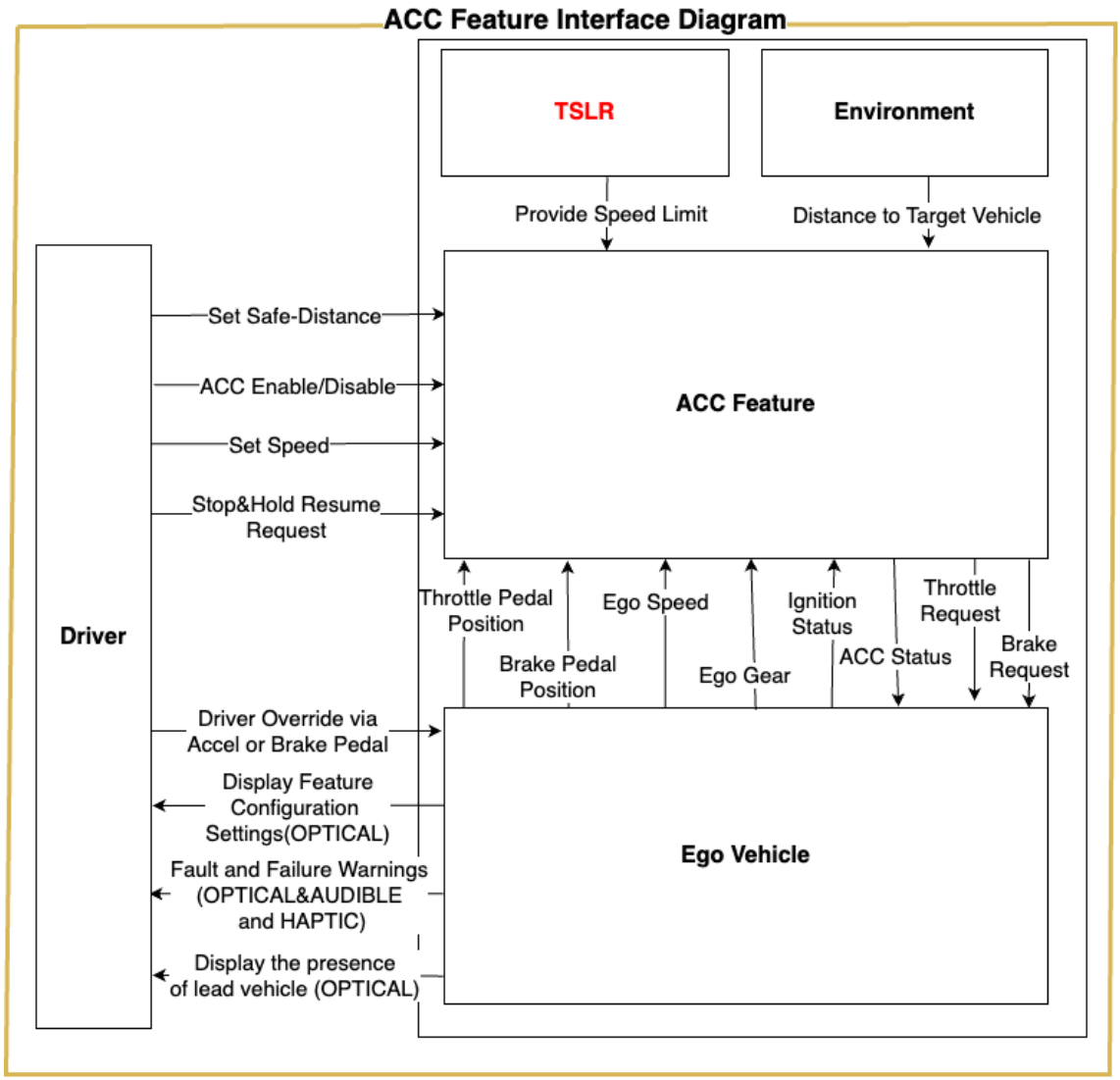

Figure 2.6. The IACC Feature Interface Diagram

The ACC feature responds to throttle and brake requests, aligning with the driver's preferences. In addition to inputs from the driver and the vehicle, the IACC feature receives information from the TSLR feature and the environment. From the TSLR feature, it acquires speed limit data, and from the surrounding environment, it gathers distance information to the target vehicle.

2.3.5 The IACC Feature Context Diagram

The Block Definition Diagram is utilized in the IACC feature context diagram. This diagram outlines the high-level environment of the IACC, encompassing the environment, the driver, the vehicle itself, and the key elements supplying input. Two distinct

environments are delineated: the system's environment and the system feature as illustrated in Figure 2.7. This section designates the action/module expected to directly influence the IACC feature at a high level. As a system property, the IACC's output is depicted as either throttle or brake. Blocks anticipated to interact externally with the system itself are presented under the environment.

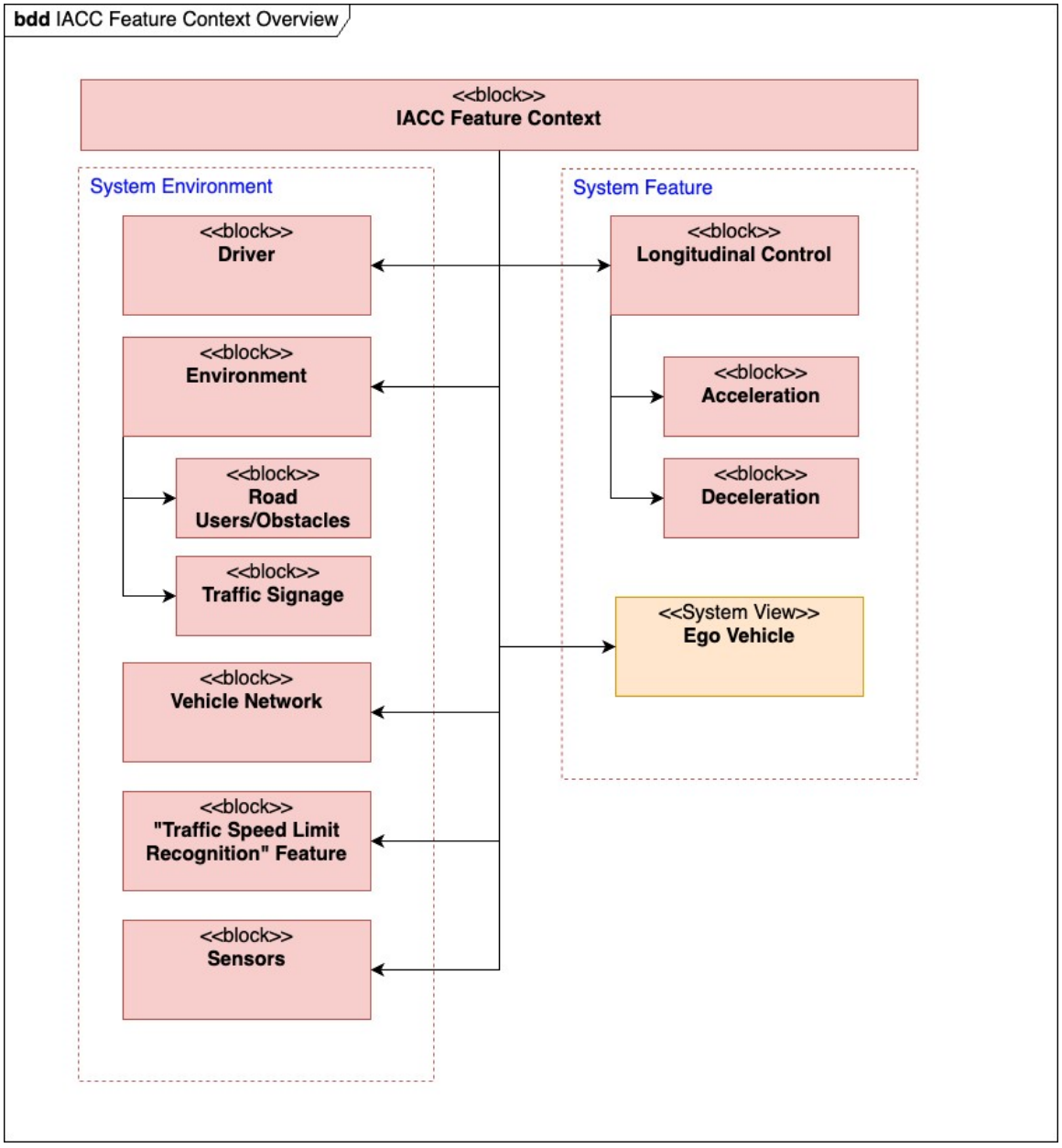

Figure 2.7. The IACC Feature Context Diagram

2.3.6 The IACC User State Diagram

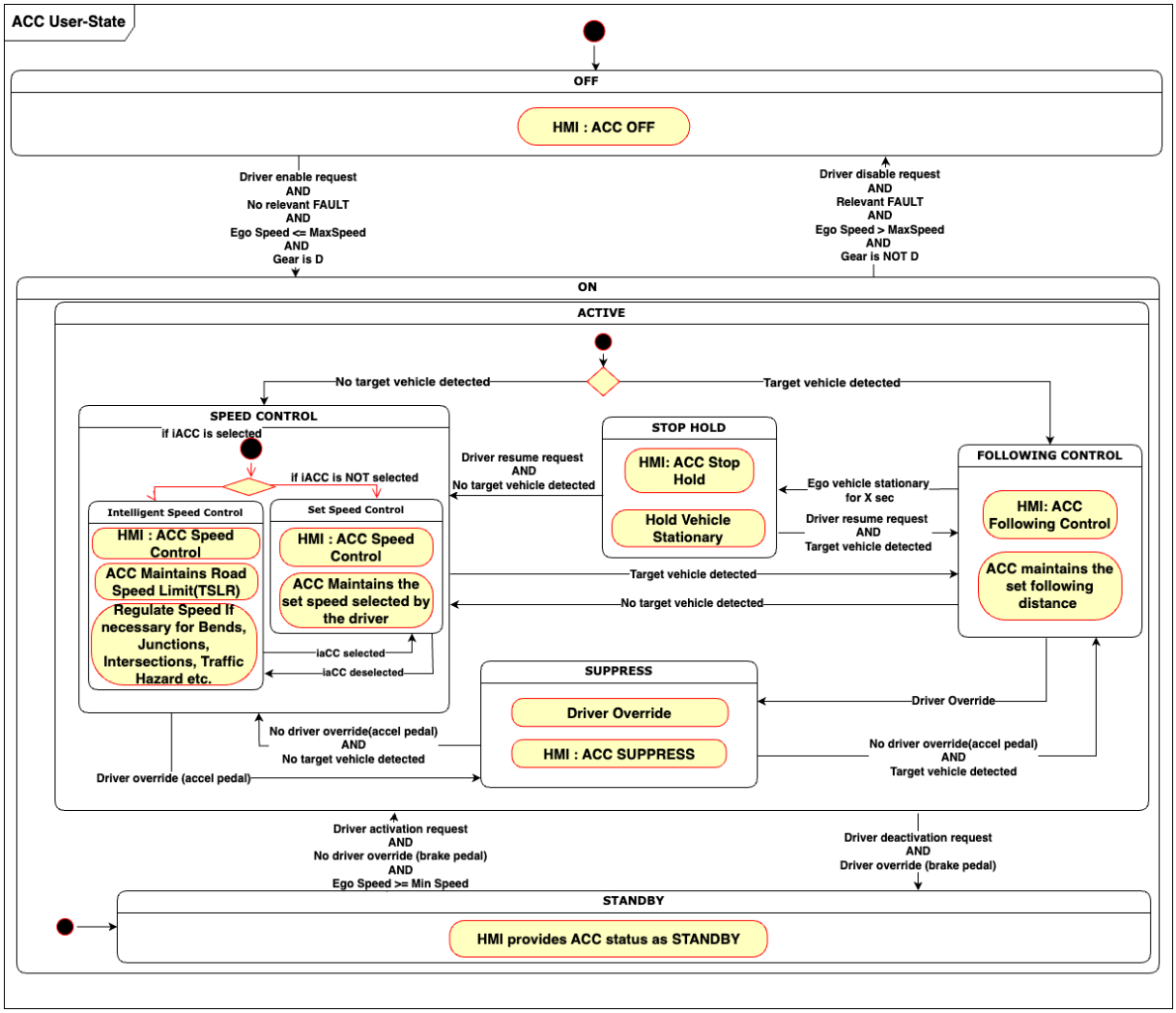

Figure 2.8. The IACC User State Diagram

User state diagrams play a crucial role in system modeling by illustrating transition conditions and scenarios for each state. The determination of transition behaviors between states contributes to the development of the system architecture. This process identifies scenarios and requirements, addressing key terms such as state, initial state, event, transition, and final states. A state signifies the condition of an object, while an event represents a specific occurrence influencing the object's timeline. Transitions, directed relationships between a source and a target, occur in response to specific events or situations. Initial and final states, special nodes indicating the start and end of the state cycle, play a vital role in diagram representation.

As depicted in Figure 2.8, the IACC features states such as OFF, ON, ACTIVE, STANDBY, SPEED CONTROL, STOP HOLD, FOLLOWING CONTROL, and SUPPRESS. Each user state is associated with specific events, providing information about the characteristics of each state. The IACC user states can be found in Table 2.1.

Table 2.1. The IACC User States

No	Event
OFF User State	HMI: ACC OFF
ON User State	NA
ACTIVE User State	NA
STANDBY User State	HMI provides ACC status as STANDBY
SPEED CONTROL User State	NA
Intelligent Speed Control User State	HMI: ACC Speed Control ACC maintains road speed limit from TSL Regulate speed if necessary for bends, junctions, intersections, traffic hazard etc.
Set Speed Control User State	HMI: ACC Speed Control ACC maintains the set speed selected by the driver
STOP HOLD User State	HMI: ACC Stop Hold Hold Vehicle Stationary
FOLLOWING CONTROL User State	HMI: ACC Following Control ACC mains the set following distance
SUPPRESS User State	Driver Override HMI: ACC Suppress

2.3.7 The IACC Block Definition Diagram

A block definition diagram serves as a high-level system diagram, modeling the system architecture without specific requirements. It aids in the creation of an internal block diagram, illustrating the logical architecture of IACC at the L0 (High Level) level. The diagram outlines key components before delving into the behavior diagram, including environmental perception, the ego vehicle's state, communication with other features, HMI environment, vehicle movement control, error/fault management, and decision-making & planning as illustrated in Figure 2.9.

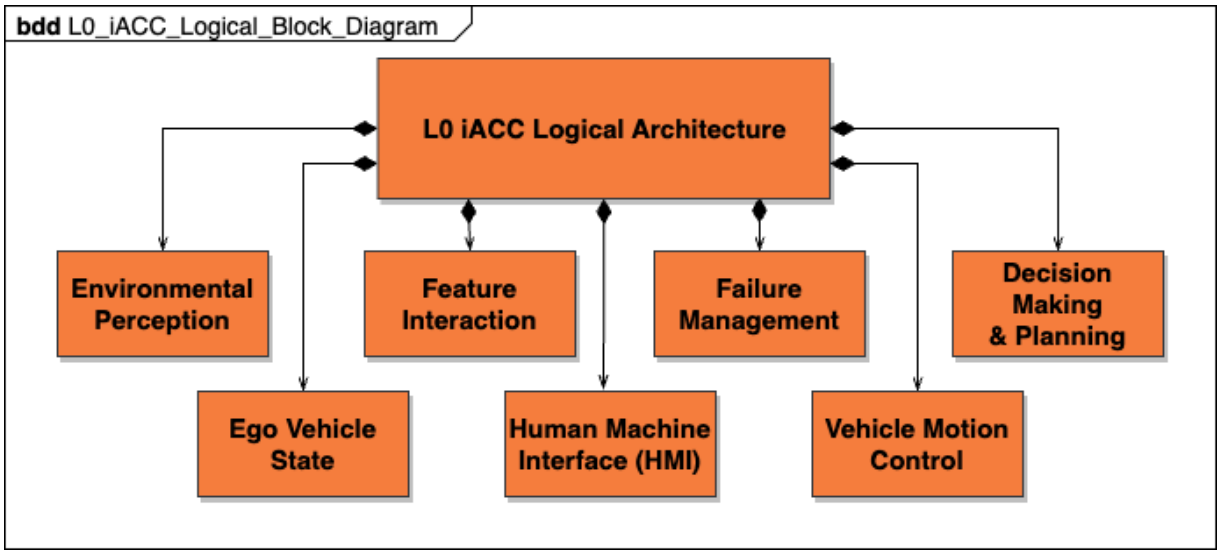

Figure 2.9. The IACC Logical Block Definition Diagram

2.3.8 The IACC Activity Diagram

The activity diagram, employed in SysML, plays a crucial role in crafting the use case diagram. This diagram delineates fundamental system functions, progressing from high-level definitions to the development of necessary behavioral functions. The definition of high-level system actions extends until a specific low level is achieved. The actions identified in the IACC activity diagram are illustrated in Figure 2.10 [20]. In this diagram, two areas were established to delineate the functions that will be influenced. The first pertains to the driver, while the second pertains to the feature itself. Activities involving the operation of the ego vehicle and the activation of the IACC under the driver's influence are detailed. Upon activation of the feature, the functions within the IACC itself come into play. A step-by-step examination of the functions reveals the user's mode selection,

triggering the activation of IACC in the system and simultaneously verifying the status of this feature. If the feature is disabled, the cycle is exited.

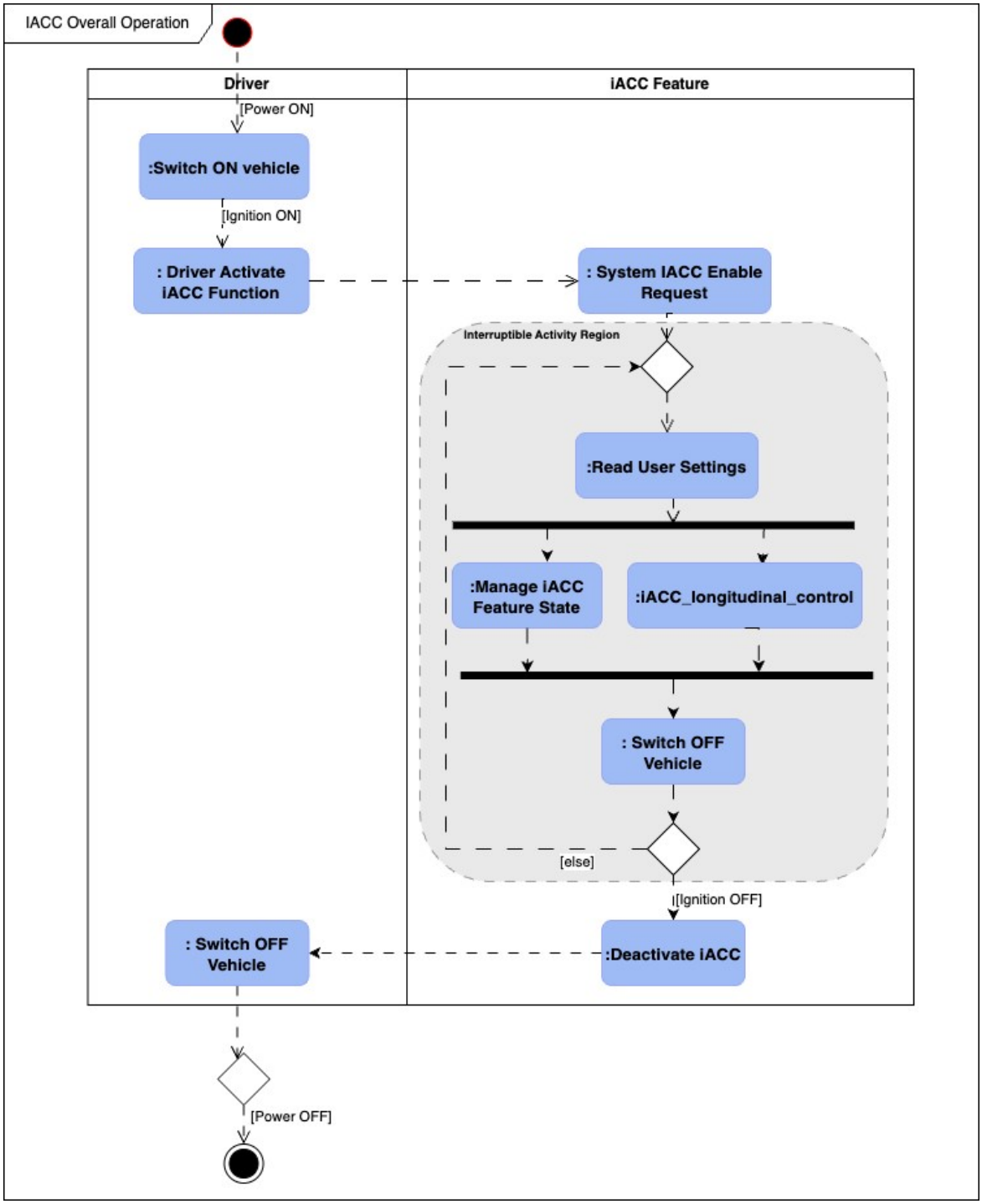

Figure 2.10. The IACC Activity Diagram

2.5 Other ADAS Features Supporting the IACC

Several ADAS features facilitate data exchange to enable control in autonomous vehicles. The speed control feature, central to this thesis, engages in data transmission with fundamental ADAS features within IACC. This data flow facilitates communication among control systems as needed. Noteworthy ADAS features collaboratively functioning with IACC include Stop&Go, TSLR (Traffic Speed Limit Recognition), AEB (Automatic Emergency Braking), and LKA (Lane Keeping Assistance System)/LCA (Lane Centering Assistance).

2.5.1 Stop&Go

Certain vehicles equipped with ACC may feature a "stop-go" capability. This enhancement allows ACC, with a minimum operational speed limit of 5 kph, to operate down to 0 kph and can even stop the engine. It automatically restarts under specific conditions, broadening the operational scope of the feature.

2.5.2 Traffic Speed Limit Recognition (TSLR)

This feature detects and processes traffic signs, with a primary focus on speed limit information. It recognizes speed while driving and shares this information with other features. If IACC receives speed limit information from TSLR, it processes and adjusts its speed accordingly, ensuring a safe journey.

2.5.3 Lane Keep Assistance (LKA) or Lane Centering Assistance (LCA)

LKA or LCA helps keep the vehicle centered in its lane during travel, preventing unintentional lane departure. If the vehicle deviates from the lane without steering input or voluntarily steers out of the lane when the feature is activated, IACC is triggered and receives relevant information.

2.5.4 Automatic Braking System (AEB)

The AEB, or automatic braking system, halts the vehicle through braking when it identifies an obstacle or moving object to prevent a collision. This function is closely related to IACC (Intelligent Adaptive Cruise Control).

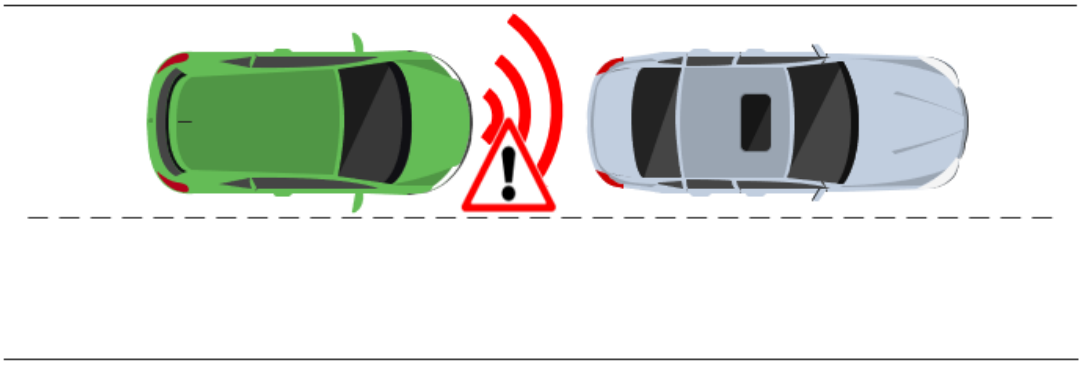

Figure 2.11 The AEB feature visualization

In a scenario depicted in Figure 2.11, where the lead vehicle suddenly halts, the AEB warns the driver at the first distance-time or time-to-collision threshold (TTC). Braking pressure is applied to reduce braking time, activating IACC's relationship with AEB and putting ACC on hold in the event of an unforeseen collision [21].

3 SIMULATION

In this section, insights into the IACC simulation study are presented. IACC, an integral component of ADAS, has been designed to address challenges and enhance functionalities in the automotive sector. One primary challenge is for the ego vehicle to identify the nearest vehicle in its lane and accurately determine its lane. The ego vehicle assesses the speed and position of the closest vehicle in front relative to itself and detects vehicles entering its lane from neighboring lanes.

3.1 The IACC System and Its Device Components

3.1.1 LiDAR-Based Sensor

The LiDAR (Light Detection and Ranging) sensors leverage light detection and ranging technology. The sensor's lens disperses and transmits laser beams to optically adjacent areas. Importantly, the beams are non-overlapping, ensuring no interference. A key advantage lies in the multi-tracking capability of laser beams, distributed at specific frequencies [22]. This technology enhances the vehicle's situational awareness. The LiDAR sensor diligently observes the vehicle's surroundings to ensure a safe distance from obstacles. By emitting laser pulses, the sensor constructs a detailed 3D representation of the environment.

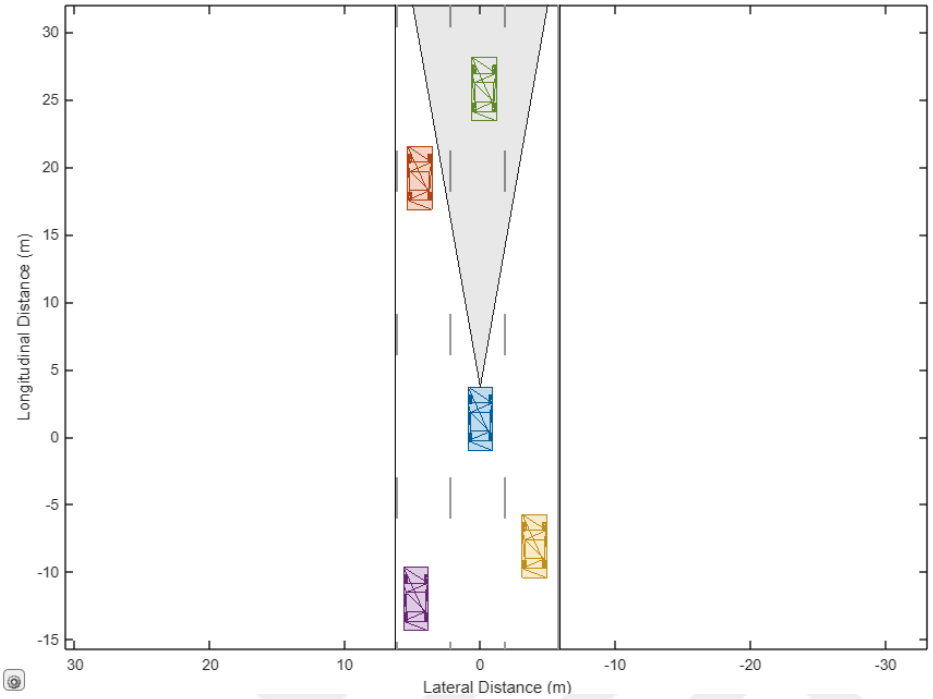

Figure 3.1. LiDAR Sensor Coverage Limit Visualization

In terms of their features, Lidar sensors are categorized into the following types: Flash LiDAR, Hybrid LiDAR, mechanical LiDAR, solid-state LiDAR, and FMCW LiDAR.

3.1.2 RADAR-Based Sensor

Another sophisticated sensor is the microwave radar. The configuration of radar information utilized in ACC and Stop&Go (S&G) systems varies based on frequency and specifications. Long-range radars are employed for extensive and high-speed detection in the ACC system. The pulses emitted by the radar device detect presence data, which is then processed to determine location and speed [22].

Vehicles must consistently recognize obstacles and humans, responding promptly to ensure safety. The forward radar detector facilitates accurate, rapid, and mobile target detection and tracking, boasting a lengthy detection range, expansive field of view, outstanding angular resolution, and an on-chip sequential modulation function. This versatility makes it well-suited for various traffic scenarios.

The front radar sensor excels in swiftly and precisely recognizing objects and individuals, benefiting from its wide detection range, excellent angular resolution, and

expansive field of view. The modulation of the chirp sequence enhances sensor perception by amplifying strong reflections. Leveraging RADAR sensor capabilities, it precisely detects objects, their positions, relative speeds, and movement directions. These features render the radar detector invaluable in congested city traffic, enabling the identification, distinction, and simultaneous tracking of multiple objects and individuals before emergency braking. Moreover, owing to the sensor's extended detection range, these functions can be executed at speeds of up to 210 kph. Front radar sensors reliably detect the positions, relative speeds, and movement directions of other vehicles and objects from a considerable distance with a single radar measurement, even at higher speeds. The high-quality front radar sensor stands out for its enhanced vertical and horizontal resolution, allowing for the unambiguous classification of small objects and vulnerable road users. For instance, it can detect a motorcyclist overtaking a truck, reliably identifying both objects even when the distance between them is minimal. As the vehicle approaches a tunnel, the radar precisely detects the motorcyclist ahead and, with excellent horizontal resolution, gauges the space between the motorcyclist and the tunnel's roof. These functionalities enable immediate height measurement and improved classification of traffic participants and potential road obstacles [23].

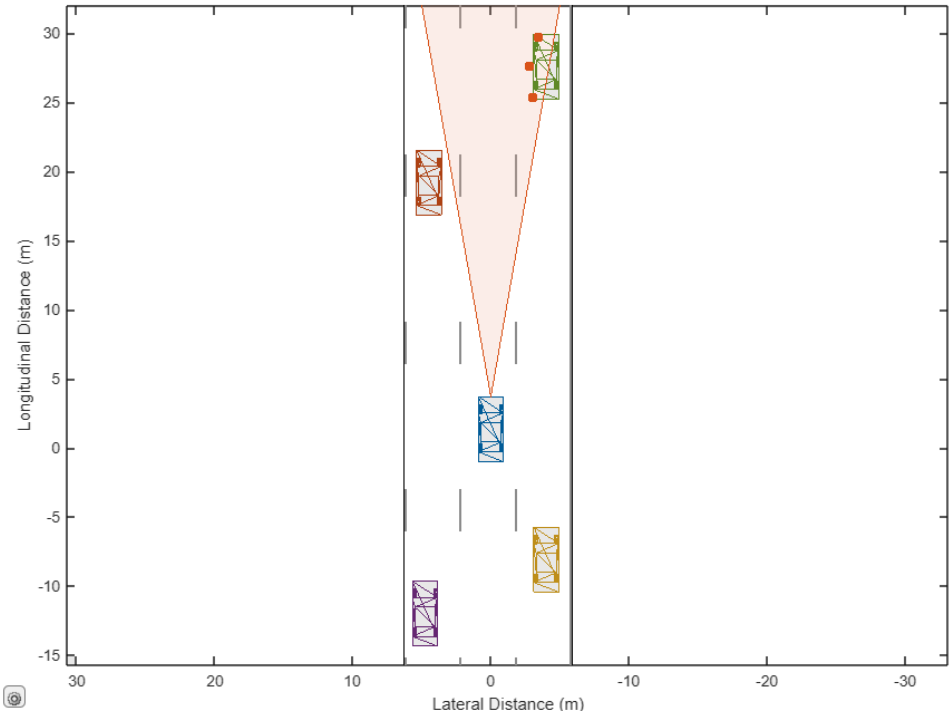

Figure 3.2. RADAR Sensor Coverage Limit Visualization

3.1.3 Camera

The camera stands out as one of the sensors that closely mimics the capabilities of the human eye. It captures a faithful representation of the environment, providing rich information and collecting valuable data. Employing vision perception, which is paramount for driving, the camera becomes a crucial source of information for collision avoidance ADAS systems. Processing the image data captured by the camera using appropriate methods allows for the extraction of vital information concerning object identification, location, and speed. The camera's operational principle involves capturing the optical projection of a physical object by the sensor and subsequently converting it into a corresponding digital signal. Through machine vision algorithms, these signals can be further processed to derive comprehensive data essential for advanced driver assistance systems [24].

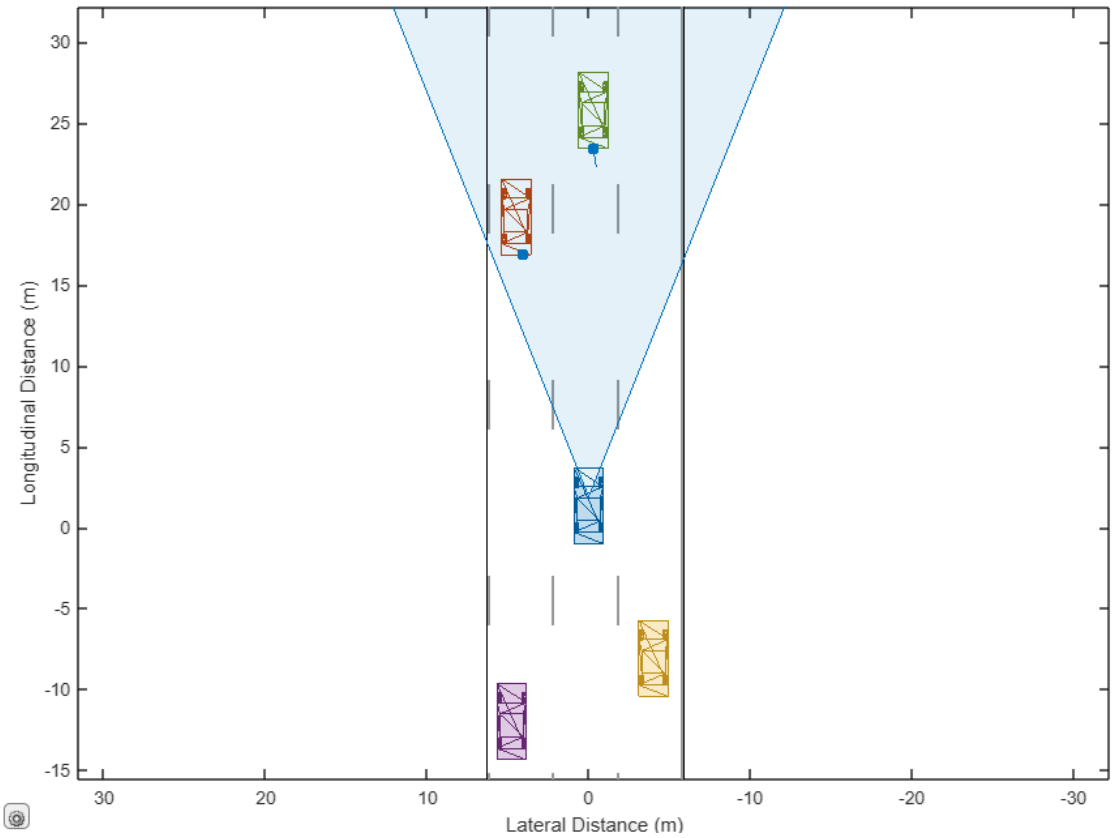

Figure 3.3. CAMERA Sensor Coverage Limit Visualization

3.1.4 Ultrasonic Sensor

Ultrasonic sensors, renowned for their close-range sensitivity, play a pivotal role in facilitating effortless parking, maneuvering, and automated parking in confined spaces. Their rapid responsiveness to diverse obstacles and pedestrians contributes to swift braking at low speeds, effectively reducing the risk of accidents and preventing collisions for drivers operating at lower speeds. As a result, ultrasonic sensors find widespread application in various industries, particularly in machinery and automation activities [25].

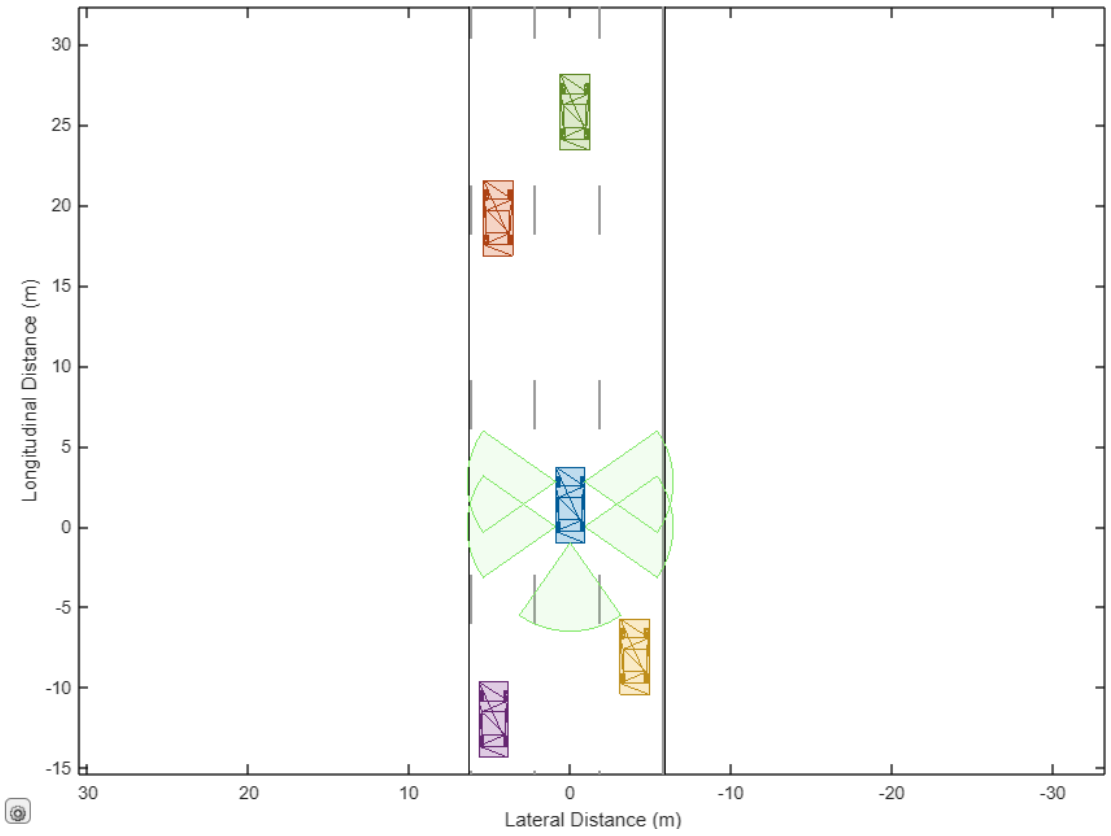

Figure 3.4. Ultrasonic Sensor Coverage Limit Visualization

3.1.5 GPS (Global Positioning System)

Global Positioning Systems (GPS) serve as comprehensive sensors, encompassing speed, location, distance, time, and real-time traffic data. Regarded as a fundamental element for navigation assistance, GPS relies on a constellation of satellites that furnish position, time, and speed information globally, wherever a clear line of sight is established with four or more satellites. In contemporary applications, advanced GPS systems not only offer navigation assistance but also continuously update maps with real-time traffic data, alerts,

delays, and other relevant information to optimize route planning [26].

3.3 Sensor Data Fusion

Before delving into scenarios, this section briefly outlines the typical sensors employed in Advanced Driver Assistance Systems (ADAS), detailing their processes and outputs. Sensor fusion and decision-making processes are pivotal components within the ADAS structure. In this context, data from all sensors undergoes processing, transforming into input for the decision-making mechanism through a logical algorithm. The logical decisions derived from this algorithm subsequently translate into outputs that are implemented in the physical environment, as illustrated in Figure 3.5 [27].

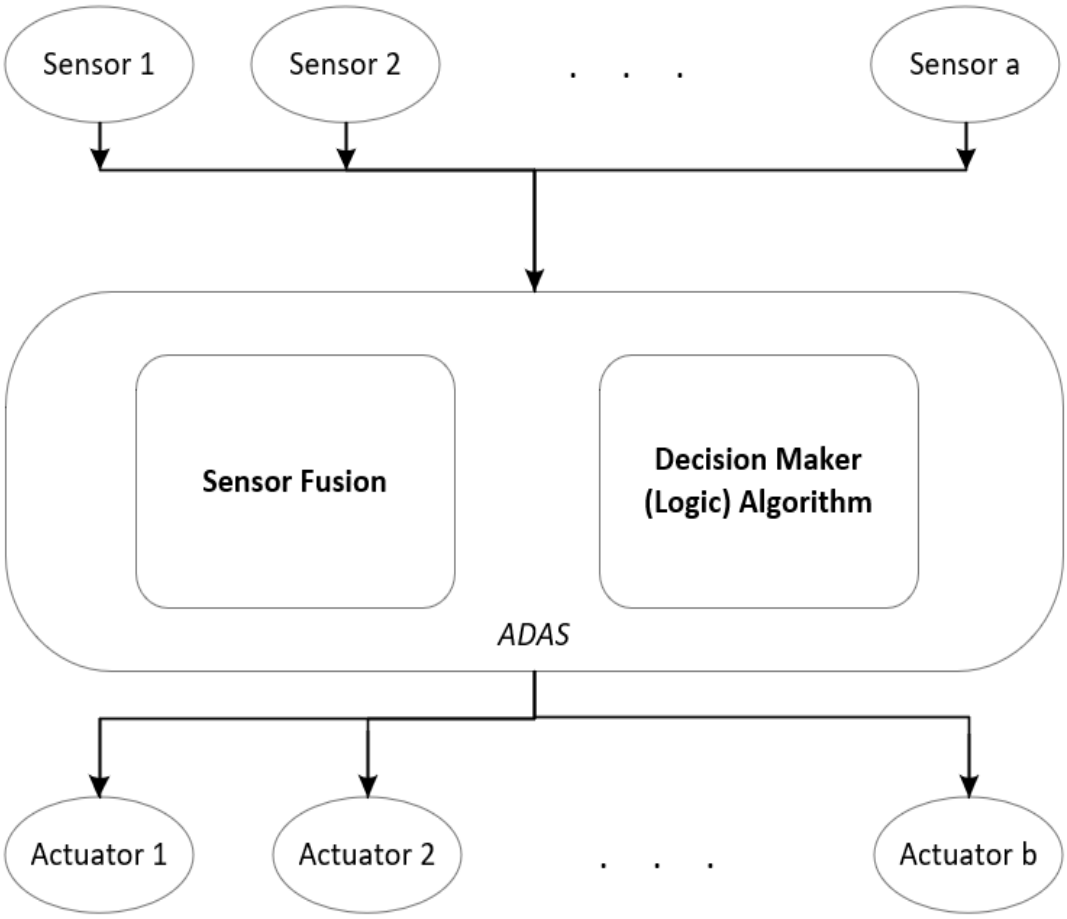

Figure 3.5. ADAS Sensor Data Fusion Structure

3.3 SCENARIOS

In this section, certain parameters and preconditions are employed before establishing test environment conditions. Utilizing the IACC User State Mode, Lead Vehicle Detection

Status, Road Type, and Traffic Speed Limit, eight distinct state scenarios are formulated for each condition. The specifics of these conditions are elucidated in Table 3.1.

Table 3.1. IACC Simulation Scenarios and Dependencies

No	IACC State	UserLead Vehicle	Road Type	Traffic Speed Limit	Expected Values (v_d / τ_{gap})
1	Speed Control User State(v_d)	Not Detected	Straight	NA	Ego Speed = v_d
2	Speed Control User State(v_d)	Not Detected	Curved	NA	Ego Speed = v_d
3	Following Control (τgap)	Detected	Straight	NA	$\tau_{gap} = \tau_{gap}$
4	Following Control (τ_{gap})	Detected	Curved	NA	$\tau_{gap} = \tau_{gap}$
5	Speed Control User State(v_d)	Not Detected	Straight	TSLR Feature Input	If v_d > TSLR input, v = TSLR;
6	Speed Control User State(v_d)	Not Detected	Curved	TSLR Feature Input	If v_d > TSLR, v = TSLR; If $v_d \leq$ TSLR input, v = v_d
7	Following Control (τ_{gap})	Detected	Straight	TSLR Feature Input	If τ_{gap} > TSLR input, τ_{gap} = TSLR; If $\tau_{gap} \leq$ TSLR input, $\tau_{gap} = \tau_{gap}$
8	Following Control (τ_{gap})	Detected	Curved	TSLR Feature Input	If τ_{gap} > TSLR input, τ_{gap} = TSLR; If $\tau_{gap} \leq$ TSLR input, $\tau_{gap} = \tau_{gap}$

3.3.1 Scenario – I

This scenario portrays a situation in which the IACC feature operates without a lead vehicle while traversing a straight road. It is noted that traffic speed limit information for the vehicle is not relayed from the pertinent ADAS feature. Given the IACC's inability to detect a lead vehicle, the ego vehicle remains in the speed control system state. If the driver inputs a desired speed value, the system adjusts the speed accordingly, considering the absence of a traffic speed limit value. Test specifications should be outlined based on parameters such as current velocity, desired velocity, road type, and velocity changes.

Table 3.2. Test Specifications: Scenario – I

Parameters	**Values**
Desired Velocity (kph)	90 kph
Speed Limit (kph)	NA
Lead Vehicle Detection	NO
Lead Vehicle Speed(if applicable)	NA
Last Ego Vehicle Velocity(kph)	90 kph

The scenario has been defined based on the test specifications provided in the table 3.2. In this context, the ego vehicle is navigating a straight road as given in Figure 3.6. As indicated in the table, the driver has set the vehicle speed to 90 kph. The scenario checks whether speed limit information is received from TSLR, another ADAS feature responsible for providing traffic speed limit information. Given the absence of speed limit information to validate against the driver-entered speed value, the entered value is designated as the IACC speed information. It was observed that the vehicle operated at this specified speed.

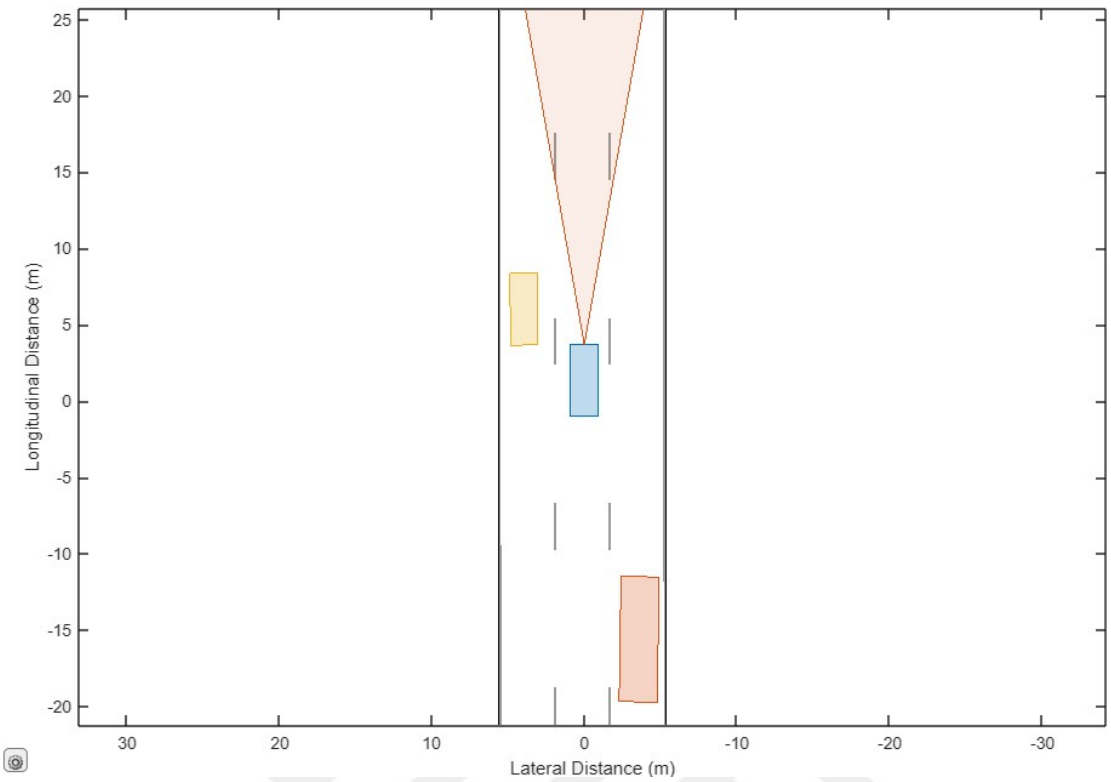

Figure 3.6. Ego Vehicle (IACC- Blue) Bird's Eye Plot: Straight Road & No Lead Vehicle

3.3.2 Scenario – II

This scenario depicts a situation where the IACC feature operates without a lead vehicle while traversing a curved road. It has been noted that traffic speed limit information for the vehicle is not relayed from the relevant ADAS feature. Given the absence of a detected lead vehicle, the ego vehicle is in the speed control system state. If the driver inputs a desired speed value, the system adjusts the speed accordingly, as there is no available traffic speed limit information.

In this particular scenario, if a lead vehicle is present on the curved road, the system processes the detected vehicle's presence based on the information obtained through GPS data.

Test specifications should be provided considering factors such as current velocity, desired velocity, road type, and velocity changes.

Table 3.3. Test Specifications: Scenario – II

Parameters	Values
Desired Velocity (kph)	80 kph
Speed Limit (kph)	NA
Lead Vehicle Detection	NO
Lead Vehicle Speed (if applicable)	NA
Last Ego Vehicle Velocity(kph)	80 kph

This scenario was defined based on the test specifications outlined in the table 3.3. As illustrated in Figure 3.7, the ego vehicle is navigating a curved road, and, as indicated in the table, the driver inputs a speed of 80 kph on the HMI. The system verifies if speed limit information is obtained from TSLR, another ADAS feature responsible for providing traffic speed limit information. Since there is no available speed limit information for comparison with the driver-entered value, the input is designated as the IACC speed information. It was observed that the vehicle operated in alignment with the specified speed.

Compared to straight roads, curved roads pose a lower probability of safe driving and a higher risk of accidents. The lead vehicle, undetectable by radar or camera blind spots, is communicated through the GPS sensor, which also transmits the speed and location of this lead vehicle.

3.3.3 Scenario – III

This scenario depicts a scenario where the IACC feature identifies a lead vehicle on a straight road. Notably, traffic speed limit information for the vehicle is not transmitted from the relevant ADAS feature.

In response to detecting a lead vehicle, the IACC feature transitions to the following control system state. If the driver inputs a desired time gap, the entered time gap is adjusted to match the current time gap, considering the absence of traffic speed limit information.

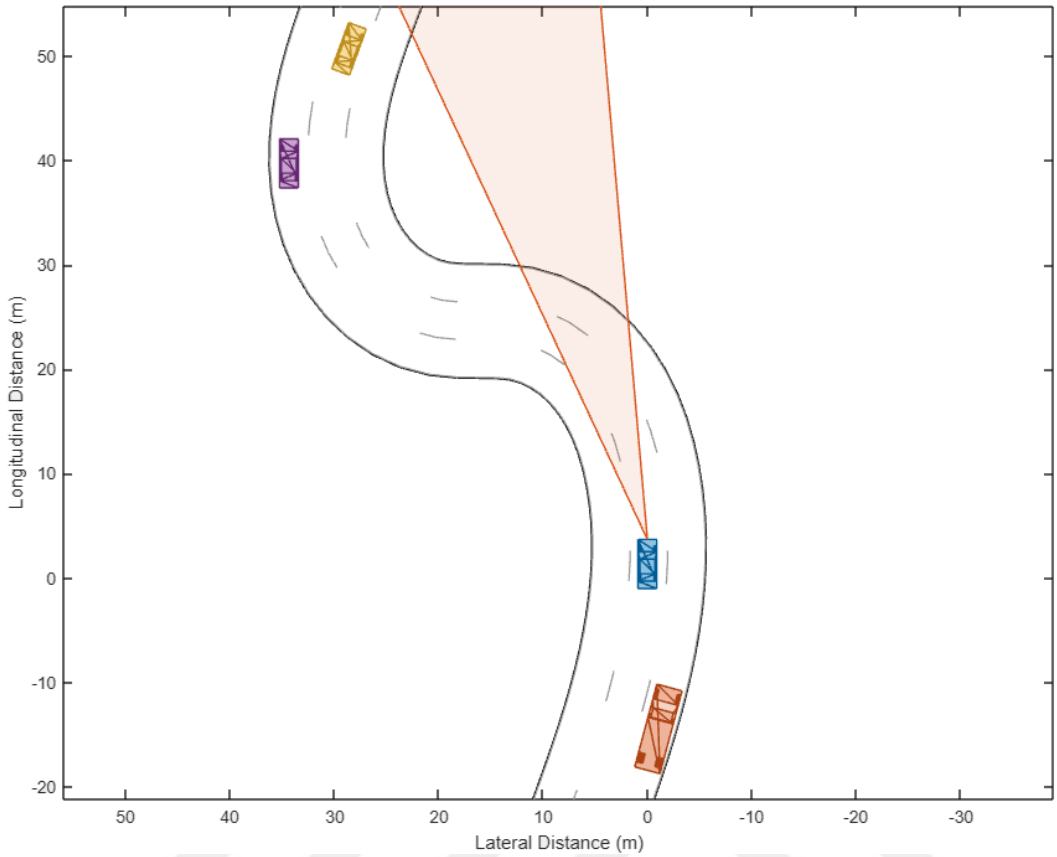

Figure 3.7. Ego Vehicle (IACC-Blue) Bird's Eye Plot: Curved Road & No Lead Vehicle

Test specifications need to be outlined based on scenarios, encompassing elements such as current velocity, desired velocity, road type, and velocity changes.

Table 3.4. Test Specifications: Scenario – III

Parameters	**Values**
Desired Velocity (kph)	80 kph
Speed Limit (kph)	NA
Lead Vehicle Detection	YES
Lead Vehicle Speed (if applicable)	50 kph
Last Ego Vehicle Velocity(kph)	50 kph

This scenario was formulated based on the specified test criteria in the table 3.4. In this particular setting, the ego vehicle is navigating a straight road as given in Figure 3.8. As outlined in the table, the driver inputted a speed of 100 kph via the Human Machine

Interface (HMI). The assessment involved checking whether speed limit information was received from the Traffic Speed Limit Recognition (TSLR), another ADAS feature from which traffic speed limit information is presently obtained.

Given the absence of speed limit information for comparison with the driver's input, the ego vehicle successfully detected the lead vehicle through its sensors. Essential information regarding the speed and location of this lead vehicle was acquired. A comparison was made between the speed of the lead vehicle (80 kph) and the desired speed entered by the driver (100 kph). In this scenario, the IACC feature adjusted the vehicle's speed to 80 kph, prioritizing safety to avoid potential collisions. The ego vehicle was observed to operate in alignment with this adjusted speed.

It is noteworthy that on straight roads, the likelihood of safe driving is lower, and the risk of accidents is comparatively higher than on curved roads. Information is communicated via the GPS sensor to the forward vehicle, not detectable by radar and camera blind spots. The GPS sensor also transmits crucial speed and position data for this leading vehicle.

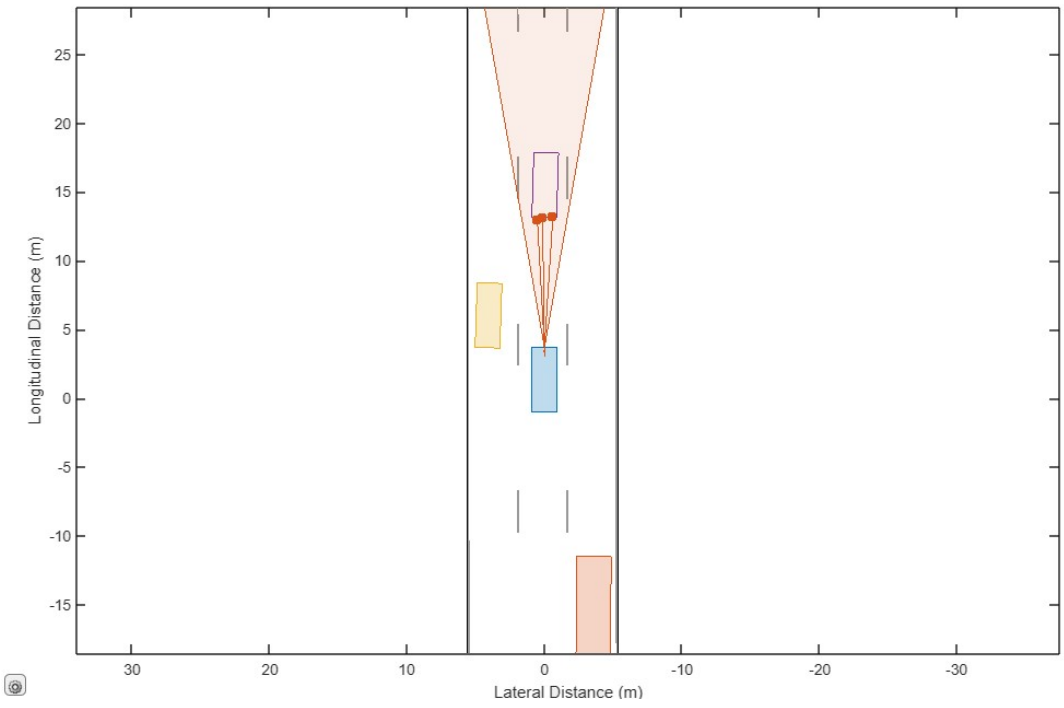

Figure 3.8. Ego Vehicle (IACC- Blue) Bird's Eye Plot: Straight Road & Detected Lead Vehicle

3.3.4 Scenario – IV

This scenario is designed to simulate a situation where the IACC feature detects a lead vehicle while navigating a curved road. It has been noted that traffic speed limit information for the ego vehicle is not relayed from the relevant ADAS feature. The IACC feature, upon detecting the lead vehicle, operates in the following control system state. If the driver inputs a desired time gap, this value is set as the time gap since there is no available traffic speed limit information.

In this scenario, with a lead vehicle identified on the curved road, the IACC feature processes the presence of this detected lead vehicle based on the information received through GPS data. Test specifications should be defined concerning parameters such as current velocity, desired velocity, road type, and velocity changes.

Table 3.5. Test Specifications: Scenario – IV

Parameters	**Values**
Desired Velocity (kph)	90 kph
Speed Limit (kph)	NA
Lead Vehicle Detection	YES
Lead Vehicle Speed (if applicable)	50 kph
Last Ego Vehicle Velocity(kph)	50 kph

This scenario is designed based on the test specifications provided in the table 3.5. In this setting, the ego vehicle navigates a curved path, and as indicated in Figure 3.9, the driver inputs a speed of 90 kph through the HMI. It was verified whether speed limit information was received from TSLR, another ADAS feature providing traffic speed limit information. In the absence of speed limit information for comparison, the ego vehicle detects a lead vehicle through its sensors, obtaining the speed and location details of this vehicle.

In this specific instance, the desired speed for the ego vehicle is set at 90 kph, and it is noted that the lead vehicle's speed is 50 kph. To prevent a potential collision, the IACC feature adjusts the vehicle's speed to 50 kph instead of the initially entered 90 kph. The system then operates at this adjusted speed. Considering the higher risk of accidents on curved roads compared to straight roads, the GPS sensor provides crucial information to

the front vehicle, not detectable by radar or camera blind spots. This information includes the speed and position of the lead vehicle.

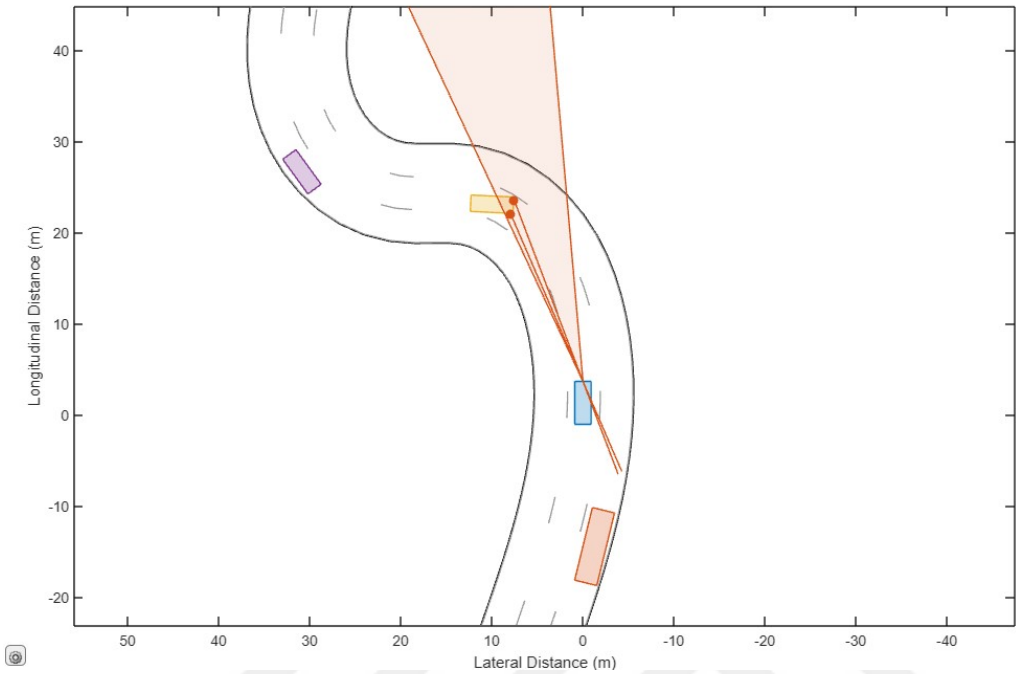

Figure 3.9. Ego Vehicle (IACC-Blue) Bird's Eye Plot: Curved Road & Detected Lead Vehicle

3.3.5 Scenario – V

This scenario is formulated based on the specified test conditions in the table 3.6. In this scenario, the IACC feature operates on a straight road without a lead vehicle as given in Figure 3.10. The relevant ADAS feature transmits the traffic speed limit value to the ego vehicle. The IACC system, being in the speed control mode due to the absence of a vehicle ahead, processes the driver's input when a desired speed is entered.

In this specific case, the IACC feature compares the entered speed value with the traffic speed limit. If the entered speed is equal to or less than the traffic speed limit, the system maintains the speed entered by the driver without any adjustments. However, if the entered speed exceeds the speed limit, the IACC feature sets the speed to the specified traffic speed limit. This ensures that the vehicle adheres to the imposed speed limit.

Test specifications should encompass parameters such as the current velocity, desired velocity, road type, and potential velocity variations for a comprehensive evaluation of this scenario.

Table 3.6. Test Specifications: Scenario – V

Parameters	Values
Desired Velocity (kph)	140 kph
Speed Limit (kph)	100 kph
Lead Vehicle Detection	YES
Lead Vehicle Speed (if applicable)	NA
Last Ego Vehicle Velocity(kph)	100 kph

This scenario is devised based on the specified test parameters. In this particular situation, the ego vehicle is traveling on a straight road, and the driver inputs a speed of 140 kph via the Human-Machine Interface (HMI). An essential check is performed to determine if the speed limit information is received from the Traffic Speed Limit Recognition (TSLR) feature, an ADAS component providing traffic speed limit details.

Upon verification, it is confirmed that the received speed limit information is 100 kph. The IACC feature compares this speed limit with the speed entered by the driver, enforcing a constraint that the user-entered speed must not surpass the imposed limit. Consequently, in this scenario, where the driver's input exceeds the speed limit, the IACC feature adjusts the ego vehicle's speed to match the specified speed limit of 100 kph.

It is crucial to emphasize that the ego vehicle's speed should remain inactive when the driver engages either the accelerator or brake pedal. Moreover, in this specific instance, the lead vehicle is not detected through the GPS sensor, leading the IACC feature to set the ego vehicle's speed to the determined limit of 100 kph. Observations affirm that the ego vehicle aligns with this speed limit during the scenario.

3.3.6 Scenario – VI

This scenario illustrates a situation where the IACC feature operates on a curved road without a preceding vehicle as given in Figure 3.11. The traffic speed limit information is received by the ego vehicle from the relevant Advanced Driver Assistance Systems (ADAS) feature. The IACC system transitions to cruise control status in the absence of a leading vehicle. Upon the driver inputting the desired speed, the IACC feature conducts a comparison between the traffic speed limit and the entered speed.

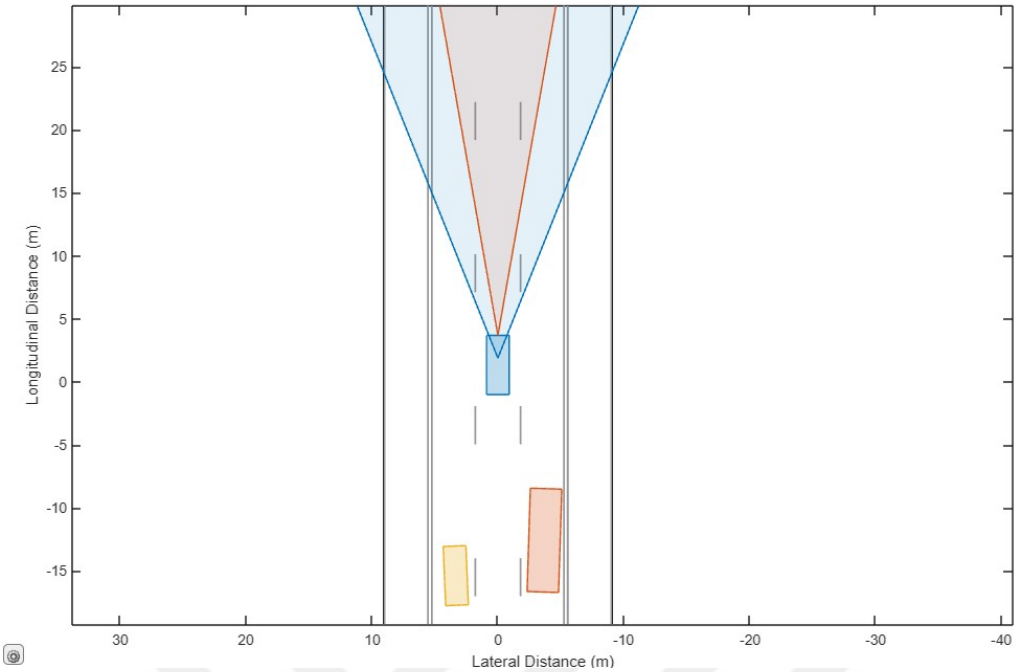

Figure 3.10. Ego Vehicle (IACC-Blue) Bird's Eye Plot: Straight Road & No Lead Vehicle & Speed Limit Input

If the speed entered by the driver is equal to or less than the traffic speed limit, the IACC feature maintains the speed value specified by the driver. However, when the entered speed exceeds the speed limit, the IACC feature adjusts the speed to align with the traffic speed limit. In this specific scenario, if a lead vehicle is detected on the curved road, the IACC feature processes this information utilizing data received through the Global Positioning System (GPS). To conduct comprehensive testing, specific test specifications must be defined, including parameters such as current velocity, desired velocity, road type, and potential velocity variations.

Table 3.7. Test Specifications: Scenario – VI

Parameters	**Values**
Desired Velocity (kph)	90 kph
Speed Limit (kph)	60 kph
Lead Vehicle Detection	NO
Lead Vehicle Speed (if applicable)	NA
Last Ego Vehicle Velocity(kph)	60 kph

This scenario has been defined based on the test specifications provided in the table 3.7. In this particular situation, the ego vehicle is navigating a curved path. As outlined in the table, the driver has input a speed of 90 kph through the Human-Machine Interface (HMI). Verification was conducted to determine whether speed limit information was received from Traffic Speed Limit Recognition (TSLR), another ADAS feature providing traffic speed limit information.It was confirmed that the received speed limit information was 60 kph. The entered speed value by the driver is then compared with the speed limit information. By the IACC feature, the speed specified by the driver should not surpass the speed limit. Consequently, in this scenario, the speed of the ego vehicle is set to the speed limit as the driver-entered speed exceeds the limit.The ego vehicle's speed should become inactive when the driver engages the accelerator or brake pedal. Additionally, the ego vehicle, unable to detect a lead vehicle via its GPS sensor in this condition, has its speed adjusted by the IACC feature to 60 kph. Observations indicate that the ego vehicle operates at this speed limit.

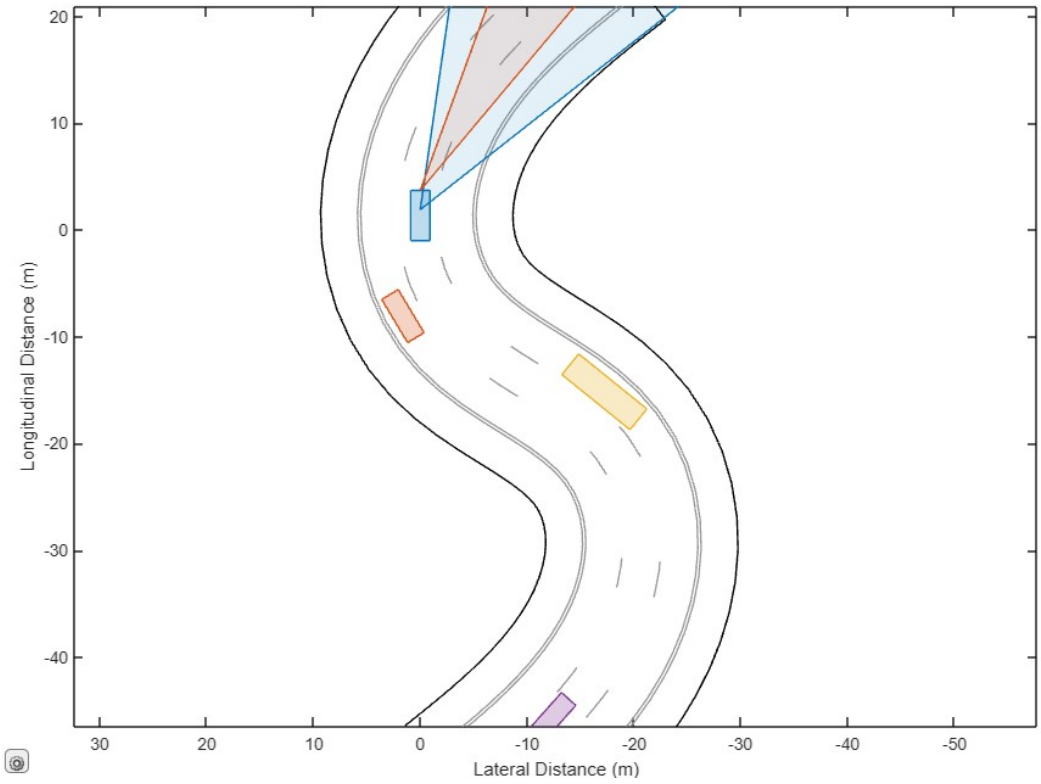

Figure 3.11. Ego Vehicle (IACC-Blue) Bird's Eye Plot: Curved Road & No Lead Vehicle & Speed Limit Input

3.3.7 Scenario – VII

This scenario depicts a situation where the IACC feature operates on a straight road with a vehicle in the lead. The traffic speed limit value is communicated to the ego vehicle from the relevant Advanced Driver Assistance System (ADAS) feature. The IACC feature transitions into a following control system state when a vehicle is detected in front. If the driver inputs the desired time-gap information, the IACC feature compares the traffic speed limit value with the specified time gap.

Should the speed information value calculated based on the time gap be equal to or less than the traffic speed limit, the IACC feature maintains the time gap value without making any adjustments. However, if the calculated speed information value surpasses the speed limit, the IACC feature modifies the time-gap value at the traffic speed limit.

Test specifications should be provided considering factors such as current velocity, desired velocity, road type, and velocity changes.

Table 3.8. Test Specifications: Scenario – VII

Parameters	**Values**
Desired Velocity (kph)	80 kph
Speed Limit (kph)	100 kph
Lead Vehicle Detection	YES
Lead Vehicle Speed (if applicable)	70 kph
Last Ego Vehicle Velocity(kph)	70 kph

The scenario was defined based on the test parameters outlined in the table 3.8. In this particular case, the ego vehicle is navigating a straight road as given in Figure 3.12. As specified in the table, the driver set the speed at 80 kph using the Human-Machine Interface (HMI). Verification was conducted to ascertain whether speed limit information was relayed from Traffic Speed Limit Recognition (TSLR), another ADAS feature responsible for providing traffic speed limit data. The received speed limit information was determined to be 100 kph.

In line with the IACC feature, the speed inputted by the driver must not surpass the speed limit. In this scenario, as the driver's input falls below the limit, the speed of the ego vehicle

is established as the entered speed. However, the ego vehicle also detected the presence of a lead vehicle. Consequently, the ego vehicle compares its entered speed to that of the lead vehicle, which is measured at 70 kph. As a result, the IACC feature adjusts the speed of the ego vehicle to 70 kph instead of the driver-entered 80 kph. It is observed that the ego vehicle operates at this speed limit.

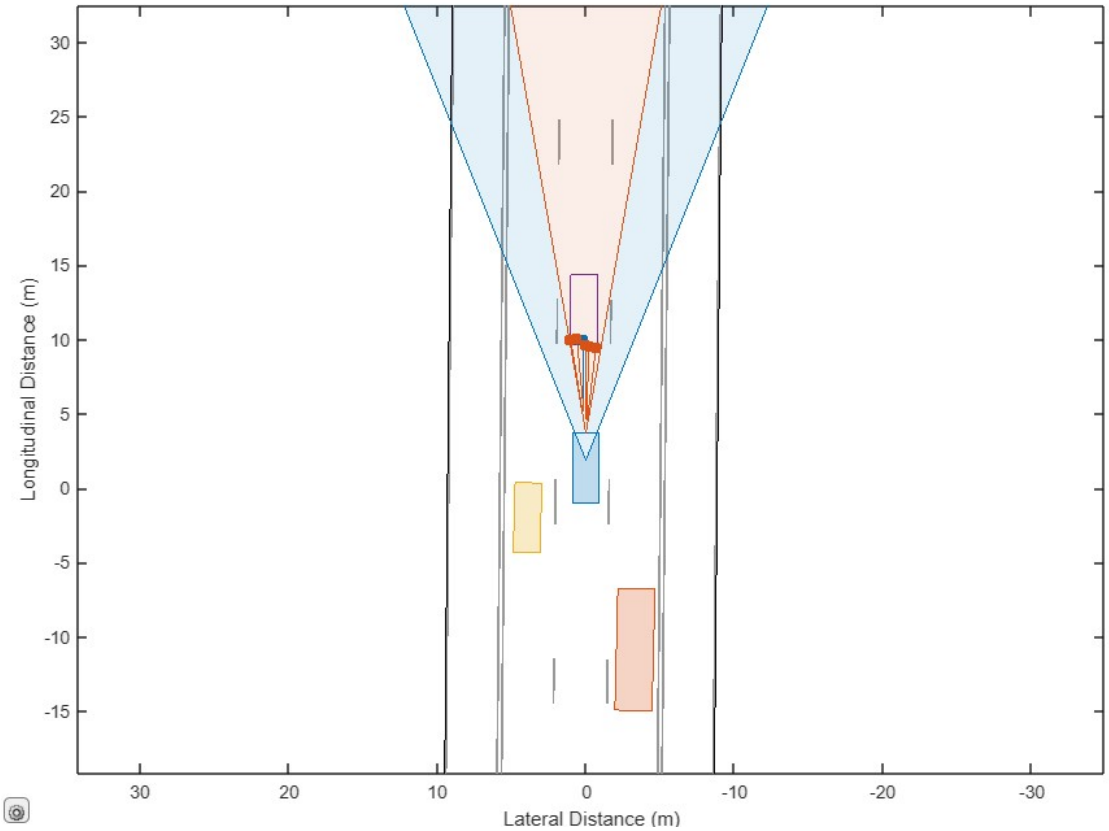

Figure 3.12. Ego Vehicle (IACC-Blue) Bird's Eye Plot: Straight Road & Detected Lead Vehicle & Speed Limit Input

3.3.8 Scenario – VIII

This scenario depicts a situation where the IACC feature is engaged while navigating a curved road with a lead vehicle ahead. The traffic speed limit value is communicated to the ego vehicle from the relevant ADAS feature. The IACC feature transitions into a following control system state when a vehicle is detected in front. If the driver inputs the desired time-gap information, the IACC feature compares the traffic speed limit value with the entered time gap value. If the speed information value, calculated based on the time gap, is equal to or less than the traffic speed limit, the IACC feature retains the time-gap

value. However, when the calculated speed information value exceeds the speed limit, the IACC feature adjusts the time-gap value by the traffic speed limit.

In this scenario, when there is a lead vehicle on the curved road, the IACC feature processes the presence of the detected vehicle based on the information received through GPS data. Test specifications should be tailored to scenarios considering parameters such as current velocity, desired velocity, road type, and velocity changes.

Table 3.9. Test Specifications: Scenario- VIII

Parameters	**Values**
Desired Velocity (kph)	70 kph
Speed Limit (kph)	60 kph
Lead Vehicle Detection	YES
Lead Vehicle Speed (if applicable)	50 kph
Last Ego Vehicle Velocity(kph)	50 kph

This scenario is devised based on the test characteristics outlined in the table 3.9. Here, the ego vehicle maneuvers along a curved path, with the driver setting a speed of 70 kph as illustrated in Figure 3.13. The presence of speed limit information from TSLR, another ADAS feature providing traffic speed limit information, was verified, and the received limit was determined to be 60 kph. The IACC feature ensures that the entered speed by the driver complies with the speed limit.

In this specific scenario, the IACC feature also identifies the presence of a lead vehicle, not detectable by radar but sharing the same lane, through the GPS sensor. The IACC feature acquires speed and location information of the lead vehicle through the GPS sensor. Given that the speed of the lead vehicle is 50 kph in this instance, the IACC feature adjusts the speed of the ego vehicle to match, setting it to 50 kph instead of the entered 60 kph speed limit. The ego vehicle is observed to move at this adjusted speed limit.

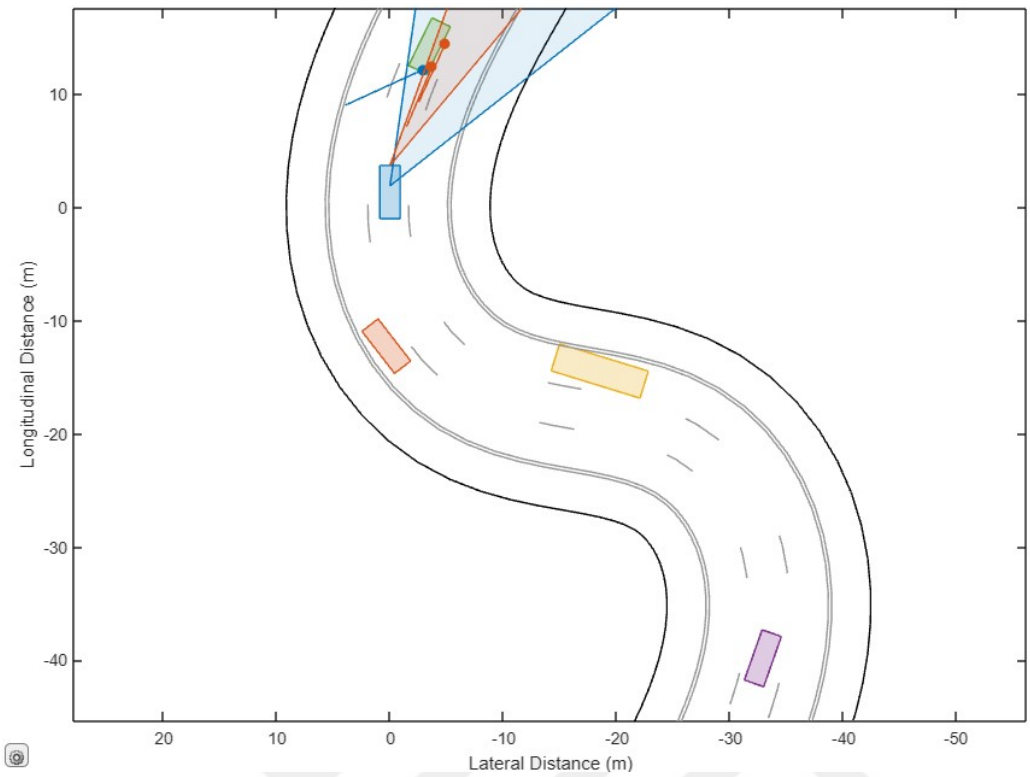

Figure 3.13. Ego Vehicle (IACC- Blue) Bird's Eye Plot: Curved Road & Detected Lead Vehicle & Speed Limit Input

3.4 Safety Assessment of the IACC

This section addresses the research findings within the scope of Adaptive Cruise Control (ACC), specifically focusing on safety considerations and the investigated scenarios. Key factors influencing the safety evaluation of ACC are outlined below:

- Unresponsive Driver Behavior
- Collision Avoidance
- System Failure

3.4.1 Unresponsive Driver Behaviour

This evaluation criterion aims to assess the ADAS feature's responsiveness to the driver. The ACC system will make efforts to engage the driver through repeated warnings, and the evaluation will observe scenarios where there is no response from the driver. It is anticipated that these systems will operate in conjunction with driver monitoring evaluations. As per the protocol, these safety tests should be conducted exclusively in a

designated restricted area on highways. The evaluation test is mandated to take place on a straight road with a minimum of two lanes.

3.4.2 Collision Avoidance

The ACC's performance is exclusively assessed within its designated lane, offering support on the same lane. For crash avoidance evaluations, the system's performance in response to adjacent vehicles on the highway is observed. This evaluation focuses on gauging the vehicle's capacity to avert a collision, employing a scoring system. When ACC and AEB systems collaborate to prevent a collision, they receive scores based on specific criteria, which vary according to the Time-to-Collision (TTC) period.

3.4.3 Failure in System

The normal operation of sensors related to driving support systems is expected during regular driving. However, these sensors (Radar, LiDAR, and camera) may occasionally experience damage, adverse effects, or malfunctions. If a sensor fails, the system's effectiveness may be compromised. Detecting such malfunctions is crucial for system reliability. To ensure system adequacy in the event of sensor failure, incorporating redundancy or multifunctional sensors is vital. Sensor blocking tests are conducted in evaluations related to this aspect, and specific criteria are applied to score system behavior [28].

3.5 Basic Safety Concepts

Understanding some fundamental safety terminology is essential. Errors refer to deviations from accuracy or correctness, hazards are situations causing harm in the form of human injury or property/environmental damage, faults are abnormal situations leading to a temporary loss of functional capability, and failures are specific events occurring at a certain point.

3.5.1 Safety Pattern Analysis of System Architecture

In designing the system flow with security considerations, the initial elements include the system architecture and basic safety components. A safety pattern is developed based on these inputs, determining where and under what conditions it will be applied. Pattern analysis facilitates the creation of system functional safety patterns and requirements, as

illustrated in Figure 3.14.

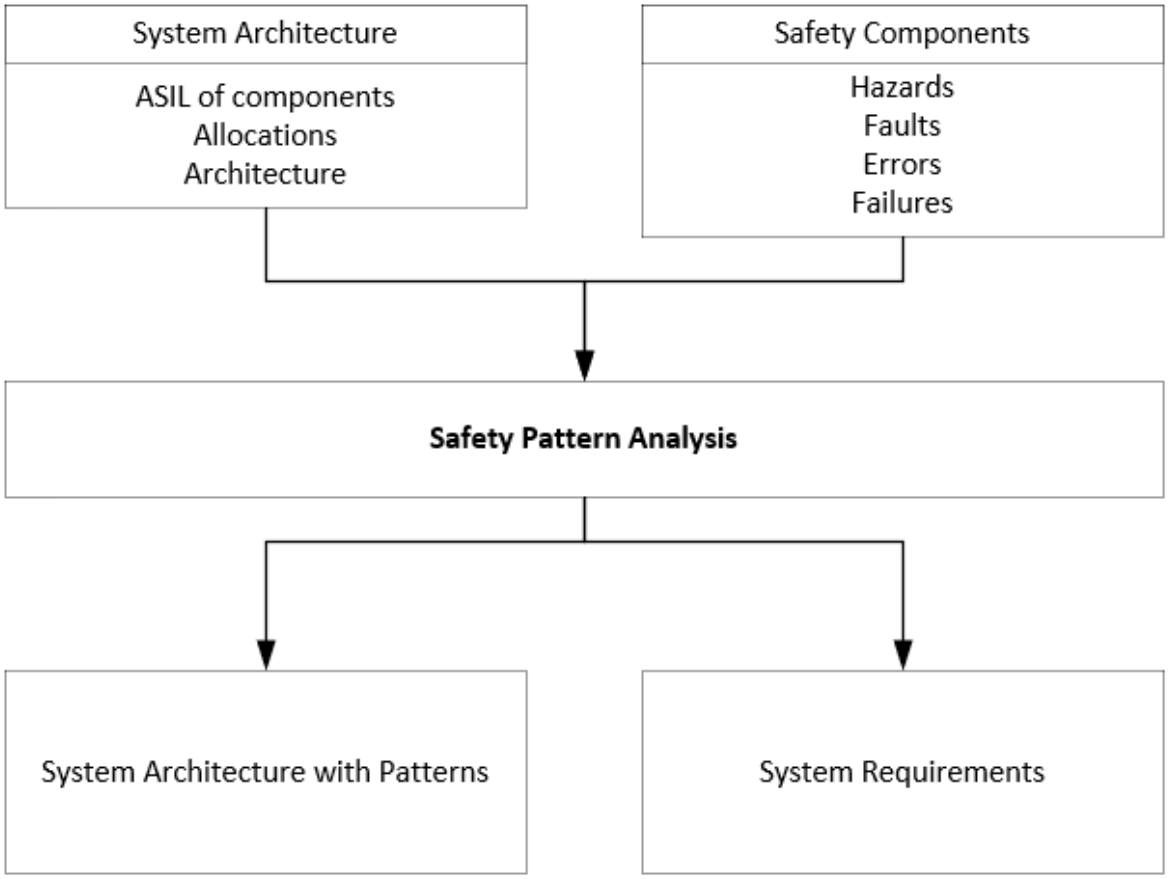

Figure 3.14. Flow Chart of Safety Pattern Analysis [29]

4 DISCUSSION AND RESULTS

4.1 Hazard Analysis and Risk Assessment (HARA) Activities

In today's automotive landscape, the significance of functions provided by electrical and electronic systems in vehicles is steadily increasing. Consequently, ensuring the safety of future autonomous and ADAS-equipped vehicles presents a formidable challenge. Designing ADAS devices requires a comprehensive understanding of all possibilities related to their operation. Road tests play a pivotal role in this context. Creating a real driving scenario and observing the vehicle's responses within a simulation environment is an effective verification method.The ISO 26262 safety lifecycle encompasses "Hazard Analysis and Risk Assessment" (HARA) activities. The primary objective is to determine an Automotive Safety Integrity Level (ASIL), setting a safety target. Key challenges

associated with HARA include ensuring validity, repeatability, and reliability. As the determination of HARA is crafted based on human knowledge and experience, maintaining these aspects becomes crucial. The ISO 26262 standard outlines parameters that significantly influence evaluation, including severity levels, controllability, and exposure [30].

Within the HARA process, designers are required to produce specific documentation. Two critical documents include one outlining operational scenarios and another presenting a detailed status document that enumerates associated hazards and error/failure situations. This structured approach facilitates the identification of potential hazards more efficiently and effectively. The primary objective of the Adaptive Cruise Control (ACC) is to safeguard its lanes in the longitudinal plane. In the event of a risk situation, a scenario can be devised where the ACC malfunctions, triggering the activation of Automatic Emergency Braking (AEB), another ADAS feature, to avert a collision. From a safety perspective, three distinct driving tasks need separate consideration: strategic, tactical, and operational. Strategic safety involves route planning strategies with minimal traffic or obstacles. This represents a higher abstraction level in terms of safety considerations. Tactical safety entails decisions regarding parameters such as ego vehicle speed and the distance between the lead vehicle and the ego vehicle. Operational safety encompasses the capability of the sensing system to perceive the environment and control ego vehicle actuators, including brake and accelerator pedals, steering, etc.

For Intelligent Adaptive Cruise Control (IACC), the tactical safety process should be applied. The following steps are adhered to in the tactical safety process:

1) Definition of Function
2) Detection of a Hazardous Situation
3) Objectification of HARA
4) Determination of ASIL
5) Control and decision-making for the determination of ASIL [31]

The verification tasks in this section are closely tied to the subsequent phase of requirement writing. During the requirement writing phase, it is crucial to specify functional safety requirements. To delineate functional safety requirements, the previously outlined steps should be systematically applied, and relevant scenarios need

to be meticulously crafted.

4.2 Discussion of Methodology

The safety performance of scenarios developed in this experiment on curved and straight roads was thoroughly analyzed. Extensive studies were conducted to enhance both driver and vehicle safety. Within the scope of this thesis, a specific segment of the designed architecture underwent simulation testing to assess its impact. The evaluation of how the vehicle's performance on the road affects safety involved a comparison between the required distance (time gap) and the actual distance between two vehicles. The experimentation utilized a MATLAB Simulink program, and the scenarios were implemented through the Model Predictive Control (MPC) toolbox, currently available in the MATLAB library. In the previous section, eight distinct scenarios were identified as high-level system test scenarios. Among these, four high-level system scenarios required processing external data from TSLR as one of the in-device control modules. The remaining scenarios were executed without TSLR input, representing another aspect of the ADAS feature.

In discussing IACC driving scenarios, variations arise based on TSLR data, road shape, and lead vehicle status. The architectural design of IACC (high-level system diagrams of IACC) was developed at an advanced level and is presented in the preceding Section 2. Alongside these architectural designs, analyses were conducted using the existing MATLAB MPC toolbox with specified scenario details. The toolbox does not contain TSLR data, leading to a safety evaluation only if the moving vehicle is the lead vehicle. Relevant scenarios (with a lead vehicle and without TSLR data) include Scenario 3 and Scenario 4. In terms of safety, the ego vehicle was expected to adjust its speed in all scenarios and maintain the safety distance at or above the minimum distance.

For Scenario 3, the ego vehicle detected the lead vehicle in front using its sensors (ultrasonic, RADAR, LiDAR, GPS). The initial speed of the ego vehicle was set at 100 kph, and the road type was determined as straight. Following the characteristics of Scenario III, the speed of the ego vehicle was adjusted to 80 kph. The speed of the vehicle in front was set at 50 kph, considering the distance. The Vset value was established as 50 kph according to the time value. The expected speed of the ego vehicle was 50 kph, accounting for the time required due to momentum. The speed change graph is depicted

in Figure 4.1, with a simulation time of 100 seconds and a sample time value of 0.1 seconds.

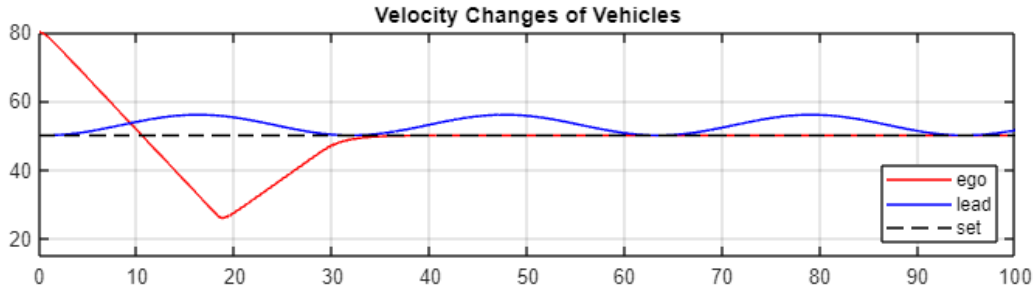

Figure 4.1. Scenario III – Velocity changes between ego & lead vehicle

Figure 4.2 presents data on the actual distance difference and the safe distance between two vehicles. In this scenario, the road type is a straight highway. It is observed that the distance is maintained when the IACC reaches the stable set speed. Due to the initial acceleration change, the vehicle's distance changes during the first 20 seconds. The analysis indicates that the primary goal of IACC is to preserve the safety distance and ensure it remains greater than the minimum value. In this specific scenario, Figure 4.2 demonstrates that the time gap is within the expected limits.

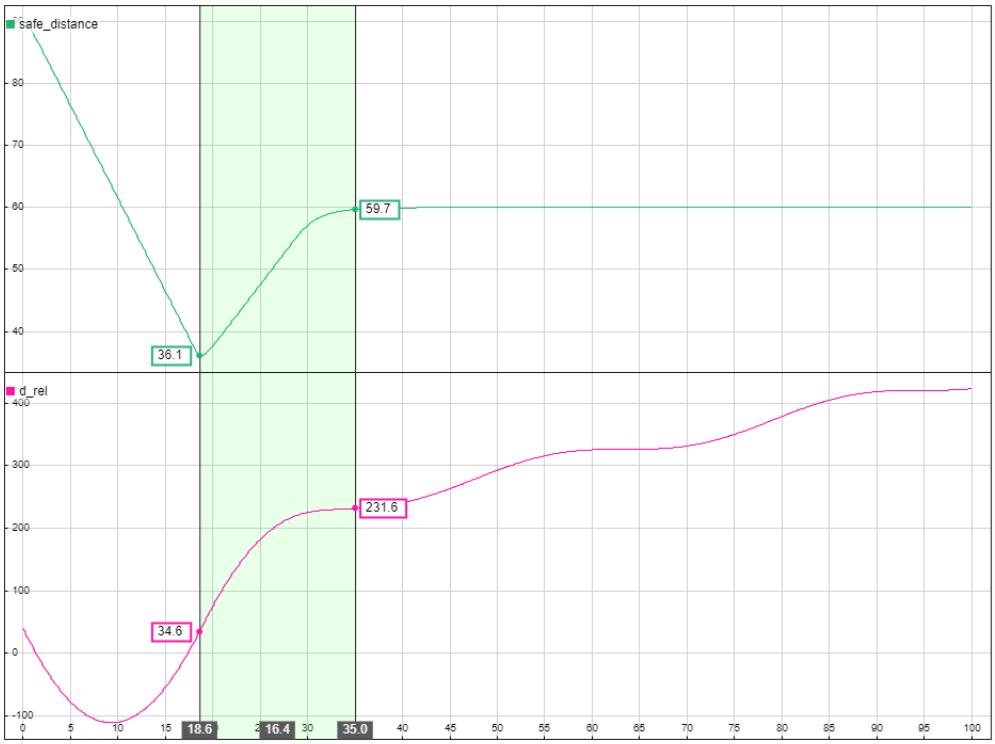

Figure 4.2. Scenario III- Safe and actual distance between ego & lead vehicle

As per the specifications outlined in Scenario IV, the speed of the ego vehicle was set to 90 km/h, while the lead vehicle speed was set to 50 km/h. In this instance, the distance was considered, and the Vset value was adjusted to 50 km/h based on the time value. Consequently, the anticipated speed of the ego vehicle is 50 km/h, accounting for the time required for the momentum-induced change. The speed change graph is depicted in Figure 4.3. The simulation time was set at 100 seconds with a sample time value of 0.1 seconds.

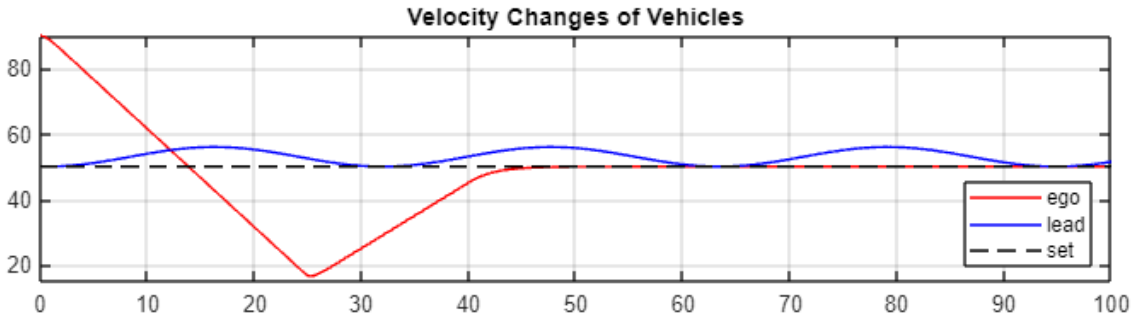

Figure 4.3. Scenario IV – Velocity changes between ego & lead vehicle

Figure 4.4 presents data on the actual distance difference and the safe distance between two vehicles. Initially, while maintaining a constant safe distance, it is observed that the actual distance between the current ego and the lead vehicle increases with the speed change of the ego vehicle. This provides valuable insights into the security and reliability of the system, indicating that the IACC system is approaching its limit in this regard. The primary objective of IACC is to sustain the safety distance and ensure it remains greater than the minimum value. Figure 4.4 demonstrates that, in this scenario, the system operates within the expected limits.

Consequently, the primary objectives of IACC, namely safe distance and speed control, were thoroughly analyzed in this thesis. High-level system diagrams were crafted using a Model-Based Systems Engineering (MBSE) approach.

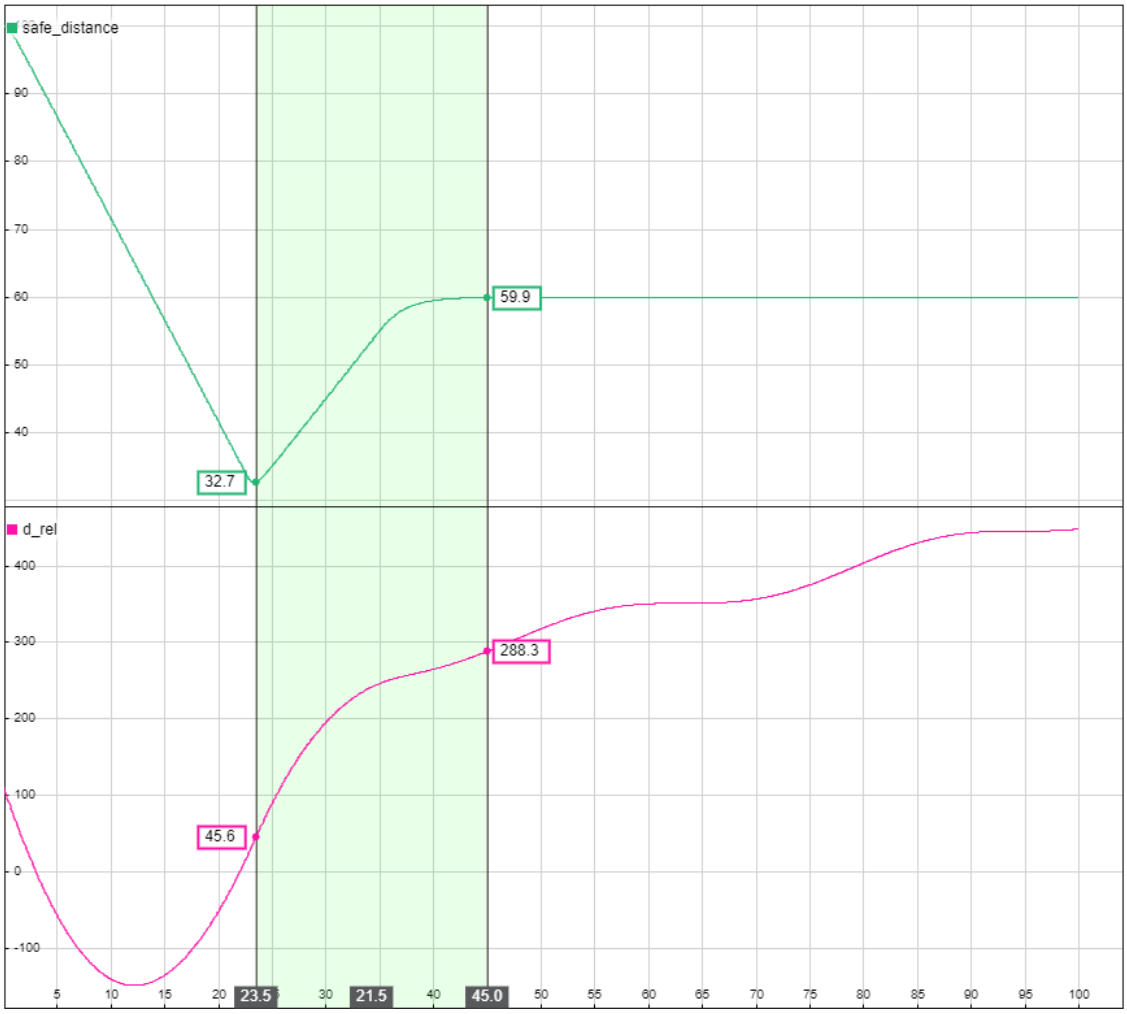

Figure 4.4. Scenario IV- Safe and actual distance between ego & lead vehicle

The analysis conducted in this study revealed that driving safety on curved roads was enhanced through the integration of the system's GPS sensor. Additionally, TSLR input information, a crucial factor for speed control, was incorporated into the system architecture. In the upcoming study, a distinct autonomous vehicle simulation incorporating additional island features will be employed for analysis, providing valuable insights into the impact of TSLR.

5 CONCLUSION

In the context of this thesis, the control system architecture for IACC safety was meticulously designed using a model-based system engineering (MBSE) approach. Employing high-level system design and development, essential diagrams were crafted to elucidate the concept of utilizing this Advanced Driver Assistance System (ADAS) feature with newly added features in future applications. The model's performance was scrutinized by test protocols and standards, utilizing the MATLAB-Simulink environment for simulation purposes. System architecture diagrams and IACC visualizations were created using MS Visio and Drawio (an online diagram editor).

The MATLAB-Simulink application was instrumental in defining the system architecture diagrams aligned with the specified requirements. Within the study, a high-level architectural design from MBSE methods was employed. System architecture diagrams, forming the top-level system structure, were designed to incorporate both existing and newly added IACC features, as outlined in Section 2. The subsequent project phase involves crafting system requirements, considering the security standards mentioned in this study. System requirements will encompass functional requirements, integral to the overall project process. Determining the hardware and software units related to these functional requirements initiates the low-level documentation and the hardware and software design process of the system.

Unlike previous studies, this research focuses on enhancing the performance and safety of the Adaptive Cruise Control (ACC) feature on curved roads. The design also aims to increase system awareness by considering traffic speed limits. The ACC has been augmented to analyze topography through GPS and detect lead vehicles not visible in blind spots through radar, LiDAR, cameras, and similar sensors. The goal is to enhance safe driving support without sole reliance on the driver and lead vehicle.

In the current ACC concept, scenarios where the driver activates the system in an environment without a lead vehicle are considered. The system processes information from the traffic speed limit ADAS feature independently, providing driving support on highways or in the city without solely depending on the driver. Future studies can explore real-time integration with Traffic Speed Limit Recognition (TSLR) input for simulation and performance analysis in architectural design.

The study evaluated the latest published standards and regulations concerning ACC. Compliance with these standards is crucial for Original Equipment Manufacturers (OEMs) to meet specific safety specifications. Potential error situations related to safety-related collision avoidance, Electrical/Electronic (E/E) system failure, and driver behavior are identified as the main risk factors, emphasizing the necessity to incorporate these issues and risks into system requirements.

Additionally, the IACC feature is designed to collaborate with other ADAS features to enhance automation. Features such as Stop&Go, TSLR, Lane Keeping Assist/Lane Centering Assist (LKA/LCA), or Automatic Emergency Braking (AEB) can complement each other, contributing to a more automated system. The identification of these features is deemed crucial for the development of ACC, as discussed in this study.

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