DISSERTATION

A NEW AUTOMOTIVE SYSTEM ARCHITECTURE FOR MINIMIZING REAR-END COLLISIONS

Submitted by

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ABSTRACT

A NEW AUTOMOTIVE SYSTEM ARCHITECTURE FOR MINIMIZING REAR-END COLLISIONS

Advanced Driver Assistance Systems, more frequently referred to as ADAS, are intelligent systems integrated into newer automotive vehicles to improve safety and minimize accidents. These systems utilize radar, sonar, lidar and camera sensors mounted around the vehicle to maintain situational awareness of the vehicle and the surrounding environment. The majority of ADAS that focus on collision avoidance modify the host vehicle's operation. Some existing ADAS will stop the vehicle, sound an audible alert, initiate internal warning lights or dash warning messages, and prevent lane change operations. The ADAS proposed and detailed here focuses on enabling the host vehicle to communicate with the inbound vehicle's driver via the brake lights so that the driver has the opportunity to modify the inbound vehicle's operation before a collision occurs. This is called the Aft Collision Assist (ACA). This work presents the Model Based System Engineering (MBSE) diagrams, SIMULINK models and simulation of the ACA, data derivation utilized in the simulations, validation with empirical data, and future work for optimizing the ACA's algorithms.

ACKNOWLEDGEMENTS

I would like to thank my thesis advisor Dr. Chandra and my committee members Dr. Margaret Cheney, Dr. Daniel Herber, and Dr. Steven Simske for the opportunity to present this work and the guidance while doing so. I would also like to thank my friends Justin Benfield, Adam Wehage, and work colleagues at Daimler Truck North America. Finally, I would like to give a special thanks to my mother West Rictor for her support.

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Chapter 1 Introduction[1]

Between 2011 and 2021 investments in Advanced Driver Assistance Systems (ADAS) increased from $5 billion to $25 billion [5]. In particular, distance warning and Automatic Emergency Braking (AEB) systems saw an investment of $5 billion [5]. ADAS that can be considered distance warning include, Forward Collision Warning (FCW), Adaptive Cruise Control (ACC), and Rear Collision Warning (RCW). Of the distance warning ADAS, ACC and AEB are specifically designed to prevent rear-end collisions, however these systems only prevent the host vehicle from rear-ending a leading vehicle [6,7]. The Aft Collision Assist (ACA) is specifically designed to prevent an inbound vehicle from rear-ending the host vehicle, regardless of vehicle age or ADAS equipment level. The ACA is the refined development of the Defensive Crash Avoidance System (DCAS) project started in the fall of 2019, presented at AUVSI XPONENTIAL 2020 and published in the SAE Journal of Passenger Vehicle Systems [8,9,10,11,12].

1.1 Problem Statement

As vehicles become more advanced with ADAS options, their cost increases significantly. As vehicle prices increase, a greater percentage of potential consumers are priced out, causing many to maintain and drive older vehicles for longer [106]. A full ADAS package can increase the price of a new vehicle by at least $1500 [108]. As of 2022, the Bureau of Transportation Statistics found that the average age of vehicles on US roadways is 12.5 years old

[1] Rictor, A. and Chandrasekar, V., “Defensive Crash Avoidance System (DCAS): A New Advanced Driver Assistance System (ADAS),” Conference Presentation at AUVSI XPONENTIAL 2020, Oct. 2020.

[104]. With vehicles manufactured prior to 2022 not required to be equipped with AEB in particular, much less any ADAS technology, there is a large percentage of vehicles on the road without ADAS safety technologies [105]. For the year 2021, the National Safety Council found that of the 9,330,000 crashes involving more than one vehicle, 41% were rear-end collisions [103]. This combination of older vehicles being driven longer, and ADAS safety requirements only existing in new vehicles leads to a widening safety concern and increased financial risk to driver's. In addition to higher purchase prices, ADAS also increases the cost of vehicle repairs significantly, according to research conducted by the American Automobile Association. From a financial perspective, higher initial costs and higher repair costs directly translates to higher insurance premiums for newer vehicles with ADAS installed [109]. This places the financial burden of new safety systems on the purchasers of new vehicles, including the financial risks without a medium for risk mitigation or prevention of being rear-ended.

1.2 Research Objectives

ADAS technologies are projected to minimize the severity, if not fully prevent approximately 62% of the automotive collisions seen today [107]. However, this is presuming all vehicles have ADAS technologies installed. This poses two challenges, the first is 100% adoption of ADAS technologies in new vehicles, which is projected to take years. Second, the ADAS technologies being adopted only modify the host vehicles operation to prevent collisions. These two challenges are an open area of research for the research presented within focuses on addressing: developing and designing a new ADAS option to prevent rear-end collisions that focuses on protecting the host vehicle from inbound vehicles; the ACA.

1.3 Proposal Overview

The proposed research herein presents the MBSE models, SIMULINK models and SIMULINK simulations of the ACA. The MBSE models presented within depict the system requirements and their convergence with the physical system implementation. The physical system implementation is expanded upon in the SIMULINK modeling, which is derived directly from the MBSE modeling. Preliminary system validation of the ACA is presented via the SIMULINK simulations. In addition, the SIMULINK simulations demonstrate the operational input and output requirements, as well as the limitations of the ACA.

Chapter 2 Background[2]

The development of Advanced Driver Assistance Systems, more commonly known as ADAS, started as early as the 1970's with the introduction of anti-lock braking systems, skid control systems or traction control systems. The systems most commonly associated with ADAS, such as Forward Collision Warning, Adaptive Cruise Control, Automatic Emergency Braking, Rear Collision Warning and Pre-Crash Warning were initially introduced in the early 2000's on luxury models [110]. Sections 2.1 through 2.6 are quoted directly from the SAE Journal of Passenger Vehicle Systems article *Model Based Systems Engineering of the Aft Collision Assist Advanced Driver Assistance System* [9].

2.1. Forward Collision Warning

Forward Collision Warning (FCW) is an ADAS that utilizes radar sensors to calculate the distance between the host vehicle and the vehicle or object immediately in front of the host vehicle. When the distance between the host vehicle and the lead vehicle or object reduces to below a set threshold based upon the host vehicles speed, the host vehicle will either sound an audible warning in the cabin or apply the host vehicle's brakes if the host vehicle is equipped with Automatic Emergency Braking (AEB) [13, 14, 15, 16].

2.2. Adaptive Cruise Control

Adaptive Cruise Control (ACC) is an ADAS that employs long range radar on the front of a host vehicle to measure the distance between the host vehicle and a lead vehicle. When the host

[2] Rictor, A. and Chandrasekar, C V, "Model-based systems engineering of the aft collision assist advanced driver assistance system," SAE Int. J. Passen. Veh. Syst., vol. 16, no. 3, doi:10.4271/15-16-03-0012, Feb. 2023. [Online]. Available: www.sae.org.

vehicle reaches the set cruising speed, the ACC reduces the host vehicle's set speed to match the lead vehicle's speed and following distance. If the distance between the host vehicle and the lead vehicle reduces to below the set following distance, then the ACC reduces the host vehicles set speed to match the lead vehicles and increases the following distance to the predefined value. The ACC is capable of being set for a predefined speed or distance, and will adjust accordingly to meet both criteria. If the distance between the host vehicle and a lead vehicle can be maintained to match the predefined following distance, then the host vehicle's speed is increased to match the pre-set speed as well [6, 7, 17].

2.3. Automatic Emergency Braking

Automatic Emergency Braking (AEB) is an ADAS that utilizes radar sensors in the front of a host vehicle to calculate the distance between the host vehicle and an object or lead vehicle in front of it. If that distance has fallen below a set threshold the host vehicle's brakes are applied to either slow or stop the host vehicle to prevent a collision [13, 14, 15, 16].

2.4. Rear Collision Warning

Rear Collision Warning (RCW) is an ADAS that employs radar sensors in the rear bumper of the host vehicle to calculate the distance between the host vehicle and an object or vehicle. It initiates an audio and visual warning if the distance between the host vehicle and another object has fallen below a set threshold [18]. *The RCW is a passive system that warns the host vehicle's driver of a potential collision. RCW systems use mid-range radar, long-range radar, or lidar that support a rapid, real-time warning system* [18].

2.5. Pre-Crash Rear

Some luxury vehicle manufacturers have introduced pre-crash rear ADAS that are similar to the ACA, but are proprietary to each manufacturer. The host vehicle utilizes scanning sensors in the rear bumper to monitor approaching vehicles. When an accident is calculated to be imminent the system responds by attempting to alert the approaching driver, proactively readying the onboard collision response systems, and/or assisting the host vehicle in maneuvering away from the impending collision. Krishman, et al [18] *utilized simulations to evaluate the potential reduction in the frequency and severity of rear-end collisions. The results of their study showed that the level of nuisance alerts or false triggers of the system were negligible.*

The primary manufacturer reviewed was Volvo. Volvo's RCW system was first offered on the XC90 starting in late 2019 [20]. *The RCW system is automatically engaged when the XC90 is started. When an accident is calculated to be imminent, the XC90 will engage the turn signal indicators to attract the drivers attention and encourage them to slow down. In circumstances where the XC90 is traveling at speeds less than 20 miles per hour, the seat belt tensioners will engage and the Whiplash Protection System will be activated. If the host vehicle is at a stop the service brake will be activated just before impact to minimize forward momentum of the host vehicle to prevent additional collisions* [20]. *Volvo's Rear Collision Warning system was introduced to the XC60 and XC4s0 in 2020* [21, 22].

2.6. Aft Collision Assist

The Aft Collision Assist (ACA) is a new ADAS, similar to the Pre-Crash Rear ADAS listed above. The ACA uses mid-range radar sensors in the rear bumper to calculate the *distance, velocity, and probability of a rear-end collision and responds in order to minimize the risk of an imminent collision. The ACA responds to the acute issue by using the host vehicle's stop lamps in a distinct pattern to attract the attention of the driver of the inbound vehicle.*

Chapter 3 Model Based System Engineering of the Aft Collision Assist

The following presents design criteria that the ACA system must adhere too. Figure 1: ACA System Requirements presents the ACA system in terms of the Requirements and Derived Requirements. The ACA's requirements are Sensor Hardware, ECU Hardware, Statutory Compliance and Cyber Security. The ACA's derived requirements include Software, Sensing, Data Processing and Communications. For Sensor Hardware, the operational range must be a minimum of 500 feet and function in all environmental conditions. The environmental conditions are defined to be sun, rain, hail, sleet, night lighting, day lighting, and all lighting conditions in-between. Data Sensing requirements are derived from the Sensor Hardware requirements and state that the sensors must be commercially available (COTS), automotive rated, able to perform data formatting, processing and quality control operations on the incoming data. The ECU Hardware must be automotive rated, operate on a 12 volt system with 12 volt signal inputs and outputs, support CAN signal inputs and outputs, and be able to calculate the time to impact between the host vehicle and inbound vehicle. Data Processing requirements are derived from the ECU Hardware and Sensor Hardware. Data Processing must be performed with sensors that have low computational overhead and be able to accept signal inputs from both existing sensors on the host vehicle that are from the Original Equipment Manufacturer (OEM) as well as aftermarket sensors that could be added to the host vehicle. The Statutory Requirements are that the ACA must comply with all lighting requirements and statutes for the United States. The Software Requirements are derived from the Statutory Requirements and ECU Requirements. The Software for the ACA must be open source and be able to integrate and support a multitude of different hardware and sensor combinations. The Communications Requirements are derived from the Software Requirements, ECU Hardware Requirements and Cyber Security. The Communications Requirements are that the ACA must be able to receive from and transmit to the host vehicle communications systems; predominately through CAN messaging using SAE J1939 standards. The Cyber Security requirements are that the ACA must comply with ISO/SAE 21434:2021 regulations. ISO/SAE 21434:2021 sets forth the requirements regarding engineering cybersecurity risk management with respect to development, manufacturing, operations and maintenance of electrical and electronics systems in road vehicles, including their constituent components and interfaces [118].

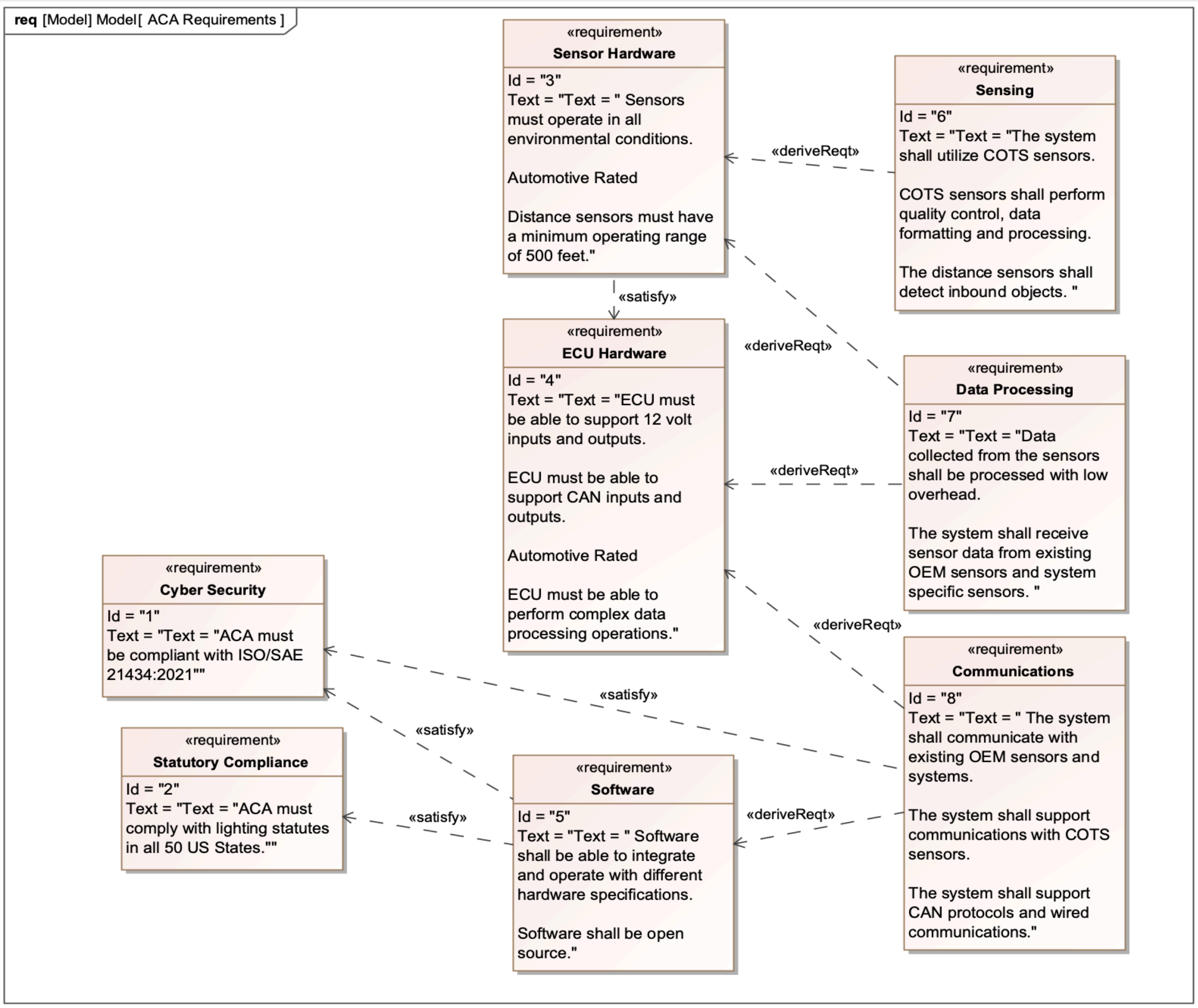

Figure 1: ACA System Requirements

The CAN message that needs to be received and comprehended from the host vehicle first and foremost is the host vehicle speed signal. The ACA will further need to be able to receive and understand ADAS related CAN messages from the host vehicle if the native ADAS sensors are being utilized for distance data. If the ACA is utilizing aftermarket sensors added to support the ACA, then the ACA must be configurable to either pull CAN signals from a second CAN network, or able to accept hardwired CAN messages directly from the sensors. The ACA output communications must be selectable to enable the ACA installation on a wide range of vehicles with differing ADAS options.

The block Statutory Compliance shown in Figure 1 is further discussed below presenting the regulatory requirements that the ACA must be compliant with. The specific statutes and regulations for each US state is presented in Table A1 of Appendix 1. In order for the ACA to be effective, the ACA needs to communicate with inbound vehicles, and how this is accomplished is the ACA's most novel aspect. To communicate with the inbound driver the host vehicles rear facing lights were reviewed and compared with the regulatory requirements to insure compliance. This included the color of lights, the light status, does it blink or does it need to be steady state, and when is the light permitted to be ignited. Reverse lights are only permitted to be ignited when the host vehicle is in reverse gear for the majority of US states, hence the reverse lights are not a compliant option for the ACA system in the majority of US states. The turn signals have a specific frequency range that they must be within in order to be compliant. This prohibits using the turn signals or hazard lights with any novel modification as a means of alerting the operator of the inbound vehicle. The brake lights must be constantly ignited when the brake is applied, and two brake lights must be visibly lit. For the ACA, the brake lights were selected as the medium to communicate with inbound drivers of the risk of an imminent collision. This communication is achieved by attenuating the intensity of the brake light illumination using a sinusoidal pattern, which is offset in phase between the left and right brake lights. In addition the minimum intensity of the brake lights is kept high enough to satisfy regulatory requirements. All of the US states specify that the brake lights must be visible for at least 100 feet, some states, such as Oregon specify at least 500 feet. The brake lights must be ignited when the brakes are applied, and remain lit and cannot be too dim or glare as well. Flashing lights are only permitted on specific vehicles, or in specific conditions, i.e. turn signals, hazard lights or specific lighting on authorized vehicles. However, the term “flashing light” does not have an the explicit legal definition. According to industry and maritime legal definitions a flashing light is a light that turns on and off at regular intervals in addition to other requirements [123, 124]. The ACA system does not turn the brake lights off, hence is not flashing them, instead, the brake light intensity is attenuated by voltage modulation.

Figure 2: Cyber Security Requirements Diagram presents CAN Security and the different risks that CAN security must be able to detect and respond to. The specific attacks and necessary considerations are from *Demonstration of MBSEsec Applied to Securing Cyber-Physical System Communications* [116].

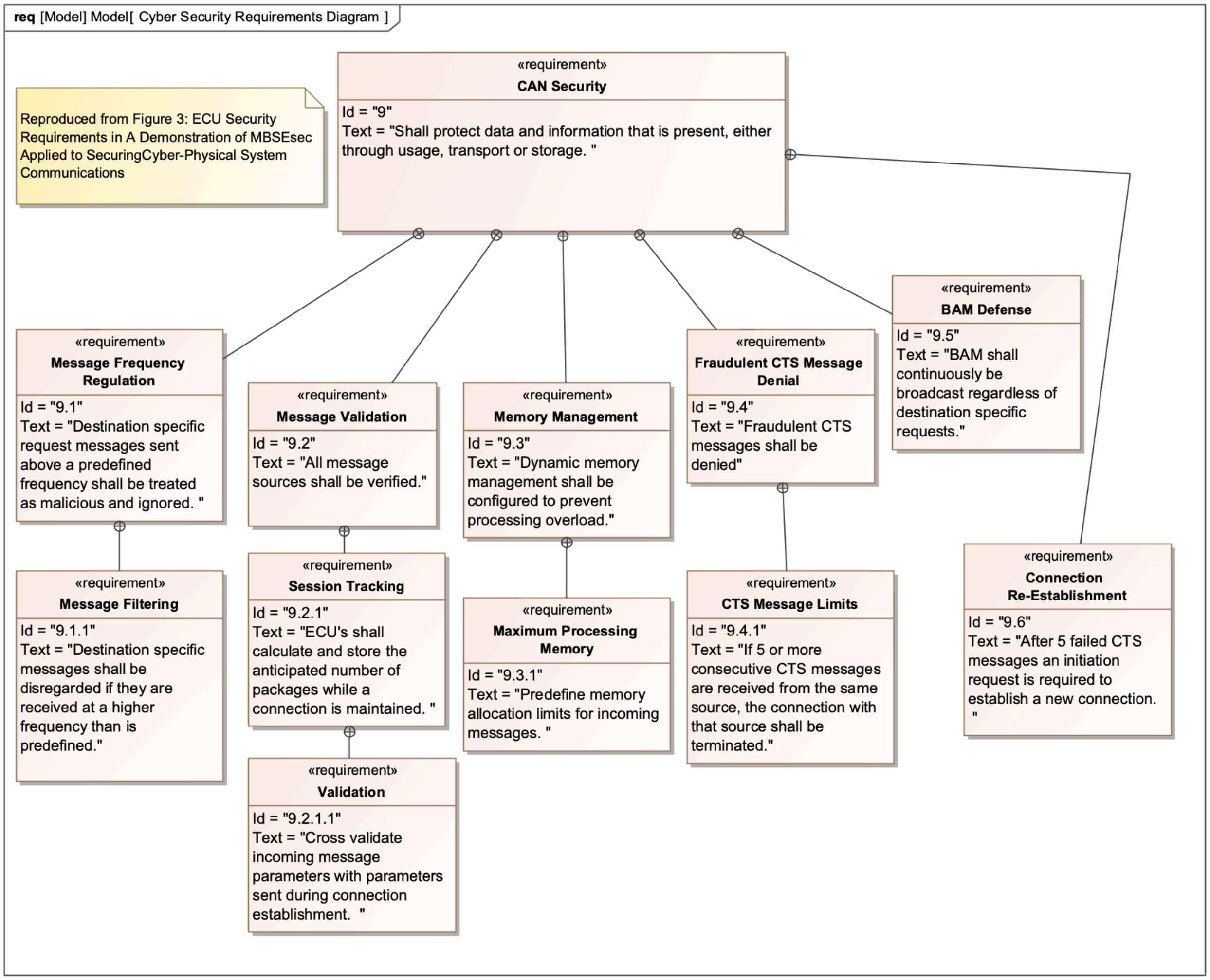

Figure 2: Cyber Security Requirements Diagram

Starting from the left, Message Frequency Regulation and the associated Message Filtering, ID 9.1 and 9.1.1 are configured to protect against destination specific threats. Destination specific messages that are sent and expected at regular intervals allow for security protocols to be written that filter out messages that are out of sync with the expected cadence. ID 9.2, 9.2.1 and 9.2.1.1, Message Validation, Session Tracking, and Validation are the next security protocols. For Message Validation, all CAN messages sent, either inbound, outbound, or internal will have their origins validated. Messages received from an unknown source will be disregarded. In addition, Session Tracking will be configured to calculate and recall the expected number of package frames sent during a sustained connection. Finally Validation, where the message parameters of all incoming messages are cross checked with the message parameters exchanged when the connection was initially established. ID 9.3 and 9.3.1 are Memory Management and Maximum Processing Memory, respectively. Memory Management shall be configured to support dynamic management to prevent processing overload. Maximum Processing Memory will be preconfigured to establish memory allocation limits for incoming messages. Message size limitations allow for initial filtering of potentially malicious messaging early on, while dynamic memory management allows for optimized message processing for peak performance, in addition to protecting against potential denial of service attacks. ID 9.4 and 9.4.1, Fraudulent CTS Message Denial and CTS Message Limits pair with Memory Management to protect against memory overloading. CTS Messages that are deemed to be fraudulent are denied processing. CTS Message Limits are set up to proactively sever a connection with a compromised source. A limit of 5 CTS messages sent from a single source will result in the connection with that source being terminated. CTS Message Limits will be paired with Connection Re-Establishment protocols that will require a new initiation request and secure connection with the source sending too many CTS messages. The final ID, ID 9.5 is BAM Defense. BAM Defense specifies that critical broadcast messages are not corrupted by destination specific messages to other destinations.

Figure 3.1: ACA State Machine depicts the ACA's operational states and the events that trigger each state to be entered. The ACA Off State is transitioned to with the *Vehicle Shut Down* signal. The ACA On State is transitioned to with the *Vehicle Start* signal. When in the ACA On state, the ACA Processing state is continuously active. The ACA Processing state is initiated and maintained with the Vehicle Running signal. The ACA Deactivated state is the first sub-state of

the system. When the *High Risk* signal is activated the ACA transitions sub-states to the ACA Activated sub-state.

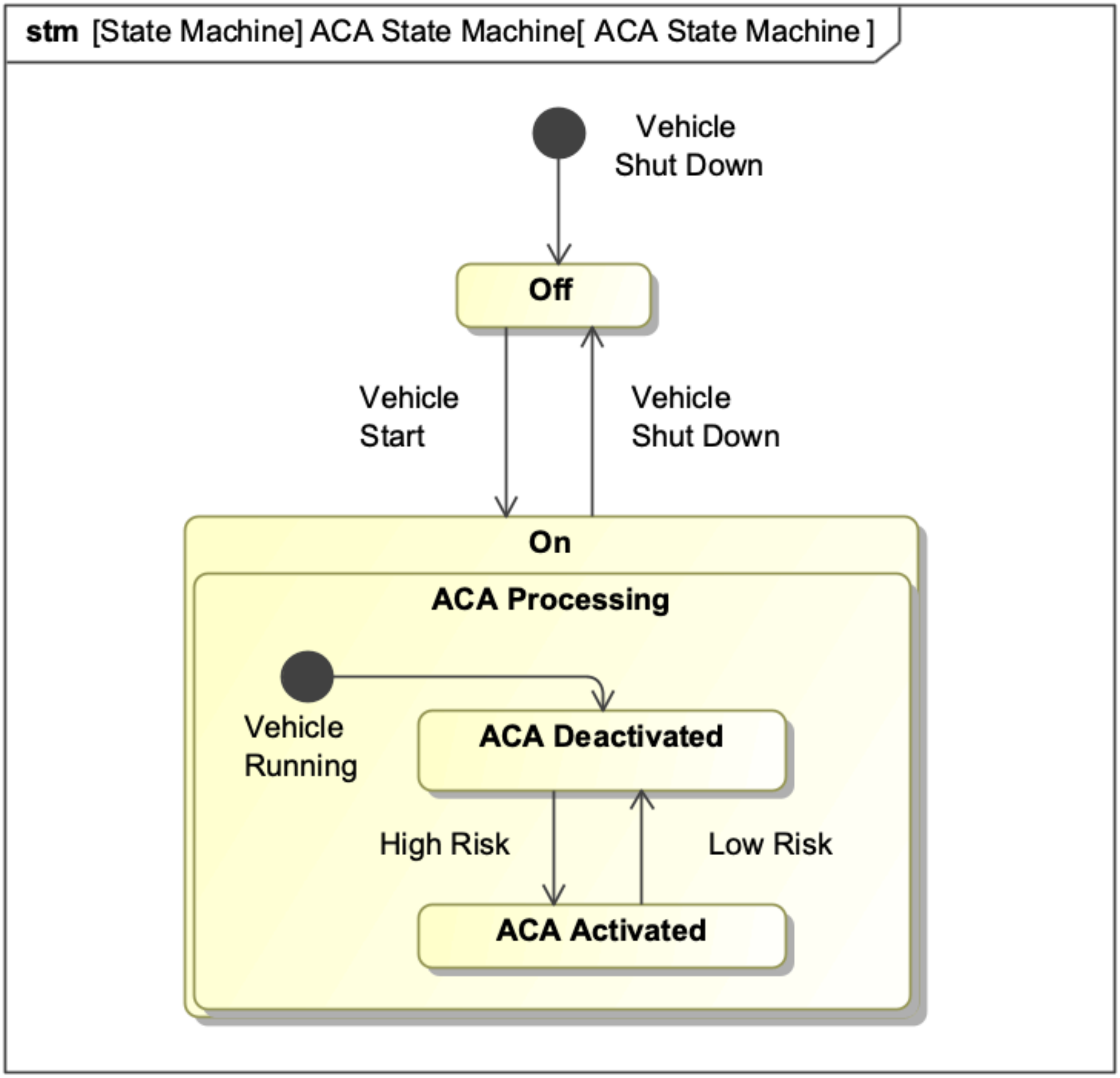

Figure 3.1: ACA State Machine

The ACA Processing state is further presented in Figure 3.2 ACA Processing Activity Diagram where the internal logic to determine *Low Risk* and *High Risk* is presented. The calculations and algorithms specifically implemented in the *Determining Collision Risk* and *Net Velocity* inputs are the primary signals that enable the ACA to function. The *Activate ACA Brake*

Light Signal and Deactivate ACA Brake Light Signal signals directly correlate with the Rear Traffic Alert Function (RTAF) Check block outputs described in Figure 23. ACA RTAF Check Block. The *Distance* and *Host Vehicle Speed* signal inputs in Figure 3.2 correlate with the inputs to the Running Initiation Block, History Initiation and History Loop SIMULINK blocks, depicted in Figures 17 through 22.

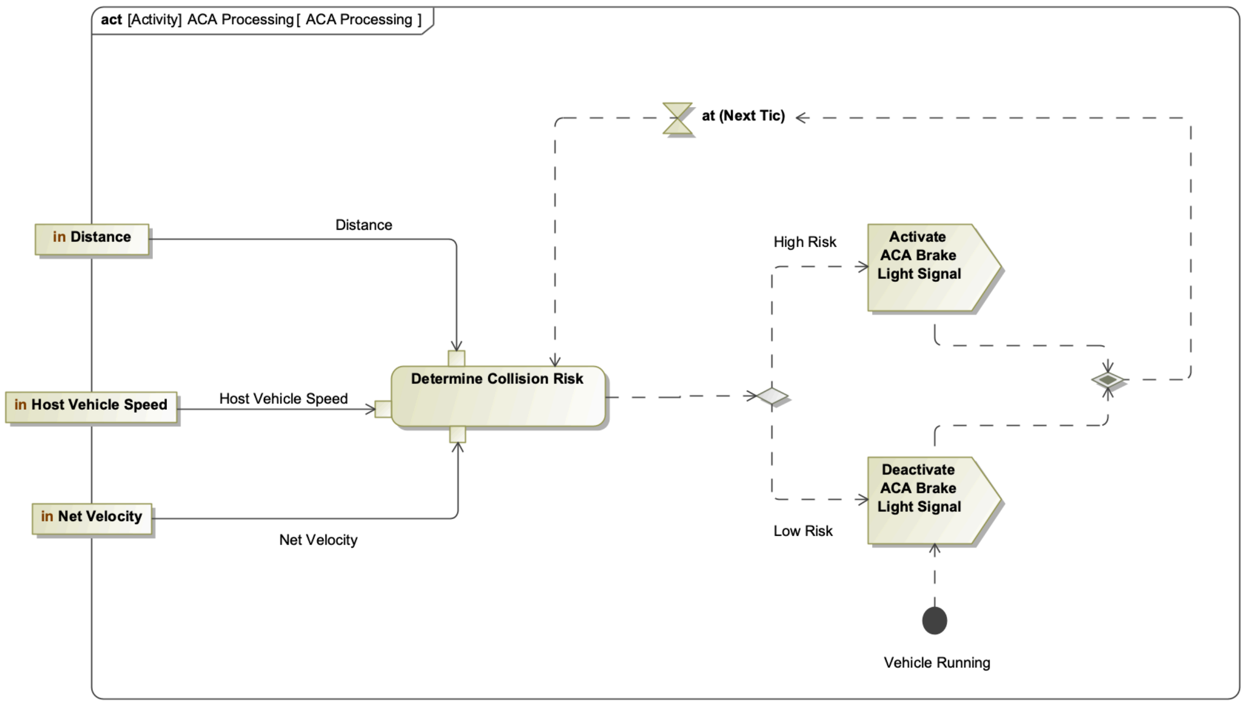

Figure 3.2: ACA Processing Activity Diagram

Figure 4: ACA Use Case depicts the generic expected operation of the ACA. The ACA Use Case figure presented in Figure 4 first appeared in publication in the Society of Automotive Engineers International Journal of Passenger Vehicle Systems [9].

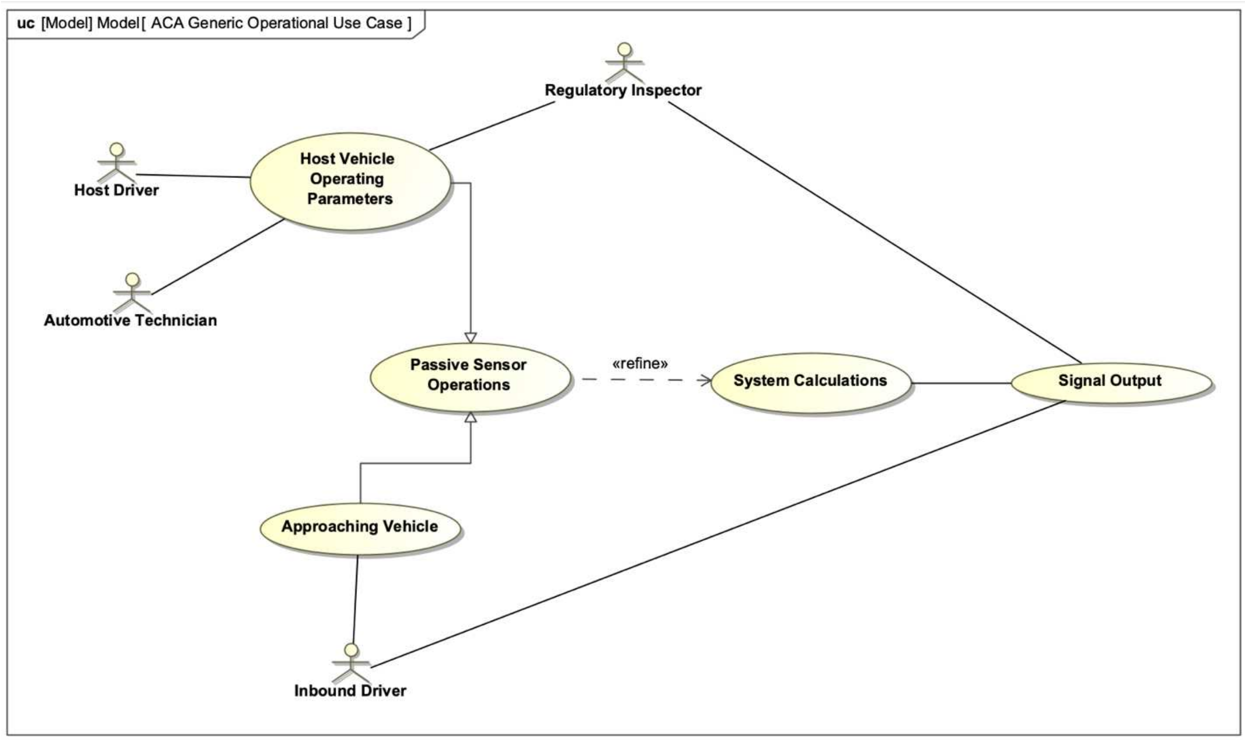

Figure 4: ACA Use Case

The Host Vehicle presented is operating on a typical roadway; either city street, highway, or freeway with the ACA passively sensing distance data. As an inbound vehicle approaches, the ACA starts processing the transmitted distance data from the rear mounted radar unit on the host vehicle to determine an appropriate output signal. If the inbound vehicle doesn't pose a threat, then the ACA returns to passive sensing mode. If the inbound vehicle does pose a threat then the ACA outputs a signal activating the brake lights accordingly. The Automotive Technician presented represents installation and configuration or servicing and repairs to the vehicle that would impact the ACA. The Regulatory Inspector represents either law enforcement or employee at the Department of Motor Vehicles doing an inspection before licensing to ensure all lights and safety systems are functional. The Regulatory Inspector and Automotive Technician infrequently interact with the ACA, but their interactions ensure the ACA is properly set up and operational.

Figure 5: ACA Conceptual Data Model depicts the *Sensors*, *ACA ECU* and *Vehicle Lighting* blocks as constituent components. The ACA Conceptual Data Model figure presented in Figure 5 first appeared in publication in the Society of Automotive Engineers International Journal of Passenger Vehicle Systems [9].

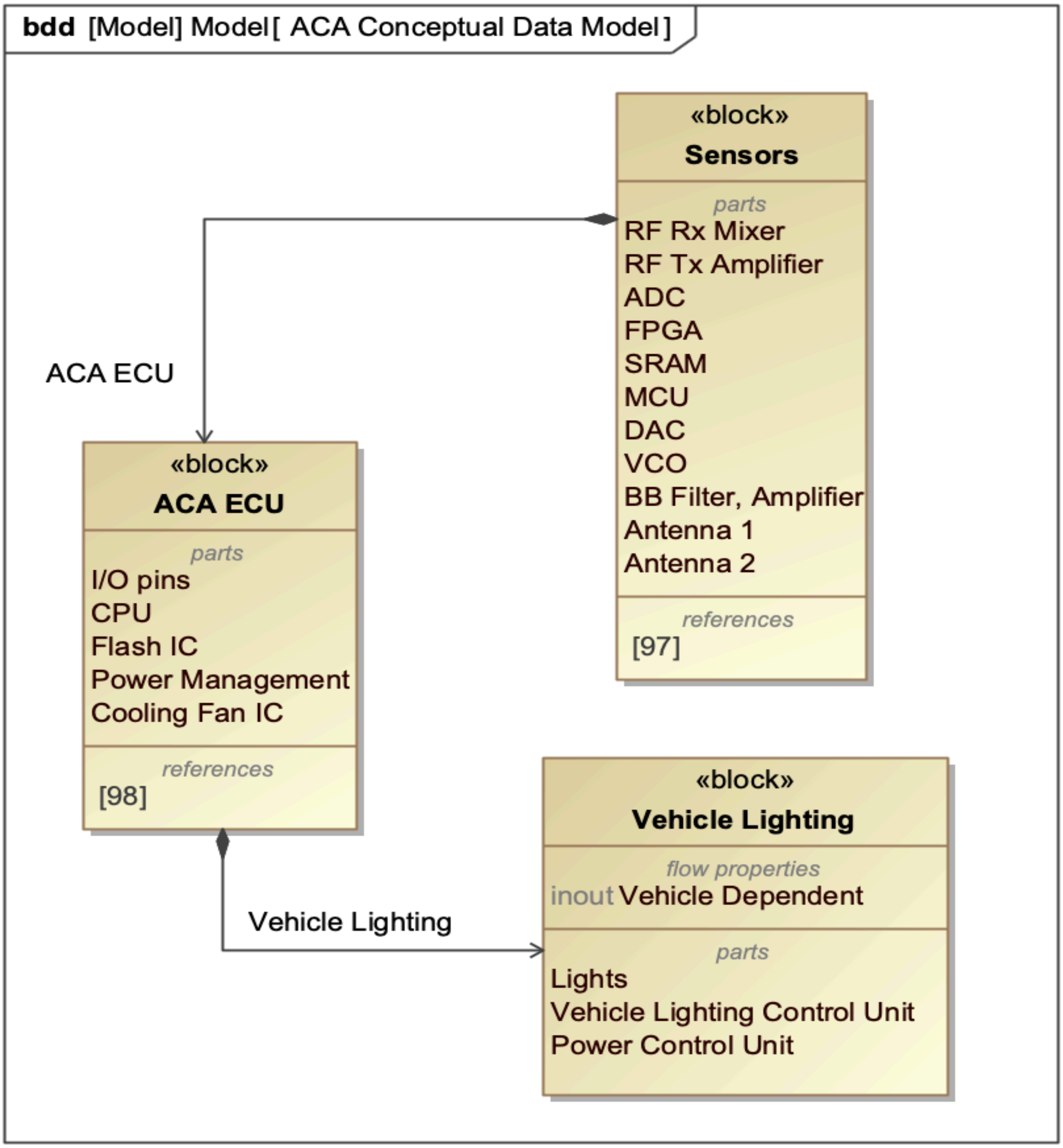

Figure 5: ACA Conceptual Data Model

The Conceptual Data Model presents the ACA in its simplest form, and generic for adaptability and optimization. Currently, the *Sensors* block represents a single Radar and vehicle speed sensor. Lidar and other forms of camera vision sensors are viable options, or integration with the native ADAS sensor suite is also an anticipated change to the ACA. The prototype *ACA ECU* will be programed with SIMULINK models, however, for production it is likely that other Electronics Control Units (ECU) with proprietary software will be utilized. Since the ACA can be installed either during production or aftermarket, it is agnostic to make and model of vehicle, the *Vehicle Lighting* block represents any vehicle.

The ACA System presented in Figure 5 has both subsystems that are integrated into the vehicle and subsystems that are potentially aftermarket additions. The subsystems that are from the Original Equipment Manufacturer (OEM) have redundancy from the OEM where appropriate, which the ACA system takes full advantage of. In addition to the subsystems, the ACA uses the Cyber Security considerations from the OEM and individual component suppliers as the initial defense against malicious activity. The security precautions and encryption used with CAN messaging between the Telematics Control Unit (TCU) and Radar Unit mitigate the liability that the ACA would normally have to assume. For the anticipated application and adoption of the ACA, the radar unit will be directly wired to the ACA ECU, minimizing access opportunities for attackers. The speed signal sent by the TCU over the OEM CAN is presumed to be protected from the OEM to ensure other ECU's have accurate speed data that is protected from corruption. Since the OBD-II port poses the most likely point of access to the CAN, the security considerations of the OEM are relied upon.

For the integrity and resiliency of the speed data, the majority of vehicles have redundant speed sensors, for which the values from each speed sensor are compiled together to determine the vehicle's speed. The redundancy of the speed sensors and multiple layers of processing from the OEM's ECUs are where the ACA's redundancy will come from for the vehicles speed data.

The vehicle's lighting system also utilizes multiple brake lights to insure redundancy. The majority of modern vehicles have three brake lights, for which, the ACA will be sending signals to the left and right brake lights to ensure that if one of the brake lights are out, there is a second light that is functional.

The radar unit used for distance data in the ACA system could either be a single radar unit or two. The quality control and dependability of the radar unit manufacturer is critical to determining how many are utilized. The adoption of two radar units is possible, but incurs an additional processing cost in combining the distance signals, though does introduce redundancy to the system. The financial cost of the Continental radar units combined with the reliability made selecting a single radar unit instead of two the preferred option currently. If the Continental radar unit does fail, then the ACA system will subsequently cease to function.

The ACA ECU is the only subsystem that does not have any form of redundancy in the ACA system, and cannot. The ACA ECU reliability from the manufacturer will be critical to the ACA system's reliability.

Figure 6: ACA MBSE ECU presents a visual of the ACA ECU hardware, similar to Figure 5: ACA Conceptual Data Model with generic components.

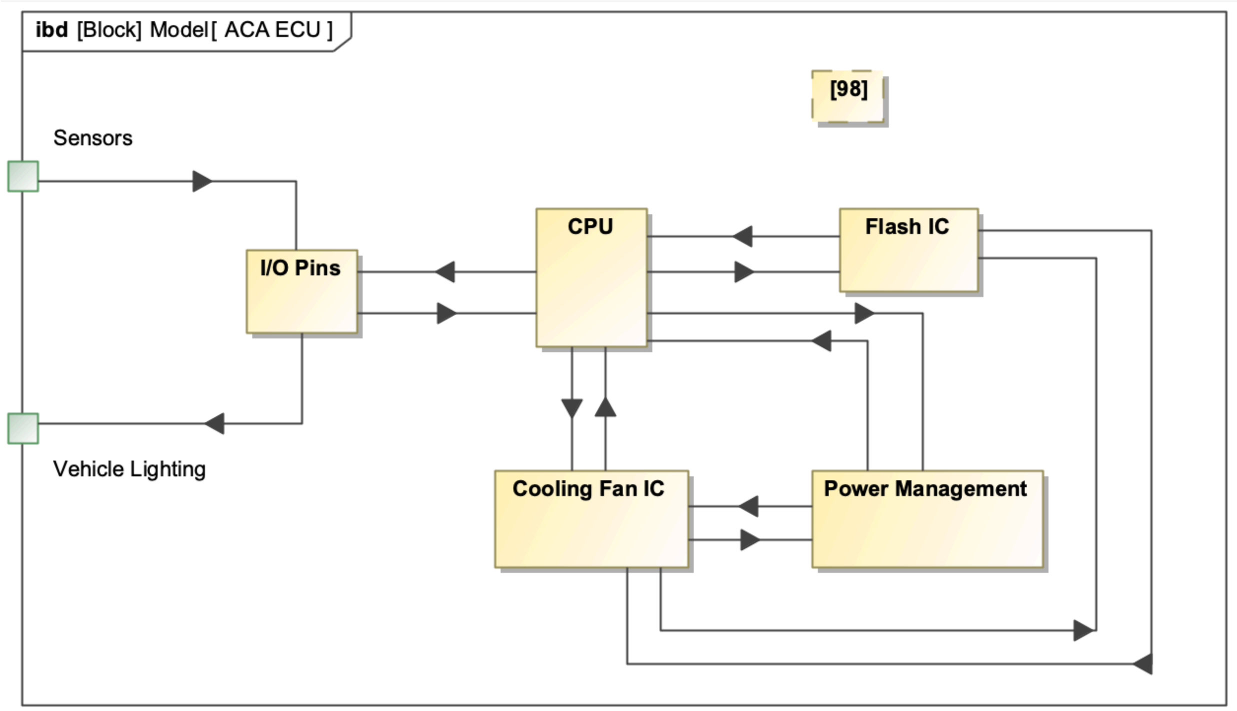

Figure 6: ACA MBSE ECU

The ACA ECU block will be updated with the CAD model of the selected ECU for each production variant and the selected prototype ECU.

Figure 7: ACA Cyber Security Block Diagram presents the ACA system inputs and where an attack is most likely to target. The ACA system incorporates both wired and CAN messaging system ports. The Telematics Control Unit (TCU) and Radar unit both communicate with CAN messaging to the ACA ECU and provides the greatest opportunity for a security breach. The wired output to the vehicle lighting is the least susceptible as it is an output from the ACA.

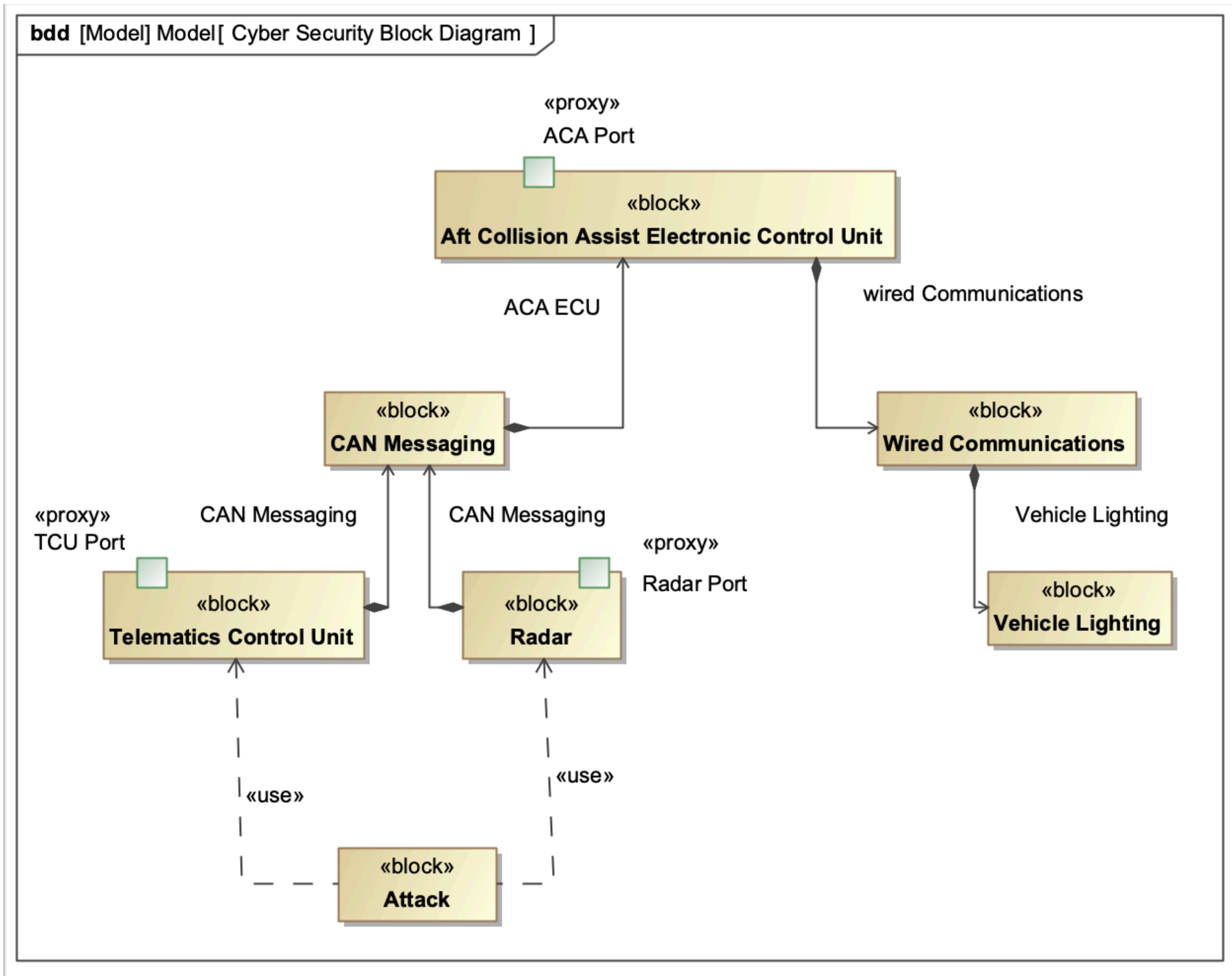

Figure 7: ACA Cyber Security Block Diagram

Malicious activity that utilizes CAN messaging is presented in different scenarios that attack the ACA, TCU, or the Radar unit directly. The malicious activity models and attack scenarios are presented below in Figures 8 through 11. They show how the ACA system shall respond holistically, and in three specific situations. The Figures 8 through 11 are based on figures presented in *A Demonstration of MBSEsec Applied to Securing Cyber-Physical System Communications* [116].

Figure 8: ACA Malicious Activity Model presents four methods for ensuring security. The four methods are: Restricting Unauthorized Access, Identifying Suspicious Activities,

Blocking Malicious Communications, and Ensuring Approved Execution Paths are Followed. This follows the STRIDE threat model proposed in *STRIDE threat model-based framework for assessing the vulnerabilities of modern vehicles* [117].

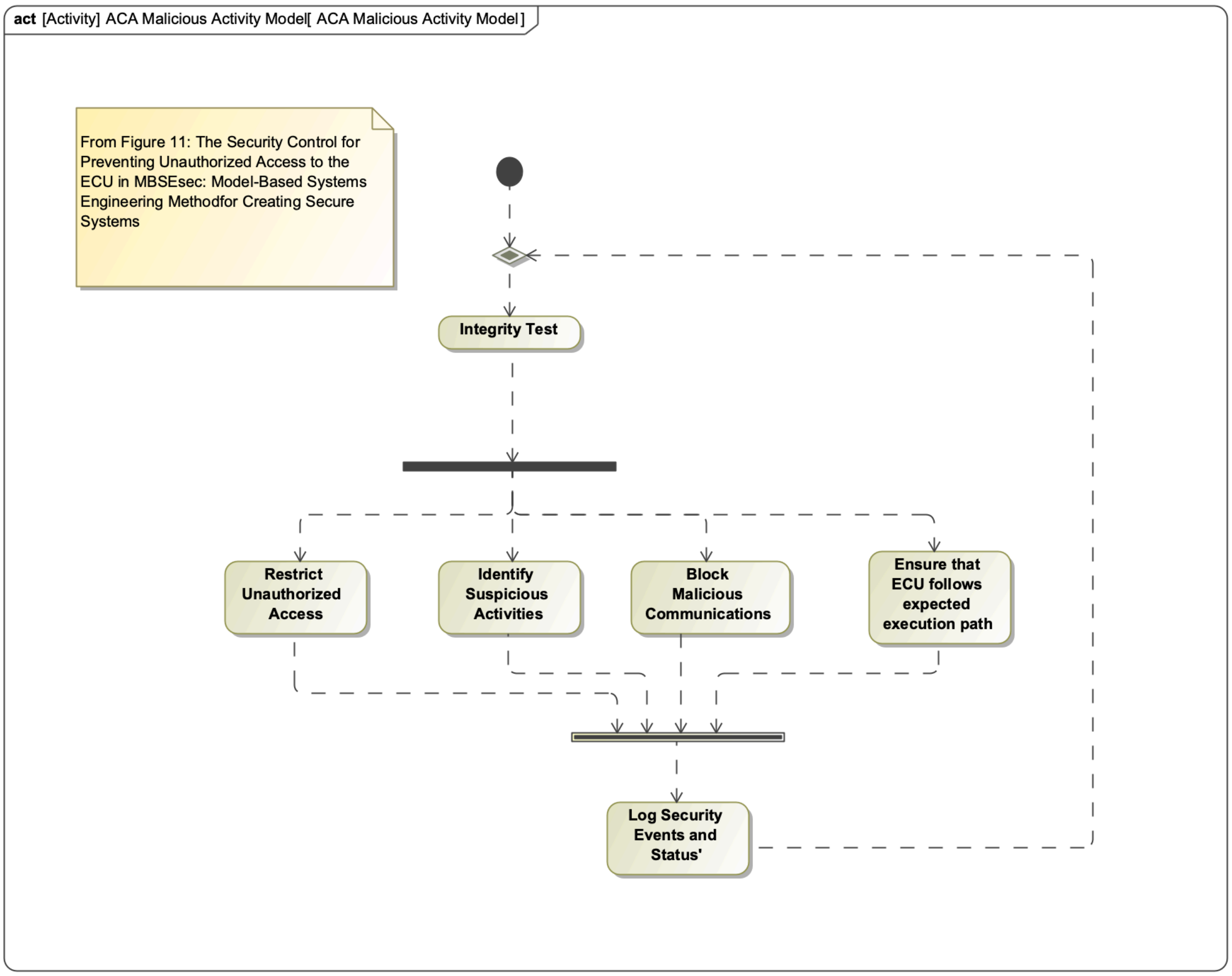

Figure 8: ACA Malicious Activity Model

The STRIDE method was selected due to compliance with the automotive cybersecurity standard ISO/SAE 21434:2021 [118].

Figure 9: Cyber Security ACA Attack Scenario presents the scenario where the ACA ECU is the direct target of a malicious attack via a fault injection through remote pairing with the OBD-II port. The attack proceeds by scanning the vehicles CAN network to collect vehicle

specific information. The Attacker can then simultaneously support normal functionality and retransmit ACA specific communication frames to a malicious server.

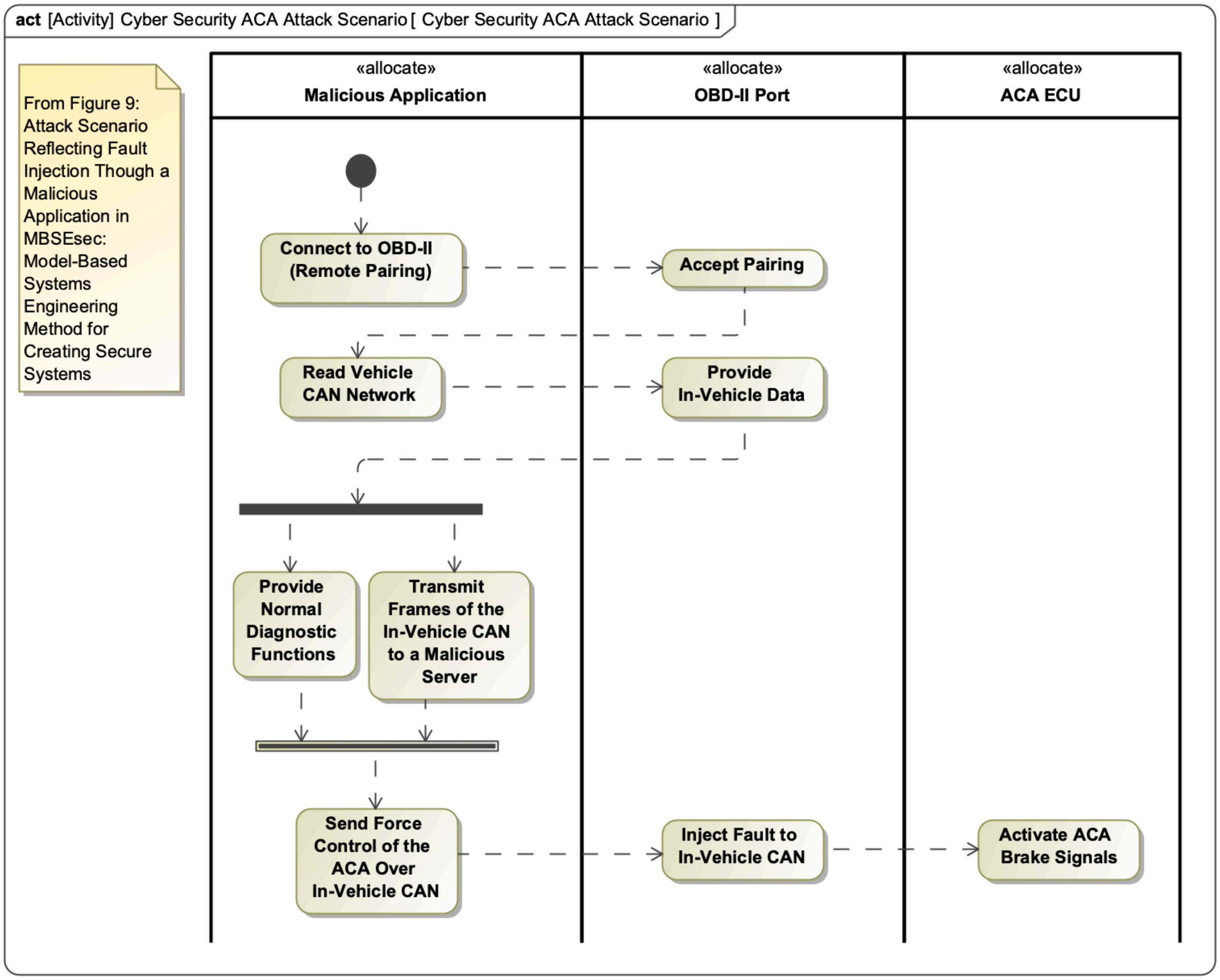

Figure 9: Cyber Security ACA Attack Scenario

The malicious server then replies in parallel with the normal frames left unmodified and frames directed to the ACA that override or corrupt native ACA software. The malicious software is injected through the OBD-II port using CAN messaging to send to the ACA ECU. The proposed attack shows the malicious software activating the ACA brake signal outputs to erroneously trigger the brake lights. The malicious software could trigger the brake signals either by sending corrupt speed or distance data, causing the ACA to respond using the native programing as usual. It could also discretely change the ACA output parameters to continuously activate the brake signals directly. Corrupting the ACA would only enable the brake lights to be engaged, never fully disabled. The ACA is only able to send an additional brake light activation signal.

Figure 10: Cyber Security Radar Unit Attack Scenario presents a similar situation to Figure 9: Cyber Security ACA Attack Scenario, only targeting the Radar Unit. The two proposed attacks start in the same manner with the attacker gaining access to the CAN network through the OBD-II port remotely. Where the attacks differ is in this scenario, the malicious server transmits erroneous ACA signals to the Radar Unit, causing the Radar Unit to be disabled or its configuration altered.

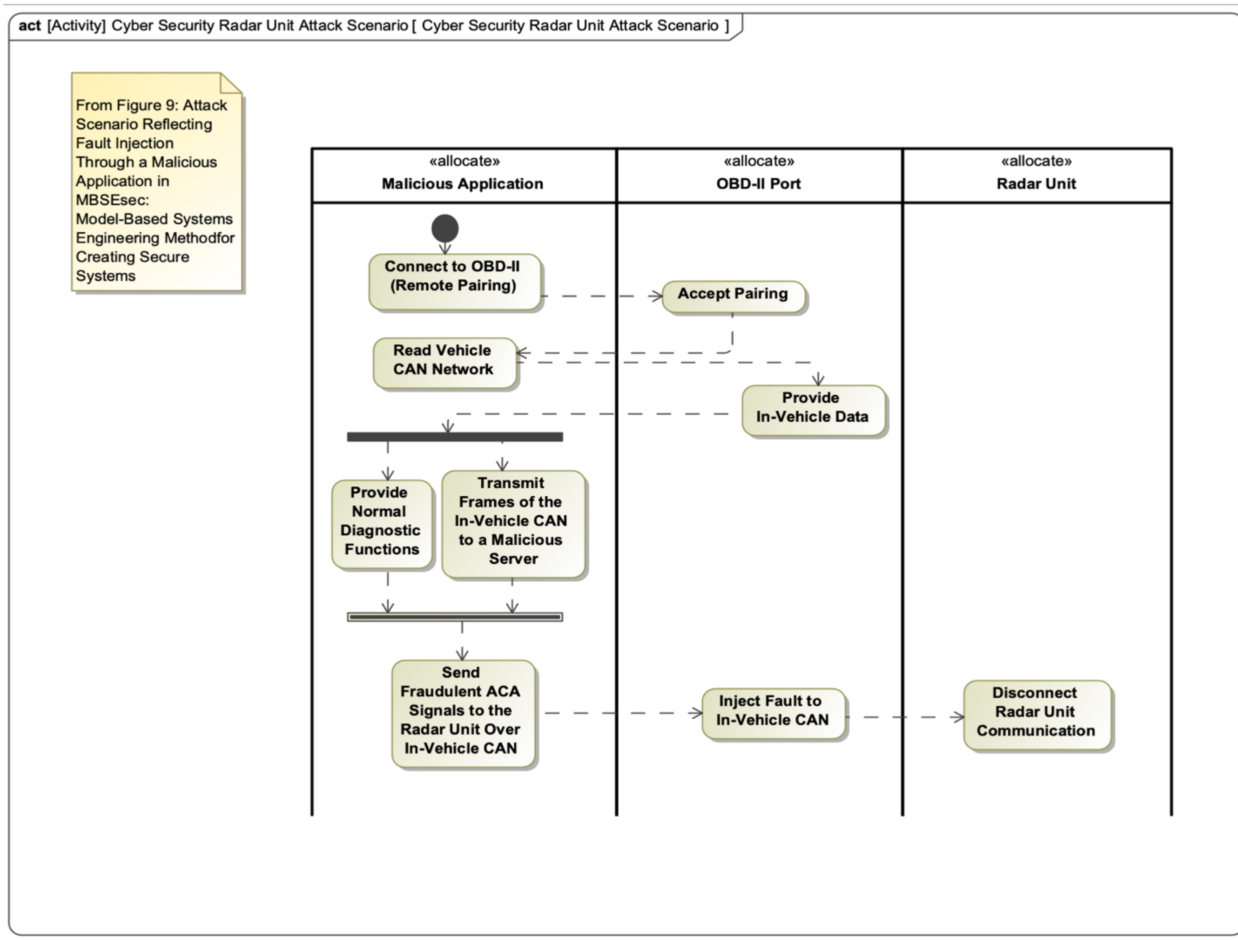

Figure 10: Cyber Security Radar Unit Attack Scenario

Disabling the Radar Unit would prevent the ACA from receiving distance data and being able to calculate and respond to warn of an imminent inbound collision. This would be the same result of the ACA being disabled or removed from the vehicle.

Figure 11: Cyber Security TCU Attack Scenario follows the same logic flow as Figure 16. Cyber Security Radar Unit Attack Scenario, only with the TCU targeted instead.

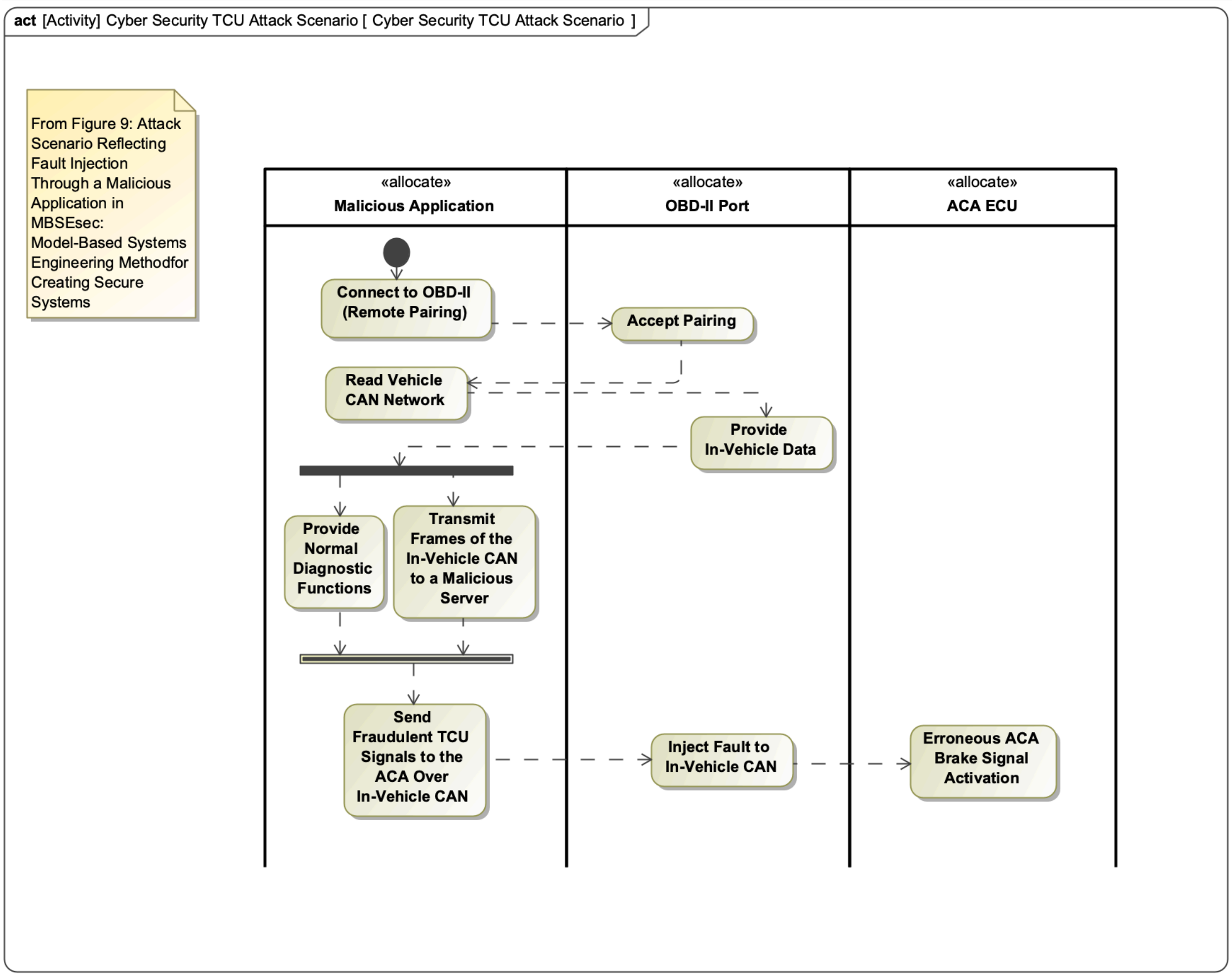

Figure 11: Cyber Security TCU Attack Scenario

The resulting attack would manipulate the speed data being transmitted to the ACA and cause the ACA to erroneously activate the brake light signals.

The afore mentioned figures show the ACA being attacked via the OBD-II port, this is the easiest and most likely attack point for the ACA system. This is due to the ACA using CAN messaging, which requires wired interfaces with the vehicle. These attacks require physical access to the OBD-II port or CAN messaging; which typically isn't feasible for most attackers. These figures apply to any vehicle using CAN messaging, with the caveat that the CAN messaging is within a closed system.

Chapter 4 SIMULINK Model of the Aft Collision Assist

From the MBSE models presented in Chapter 3, a SIMULINK model is presented satisfying the Design Requirements from the MBSE models. The SIMULINK modeled ACA system utilizes six different inputs to calculate and determine an appropriate response provided via two outputs. The two outputs are the *Brake Signal Initiation Left (BSIL)* and *Brake Signal Initiation Right (BSIR)*. The inputs to the ACA ECU are *Time*, *Host Vehicle Speed (HVS)*, *Midrange Distance (MRD)*, *Long Range Distance (LRD)*, *Brake Light Right* (*BLR)* and *Brake Light Left* (*BLL)* signals. For simulation purposes an excel spread sheet is used to provide data for each input. Figure 12: ACA SIMULINK Data Inputs & Outputs depicts these ports.

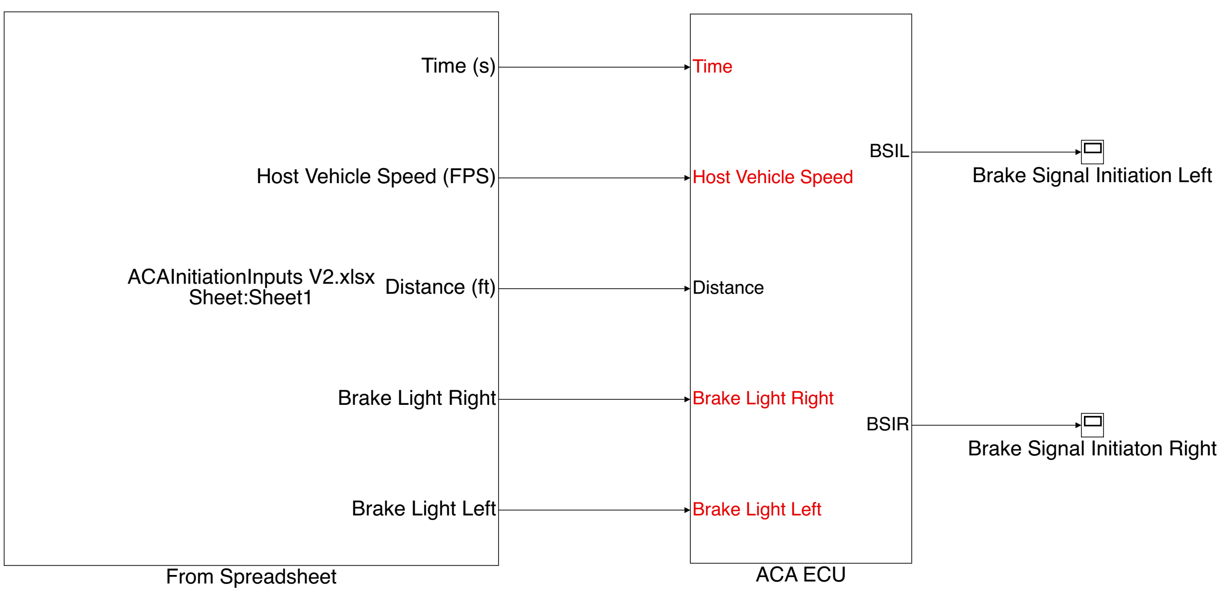

Figure 12: ACA SIMULINK Data Inputs & Outputs

The *HVS* is read from the host vehicle's internal CAN for newer vehicles, and for older vehicles from a wired sensor signal. Future validation efforts will pull the vehicle speed from the internal CAN networks; specifically, for my personal vehicle, CAN signal ID 158. The *BLR* and *BLL* signals will be hardwired inputs from the host vehicles brake lights to the ACA ECU. The brake signals will be modified in such a way that if the ACA system was rendered inoperable the brake lights would still function, keeping the vehicle road legal. The wires going to the brake lights will be disconnected from the brake lights and wired to the ACA ECU. The output signals *BSIR* and *BSIL* reconnect to the brake lights directly. ACA ECU output pins are the same as the brake light signals fed into the ACA ECU. The *MRD* and *LRD* will either be CAN messages or hardwired inputs, depending on the radar utilized. For simulation purposes, these two signals are provided the same values in the excel spreadsheet.

Figure 13: ACA SIMULINK ECU shows all of the internal blocks used in the ACA ECU. The ACA first processes the *HVS*, *LRD* and *MRD* inputs to calculate the *Inbound Vehicle Speed* and *Inbound Vehicle Acceleration*.

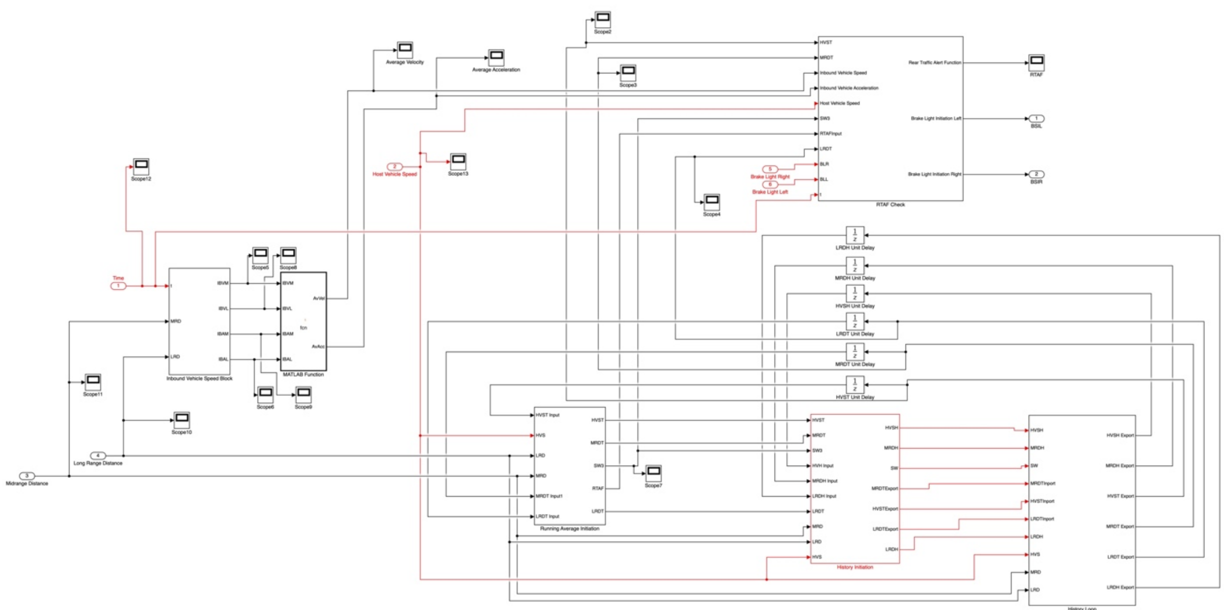

Figure 13: ACA SIMULINK ECU

Following the derivation of these variables, the ACA builds up a working memory of distance, velocity, and acceleration data. The three blocks, *Running Average Initiation*, *History Initiation* and *History Loop* represent the three different modes of operation for the ACA system. When the system is initialized the *Running Average Initiation* block is the only active block of the three. After the Running Average Initiation block generates the first running average, the *History Initiation* block is activated and the other *Running Average Initiation* block is deactivated. Additionally the *RTAF Check* block is now active. Once the History Initiation block has completed generating a full history, the *History Loop* block is activated and the *History Initiation* block is deactivated; the *RTAF Check* block remains active. The system state where the *History Loop* block is active represents the normal operating state of the system once the initialization process is complete. The working memory built up through the initialization states and maintained in the history loop state allows the system to work off of averages instead of raw data inputs, which may have extreme values, errors, or momentary events that could trigger the ACA erroneously. The results of the *History Loop* block are fed to the *RTAF Check* block where the ACA determines the appropriate course of action given the internal algorithms. The *RTAF Check* block either outputs the ACA brake light signals or directly passes through the brake light signal as it was fed into the ACA ECU.

Figure 14: ACA Inbound Vehicle Speed Block (IVS) is where the distances calculated by the radar are first fed into and processed by the ACA ECU. The distances and time stamp associated with the input of a specific distance value are fed in. This value is then fed back into the *IVS* block after passing through a unit delay to build a short term history.

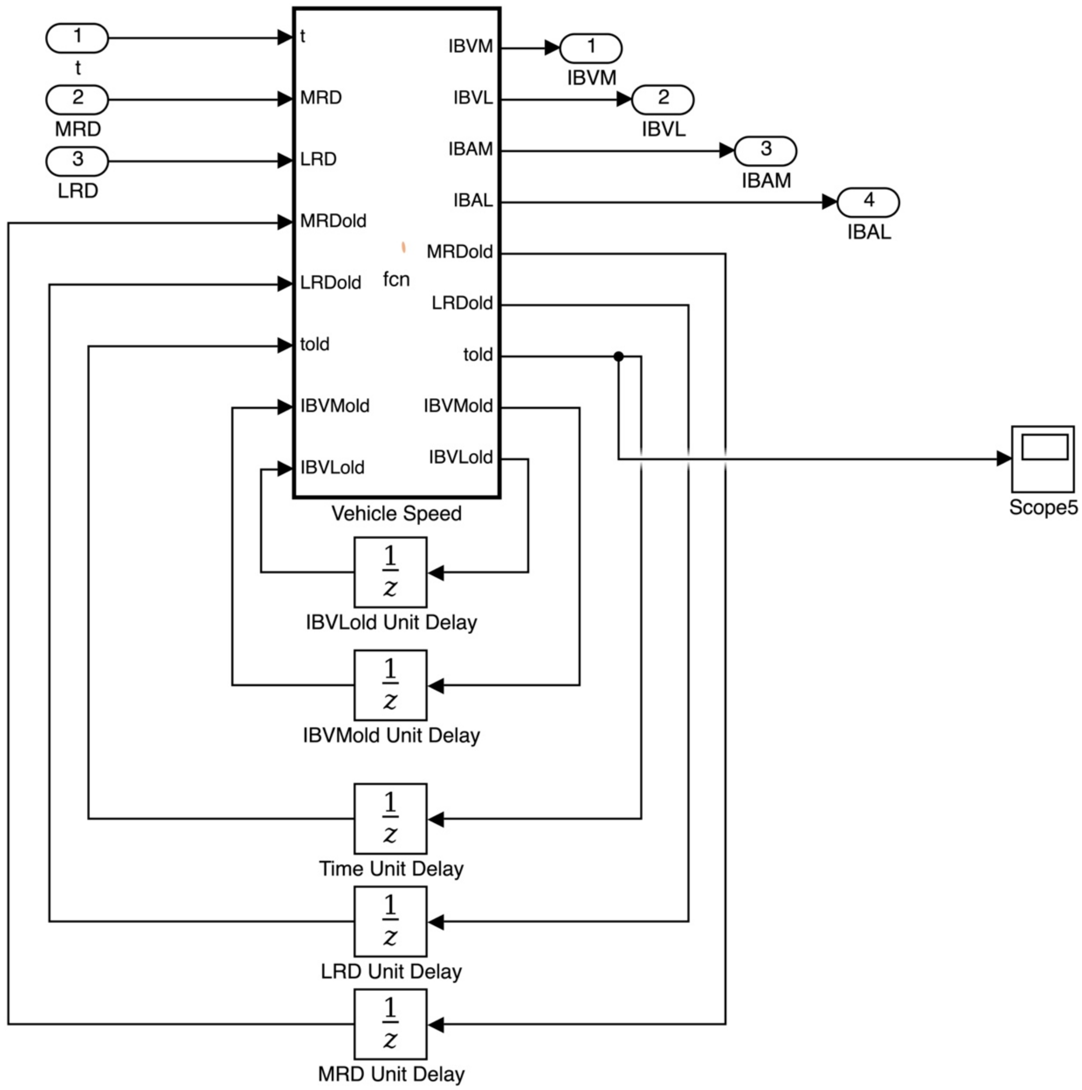

Figure 14: ACA Inbound Vehicle Speed Block

The difference between the new distance value and the old distance value is used to determine the inbound vehicle's velocity and acceleration for further data processing. The ACA Inbound Vehicle Speed Block has a configurable Sample Rate value to configure the system for different sampling rates. The SR value is used to ensure accurate calculation of the inbound vehicle speed and acceleration are calculated correctly. The ACA Velocity & Acceleration Combination combines the *Medium Range* and *Long Range* derived velocity and acceleration values into a single velocity and single acceleration variable. For simulation purposes the same distance value is input for *Long Range* and *Medium Range* inputs. The need for a *Long Range* and *Medium Range* input port depends on the radar unit or units utilized. The Long Range and Midrange Distances are combined by calculating the arithmetic mean between the two values.

Figure 15: ACA Running Average Initiation Block shows the first of the three blocks used to compile a working database of inbound vehicle distances.

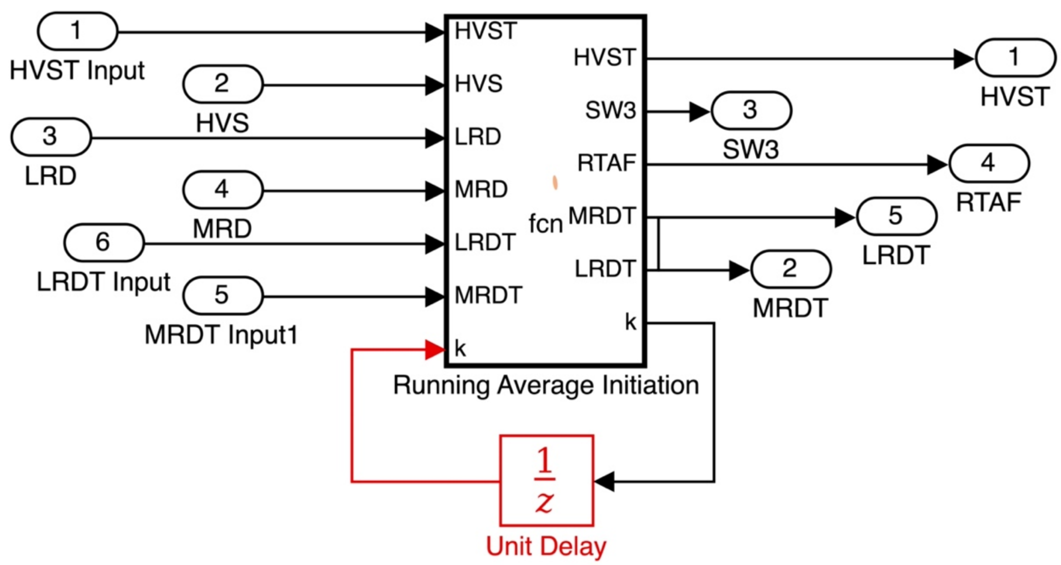

Figure 15: ACA Running Average Initiation Block

The variable inputs to the *Running Average Initiation Block* are the *Host Vehicle Speed Trend (HVST)*, *Host Vehicle Speed (HVS)*, *Long Range Distance (LRD)*, *Midrange Distance (MRD)*, *Long Range Distance Trend (LRDT)*, *Midrange Distance Trend* (MRDT) and a unit delay variable. The outputs are the *HVST*, *LRDT*, *MRDT*, *Rear Traffic Alert Function* (*RTAF*) value and a switching value, *SW3*. The RTAF value is initially set in this block, and is passed forward to the *RTAF Check Block* at the end of each computation cycle. SW3 is utilized by the *RTAF Check Block* as well as the *History Initiation Block*. The ACA Running Average Initiation Block initiates and sets the *RTAF* value to one, activating the *RTAF Check Block* downstream. A unit delay variable, k, is used to increment this block for an iteration loop count of 30 steps. An iteration loop of 30 steps was selected based upon specifications looked up for radar baud rates. Allowing the *History Initiation Block* to compile 30 values before processing the data allows for a smoother data set. When the step counter reaches 31, the switching value is set to one to transmit data to the *History Initiation Block*. After the switch is set to one, the block simply passes the input data through to the subsequent blocks.

Figure 16: ACA History Initiation Block utilizes the outputs and inputs from the *Running Average Initiation Block* in Figure 15 to develop a *Long Range Distance History (LRDH)*, *Midrange Distance History (MRDH)*, and *Host Vehicle Speed History (HVH)*.

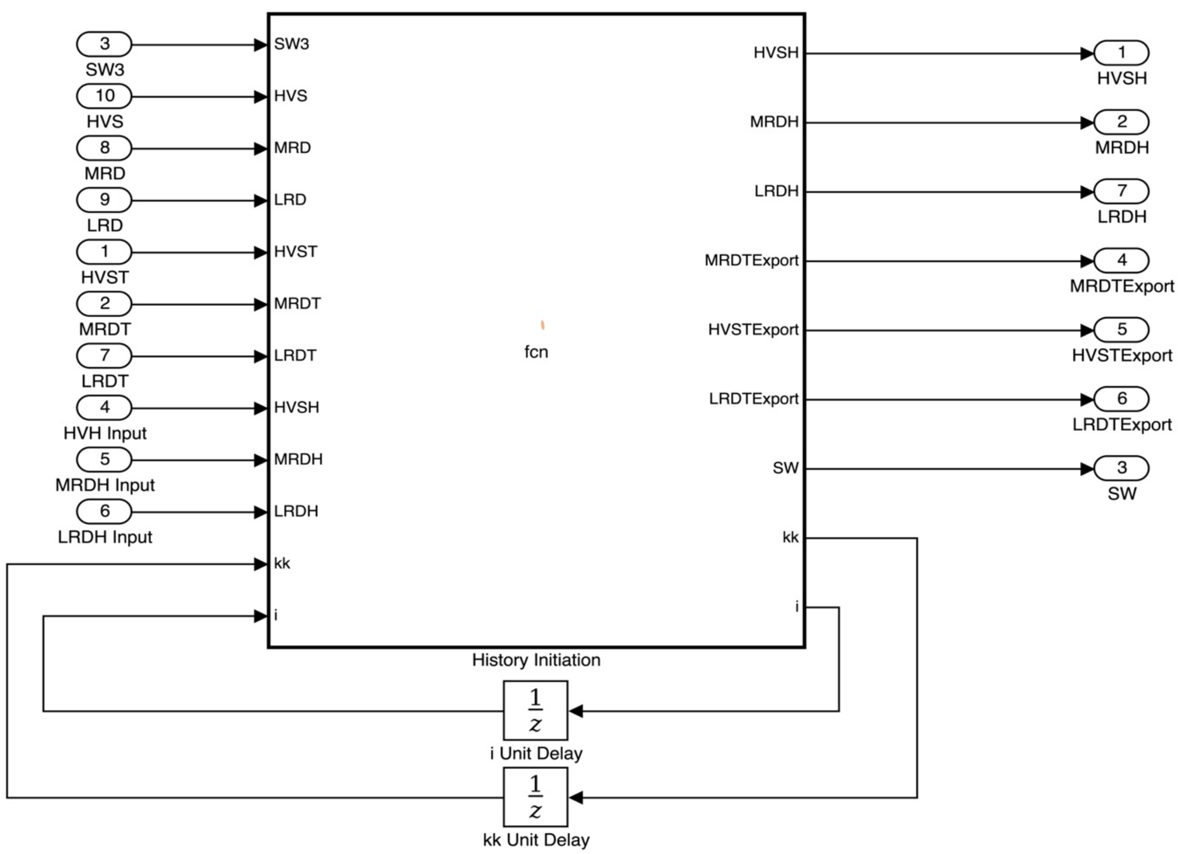

Figure 16: ACA History Initiation Block

The ACA History Initiation Block utilizes two unit delay variables with the aforementioned inputs to produce a *HVH*, *HVST Export*, *LRD,* and *MRDH* as well as *Long Range (LRD)* and *Midrange Distance (MRD) Export* values. The i iterator is used to compile a matrix of 30 values, which on the 31st iteration the average of the 30 compiled values is calculated and concatenated onto the *Distance* and *Velocity History* matrices, and the iterator i is reset to 1. The kk iterator configures the *History Initiation Block* to cycle for 20 iterations of history building before passing the *Distance* and *Velocity* History of averages on to the *History Loop* block. The velocity history and distance history variables are matrices of the average of the distance and velocity trend values, respectively. Averaging 30 iterations of the trend data filters out incorrect or noisy data that the ACA should not be responding to. The ACA *History Initiation Block* utilizes the external *SW3* variable to control when the blocks calculations are performed. *SW3* prevents the *History Initiation Block* from performing any calculations until the *Running Average Initiation Block* has compiled the first averages for the *MRD*, *LRD* and *HVH*. The *History Initiation Block* uses the *SW* variable that it sets to zero initially to control when the *History Initiation Block* passes the *Distance History* and *Velocity History* matrices onto the following block. At the end of the 20 sets of 30 cycles, the first history matrices are complete and the internal *SW* variable is switched to one to activate the *History Loop* block and deactivate the *History Initialization* block.

Figure 17: ACA History Loop Block pulls the raw vehicle speed data, the velocity trend and velocity histories, in addition to the raw distance data, distance trend and history data. These inputs are processed to generate updated velocity and distance trends and history values.

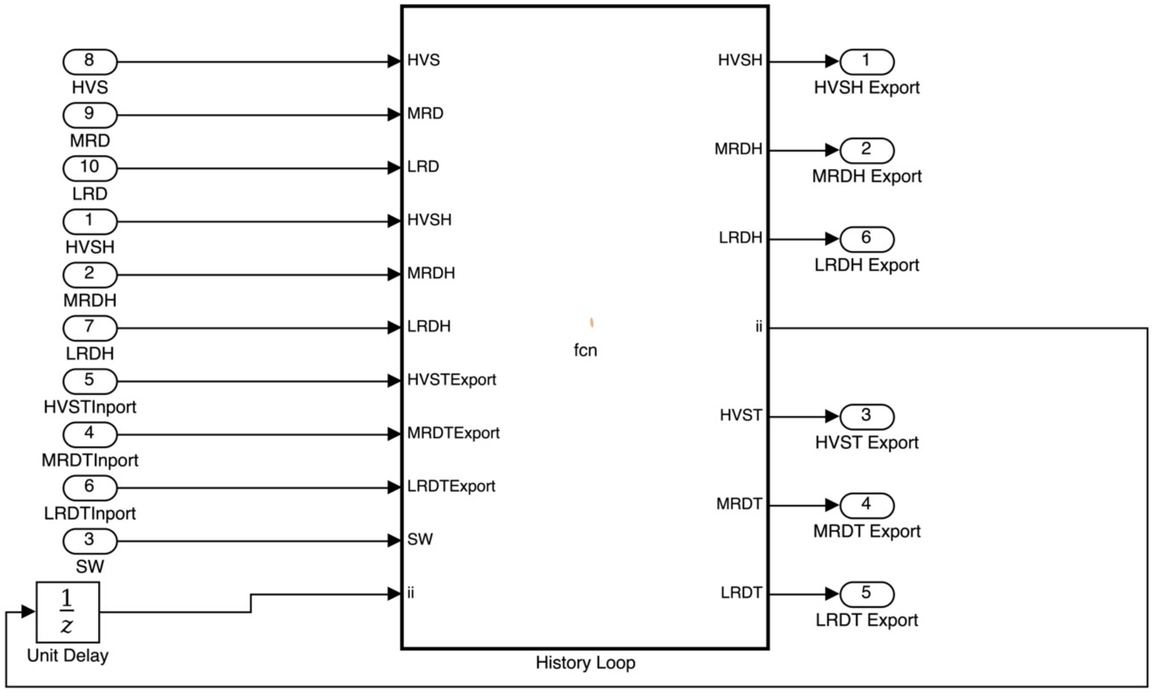

Figure 17: ACA History Loop Block

The updated histories are then fed back as inputs to the *History Initiation* block, while the trend data is fed through a unit delay function before being fed into the *Running Average Initiation Block*; both of the aforementioned blocks will not perform any computations once the *History Loop* block is activated by the *History Initiation* block setting *SW* to one. The velocity and distance trend data prior to being fed through the unit delay functions is also fed to the *RTAF Check Block*. The *History Loop* block does not perform any computations itself, until *SW* is set to one. Once the *History Loop* block is activated, an internal iterator, ii, is initiated to append the raw vehicle speed and distance data to the vehicle speed and distance trend data, respectively. When the iterator cycles through 30 iterations, the average of the trend data is calculated and compiled in the velocity and distance histories. With each iteration of the internal iterator, the updated trend and history data are output to the *History Initiation, Running Average Initiation* and *RTAF Check* blocks.

Figure 18: ACA RTAF Check Block is the final block of the ACA ECU and is where the ACA determines if any inbound vehicles pose a hazard to the host vehicle. The velocity trends, distance trends, raw vehicle speed, and distance data are fed in with the *RTAF* value and *SW3* initiation. The outputs of the *RTAF Check* block are the *RTAF* value reset, the *Brake Light Initiation Left*, and *Brake Light Initiation Right* signals. Of the three outputs, only the *Brake Light Initiation Left* and *Right* signals are directly integrated back into the native lighting system.

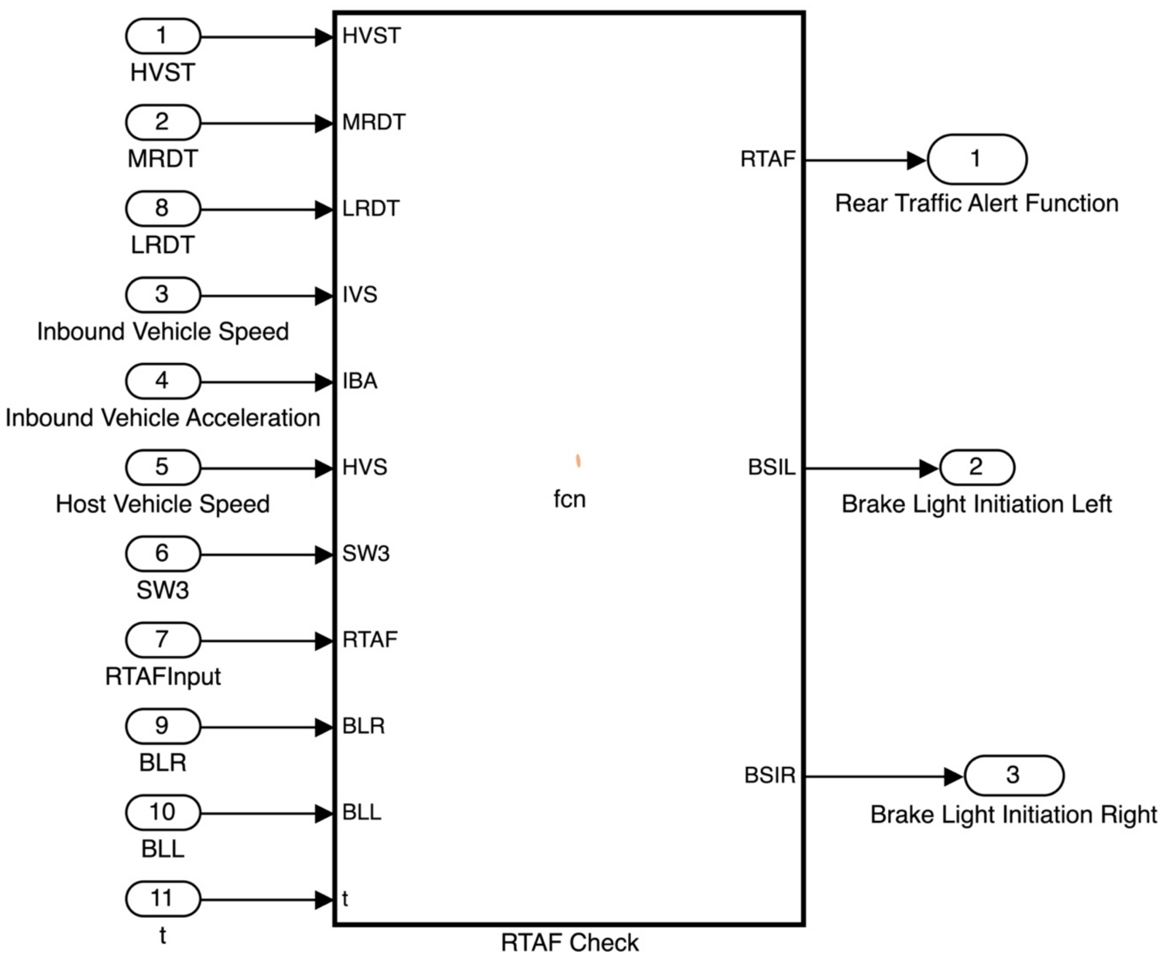

Figure 18: ACA RTAF Check Block

The velocity trend and distance trend data are averaged again to ensure that the *RTAF Check* block uses the most up to date average possible to determine if any inbound vehicle poses a hazard. The calculated IVS data is then compared to the HVA to determine the velocity change between the inbound and host vehicles. Using generally accepted equations and constant conditions for stopping distance based upon the calculated velocity change, a safe stopping distance is calculated for the inbound vehicle [111,112,113,114,115]. The friction coefficient is generalized to be 0.5 based on values presented in the article *Sensors* [111]. The friction coefficient for the roadway is based on pavement type and weather conditions, which is treated as a static variable for the ACA. The time variables that impact breaking response time for the inbound vehicle are pre-set to generally accepted values presented in *Sensors* [111]. The factor of safety selected is 1.5, which in the article *Permissible Distance* was arbitrarily chosen [114]. The stopping distance for the inbound vehicle is based on the host vehicle's speed; the stopping distance for the inbound vehicle is based on the derived IVS. The stopping distance formula also includes a variable for road gradient; which in the simulation is set to 0 for a flat road. Finally, the difference between the host vehicle speed and inbound vehicle speed is calculated to determine the expected safe deceleration rate for the inbound vehicle. The ACA's brake light signal modifications are to apply a sinusoidal function to the lights input power. To achieve an attenuated pattern the left brake light signal is modified with a sine wave, while the right brake light signal is modified with a cosine wave. The sample rate value from Figure 15: ACA Inbound Vehicle Speed Block Function is used to ensure that the rate of oscillation of the sinusoidal output functions is the same regardless of the sample rate. Utilizing sinusoidal waves to modify the brake light signal ensures the lights are always lit, and are phase offset to attract a distracted driver's attention.

To remain compliant, the law states that once the brake lights are ignited, they must remain on and cannot be glaring or too dim. In addition, there must be two brake lights visibly on. Applying a 50% duty cycle to the sinusoidal functions ensures that the brake light voltage is never reduced to the point that they are no longer visible. In addition, the phase offset sinusoidal waves will ensure a minimum of two brake lights are always visibly lit.

The logic for initiating the ACA brake light signals is first dependent upon the Midrange Distance Average being less than the Safe Stopping Distance, and the Host Vehicle Speed Average being above a minimum speed threshold, currently set to 5 miles per hour. Next, the Safe Deceleration Rate must be less than the Inbound Vehicles Acceleration and the Midrange Distance Average must be less than the Safe Stopping Distance. Last, the Long Range Distance Average equal to or less than the Safe Stopping Distance, the Average Velocity Trend greater than 55 miles per hour, and the Host Vehicle Speed must be less than the Inbound Vehicles Speed. The 55 miles per hour speed was chosen based on Oregon's Highway and Freeway posted and unposted default speeds. When these criteria are not met, then the Brake Light Signal outputs from the ACA ECU are the same as the input Brake Light signals fed into the ACA ECU.

Chapter 5 Distance Data

The distance data utilized to validate the ACA SIMULINK model was derived using Oregon Department of Transportation (ODOT) traffic data that tracked traffic flow volumes at specific check points on an Oregon Freeway, Highway, and City thoroughfare [100,101]. Table 1. Traffic Data & Calculations presents the Number of Vehicles, Road Type, Name, Lane Count, Date of Study, Hour of Study, Posted Speed, Standard Deviation, and Mean.

Table 1: Traffic Data & Calculations

Number of Vehicles	**Road Type**	**Name**	**Lane Count**	**Date of Study**	**Hour of Study**	**Posted Speed (MPH)**	**Standard Deviation (Feet)**	**Mean (Feet)**
7712	Freeway	I5 Wilsonville Exit	6	5/29/21	1100 to 1200	65	83.34	250.04
637	Highway	213 Carus - Milino	2	7/30/21	1600 to 1700	55	298.74	896.21
447	City	Molalla South of Beavercreek Road, Oregon City	2	11/16/21	1100 to 1200	35	269.95	809.85

The number of vehicles recorded passing through the specific checkpoint was divided by the number of lanes and then multiplied by the mean vehicle length on that roadway to determine the vehicle feet per minute for that check point; presented in Eq. 1.

$$(\text{Total Vehicles} / \text{Number of Lanes}) * (1/(60 \text{ Minutes per Hour})) = \text{Vehicles per Minute} \quad \text{Eq. 1}$$

The posted speed limit multiplied by the conversion from miles to feet was used to determine the feet per minute that checkpoint could conduct; shown in Eq. 2.

(5280 Feet per Mile) * (Miles per Hour) * (1/ (60 Minutes per Hour)) = Feet per Minute   Eq. 2

The mean vehicle length on the roadways was estimated to be approximately 17ft. This is determined by averaging together the mean lengths of each vehicle classification: mini car, small car, SUV, small truck, etc. sourced from the article *Average Car Length: All You Need to Know About It* [102] and incorporating in a small factor to account for commercial trucks and tractor trailers.

Multiplying the vehicles per min by the mean vehicle length, Eq. 3 yields the vehicle feet per minute.

(Vehicles per Minute) * (Mean Vehicle Length) = Vehicle Feet per Minute   Eq. 3

Subtracting the vehicle feet per minute from the feet per minute and multiplying by the vehicles traveling per minute yielded the mean feet per vehicle traveled on that stretch of road.

((Feet per Minute) - (Vehicle Feet per Minute)) / (Vehicles per Minute) = Mean Feet per Vehicle Eq. 4

Using the assumption that all values would need to be positive and greater than zero, otherwise two vehicles would be occupying the same location, in other words an accident occurred in that instance. This assumption about positive values, and the derived mean value can be utilized to calculate the standard deviation for the vehicle distance for a mile of roadway, given that check points recorded traffic flow volume.

$$\text{Mean Feet per Vehicle} - 3 * \text{Sigma} = 0 \qquad \text{Eq. 5}$$

The standard deviation and average were then applied to a Gaussian number generator function in Excel to generate distance values to be fed through the ACA SIMULINK model. The resulting simulations show significantly more dynamic distance values passing through the ACA than the actual system would receive as value inputs, but the system responds accordingly and appropriately. The SIMULINK simulation results show the ACA receiving and processing data inputs, and responding accordingly with the appropriate ACA output signals.

Chapter 6 SIMULINK Simulation of the Aft Collision Assist

Using the data generated with the theoretical model presented in Chapter 5, this chapter presents the SIMULINK modeling of the ACA system in three different driving scenarios: City, Highway and Freeway. The main purpose of these simulations is to show the ACA system correctly handling the brake lights signals in different scenarios.

Figure 19: ACA City Brake Lights Off presents the city simulation with the brake lights initially off. Figures 19.1 and 19.2 ACA City Brake Lights Off Brake Signal Left and Brake Signal Right are the ACA outputs. Figures 19.3 is the Host Vehicle Speed and Figure 19.4 is the Radar Distance. The brake light signal starts low and goes high at about a quarter second when the ACA determines that the distance trend data poses a threat to the host vehicle. At six seconds the ACA Brake Light signal turns off, which correlates with the Radar Distance value of 1800 feet at about five and a quarter seconds. The ACA has a time step delay of about three quarters of a second which is due to the distance data being processed. The data processing delay seen in the ACA plots causes the time stamps between the distance plot and the brake signal plots to be offset. The ACA turning off twice in the first quarter second is interesting because the distance data shows a large variance in values. The ACA activates and remains activated until the six second mark due to the distance values going extremely low. The negative values would indicate being rear-ended. The negative values are present due to the distance data being generated from a Gaussian random number generator. The incorporation of negative values, and multiple instances of very large values explains why the ACA deactivates three times in the simulation. Since the

ACA is set up to process sets of 30 data points, the distance values that the ACA is actually activating off of falls between 500 and 1000 feet, in Figure 19.4.

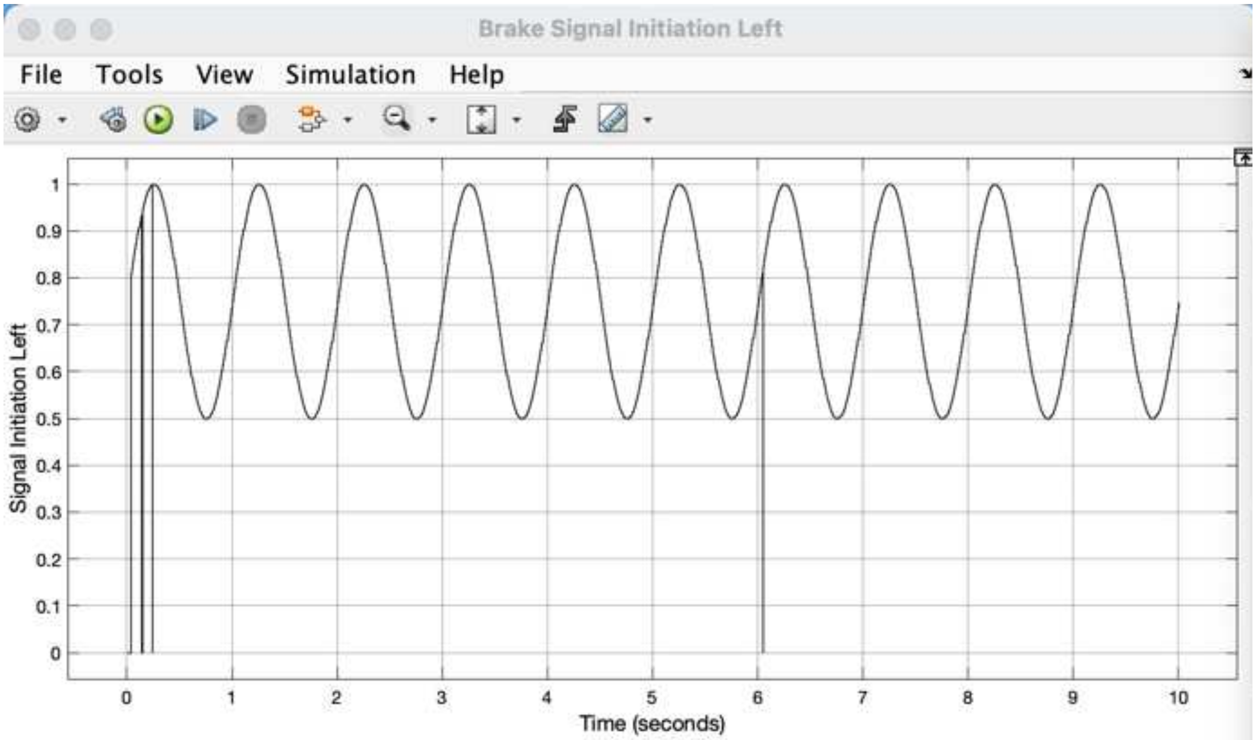

Figure 19.1: ACA City Brake Lights Off Brake Signal Initiation Left

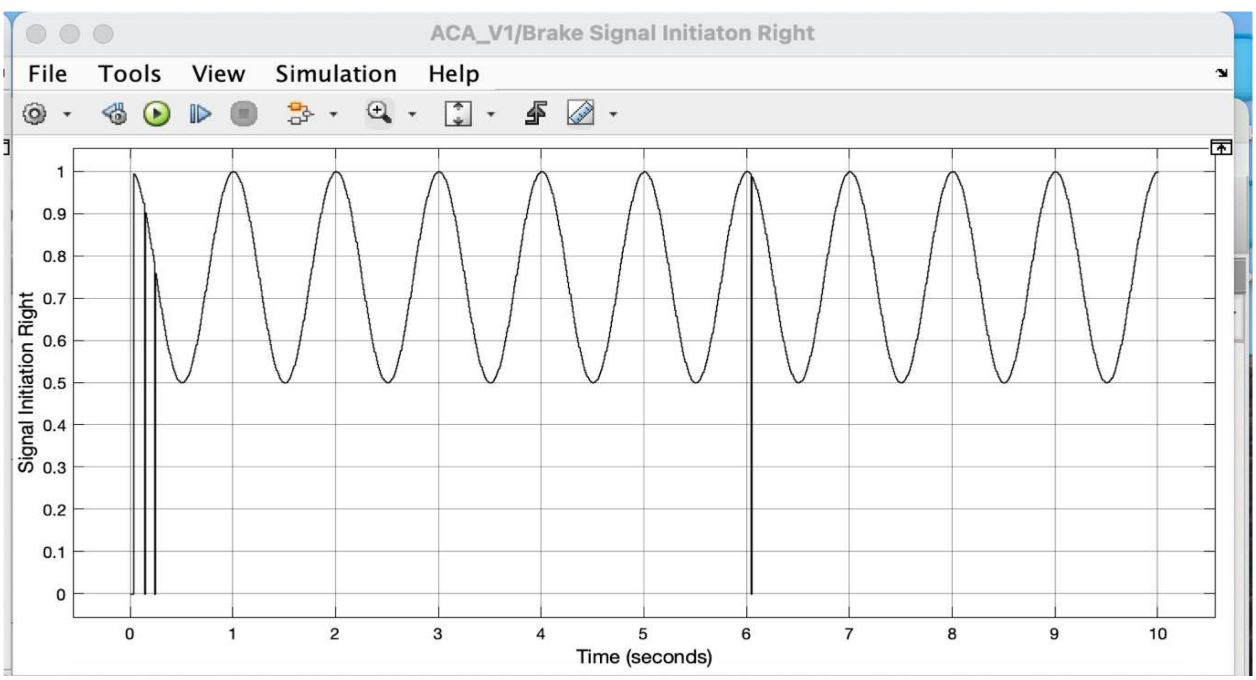

Figure 19.2: ACA City Brake Lights Off Brake Signal Initiation Right

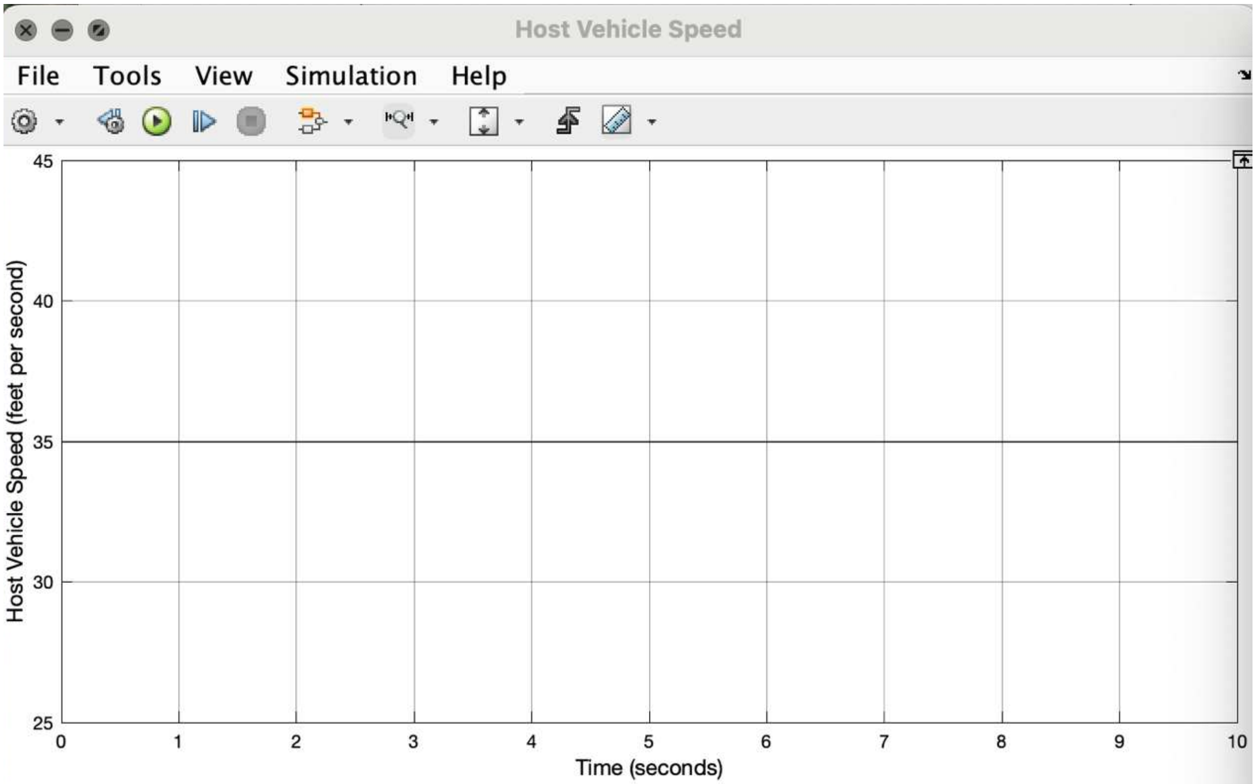

Figure 19.3: ACA City Brake Lights Off Host Vehicle Speed

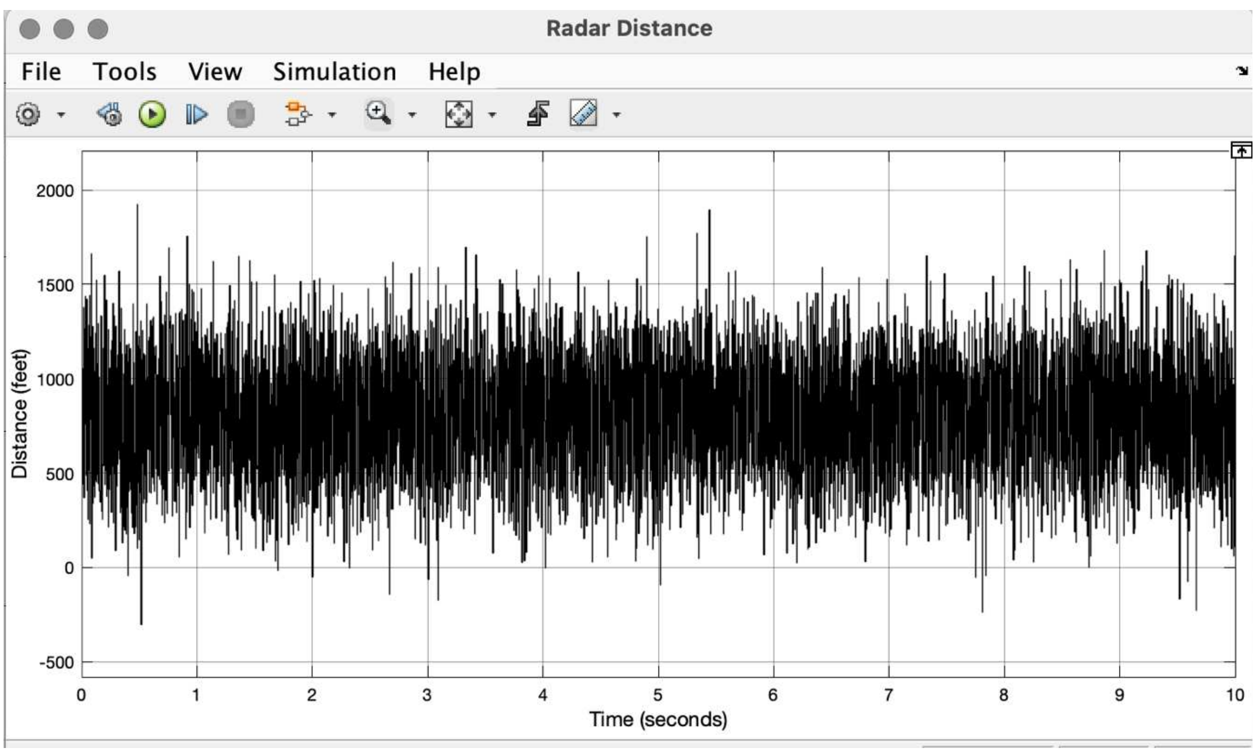

Figure 19.4: ACA City Brake Lights Off Radar Distance

Figure 20: ACA City Brake Lights On shows a city simulation with the brake light signal initially on. The ACA activates almost instantaneously, and then briefly deactivates at about half a second. The remainder of the run time shows the ACA active, in Figures 20.1 and 20.2. The majority of the distance values fall above 500 feet, and there are only a few instances of distance values that are negative; Figure 20.4. Similar to the distance values in Figure 19.4, the average distance values the ACA is activating off of falls between 600 feet and 1000 feet. The larger distance data at about two and a half second and just after three seconds is minimized due to the larger quantity of distance values falling below 500 feet, thus reducing the average distance that the ACA basis it's logic off of.

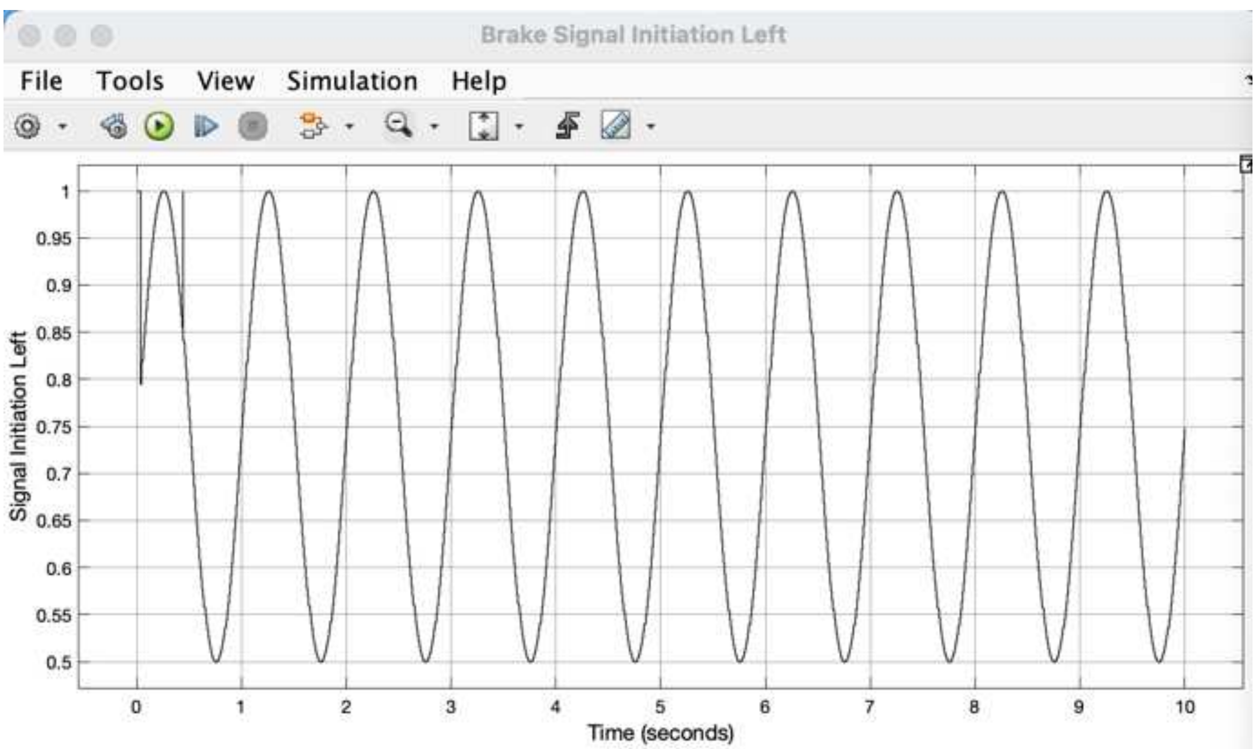

Figure 20.1: ACA City Brake Lights On Brake Signal Initiation Left

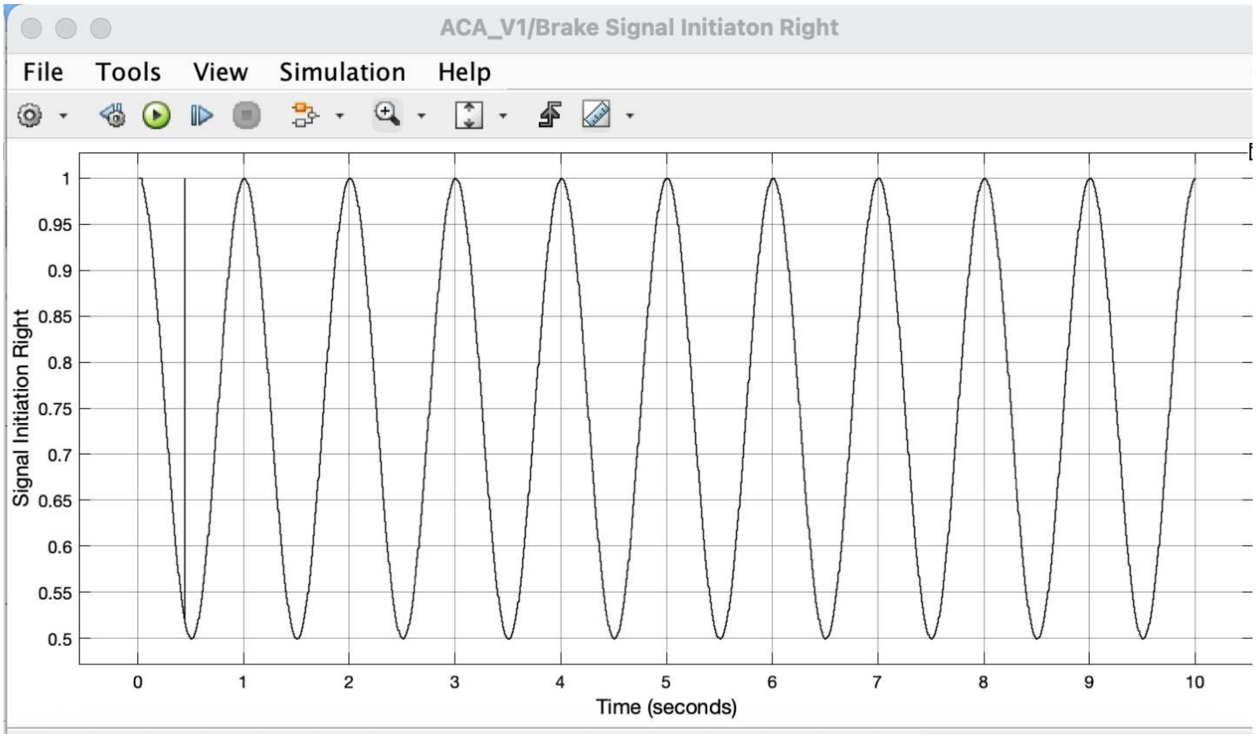

Figure 20.2: ACA City Brake Lights On Brake Signal Initiation Right

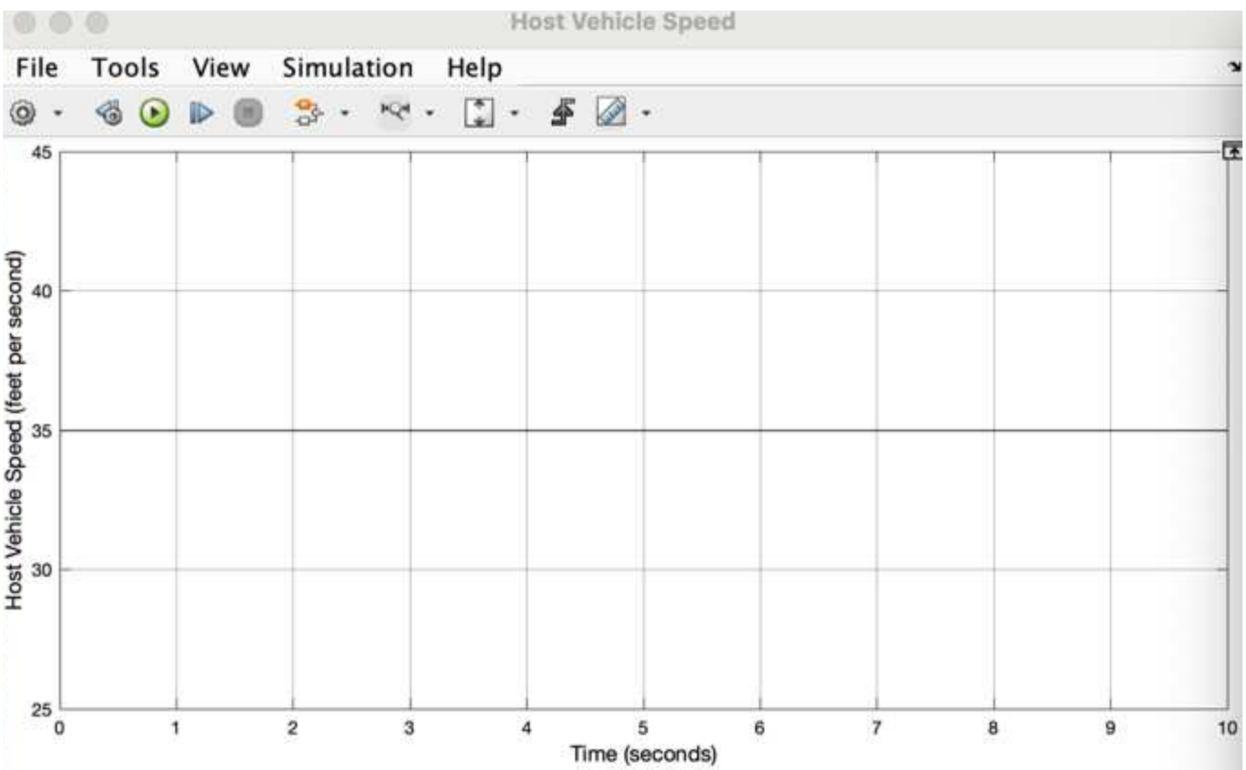

Figure 20.3: ACA City Host Vehicle Speed

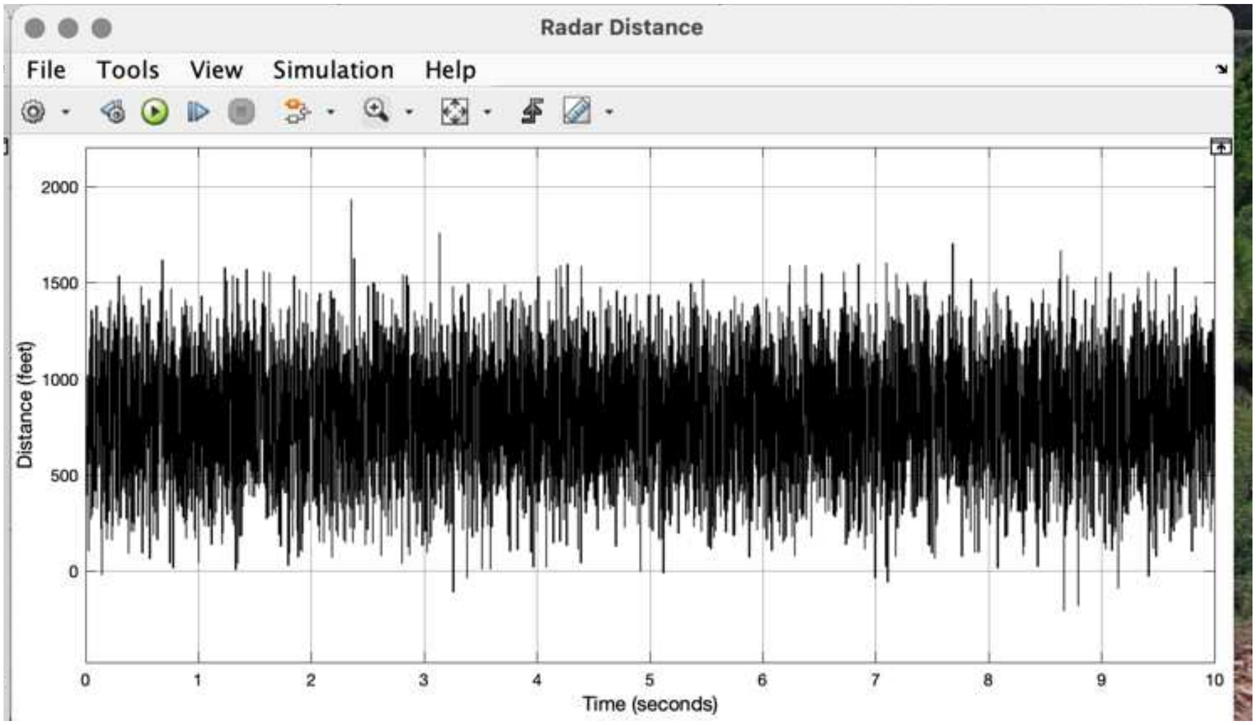

Figure 20.4: ACA City Radar Distance

Figure 21.1: ACA Freeway Brake Lights Off Brake Signal Initiation Left and Figure 21.2: ACA Freeway Brake Lights Off Brake Signal Initiation Right show the activation of the ACA at time stamp at about a quarter second. The lag time observed in Figures 19.1 and 19.2 is not apparent in Figures 21.1 and 21.2. The maximum distance seen in Figure 21.4 is about 575 feet, which isn't uncommon on the Freeway. There are some negative distances, which keeps the ACA activated for the entire 10 second run time simulated.

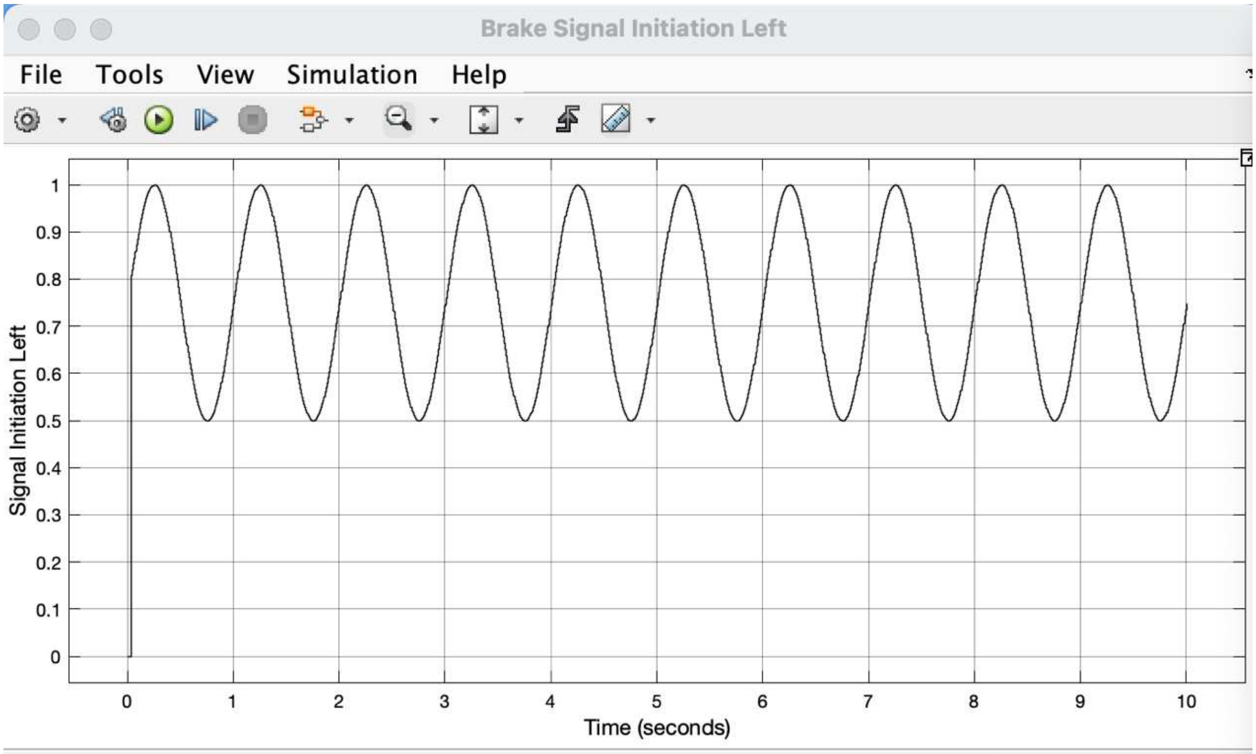

Figure 21.1: ACA Freeway Brake Lights Off Brake Signal Initiation Left

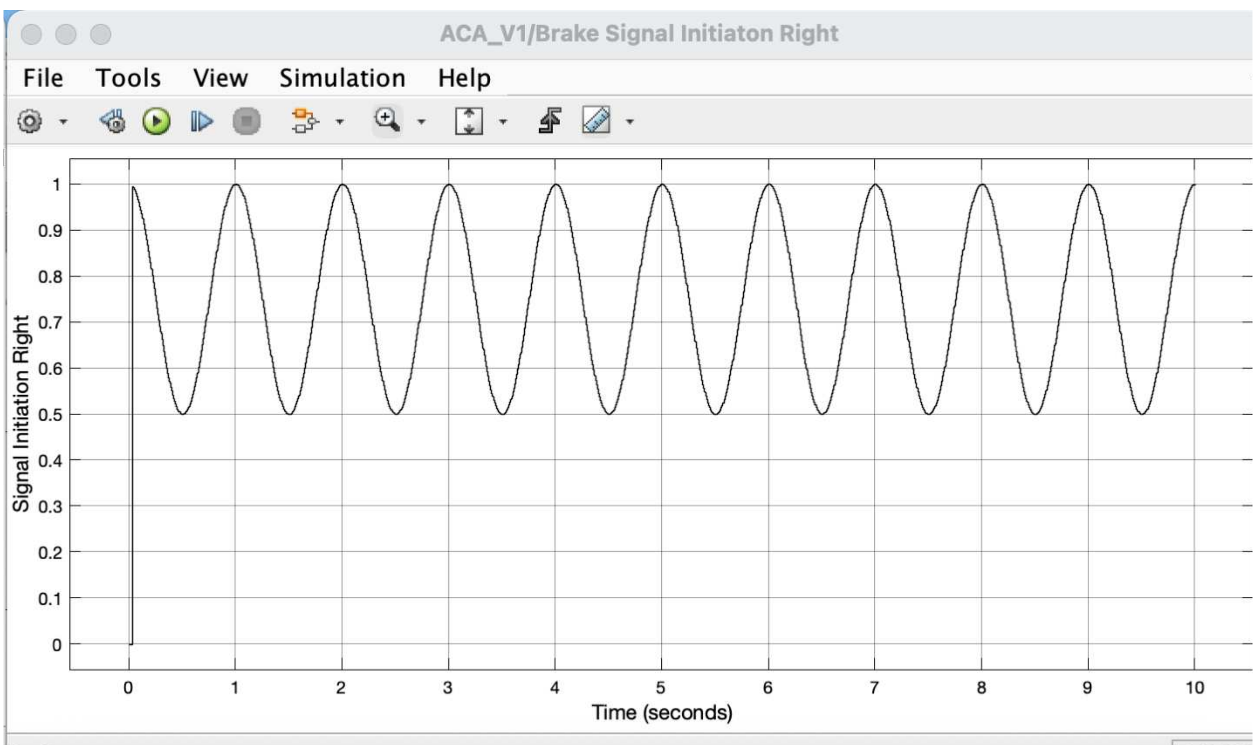

Figure 21.2: ACA Freeway Brake Lights Off Brake Signal Initiation Right

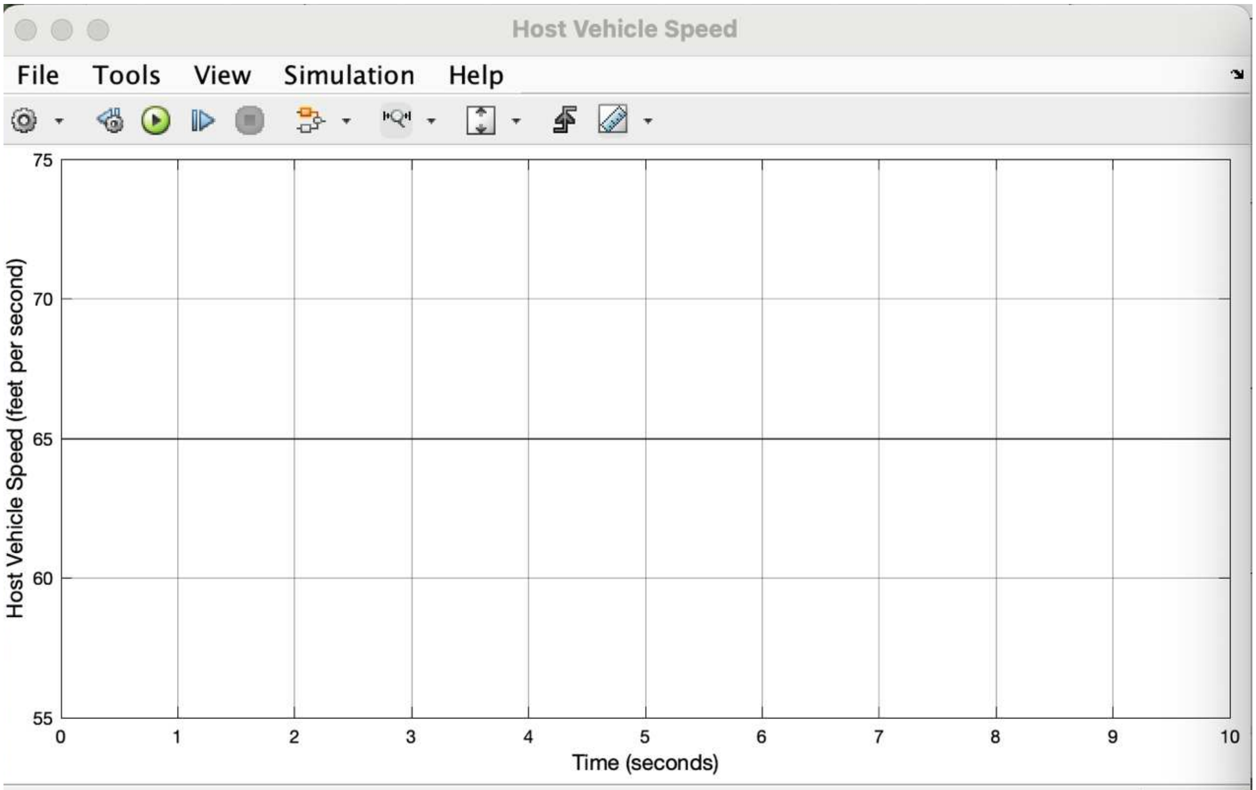

Figure 21.3: ACA Freeway Brake Lights Off Host Vehicle Speed

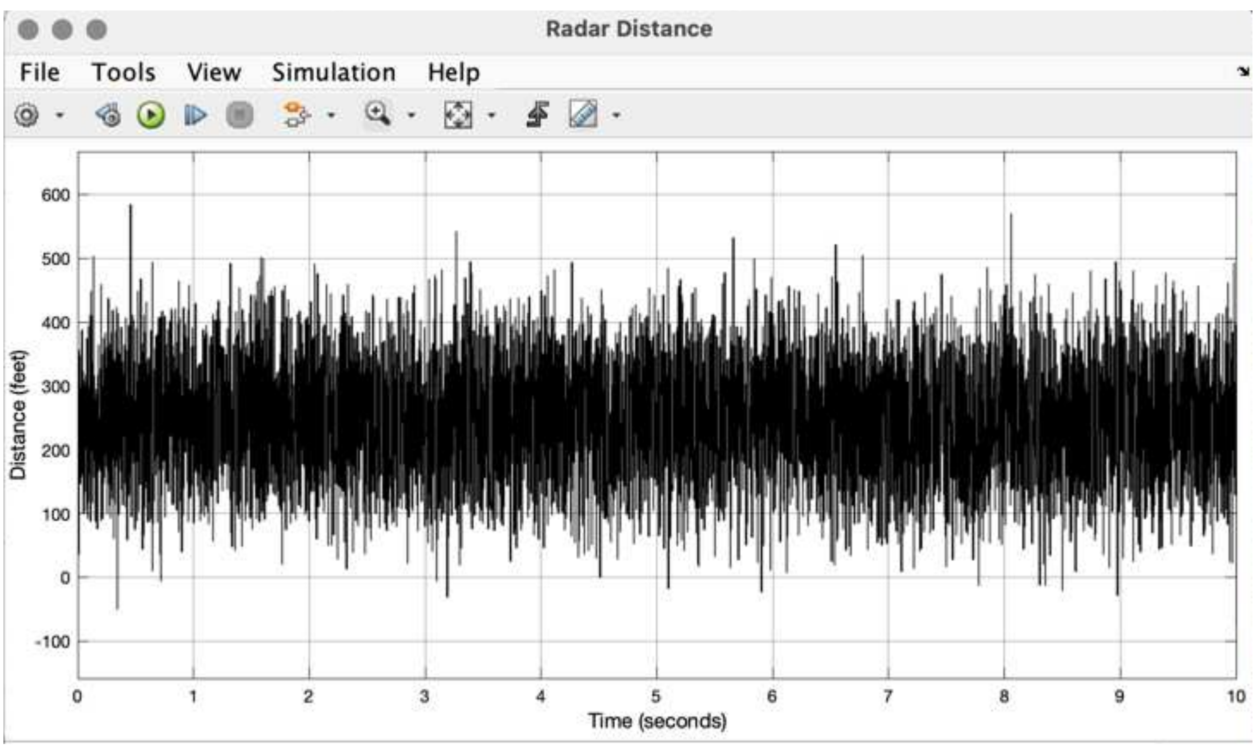

Figure 21.4: ACA Freeway Brake Lights Off Host Radar Distance

Figure 22: ACA Freeway Brake Lights On simulates the host vehicle traveling on a Freeway with the brake lights on when the ACA is activated. The ACA activates at about a quarter second, and briefly deactivates at about three and a half seconds. The distance values seen in Figure 22.4 fall mostly between 200 and 300 feet for the first five seconds. Between five and seven seconds there are multiple instances where the distance values are negative, at the same time there are several instances where the distance is above 500 feet. Due to the ACA using distance averages to make decisions, these extrema are mitigated.

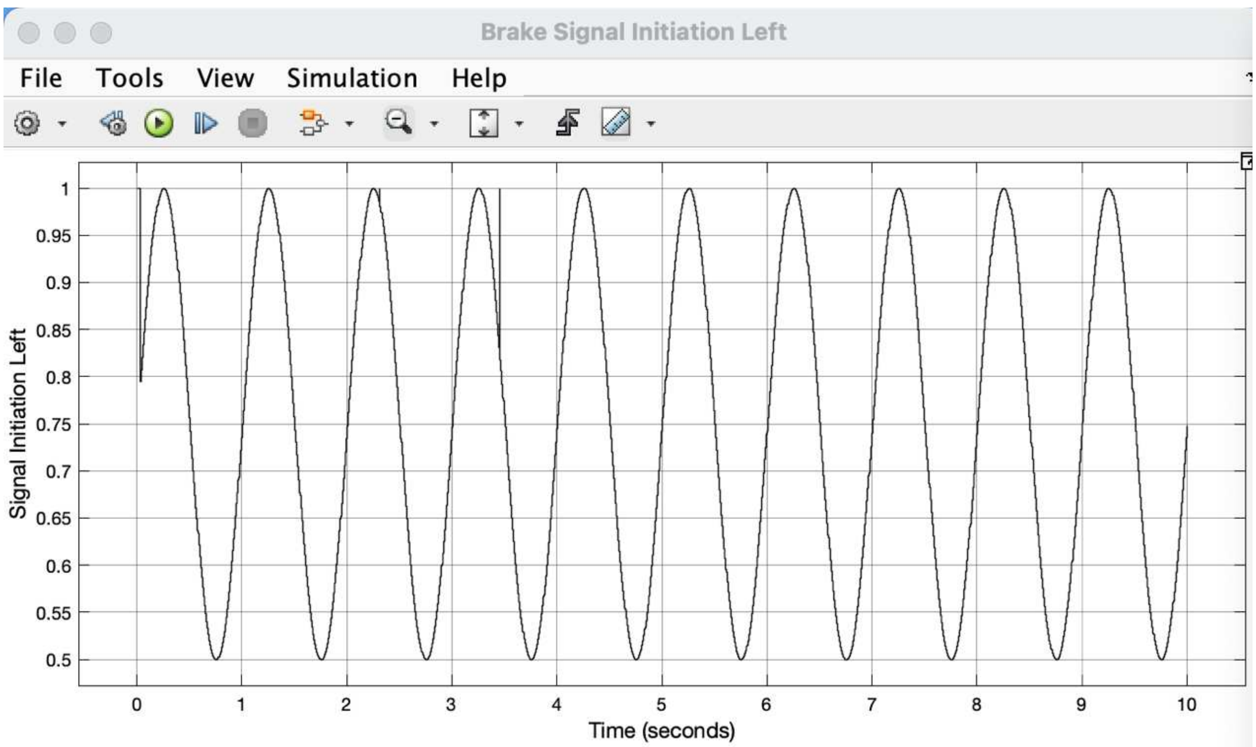

Figure 22.1: ACA Freeway Brake Lights On Brake Signal Initiation Left

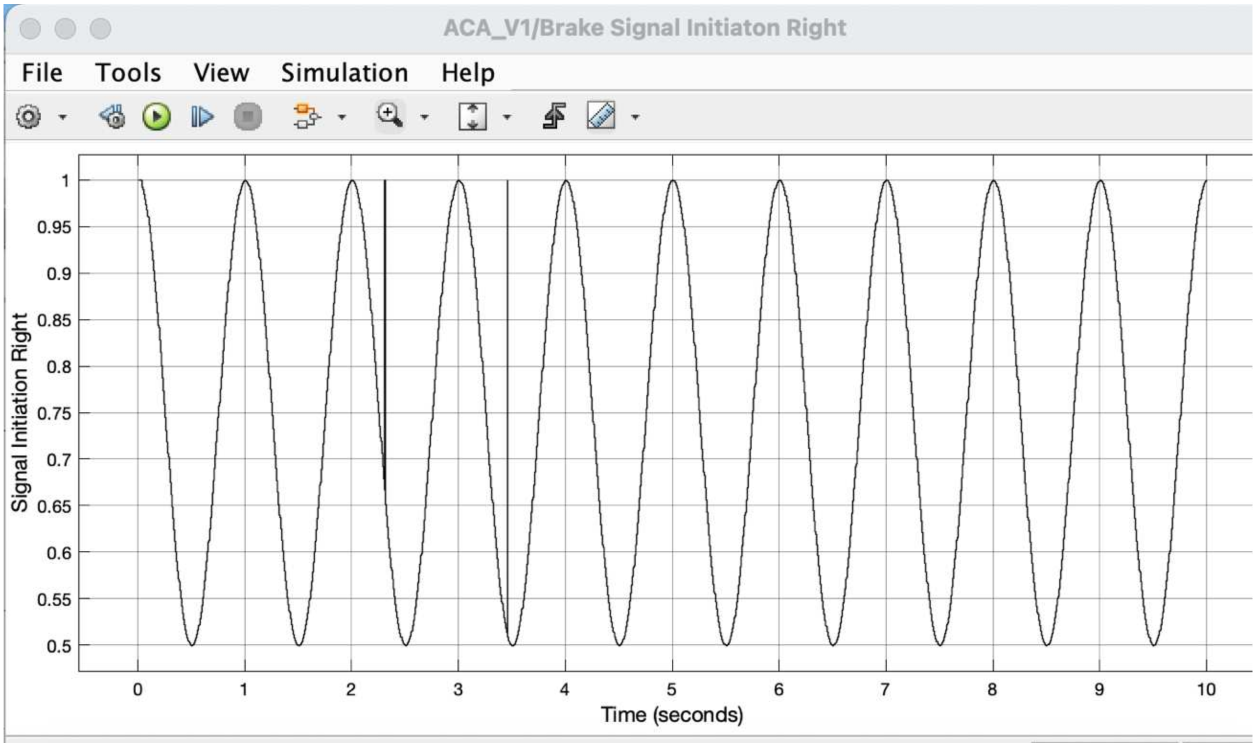

Figure 22.2: ACA Freeway Brake Lights On Brake Signal Initiation Right

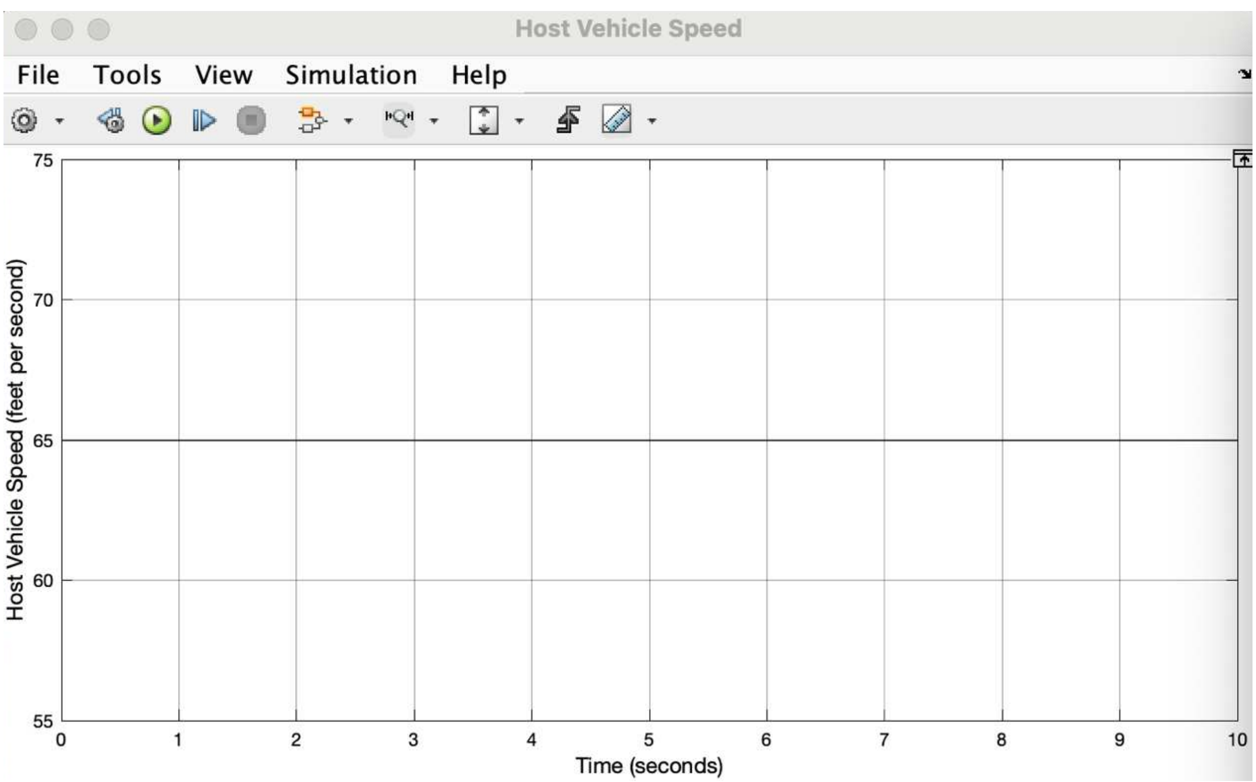

Figure 22.3: ACA Freeway Brake Lights On Host Vehicle Speed

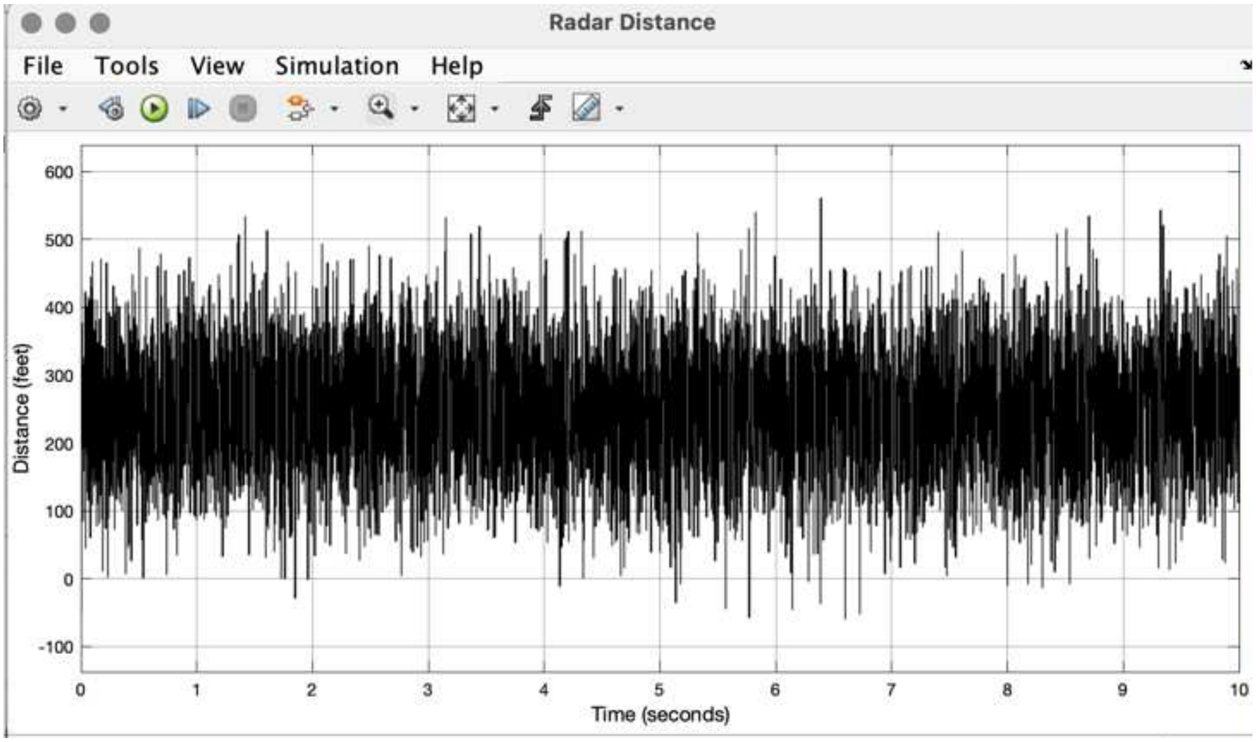

Figure 22.4: ACA Freeway Brake Lights On Radar Distance

Figure 23: ACA Highway Brake Lights Off shows the response of the ACA on a rural highway, at highway speeds with the brake lights off. The ACA activates nearly instantaneously, but then at one second, four and a half seconds and about six seconds, deactivates momentarily; Figures 23.1 and 23.2. From Figure 23.4 at one second there is a large number of distance values close to 2000 feet; similarly at six seconds as well. The distance data at four and half seconds shows the distance values clustered between 500 and 1200 feet, however at four seconds multiple distance values are above 1500 feet. At a half second and at five and half seconds there is a surge in distance values above 1000 feet as well. The increase in number of large distance values a half second before the ACA deactivates suggests the ACA Highway Brake Lights Off simulation demonstrates a half second lag time. Between eight and a half seconds and ten seconds there is another surge in large distance values presented, but the ACA remains active.

The ACA remaining active can be attributed to the number of small distance, especially the negative distance values decreasing the distance averages.

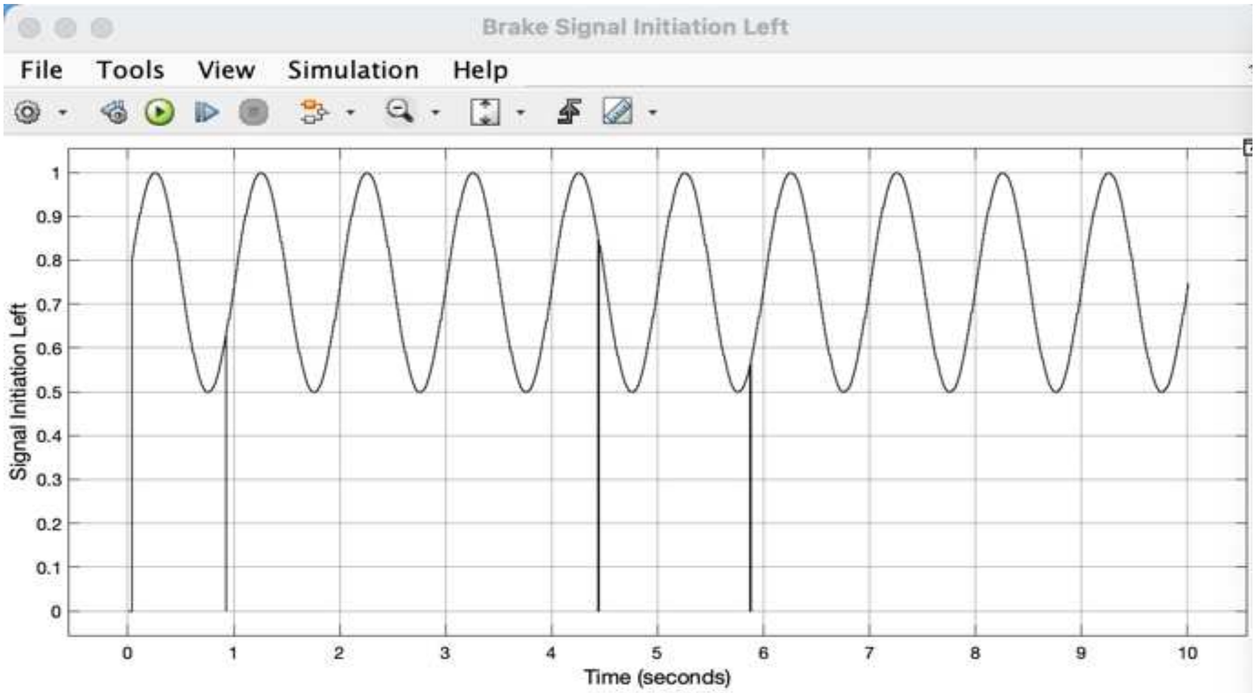

Figure 23.1: ACA Highway Brake Lights Off Brake Signal Initiation Left

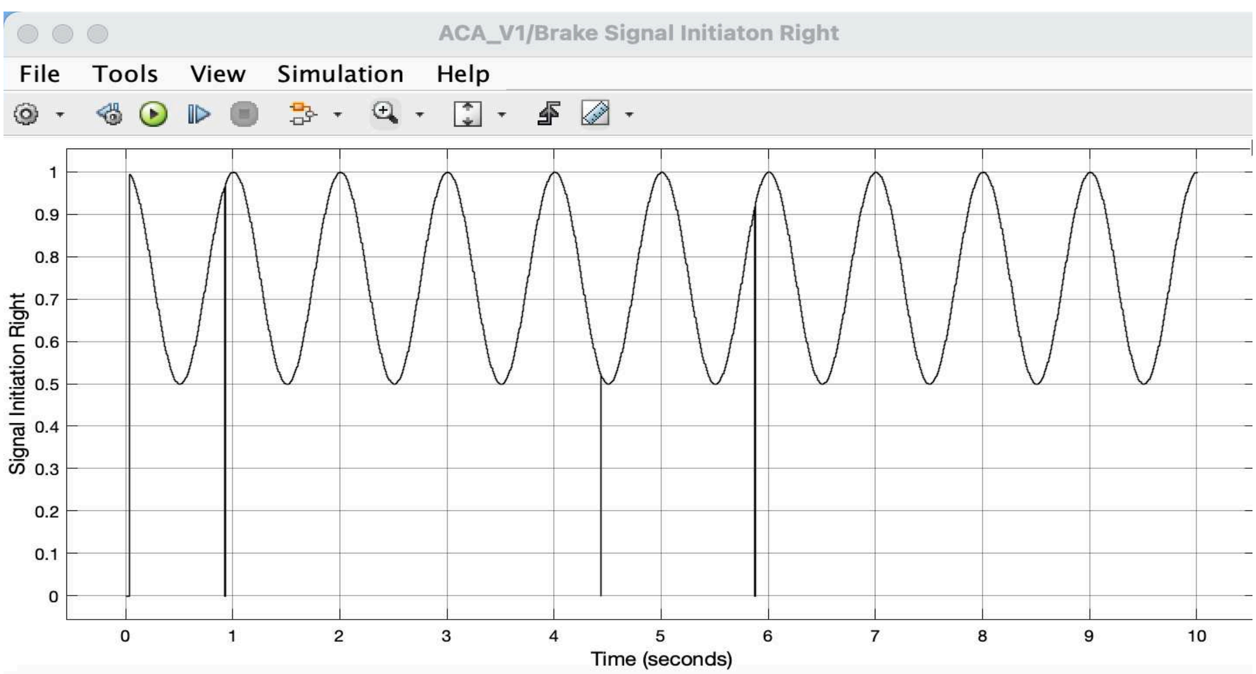

Figure 23.2: ACA Highway Brake Lights Off Brake Signal Initiation Right

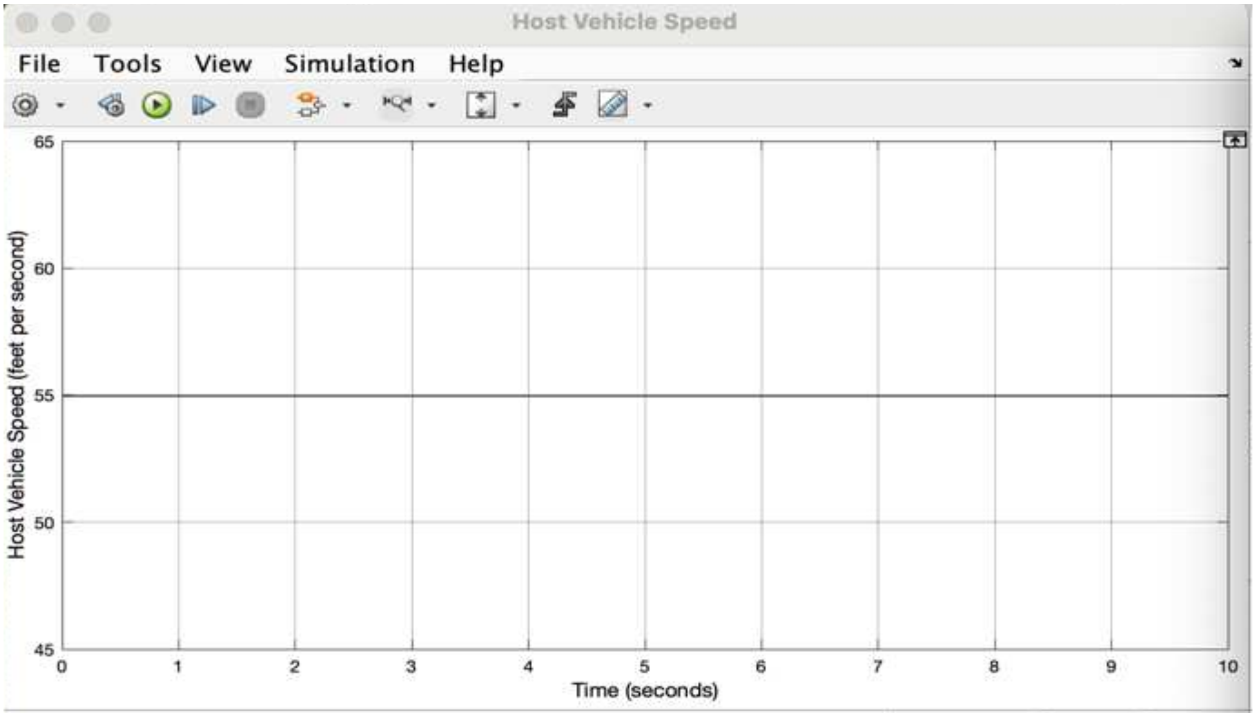

Figure 23.3: ACA Highway Brake Lights Off Host Vehicle Speed

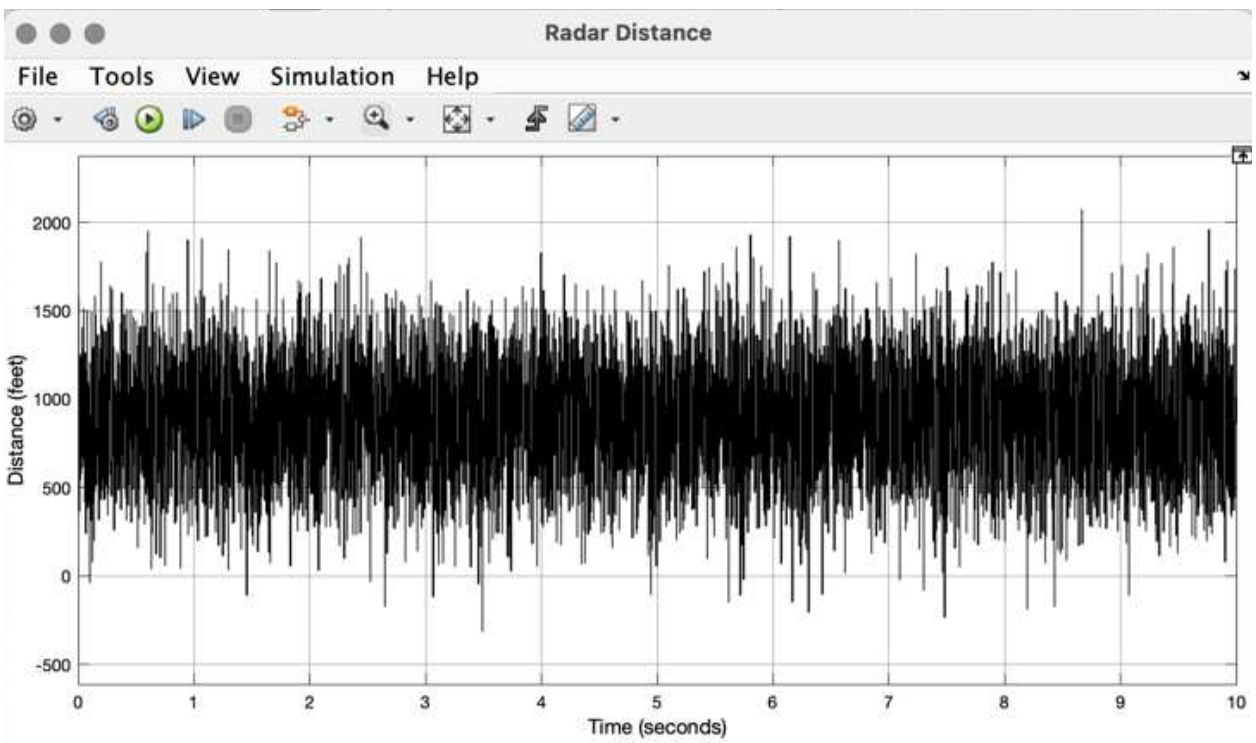

Figure 23.4: ACA Highway Brake Lights Off Brake Radar Distance

Figure 24: ACA Highway Brake Lights On shows a simulation of the host vehicle on a rural highway with the brake lights off initially. The first instance of the ACA presenting as activated is pretty much instantaneous, Figure 24.1 and Figure 24.2. This correlates with a large quantity of the following distances observed in Figure 24.4 being below 500 feet. The ACA deactivates at seven and a half seconds, which is in character of the half second lag time, since there is multiple distance values above 1500 feet at seven seconds.

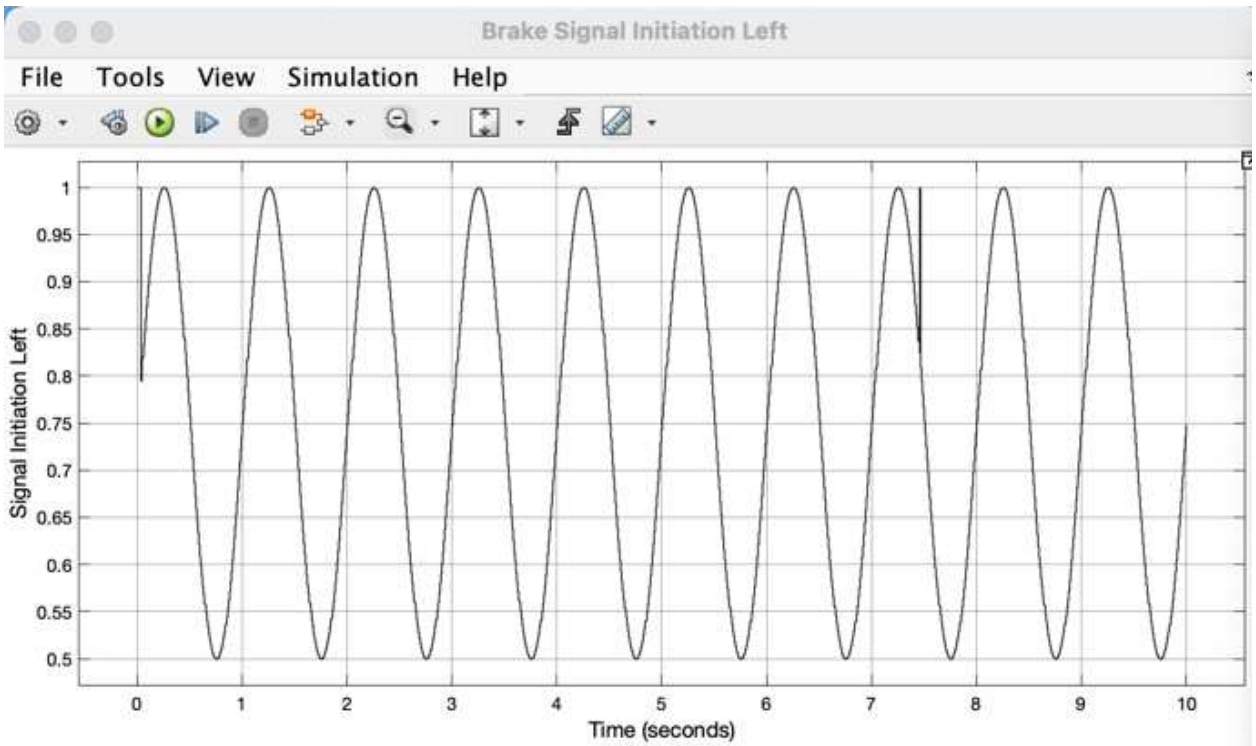

Figure 24.1: ACA Highway Brake Lights On Brake Signal Initiation Left

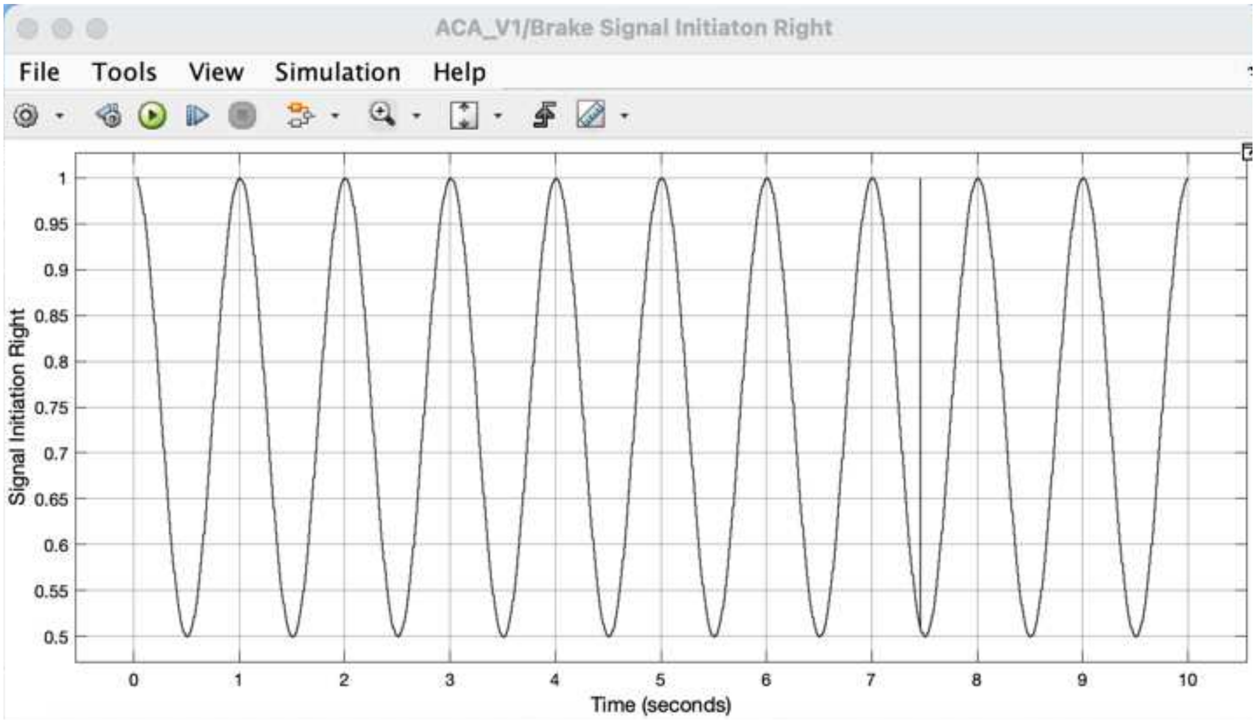

Figure 24.2: ACA Highway Brake Lights On Brake Signal Initiation Right

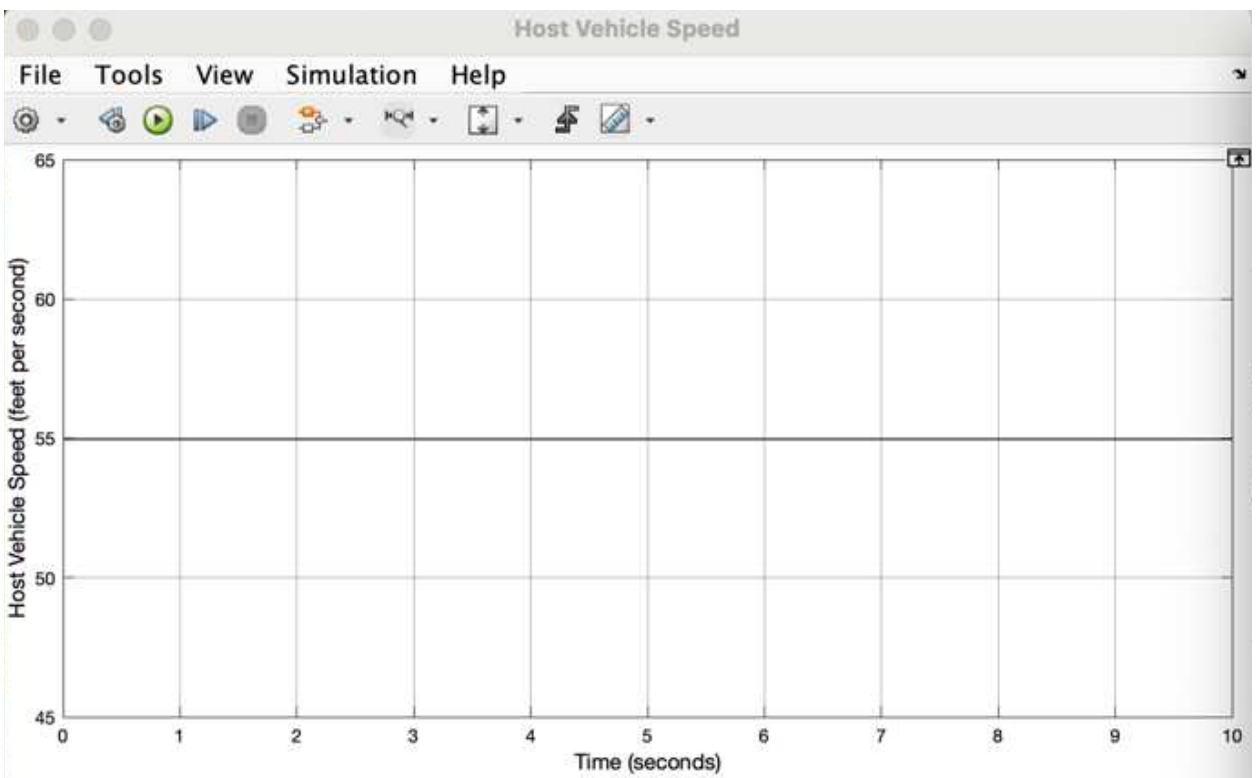

Figure 24.3: ACA Highway Brake Lights On Host Vehicle Speed

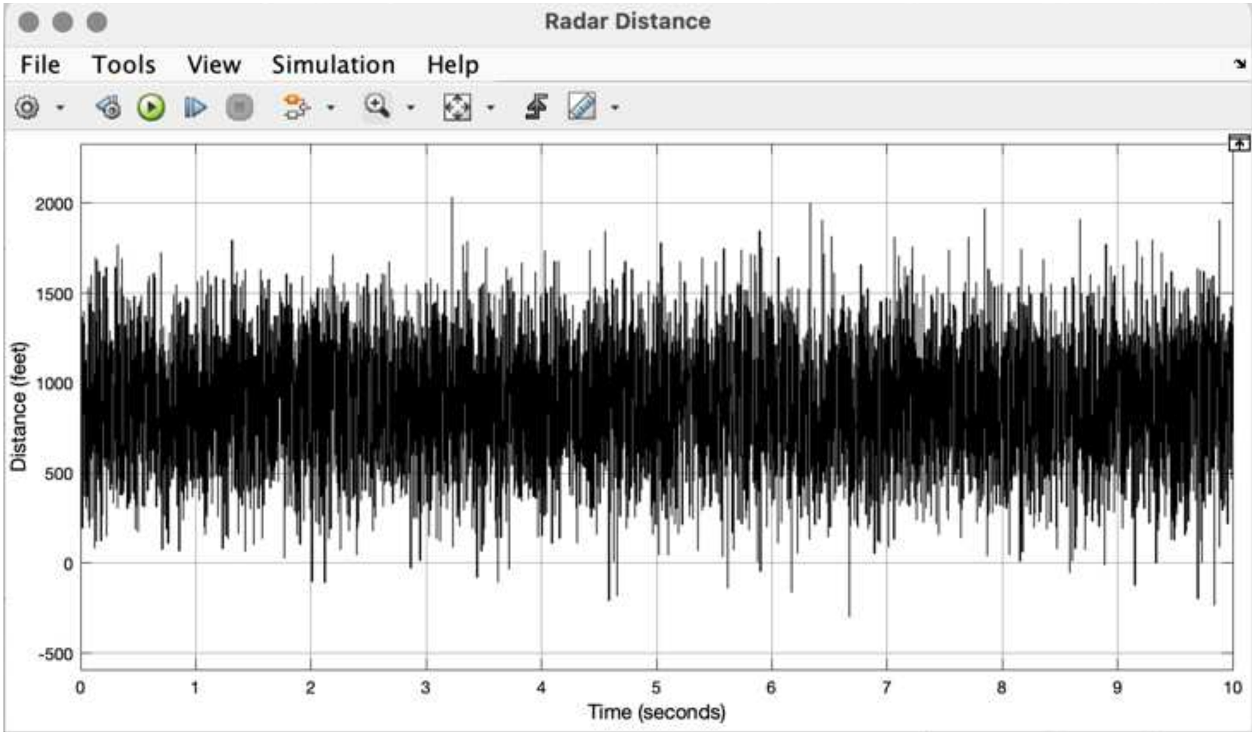

Figure 24.4: ACA Highway Brake Lights On Radar Distance

All of the figures in this Chapter 6 show to a varying extent that the SIMULIINK model has a delay. The delay in Figure 19 looks to be three quarters of a second, while the delay in Figure 24 is about a half second. Figures 20 through 23 have the same processing delay, however the impact of the delay is less obvious. The delay is attributed to the ACA having multiple blocks that collect and average the incoming data. The data is collected in batches of 20 and 30, before the average is taken and fed forward to the next block, resulting in an activation or deactivation delay for the ACA.

Chapter 7 Empirical Data Modeling[3]

In order to examine how the ACA system responds to real world driving conditions, empirical driving data was collected using the ARS 408 radar unit on my personal vehicle. Figure 25: ACA Inputs Revised presents the ACA ECU with 5 inputs and 2 outputs, instead of the 7 inputs and 3 outputs presented in Chapter 4 Figure 12. ACA SIMULINK Data Inputs and Outputs due to refinements in method of obtaining distance data. The Radar unit collecting inbound vehicle following distances, the Continental ARS 408 has a 77 Giga Hertz (GHz) Long Range Radar Sensor, large enough to provide both the long range and midrange data the ACA was originally designed for [120]. The reduction in inputs also enabled some of the internal logic and outputs to be consolidated.

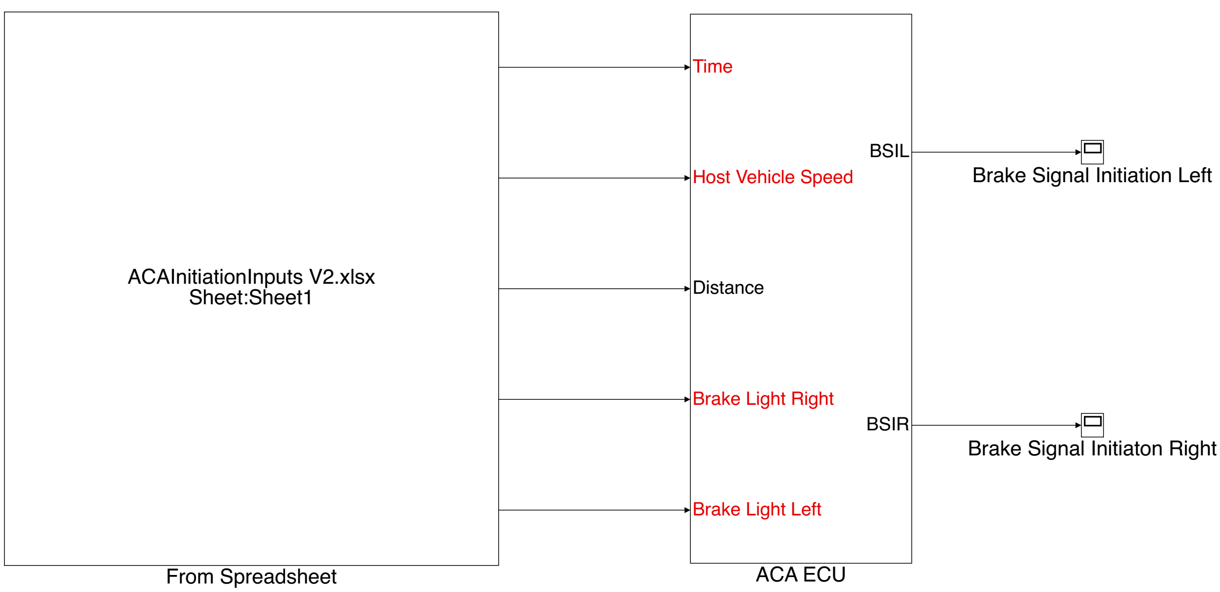

Figure 25: ACA Inputs Revised

[3] Rictor A. and Chandrasekar V., "Modeling and Analysis of the Aft Collision Assist Advanced Driver Assistance System," *IEEE International Conference on Digital Twins & Parallel Intelligence 2024*, Oct. 2024 .

With Distance data processing reduced, the need for the RTAF Check signal was eliminated. The resulting system is thus dependent upon the following inputs: Time, Host Vehicle Speed, Distance, Brake Light Right and Brake Light Left. The outputs are reduced to: Brake Signal Initiation Left and Brake Signal Initiation Right. Figure 25 was first published at the 2024 IEEE International Conference on Digital Twins & Parallel Intelligence [119].

Figure 26: ACA ECU Revised presents the optimized internal functions of the ACA ECU. Figure 26 was first published at the 2024 IEEE International Conference on Digital Twins & Parallel Intelligence [119]. Consolidating distance data to a single data input eliminated the History Block. The internal blocks were thus reduced to: Inbound Vehicle Speed, Running Average Initiation, History Initiation and RTAF Check. The processing of the Distance and Speed data were further reduced to a single feedback loop from the History Initiation block to the Running Average Initiation block.

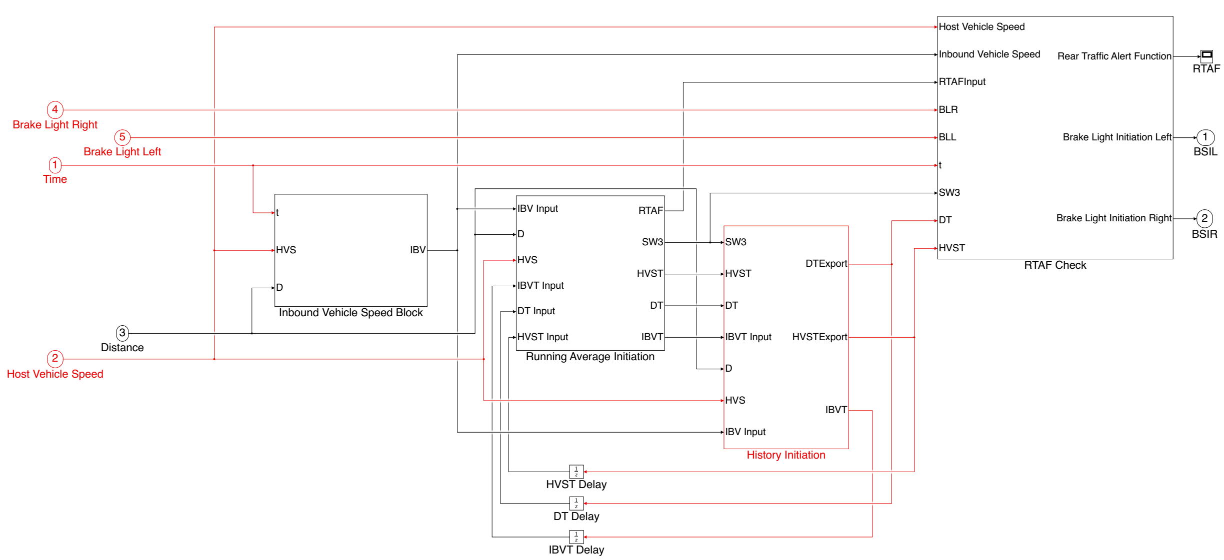

Figure 26: ACA ECU Revised

The variables needed to calculate stopping distance and safe stopping distance are configured for a flat road being driven in the fall. The coefficient of road friction was set to 0.5, since the empirical data was collected after a recent rain and the pavement was still wet. The road gradient was left at 0 since the road where the empirical data was collected was generally flat. The time constants for thinking time, reaction time and braking time were set to 0.5, 0.2 and 0.3 seconds, respectively in the stopping distance calculation. These values were based on the research presented in the Sensors article "Safe Driving Distance and Speed for Collision Avoidance in Connected Vehicles" [111]. A factor of safety of 1.5 was maintained for the calculation of a safe stopping distance. The factor of safety selected aligns with the value recommended in the article "Permissible Distance – Safety System of Vehicles in Use" [114].

Figure 27: Distance Time Data Interpolation Function was first published at the 2024 IEEE International Conference on Digital Twins & Parallel Intelligence [119] and presents the interpolation function required for the ACA to process the asynchronous speed data and distance data. The speed data provided by the host vehicle has a data rate of one packet every 20 milliseconds. The distance data provided by the radar unit has a data rate of one packet every 70 milliseconds. This leads to the challenge of having roughly three speed data points for every one distance data point.

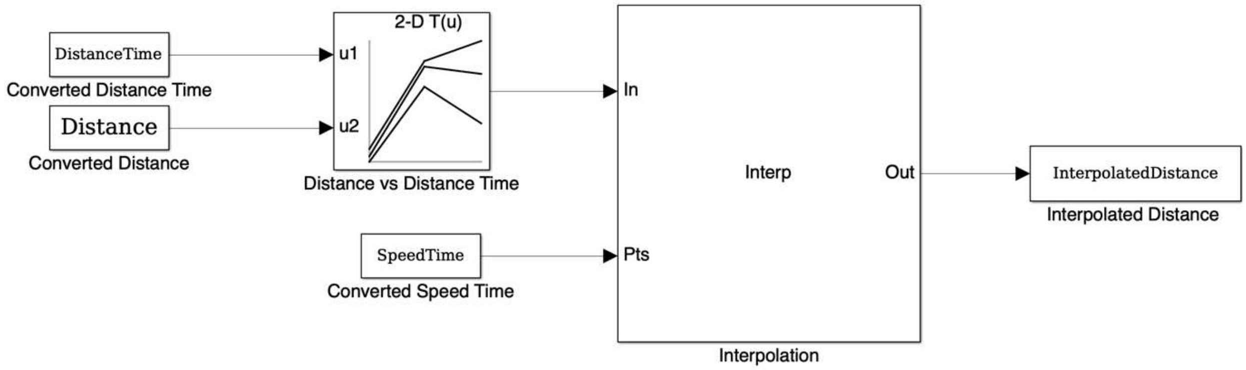

Figure 27: Distance Time Data Interpolation Function

An interpolation function is required for the ACA to process the asynchronous speed and distance data input intervals.

Figure 28: Radar Distance Data Conversion Function presents the data conversion function from the ARS 408 to usable distance data. Figure 28: Radar Distance Data Conversion Function was first published at the 2024 IEEE International Conference on Digital Twins & Parallel Intelligence [119]. The ARS 408 stores and transmits the distance data as hexadecimal longitudinal and hexadecimal lateral values. These values are extracted from the hexadecimal frame, converted to binary, then converted to decimal where the extracted values are converted to longitudinal and lateral distances and then converted into a distance value in decimal units of feet for further processing.

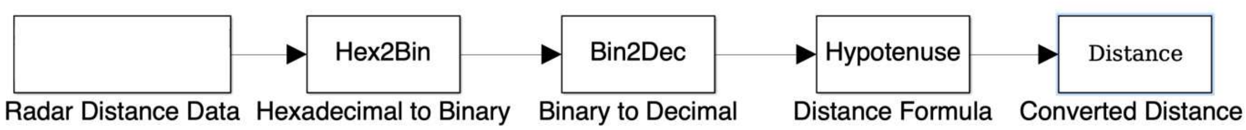

Figure 28: Radar Distance Data Conversion Function

Figure 29: Radar Quality Data Conversion Function presents the extraction and conversion of the hexadecimal values transmitted by the ARS 408 radar unit into quality data with decimal units. The ARS 408 can assign a certainty probability to the objects it detects and

an object classification too [121]. The object classification levels are: Car, Truck, Motorcycle, Bicycle, Point, or Wide. The associated probability of correctly classifying an object into one of these six objects has seven classification levels, with one being less than 25%, two being less than 50%, three being less than 75%, four being less than 90%, five being less than 95%, six being less than 99.9% and seven being less than 100% [122].

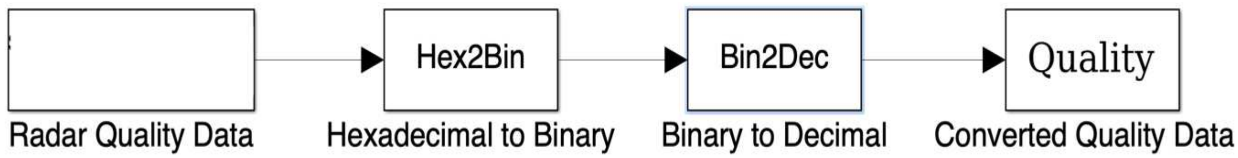

Figure 29: Radar Quality Data Conversion Function

The ability to filter distance data from the ARS 408 down to objects that are only cars and trucks, and then further filter distance data down by the probability of an object being correctly classified greatly reduces the amount of data that the ACA has to process and improves efficiency.

Figure 30: Speed Data Conversion Function presents the extraction and conversion of the speed data from the hexadecimal CAN message read from the host vehicles onboard CAN messages to the converted speed value inside the ACA ECU. Figure 30 was first published at the 2024 IEEE International Conference on Digital Twins & Parallel Intelligence [119]. The speed conversion factor specified was empirically derived for my personal vehicle, a RAM 1500. The vehicle speed is present on CAN ID 158.

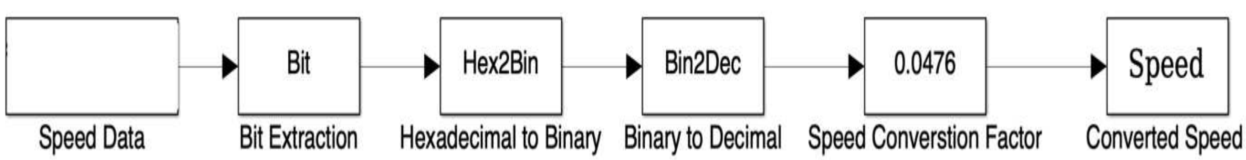

Figure 30: Speed Data Conversion Function

Figure 31: Brake Signal Initiation Left, Brake Signal Initiation Right, Distance Host Speed Data Comparison presents the host vehicle speed, the distance between the host vehicle and the inbound vehicle and the left and right brake signals. Figure 31 was first published at the 2024 IEEE International Conference on Digital Twins & Parallel Intelligence [119]. As the host vehicle speed increases and the inbound vehicles distance increases, the ACA's brake signal initiation is not triggered. From time instance 100 through 400 seconds the brake signal initiation is triggered repeatedly due to the inbound vehicles distance ranging from 20 feet to 50 feet behind the host vehicle. The host vehicles speed ranges between 15 feet per second (fps) and 30 fps, which is between 10 miles per hour (mph) and 20 mph. The ACA is no longer triggered when the distance is 50 feet and the host vehicle is going 20 mph.

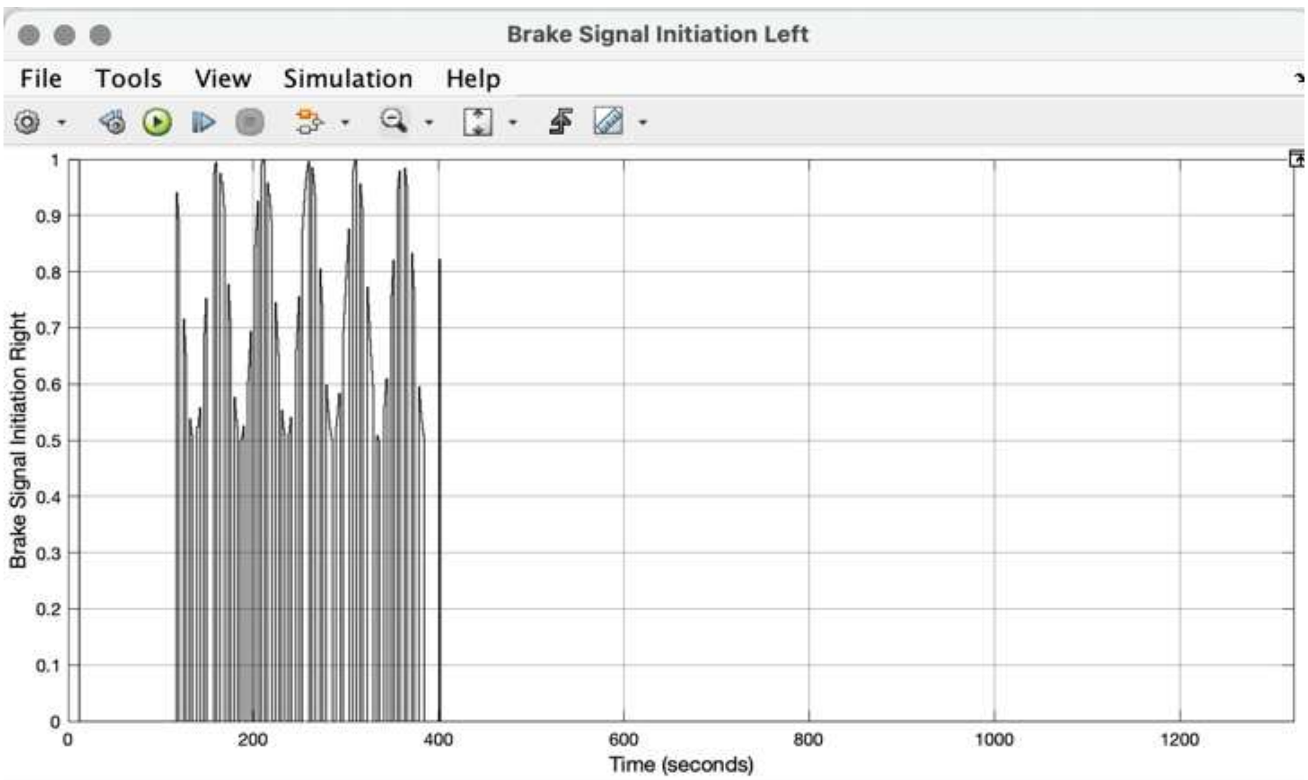

Figure 31.1: Empirical Data Brake Signal Initiation Left

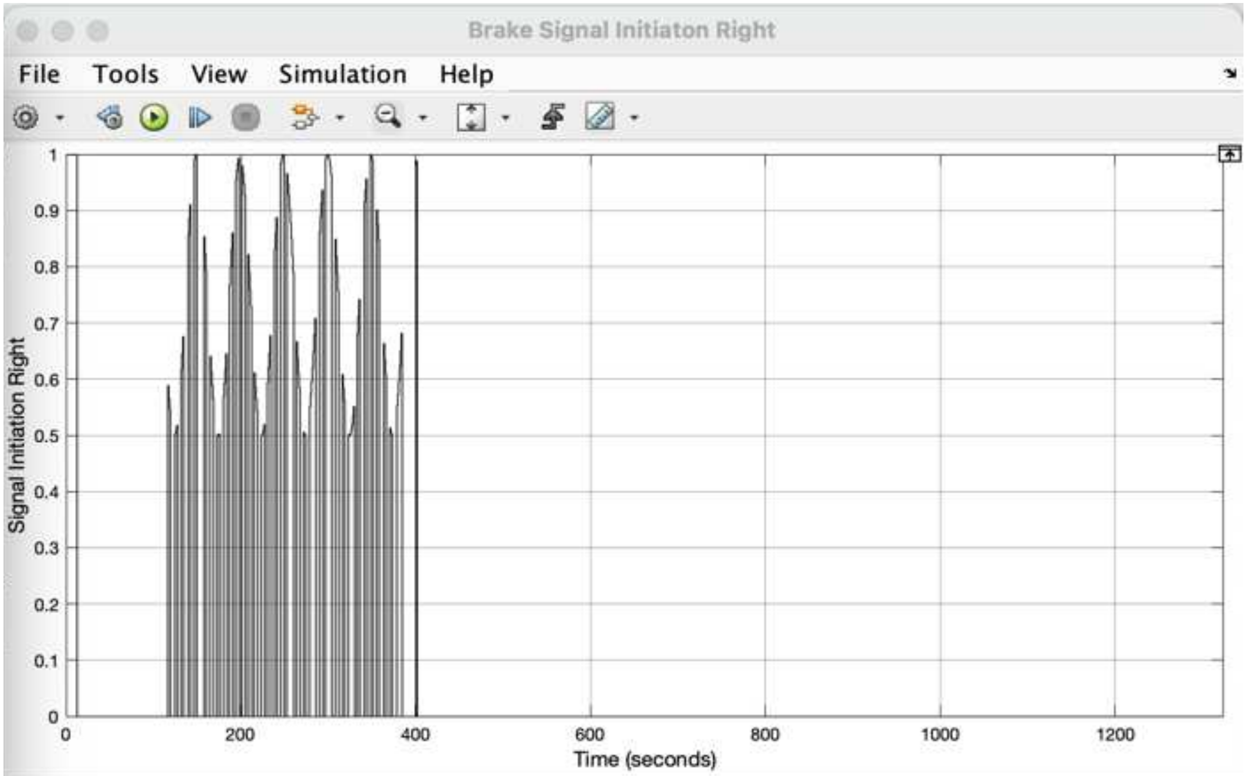

Figure 31.2: Empirical Data Brake Signal Initiation Right

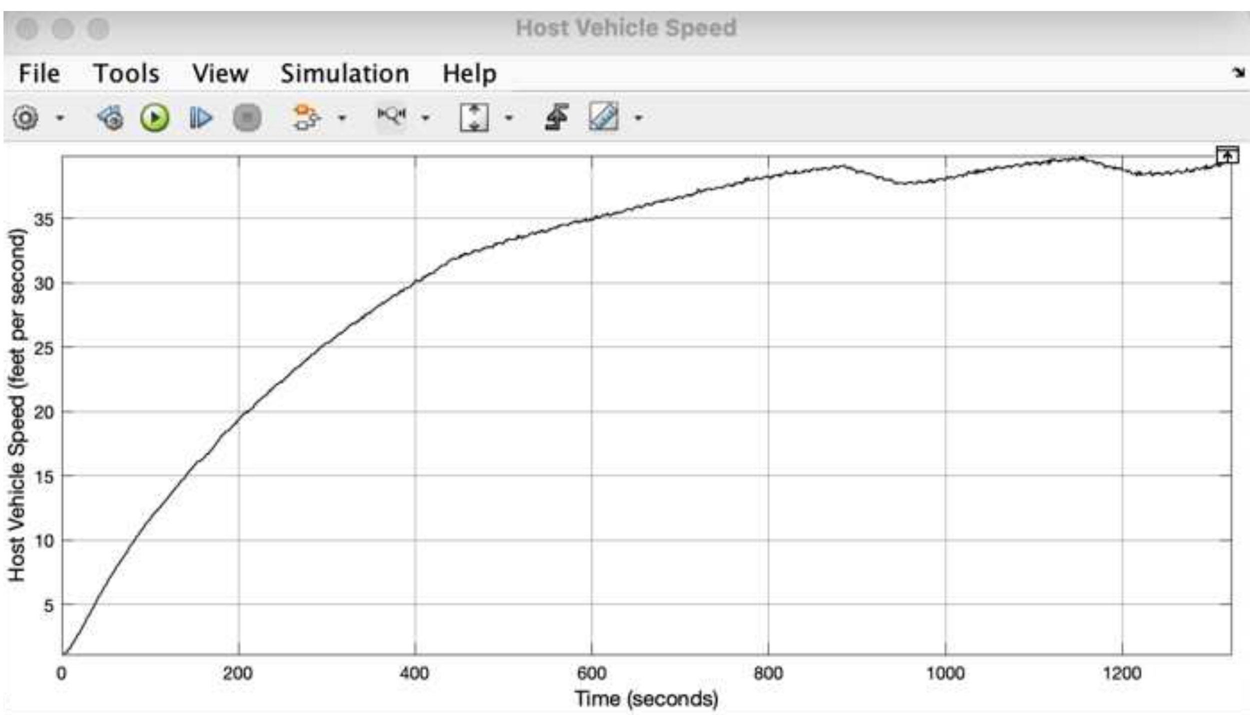

Figure 31.3: Empirical Host Speed Data

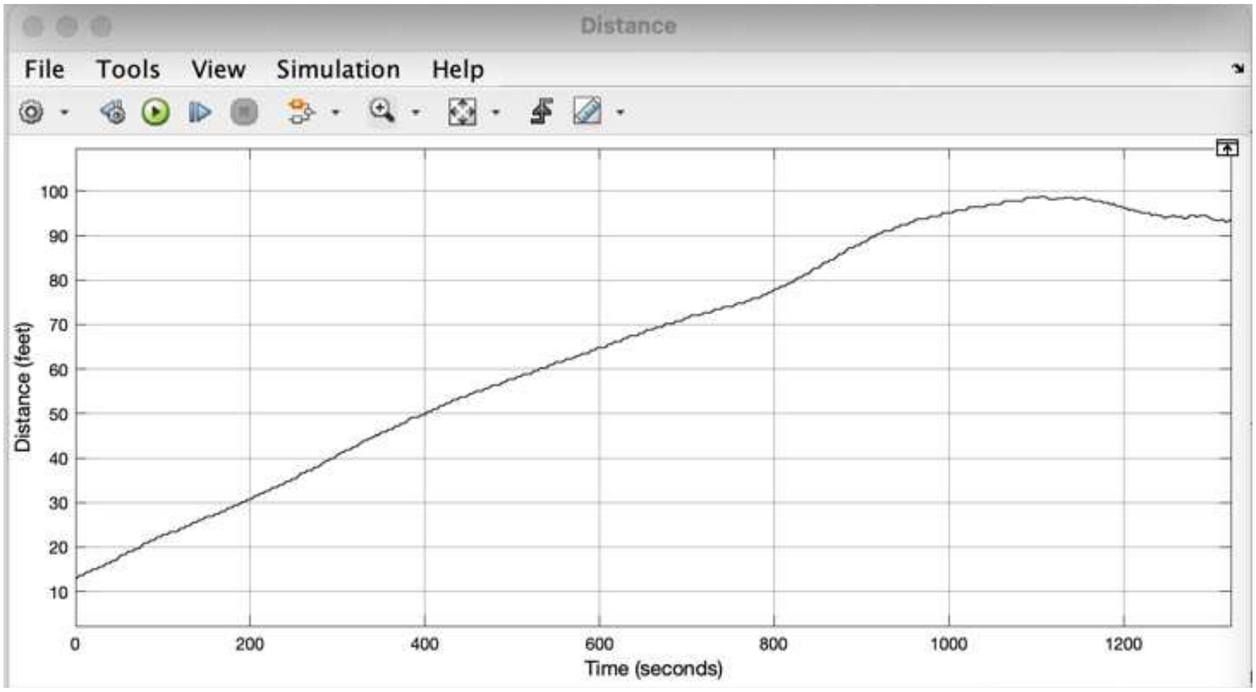

Figure 31.4: Empirical Radar Distance Data

The scenario that is presented in the data is a city driving situation where the host vehicle was initially stopped at a stop light, and the inbound vehicle came up when the host vehicle was starting to pull away after the light changed. The response of the ACA is as expected with the inbound vehicle initially being 10 feet from the host vehicle.

The empirical data modeled, unlike the modeled data presented in Chapter 6 shows the ACA activating and deactivating without the processing delay. This is attributed to the removal of the History Loop block, and the six feedback loops going to the Running average initiation as well as the History Initiation block.

Chapter 8 Summary & Future Work

The ACA presented within is shown through three different mediums of system modeling: documentation and validation, Model Based Systems Engineering, and SIMULINK. From the MBSE diagrams presented in Chapter 3 Model Based System Engineering of the Aft Collision Assist, the regulatory requirements presented have the largest impact on system development and functionality. From the regulatory statutes, modifying the brake lamps is the optimal output from the ACA ECU to satisfy both regulatory constraints and ultimate functionality of the ACA: reengaging a distracted driver. Following the regulatory requirements, the ECU hardware requirements, derived Data Processing requirements, derived Communications requirements and ACA State Machine diagrams directly translate to the SIMULINK model presented in Chapter 3. The SIMULINK diagrams in Chapter 4 SIMULINK Model of the Aft Collision Assist presents the internal algorithms and data processing methodology elected to process the host speed and inbound vehicle distance data streaming into the ACA. The data derivation presented in Chapter 5 Distance Data presents how the distance data used in the ACA simulations was acquired and the limitations of this derived data. The simulation models presented in Chapter 6 SIMULINK Simulation of the Aft Collision Assist show that the ACA functions with simulated inputs and provides conceptual validation of the ACA. The graphical figures presented in Chapter 6 also raise concerns regarding data processing times and transmission delays between the radar hardware and the ACA ECU. The timing of these concerns is ideal since they can be addressed early on with further simulations and optimization efforts, instead of during prototyping or physical validation efforts on a test vehicle. The ACA's operation with regards to activation and deactivation is shown to behave as desired and expected. The large difference in detected distance between two sequential time steps confirms that the ACA's logic can appropriately respond to sudden changes in following distances immediately aft of the host vehicle. Chapter 7 Empirical Data Modeling presents the ACA responding to speed data and distance data collected simultaneously and input to the ACA SIMULINK model. The ACA's response time with the reduced internal logic and with empirical data shows the ACA ECU responding in about a tenth of the time that the SIMULINK models in chapter 6 presented. Activation of the ACA output isn't instantaneous, confirming that the ACA logic engages and disengages based upon the distance and speed inputs.

The RTAF Check Block algorithms are based upon driving studies, generally accepted recommendations by insurance companies and the National Highway Traffic Safety Administration for safe driving distances [111,112,113,114,115]. This tailors the ACA response to be based upon idealized circumstances and driving conditions, which as shown in Figures 19 through 24, and Figure 31 provides appropriate responses. Following the derived distances, the ACA system shows simulation results based upon empirical data from real-world driving scenarios fed to the system. Utilizing speed data that fluctuates with dynamic distance data presents smoother ACA responses. Smoother data sets enable the potential derivation of more precise algorithms for different driving environments; Freeways vs Highways vs Cities.

Dynamic tuning of the roadway slope, coefficient of friction and factor of safety are all areas for future research. The Continental ARS 408 radar unit contains an internal gyroscope, which presents the opportunity to study incorporating the vehicle slope as a variable that can be tuned during driving operations. The factor of safety applied to the safe stopping distance calculation has the potential to be tuned based upon host vehicle speed. The benefit of having the factor of safety adjust for the vehicle speed would be improved responsiveness of the ACA in more hazardous driving situations, while simultaneously reducing errant activation in less hazardous driving situations. The computational costs compared to the potential benefits of a more agile system that is dynamically updated requires further modeling and simulations with empirical data.

The time duration of the ACA's sinusoidal brake signal outputs are currently configured to be dynamic and tuned to the radar that the ACA is paired with. The calculations, matrix and vector sizes utilized throughout the ACA ECU modeling are based upon baud rates for the radar sensor. An area for potential development is the time duration of the ACA signal. Research into optimizing and configuring the ACA to have dynamic sinusoidal periods to utilize real time historical following and stopping distances, which are based on system observations and records could potentially minimize false positive activations of the ACA. A city driving scenario with no vehicles could be left with a default value that the system could update with a dynamically changing variable to be tuned during heavier traffic flows.

Analyzing distance and velocity data collected from real world driving, independent of the ACA, presents an opportunity to model driving behaviors and patterns that are typically anecdotally shown. Since most traffic pattern research and traffic flow data shows vehicle volume rates from the perspective of a fixed point, collecting distance and velocity data from a vehicle in the midst of the traffic flow has the potential to elaborate upon and model minute changes in traffic flow patterns. Potential minute deltas that significantly change the probabilities of being rear-ended, present opportunities to either improve ACA sensitivity during certain times of day, or model dynamic situations based upon historical precedence.

Removing two blocks and the associated feedback loops from the ACA model significantly improved the SIMULINK model run time, however, further run time improvements will require converting the SIMULINK model to a compiled script. This was demonstrated with the creation of a conversion script for the speed data and distance data. The conversion scripts each run in a minute or two, verses several hours with the Matlab scripts.

The last figure in Chapter 7 Empirical Data Modeling shows the ACA outputting the correct output brake signal when the ACA is not activated, and then demonstrating the ACA's outputs triggering and shutting down when the inbound vehicle is no longer determined to be an imminent threat to the host vehicle. Figures 31.1 through 31.4: Empirical Data Brake Signal Initiation Left, Empirical Data Brake Signal Initiation Right, Empirical Distance Data, and Empirical Host Speed Data succinctly presents the ACA responding appropriately to real world data.

An area of future work that requires a prototype for testing is the cost benefit analysis of the ACA in quantizing the number of accidents the ACA prevents. Recording the following distances of inbound vehicles before the ACA activates and comparing to the following distances of vehicles after the ACA deactivates would be a good starting point to conduct a cost benefit analysis. Comparing the starting and ending following distance of an inbound vehicle to the following distances recorded by a vehicle that only recorded following distances would provide a direct comparison for showing the ACA's value to protecting the vehicle it is installed on.

The ACA system presented within this work demonstrates a significant advance in the design of rear-end collision avoidance ADAS technology. The ACA system addresses several limitations present in previous systems of this type and additionally generalizes the variety of conditions under which this type of system can both practically and legally operate. The ACA system functions in all driving scenarios: city, highway and freeway making it the first system of its kind that provides a complete solution for rear-end collision prevention.

References

1. Becker Law Office, “2.5 Million Rear End Collisions Every Year Make It Most Common Type Of Crash.” , Becker Law Office, June 2021, accessed March 2022, beckerlaw.com.

2. Indiana Injury Lawyers, “Can Automatic Emergency Braking Systems Reduce Accidents?,” Indiana Injury Lawyers, Dec. 2021, accessed March 2022, www.indianapilaw.com.

3. Elliott, C., “Are Vehicle Safety Features Actually Reducing Car Accidents?,” Forbes.com, updated Sept. 2020, accessed March 2022, www.forbes.com.

4. Golson, J., “Rear-end crashes go way down when cars can brake themselves,” The Verge, Jan. 2016, accessed March 2022, www.theverge.com.

5. Chang, J., “Speeding through the ADAS market 0-60,” E2e.ti.com, Dec. 2015, accessed March 2022, e2e.ti.com.

6. Bernsteiner, S., “Integration of Advanced Driver Assistance Systems on Full-Vehicle Level Parametrization of an Adaptive Cruise Control System Based on Test Drives,” Doctoral Thesis, Graz University of Technology, 2015.

7. Moslemi, M., “Autonomous Cars & ADAS: Complex Scenario Generation, Simulation and Evaluation of Collision Avoidance Systems,” Master’s Degree Thesis, POLITECNICO DI TORINO, 2019.

8. Rictor, A. and Chandrasekar, V., “Defensive Crash Avoidance System (DCAS): A New Advanced Driver Assistance System (ADAS),” Conference Presentation at AUVSI XPONENTIAL 2020, Oct. 2020.

9. Rictor, A. and Chandrasekar, C V, “Model-based systems engineering of the aft collision assist advanced driver assistance system,” SAE Int. J. Passen. Veh. Syst., vol. 16, no. 3, doi:10.4271/15-16-03-0012, Feb. 2023. [Online]. Available: www.sae.org.

10. Basa, I. and Rictor, A., “Engineering Development and Post-Development of a new Advanced Driver Assistance System: The Defensive Crash Avoidance System,” Course Project at Colorado State University, Fort Collins, Dec. 2019.

11. Basa, I. and Rictor, A., “Systematic Overview and Operational Analysis of Advanced Driver Assistance Systems,” Course Project at Colorado State University, Fort Collins, Oct. 2019.

12. Basa, I. and Rictor, A., “System Engineering of the Defensive Crash Avoidance System (DCAS),” Course Presentation at Colorado State University, Fort Collins, Dec. 2019.

13. Teschler, L., "The basics of automotive radar," Design World, Nov. 2019, accessed March 2022, www.designworldonline.com.

14. Yeong, D., Velasco-Hernandez, G., Barry, J. and Walsh, J., "Sensor and Sensor Fusion Technology in Autonomous Vehicles: A Review," Sensors 2021, 21(6), 2140, doi.org/10.3390/s21062140.

15. Shahian Jahromi, B., Tulabandhula, T. and Cetin, S., "Real-Time Hybrid Multi-Sensor Fusion Framework for Perception in Autonomous Vehicles," Sensors 2019, 19(20), 4357, doi.org/10.3390/s19204357.

16. Wardlaw, C., "How Does Forward Collision Warning Work?," Kelly Blue Book, Aug. 2021, accessed March 2022, www.kbb.com.

17. Reports, C., "Guide to Adaptive Cruise Control How this convenience feature works to reduce your stress on long drives," Consumer Reports, updated May 2022, accessed March 2022, consumerreports.org.

18. Krishnan, H., Gibb, S., Steinfeld, A. and Shladover, S., "Rear-End Collision–Warning System Design and Evaluation via Simulation," Committee on Vehicle User Characteristics, accessed March 2022, www.cs.cmu.edu.

19. Chen, Y., Chiu, S. and Hsiau, S., 2019, "Safe Technology with a Novel Rear Collision Avoidance System of Vehicles," *International Journal of Automotive Technology*, no. 20 (2019): 693-699, doi.org/10.1007/s12239-019-0065-0

20. Volvocars.com, "Rear Collision Warning | Rear Collision Warning | Driver support | XC90 2019 Late | Volvo Support," Volvo Support, accessed March 2022, www.volvocars.com.

21. Volvocars.com, "Rear Collision Warning* | Rear Collision Warning | Driver support | XC40 2020 Late | Volvo Support," Volvo Support, accessed March 2022, www.volvocars.com.

22. Volvocars.com, "Rear Collision Warning* | Rear Collision Warning | Driver support | XC60 2020 Early | Volvo Support," Volvo Support, accessed March 2022, www.volvocars.com.

23. Findlaw.com, "Alabama Code Title 32. Motor Vehicles and Traffic 32-5-241," Findlaw, accessed March 2022, codes.findlaw.com

24. Findlaw.com, "Alabama Code Title 32. Motor Vehicles and Traffic 32-5-240," Findlaw, accessed March 2022, codes.findlaw.com

25. Juneau, AK Code of Ordinances, "Article III: Lighting," AK Code of Ordinances Chapter 72 Section 04.

26. Casetext.com, "13 Alaska Admin. Code 04.035," casetext, accessed Feb. 2022, casetext.com.

27. Findlaw.com, "Arizona Revised Statutes Title 28. Transportation § 28-939. Signal lamps and devices," Findlaw, accessed Feb. 2022, codes.findlaw.com.

28. Law.Justia.com,"2010 Arkansas Code Title 27 – Transportation Subtitle 3- Motor Vehicles And Their Equipment Chapter 36 – Lighting Regulations Sub chapter 2 - Lighting Requirements Generally § 27-36-215 - Tail lamps and reflectors," Justia Law, accessed Feb. 2022, law.justia.com.

29. Law.Justia.com,"2010 Arkansas Code Title 27 – Transportation Subtitle 3 - Motor Vehicles And Their Equipment Chapter 36 - Lighting Regulations Sub chapter 2 - Lighting Requirements Generally § 27-36-216 - Signal lamps and signal devices," Justia Law, accessed Feb. 2022, law.justia.com.

30. Leginfo.legislature.ca.gov, "California Legislative Information Code Section VEH 24603," Legislative Information Code Section, accessed February 2022, leginfo.legislature.ca.gov.

31. Leginfo.legislature.ca.gov, "California Legislative Information Code Section VEH 24606," Legislative Information Code Section, accessed Feb. 2022, leginfo.legislature.ca.gov.

32. Coloradospringssports.org, "Colorado Revised Statutes 2018 Title 42 Vehicles and Traffic," CRS 2018 Title 42, accessed March 2022, www.coloradospringssports.org.

33. OLR Research Report, "OLR Research Report RE: Motor Vehicle Brake Lights," The Connecticut General Assembly, accessed Feb. 2022, www.cga.ct.gov.

34. Law.Justia.com,"2012 Connecticut General Statutes Title 14 - Motor Vehicles. Use of The Highway By Vehicles. Gasoline Chapter 246 – Motor Vehicles Section 14-96p - Color of lights. Flashing or revolving lights. Authorized use of blue or green lights," Justia Law, accessed Feb. 2022, law.justia.com/.

35. CGA.CT.gov, "Sec. 14-96e. Stop lamps. Turn signals," Connecticut General Assembly, accessed Feb. 2022, www.cga.ct.gov.

36. Law.Justia.com,"2017 Delaware Code Title 21- Motor Vehicles CHAPTER 43. EQUIPMENT AND CONSTRUCTION OF VEHICLES Subchapter II Lights § 4353. Special restrictions on lamps," Justia Law, accessed March 2022, law.justia.com.

37. Casetext.com, "Fla. Stat. 316.222," casetext, accessed March 2022, casetext.com.

38. Casetext.com, "Fla. Stat. 316.234," casetext, accessed March 2022, casetext.com.

39. Casetext.com, "Fla. Stat. 316.235," casetext, accessed March 2022, casetext.com.

40. Findlaw.com, "Georgia Code Title 40. Motor Vehicles and Traffic," Findlaw, accessed Feb. 2022, codes.findlaw.com.

41. Law.Justia.com,"2013 Hawaii Revised Statutes TITLE 17. MOTOR AND OTHER VEHICLES 291. Traffic Violations 291-31 Tail lights on vehicles, motorcycles and motor scooters," Justia Law, accessed Feb. 2022, law.justia.com.

42. Legislature.idaho.gov, "TITLE 49 MOTOR VEHICLES CHAPTER 9 VEHICLE EQUIPMENT 49-906," Idaho Statutes, accessed Feb. 2022, legislature.idaho.gov.

43. Legislature.idaho.gov, "TITLE 49 MOTOR VEHICLES CHAPTER 9 VEHICLE EQUIPMENT 49-908," Idaho Statutes, accessed Feb. 2022, legislature.idaho.gov.

44. Law.Justia.com,"625 ILCS 5/ Ch.12 Art. II heading ARTICLE II. LIGHTS AND LAMPS," Justia Law, accessed Feb. 2022, law.justia.com.

45. Findlaw.com, "Indiana Code Title 9. Motor Vehicles 9-19-6-7," Findlaw, accessed Feb. 2022, codes.findlaw.com.

46. Legis.iowa.gov, "Chapter 321 Motor Vehicles and Law of the Road," Iowa Legislature Docs, accessed Feb. 2022, www.legis.iowa.gov.

47. Findlaw.com, "Kansas Statutes Chapter 8. Automobiles and Other Vehicles 8-1706. Tail lamps," Findlaw, accessed Feb. 2022, codes.findlaw.com.

48. Findlaw.com, "Kansas Statutes Chapter 8. Automobiles and Other Vehicles 8-1721. Stop lamps and signal lamps; color; visibility," Findlaw, accessed Feb. 2022, codes.findlaw.com.

49. Casetext.com, "Ky. Rev. Stat. 189.055," casetext, accessed Feb. 2022, casetext.com.

50. Casetext.com, "Ky. Rev. Stat. 189.050,", casetext, accessed Feb. 2022, casetext.com.

51. Apps.legislature.ky.gov, "189.040 Front Lights – Flashing Lights," KY Legislature, accessed Feb. 2022, apps.legislature.ky.gov.

52. Law.Justia.com,"2011 Louisiana Laws Revised Statutes TITLE 32 — Motor vehicles and traffic regulation RS 32:319 — Signal lamps and signal devices," Justia Law, accessed Feb. 2022, law.justia.com.

53. Law.Justia.com,"2011 Louisiana Laws Revised Statutes TITLE 32 — Motor vehicles and traffic regulation RS 32:320 — Additional lighting equipment," Justia Law, accessed February 2022, law.justia.com.

54. Law.Justia.com,"2011 Louisiana Laws Revised Statutes TITLE 32 — Motor vehicles and traffic regulation RS 32:327 — Special restrictions on lamps," Justia law, accessed Feb. 2022, law.justia.com.

55. Mainelegislature.gov, "1905-B. Brake lights," Maine Legislature, accessed March 2022, www.mainelegislature.org.

56. Mainelegislature.gov, “1905-A. Turn signal,” Maine Legislature, accessed March 2022, www.mainelegislature.org.

57. Mainelegislature.gov, “1905. Rear lights,” Maine Legislature, accessed March 2022, www.mainelegislature.org.

58. Law.Justia.com,“2010 Maryland Code TRANSPORTATION TITLE 22 - VEHICLE LAWS – EQUIPMENT OF VEHICLES Subtitle 2 - Lamps and Other Lighting Equipment Section 22-206 - Stop lamps and turn signals,” Justia Law, accessed Feb. 2022, law.justia.com.

59. Law.Justia.com,“2015 Maryland Code TRANSPORTATION Title 22 - VEHICLE LAWS EQUIPMENT OF VEHICLES Subtitle 2 - LAMPS AND OTHER LIGHTING EQUIPMENT § 22-221 - Additional lighting equipment,” Justia Law, accessed Feb. 2022, law.justia.com.

60. Govt.westlaw.com, “22-219. Stop lamps and turn signal devices,” Westlaw.com, accessed March 2022, govt.westlaw.com.

61. Mass.gov, “540 CMR 22.00: Miscellaneous motor vehicle and trailer equipment and operations requirements,” Mass.gov, accessed March 2022, www.mass.gov.

62. Revisor.mn.gov, “Chapter 169. Traffic Regulations,” 2021 Minnesota Statutes, accessed March 2022, revisor.mn.gov.

63. Unicourt.github.io, ”Title 63. Motor Vehicles and Traffic Regulations,” accessed March 2022, unicourt.github.io.

64. Casetext.com, “Mo. Rev. Stat. 307.085,” casetext, accessed February 2022, casetext.com.

65. Leg.mt.gov, “61-9-206. Stop lamps -- when required,” Montana Code Annotated 2021, accessed March 2022, leg.mt.gov.

66. Leg.mt.gov, “61-9-219. Additional lighting equipment,” Montana Code Annotated 2021, accessed March 2022, leg.mt.gov.

67. Nebraskalegislature.gov, “60-6-226. Brake and turn signal light requirements; exceptions; signaling requirements,“ Nebraska Legislature, accessed March 2022, nebraskalegislature.gov.

68. Dmv.nv.gov, “Motor Vehicle Equipment Requirements,” Nevada DMV, accessed Feb. 2022, dmv.nv.gov.

69. Law.Justia.com, “2015 New Hampshire Revised Statutes Title XXI - MOTOR VEHICLES Chapter 266 – EQUIPMENT OF VEHICLES Section 266:38 - Stop Lamps,” Justia Law, accessed March 2022, law.justia.com.

70. Lawserver.com, "New Hampshire Revised Statutes 266:41 – Backup Lamps," Law Server, accessed March 2022, www.lawserver.com.

71. Findlaw.com, "New Jersey Statutes Title 39. Motor Vehicles and Traffic Regulation," Findlaw, accessed March 2022, codes.findlaw.com.

72. Law.Justia.com,"2011 New Mexico Statutes Chapter 66: Motor Vehicles Article 3: Registration Laws; Security Interests; Anti-Theft Provisions; Bicycles; Equipment; Unsafe Vehicles; Off-Highway Motor Vehicles; Other Vehicles, 66-3-1 through 66-3-1103 Section 66-3-828: Signal lamps and signal devices," Justia Law, accessed March 2022, law.justia.com.

73. Findlaw.com, "New York Consolidated Laws, Vehicle and Traffic Law - VAT § 375. Equipment," Findlaw, accessed March 2022, codes.findlaw.com.

74. Findlaw.com, "North Carolina General Statutes Chapter 20. Motor Vehicles § 20-129.Required lighting equipment of vehicles," Findlaw, accessed March 2022, codes.findlaw.com.

75. Findlaw.com, "North Carolina General Statutes Chapter 20. Motor Vehicles § 20-130.3. Use of white or clear lights on rear of vehicles prohibited; exceptions," Findlaw, accessed March 2022, codes.findlaw.com.

76. Casetext.com, "N.D. Cent. Code § 39-21-06.1," casetext, accessed March 2022, casetext.com.

77. Casetext.com, "N.D. Cent. Code § 39-21-19," casetext, accessed March 2022, casetext.com.

78. Codes.ohio.gov, "Section 4513.071| Stop Light," Ohio.gov, accessed March 2022, codes.ohio.gov.

79. Oksenate.gov, "Oklahoma Statutes Title 47. Motor Vehicles," oksenate.gov, accessed March 2022, oksenate.gov.

80. Oregon.gov, "Chapter 816 Vehicle Equipment: Lights," Oregon.gov, accessed Feb. 2022, www.oregon.gov.

81. Law.cornell.edu, "67 Pa. Code § 175.125 - Lighting and electrical systems," Cornell.edu, accessed March 2022, www.law.cornell.edu.

82. Findlaw.com, "Pennsylvania Statutes Title 75 Pa.C.S.A. Vehicles § 4303. General lighting requirements," Findlaw, accessed March 2022, codes.findlaw.com.

83. Findlaw.com, "Rhode Island General Laws Title 31. Motor and Other Vehicles § 31-24-31. Flashing lights--Forward viewing or rotary beam lights," Findlaw, accessed March 2022, codes.findlaw.com.

84. Law.justia.com,“2013 Rhode Island General Laws Title 31 – Motor and Other vehicles Chapter 31-24 Lighting Equipment and Reflectors Section 31-24-7 - Tail lamps required,” Justia Law, accessed March 2022, law.justia.com.

85. Law.justia.com,“2017 South Carolina Code of Laws Title 56 – Motor Vehicles CHAPTER 5 UNIFORM ACT REGULATING TRAFFIC ON HIGHWAYS,” Justia Law, accessed March 2022, law.justia.com.

86. Sdlegislature.gov, “32-17-8.1. Stop lamps required – Mounting – Visibility – Violation as petty offense,” sdlegislature.gov, accessed March 2022, sdlegislature.gov.

87. Casetext.com, “Tenn. Code § 55-9-402,” casetext, accessed March 2022, casetext.com.

88. Dps.texas.gov, “Lighting,” Texas.gov, accessed March 2021, www.dps.texas.gov.

89. Lawserver.com, “Utah Code 41-6a-1601. Operation of unsafe or improperly equipped vehicles on public highways — Exceptions,” Law Server, accessed March 2022, www.lawserver.com.

90. Legislature.vermont.gov, “The Vermont Statutes Online: Title 23 : Motor Vehicles Chapter 013 : Operation Of Vehicles Subchapter 014: Equipment 1243. Lights,” Vermont Legislature, accessed Feb. 2022, legislature.vermont.gov.

91. Legislature.vermont.gov, “The Vermont Statutes Online: Title 23: Motor Vehicles Chapter 013: Operation Of Vehicles Subchapter 014: Equipment 1248. Taillights,” Vermont Legislature, accessed Feb. 2022, legislature.vermont.gov.

92. Vacode.org, “ 46.2-1020 Other permissible lights,” Virginia Code, accessed Feb. 2022, https://vacode.org.

93. Law.lis.virginia.gov, “46.2-1014. Brake lights,” Virginia.gov, accessed Feb. 2022, law.lis.virginia.gov.

94. App.leg.wa.gov, “Chapter 46.37 RCW VEHICLE LIGHTING AND OTHER EQUIPMENT,” Washington State Legislature, accessed Feb. 2022, app.leg.wa.gov.

95. Wvlegislature.gov, “CHAPTER 17C. TRAFFIC REGULATIONS AND LAWS OF THE ROAD. ARTICLE 15. EQUIPMENT.17C-15-18. Signal lamps and signal devices,” West Virginia Legislature, accessed Feb. 2022, www.wvlegislature.gov.

96. Docs.legis.wisconsin.gov, “347.14 Stop lamps,” Wisconsin.gov, accessed March 2022, docs.legis.wisconsin.gov.

97. Law.justia.com, “2021 Wyoming Statutes Title 31 - Motor Vehicles Chapter 5 - Regulation of Traffic on Highways Article 9 – Equipment Section 31-5-931 - Backup and Side Marker Lamps,” Justia Law, accessed Feb. 2022, https://law.justia.com.

98. Legislature.mi.gov, “257.697 Signal lamps or devices; exemption,” Michigan.gov, accessed June 2022, www.legislature.mi.gov.

99. Legislature.mi.gov, “257.686 Rear lamps; exemption; requirements for implement of husbandry; pickup camper,” Michigan.gov, accessed June 2022, www.legislature.mi.gov.

100. Quality Counts, LLC, “Molalla Avenue Volume Counts, Speed Studies, and Classification Studies: Molalla Ave S of Beavercreek Rd 2021 Volume Count,” distributed by Oregon City Public Works, Nov. 2021, accessed July 2023, www.orcity.org.

101. Crownover, D, “ODOT Traffic Monitoring: Transportation Volume Tables 2021,” distributed by Oregon Department of Transportation, 2021, accessed July 2023, www.oregon.gov.

102. Stevens, G, “Average Car Length: All You Need To Know About It,” www.way.com, accessed Sept. 2023, www.way.com.

103. Injury Facts, “Types of Crash,” accessed Sept. 2023, injuryfacts.nsc.org.

104. Bureau of Transportation Statistics, “Average Age of Automobiles and Trucks in Operation in the United States,” www.bts.com, accessed Sept. 2023, www.bts.gov.

105. CARADAS,“ADAS Statistics: BSW, LDW, ACC & LKA,” April 2022, accessed Sept. 2023, caradas.com.

106. Weisbaum, H., “Americans Are Keeping Their Cars Longer than Ever,” Consumers’ Checkbook Magazine, May 2023, accessed Sept. 2023, www.checkbook.org.

107. Injury Facts, “Advanced Driver Assistance Systems-Data Details,” accessed Sept. 2023, injuryfacts.nsc.org.

108. Charette, R., “New Auto Safety Technologies Push Repair Bills up,” Spectrum.ieee.org, IEEE Spectrum, updated Nov. 2018, accessed Sept. 2023, spectrum.ieee.org.

109. Robinson, D., “New vs. Used Car Insurance Comparison: Cheapest Companies,” MarketWatch, updated Sept. 2023, accessed Sept. 2023, www.marketwatch.com.

110. Charlton, C., “Quick ADAS Overview & Reference Guide: Categories, Functionality, History & More,” Auto Vision News, June 2021, accessed Sept. 2023, www.autovision-news.com.

111. Elsagheer, M., Samir, A., et al. “Safe Driving Distance and Speed for Collision Avoidance in Connected Vehicles,” *Sensors*, vol. 22, no. 18, Sept. 2022, p. 7051, accessed Oct. 2023, https://doi.org/10.3390/s2218705.

112. "Federal Motor Vehicle Safety Standards," *Www.govinfo.gov*, Dec. 1971, accessed Oct. 2023, www.govinfo.gov.

113. Queensland Government. "Stopping Distances: Speed and Braking | Transport and Motoring | Queensland Government," *Qld.gov.au*, Nov. 2016, accessed Oct. 2023, www.qld.gov.au.

114. Olejnik, K., "Permissible Distance – Safety System of Vehicles in Use," *De Gruyter*, De Gruyter Open Access, Jan. 2021, accessed Oct. 2023, www.degruyter.com.

115. "Stopping Distances," *Brake*, accessed Oct. 2023, www.brake.org.uk.

116. Salinger G., Span T., Chatterjee R., Jepson J., and Daily J., "A Demonstration of MBSEsec Applied to Securing Cyber-Physical System Communications," *IEEE Aerospace Conference,* 2-9, March 2024, accessed April 2024.

117. Abuabed Z., Alsadeh A., and Taweel A., "STRIDE threat model-based framework for assessing the vulnerabilities of modern vehicles," *Computers & Security*, 133 (2023), 103391, accessed April 2024, https://doi.org/10.1016/j.cose.2023.103391.

118. "ISO/SAE 21434:2021 Road Vehicles – Cybersecurity Engineering," *iso.org*, August 2021, accessed April 2024, https://www.iso.org/standard/70918.html.

119. Rictor A. and Chandrasekar V., "Modeling and Analysis of the Aft Collision Assist Advanced Driver Assistance System," *IEEE International Conference on Digital Twins & Parallel Intelligence 2024*, Oct. 2024 .

120. Continental, "Short Description ARS 408-21 Long Range Radar Sensor 77 GHz," XR-2020-001, pp. 6, Dec. 2020, v 2.1, accessed Oct. 2023.

121. Continental, "Standard Radar Interface Technical Documentation ARS 408-21," pp. 56 – 57, Oct. 2019, v 1.12, accessed Oct. 2023.

122. Continental, "Standard Radar Interface Technical Documentation ARS 408-21," pp. 28, Oct. 2019, v 1.12, accessed Oct. 2023.

123. Flashing Light - International Dictionary of Marine Aids to Navigation, "Flashing Light," www.iala-aism.org, accessed Sept. 2024.

124. Law Insider, "Flashing light definition: 158 samples," www.lawinsider.com, accessed Sept. 2024.

Appendix 1: Individual State Lighting Regulations and Statutes

Table A1: Individual State Lighting Regulations and Statutes

State	Lighting Statutes/Regulations	ACA Compliant?
Alabama [23, 24]	**(1)** Flashing lights may be used on motor vehicles as a means of indicating a right or left turn; a stop lamp may pulsate with different intensities provided that it meets at all intensities the provisions of subdivision (2) of subsection (b) of this section; and the warning lights on emergency vehicles may flash. **(2)** Any motor vehicle may be equipped with not more than two back-up lamps either separately or in combination with other lamps, but any such back-up lamp shall not be lighted when the motor vehicle is in forward motion.	Yes
Alaska [25, 26]	**(1)** Except as otherwise provided in this chapter, a vehicle must be equipped with two or more stop lights meeting the requirements of subsection (b) of this section, except that passenger cars manufactured or assembled before January 1, 1958, must be equipped with at least one stop light. On a combination of vehicles, only the stop lights on the rearmost vehicle need actually be seen from the distance specified in subsection(b) of this section. **(2)** The stop lights required in subsection (a) of this section must be mounted on the rear of the vehicle and must display a red light, or a shade of red, visible from a distance of at least 300 feet to the rear in normal sunlight. The lights must be illuminated by application of the service or foot brake.	Tentatively
Arizona [27]	**(1)** A motor vehicle may be equipped and if required under this article shall be equipped with the following: a) A stop lamp on the rear that emits a red or yellow light, that is actuated on application of the service or foot brake and that may be incorporated with a tail lamp. b) One or more lamps or a mechanical signal device that is capable of clearly indicating an intention to turn either to the right or to the left and that is visible both from the front and rear. **(2)** A stop lamp shall be plainly visible and understandable from a distance of one hundred feet to the rear both during normal	Tentatively

	sunlight and at nighttime. A signal lamp or lamps indicating the intention to turn shall be visible and understandable during daytime and nighttime from a distance of one hundred feet both to the front and rear. If a vehicle is equipped with a stop lamp, tail lamp or other signal lamp, each lamp shall: a) Be maintained at all times in good working condition. b) Not project a glaring or dazzling light. **(3)** A mechanical signal device shall be self-illuminated when in use at the times provided in section 28-922.	
Arkansas [28, 29]	**(1)** Any motor vehicle may be equipped, and when required under this subchapter shall be equipped, with a stop lamp or lamps on the rear of the vehicle which shall display a red or amber light, or any shade of color between red and amber, visible from a distance of not less than one hundred feet (100') to the rear in normal sunlight. **(2)** They shall be actuated upon application of the service or foot brake, which may, but need not, be incorporated with one (1) or more other rear lamps. **(3)** The lamps showing to the rear shall be located at the same level and as widely spaced laterally as practicable and when in use shall display a red or amber light, or any shade of color between red and amber, visible from a distance of not less than one hundred feet (100') to the rear in normal sunlight. **(4)** No stop lamp or signal lamp shall project a glaring light.	Tentatively
California [30, 31]	**(1)** Stop lamps shall be activated upon application of the service (foot) brake and the hand control head for air, vacuum, or electric brakes. In addition, all stop lamps may be activated by a mechanical device designed to function only upon sudden release of the accelerator while the vehicle is in motion. Stop lamps on vehicles equipped with a manual transmission may be manually activated by a mechanical device when the vehicle is downshifted if the device is automatically rendered inoperative while the vehicle is accelerating. **(2)** All stop lamps shall be plainly visible and understandable from a distance of 300 feet from the rear of the vehicle both during normal sunlight and at nighttime, except that stop lamps on a vehicle of a size required to be equipped with	Tentatively

	clearance lamps shall be visible from a distance of 500 feet from the rear of the vehicle during those times. **(3)** Backup lamps shall not be lighted except when the vehicle is about to be or is backing or except in conjunction with a lighting system which activates the lights for a temporary period after the ignition system is turned off.	
Colorado [32]	**(1)** Any motor vehicle may be equipped, and when required under this article shall be equipped, with a stop lamp or lamps on the rear of the vehicle which, EXCEPT AS PROVIDED IN SECTION 42-4-215.5, shall display a red or amber light, or any shade of color between red and amber, visible from a distance of not less than one hundred feet to the rear in normal sunlight, and which shall be actuated upon application of the service (foot) brake, and which may but need not be incorporated with one or more other rear lamps. Such stop lamp or lamps may also be automatically actuated by a mechanical device when the vehicle is reducing speed or stopping. If two or more stop lamps are installed on any motor vehicle, any device actuating such lamps shall be so designed and installed that all stop lamps are actuated by such device. **(2)** Any vehicle may be equipped with lamps which may be used for the purpose of warning the operators of other vehicles of the presence of a vehicular traffic hazard requiring the exercise of unusual care in approaching, overtaking, or passing and, when so equipped and when the said vehicle is not in motion or is being operated at a speed of twenty-five miles per hour or less and at no other time, may display such warning in addition to any other warning signals required by this article. The lamps used to display such warning to the front shall be mounted at the same level and as widely spaced laterally as practicable and shall display simultaneously flashing white or amber lights, or any shade of color between white and amber. The lamps used to display such warning to the rear shall be mounted at the same level and as widely spaced laterally as practicable and, EXCEPT AS PROVIDED IN SECTION 42-4-215.5, shall show simultaneously flashing amber or red lights, or any shade of color between amber and red. These warning lights shall be visible from a distance of not less than five hundred feet under normal atmospheric conditions at night.	Tentatively
Connecticut [33, 34, 35]	**(1)** One law requires vehicles to have stop lights that activate when the service or foot brake is applied. These lights must	Tentatively

	be displayed on the vehicle. These vehicle's rear and must be colored red, amber, or a shade between those two colors (CGS § 14-96r). rear There are two laws that generally govern the use and color of any type of flashing lights on a motor vehicle. One states that no light other than a red, yellow, amber, or white one may be displayed from the rear of a motor vehicle unless the Department of Motor Vehicles issues a written permit for it. It also specifies that certain kinds of vehicles such as those operated by fire departments, emergency medical services organizations, volunteer fire personnel and some other groups can use regular or flashing lights of certain specific colors (CGS § 14-96p). **(2)** The second law repeats many of these same restrictions with regard to flashing lights only. It prohibits any type of flashing lights on a vehicle with exceptions for turn signals, volunteer fire personnel, emergency and maintenance vehicles under permit, volunteer ambulance personnel, and ambulances. It also allows flashing or revolving yellow lights for rural mail carriers and escorts for oversized vehicles and loads traveling under special Department of Transportation permits. The law also allows fire police to use flashing red lights on a stationary vehicle while directing traffic at a fire scene. **(3)** Any motor vehicle may be equipped with one or more backup lamps either separately or in combination with other lamps, but any such backup lamp or lamps shall not be lighted when the motor vehicle is in forward motion.	
Delaware [36]	**(1)** Flashing lights are prohibited except on an authorized emergency vehicle, school bus, snow removal equipment, vehicles authorized by the Secretary of Safety and Homeland Security if determined to be in the interest of public safety, or on any vehicle as a means of indicating a right or left turn or the presence of a vehicular hazard requiring unusual care in approaching, overtaking or passing, or when included in a motorcycle, moped, or motorized scooter brake light system in which the brake lamp pulses rapidly for no more than 5 seconds when the brake is applied, and then converts to a continuous light as a normal brake lamp until the time that the brake is released.	Tentatively
Florida [37, 38, 39]	**(1)** Any vehicle may be equipped and, when required under this chapter, shall be equipped with a stop lamp or lamps on the rear of the vehicle which shall display a red or amber light, visible from a distance of not less than 300	Tentatively

	feet to the rear in normal sunlight, and which shall be actuated upon application of the service (foot) brake, and which may but need not be incorporated with one or more other rear lamps. An object, material, or covering that alters the stop lamp's visibility from 300 feet to the rear in normal shall be equipped with electric turn signals which shall indicate an intention to turn by flashing lights showing to the front and rear of a vehicle or on a combination of vehicles on the side of the vehicle or combination toward which the turn is to be made. The lamps showing to the front shall be mounted on the same level and as widely spaced laterally as practicable and, when signaling, shall emit white or amber light. The lamps showing to the rear shall be mounted on the same level and as widely spaced laterally as practicable, and, when signaling, shall emit a red or amber light. Turn signal lamps on vehicles 80 inches or more in overall width shall be visible from a distance of not less than 500 feet to the front and rear in normal sunlight, and an object, material, or covering that alters the lamp's visibility from a distance of 500 feet to the front or rear in normal sunlight may not be placed, displayed, installed, affixed, or applied over a turn signal lamp. Turn signal lamps on vehicles less than 80 inches wide shall be visible at a distance of not less than 300 feet to the front and rear in normal sunlight, and an object, material, or covering that alters the lamp's visibility from a distance of 300 feet to the front or rear in normal sunlight may not be placed, displayed, installed, affixed, or applied over a turn signal lamp. Turn signal lamps may, but need not be, incorporated in other lamps on the vehicle. **(2)** Any motor vehicle may be equipped with one or more backup lamps either separately or in combination with other lamps, but any such backup lamp or lamps shall not be lighted when the motor vehicle is in forward motion.	
Georgia [40]	**(1)** A brake light on the rear which shall emit a red light and which shall be actuated upon application of the service(foot) brake and which may but need not be incorporated with a taillight; and **(2)** A light or lights or mechanical signal device capable of clearly indicating any intention to turn either to the right or to the left and which shall be visible from both the front and the rear.	Tentatively

	(3) Every brake light shall be plainly visible and understandable from a distance of 300 feet to the rear both during normal sunlight and at nighttime, and every signal light or lights indicating intention to turn shall be visible and understandable during daytime and nighttime from a distance of 300 feet from both the front and the rear. When a vehicle is equipped with a brake light or other signal lights, such light or lights shall at all times be maintained in good working condition. No brake light or signal light shall project a glaring or dazzling light.	
Hawaii [41]	**(1)** Steady burning. Must be activated upon application of the service brakes. When optically combined with a turn signal lamp, the circuit must be such that the stop signal cannot be activated if the turn signal lamp is flashing. **(2)** May also be activated by a device designed to retard the motion of the vehicle. **(3)** Steady burning. Must be activated when the ignition switch is energized and reverse gear is engaged. Must not be energized when the vehicle is in forward motion.	Tentatively
Idaho [42, 43]	**(1)** SIGNAL LAMPS AND SIGNAL DEVICES. (1) Any motor vehicle may be equipped and when required under this chapter shall be equipped with stop lamps on the rear of the vehicle which shall display a red or amber light, or any shade of color between red and amber, visible from a distance of not less than one hundred (100) feet to the rear in normal sunlight, and which shall be actuated upon application of the service (foot) brake, and which may but need not, be incorporated with one or more other rear lamps.	Tentatively
Illinois [44]	**(1)** Every vehicle other than an antique vehicle displaying an antique plate or an expanded-use antique vehicle displaying expanded-use antique vehicle plates operated in this State shall be equipped with a stop lamp or lamps on the rear of the vehicle which shall display a red or amber light visible from a distance of not less than 500 feet to the rear in normal sunlight and which shall be actuated upon application of the service (foot) brake, and which may but need not be incorporated with other rear lamps. During times when lighted lamps are not required, an antique vehicle or an expanded-use antique vehicle may be equipped with a stop lamp or lamps on the rear of such vehicle of the same type originally installed by the manufacturer as original equipment and in working order. However, at all other times, except as provided in	Tentatively

	subsection (a-1), such antique vehicle or expanded-use antique vehicle must be equipped with stop lamps meeting the requirements of Section 12-208 of this Act. **(2)** Any motor vehicle may be equipped with one or more back-up lamps either separately or in combination with other lamps which shall emit a white or amber light without glare; but any such back-up lamp or lamps shall not be lighted when the motor vehicle is in forward motion.	
Indiana [45]	**(1)** A motor vehicle may be equipped, and when required under this chapter must be equipped, with a stop lamp or lamps on the rear of the vehicle that: a) Displays only a red light, visible from a distance of not less than one hundred (100) feet to the rear in normal sunlight; b) Will be actuated upon application of the service (foot) brake; and c) May be incorporated with at least one (1) other rear lamp. **(2)** A motor vehicle may be equipped and when required under this chapter must be equipped with lamps or mechanical signal devices showing to the front and rear for the purpose of indicating an intention to turn either to the right or left. If lamps are used for this purpose, the lamps showing to the front must be located on the same level and as widely spaced laterally as practicable and when in use must display only a white or an amber light, or any shade of color between white and amber, visible from a distance of not less than one hundred (100) feet to the front in normal sunlight. The lamps showing to the rear must be located at the same level and as widely spaced laterally as practicable and when in use must display only a red or an amber light, or any shade of color between red and amber, visible from a distance of not less than one hundred (100) feet to the rear in normal sunlight. When actuated the lamps must indicate the intended direction of turning by flashing the lights showing to the front and rear on the side toward which the turn is made. **(3)** Stop lamp or signal lamp or device may not project a glaring light.	Tentatively

	(4) A lighting device mounted on the rear of the vehicle may not display any color other than red except as follows: a) A signal lamp or device must be red or amber or any shade of color between red and amber. b) The light illuminating the license plate must be white. c) The light emitted by a back-up lamp must be white or amber.	
Iowa [46]	**(1)** A flashing light on or in a motor vehicle is prohibited except as follows: a) On a vehicle as a means of indicating a right or left turn, a mechanical failure, or an emergency stop or intent to stop.	Yes
Kansas [47, 48]	**(1)** Any vehicle may be equipped and when required under this act shall be equipped with a stop lamp or lamps on the rear of the vehicle which shall display a red or amber light, or any shade of color between red and amber, visible from a distance of not less than three hundred (300) feet to the rear in normal sunlight, and which shall be actuated upon application of the service or foot brake, and which may, but need not, be incorporated with one (1) or more other rear lamps.	Tentatively
Kentucky [49, 50, 51]	**(1)** A person shall not operate any vehicle required by law to be licensed upon a highway unless it is equipped with a mechanical signal device which would indicate an intention to stop or suddenly decrease speed by illuminating at least two (2) red lights on the rear of the vehicle, which are visible from the rear a distance of not less than five hundred (500) feet, unless the vehicle was originally manufactured with only one (1) such red light on the rear of the vehicle. **(2)** Flashing lights are prohibited on all motor vehicles except as a means for indicating a right or left turn or for the purpose of warning the operators of other vehicles of the presence of a vehicular traffic hazard requiring the exercise of unusual care in approaching, overtaking or passing. **(3)** When in operation between sunset and sunrise on any highway, motor less vehicles, except bicycles and electric low-speed scooters, shall have in operation:	Tentatively

	a) A four (4) way flasher system, with two (2) flashing yellow or amber lights visible from the front of the vehicle for a distance of at least five hundred (500) feet and two (2) flashing red lights visible from the rear of the vehicle for a distance of at least five hundred (500) feet; or b) Two (2) reflective lanterns, one (1) on either side of the rear of the vehicle, showing white to the front of the vehicle and red to the rear of the vehicle, with the lantern on the left side of the vehicle situated at least twelve (12) inches higher than the lantern on the right.	
Louisiana [52, 53, 54]	**(1)** Flashing lights are prohibited except on authorized emergency vehicles, school buses, or on any vehicle as a means of indicating a right or left turn, or the presence of a vehicular traffic hazard requiring unusual care in approaching, overtaking or passing. **(2)** Any motor vehicle may be equipped with not more than two backup lamps either separately or in combination with other lamps, but any such backup lamp shall not be lighted when the motor vehicle is in forward motion. **(3)** Any vehicle may be equipped and when required under this chapter, shall be equipped with a stop lamp or lamps on the rear of the vehicle which shall display a red light, visible from a distance of not less than 300 feet to the rear in normal sunlight, and which shall be actuated upon application of the service (foot) brake, and which may, but need not be, incorporated with one or more other rear lamps.	Tentatively
Maine [55, 56, 57]	**(1)** All factory-installed brake lights or equivalent replacements on a motor vehicle, tiny home, trailer or semitrailer must be present and operating properly and must emit a steady red light when a slight pressure is placed on the brake pedal, and the light emitted must be visible for a distance of at least 100 feet behind the vehicle. For purposes of this section, "steady red light" means a red light that is either immediately constant and not pulsating or that pulsates for a short period and then becomes constant.	Tentatively

	(2) Flash means a cycle of activation and deactivation of a lamp by automatic means continuing until stopped either automatically or manually. **(3)** The stop lamps on each vehicle shall be activated upon application of the service brakes. The high-mounted stop lamp on each vehicle shall be activated only upon application of the service brakes.	
Maryland [58, 59, 60]	**(1)** Backup lamps. -- Any motor vehicle may be equipped with one or more backup lamps, either separately or in combination with other lamps, but any such backup lamp may not be lighted when the motor vehicle is in forward motion. **(2)** Warning lamps -- Permitted. -- Any vehicle may be equipped with lamps used for the purpose of warning the drivers of other vehicles of the presence of a vehicular traffic hazard requiring the exercise of unusual care in approaching, overtaking, or passing, and, when so equipped, may display the warning in addition to any other warning signals required by the Maryland Vehicle Law. **(3)** Warning lamps -- Mounting. -- The lamps used to display this warning to the front shall be mounted at the same level and as widely spaced laterally as practicable and shall display simultaneously flashing white or amber lights, or any shade of color between white and amber. The lamps used to display this warning to the rear shall be mounted at the same level and as widely spaced laterally as practicable and shall display simultaneously flashing amber or red lights, or any shade of color between amber and red. **(4)** Any vehicle may be equipped with and, when required under the Maryland Vehicle Law,1 shall be equipped with a stop lamp or lamps on the rear of the vehicle, which: a) Shall display a red light, visible from a distance of not less than 300 feet to the rear in normal sunlight; b) Shall be actuated on application of the service brake; and c) May, but need not, be incorporated with one or more other rear lamps.	Tentatively

Massachusetts [61]	**(1)** No motor vehicle so operated shall mount or display a flashing, rotating or oscillating light in any direction except pursuant to section seven E of this chapter; provided, however, that this shall not apply to the use of rear directional signals nor to the proper use of vehicle hazard warning signals as provided for by this section.	Tentatively
Michigan [98, 99]	257.686 Rear lamps; exemption; requirements for implement of husbandry; pickup camper. Sec. 686. **1)** A motor vehicle, trailer, semitrailer, pole trailer, or vehicle which is being drawn in a train of vehicles shall be equipped with at least 1 rear lamp mounted on the rear, which, when lighted as required by this act, shall emit a red light plainly visible from a distance of 500 feet to the rear. **2)** Either a tail lamp or a separate lamp shall be constructed and placed so as to illuminate with a white light the rear registration plate and render it clearly legible from a distance of 50 feet to the rear. A tail lamp or tail lamps, together with any separate lamp for illuminating the rear registration plate, shall be wired so as to be lighted whenever the head lamps or auxiliary driving lamps are lighted. 257.697 Signal lamps or devices; exemption. Sec. 697. **3)** A motor vehicle may be equipped and when required under this chapter shall be equipped with the following signal lamps or devices: a) A stop lamp on the rear which shall emit a red or amber light and which shall be actuated upon application of the service or foot brake and which may but need not be incorporated with a tail lamp. b) A lamp or lamps or mechanical signal device which conveys an intelligible signal or warning to another driver approaching from the rear. **4)** A stop lamp shall be capable of being seen and distinguished from a distance of 100 feet to the rear both during normal sunlight and at nighttime and a signal lamp or lamps indicating intention to turn shall be capable of being seen and distinguished during daytime	Tentatively

	and nighttime from a distance of 100 feet both to the front and rear. When a vehicle is equipped with a stop lamp or other signal lamps, the lamp or lamps shall at all times be maintained in good working condition. A stop lamp or signal lamp shall not project a glaring or dazzling light.	
Minnesota [62]	**5)** White light.(a) It is unlawful to project a white light at the rear of a vehicle while traveling on any street or highway, except: a) For a vehicle moving in reverse **6)** Stoplights.(a) Any vehicle may be equipped and when required under this chapter, shall be equipped with at least two stop lamps on the rear which shall emit a red or yellow light and which shall be actuated upon application of the service (foot) brake and which may, but need not be, incorporated with the tail lamps and which shall be plainly visible and understandable from a distance of 100 feet to the rear during normal sunlight and at night.	Tentatively
Mississippi [63]	**(1)** Backing lights of any color may be mounted on the rear of any motor vehicle if the switch controlling such lights be so arranged that they may be turned on only when the vehicle is in reverse gear. Such backing lights when unlighted shall be so colored or otherwise arranged as not to reflect objectionable glare in the eyes of drivers of vehicles approaching from the rear. **(2)** Any lamps illuminated when the vehicle is in motion, other than those expressly required or permitted by the provisions of this chapter, shall, if visible from the front, display a white or amber light; if visible from either side, display an amber light; and if visible from the rear, display a red light. **(3)** Auxiliary white lights mounted on or near the rear of a motor vehicle, or visible from the rear of the vehicle, shall not be prohibited under the provisions of this section if (a) the vehicle's gross weight is less than twelve thousand one (12,001) pounds, and (b) the lights are designed by the motor vehicle manufacturer or an after-market parts manufacturer so that they may only be illuminated whenever the vehicle is not in motion and the transmission of the vehicle is not capable of transmitting power to the wheels.	Tentatively

	(4) Any lamps illuminated when the vehicle is in motion, other than those expressly required or permitted by the provisions of this chapter, shall, if visible from the front, display a white or amber light; if visible from either side, display an amber light; and if visible from the rear, display a red light.	
Missouri [64]	**(1)** Any motor vehicle may be equipped with not more than two side cowl or fender lamps which shall emit a white or yellow light without glare. Any motor vehicle may be equipped with not more than one running board courtesy lamp on each side thereof which shall emit a white or yellow light without glare. Any motor vehicle may be equipped with a backup lamp either separately or in combination with another lamp; except that no such backup lamp shall be continuously lighted when the motor vehicle is in forward motion.	Tentatively
Montana [65, 66]	**(1)** A person may not sell a new motor vehicle in this state or drive a vehicle on the highways unless it is equipped with at least two properly functioning stop lamps. A vehicle manufactured before January 1, 1956, and all motorcycles, quadricycles, and motor-driven cycles must be equipped with at least one properly functioning stop lamp. **(2)** The stop lamp or lamps on the rear of a vehicle must display a red light that is actuated upon application of the service (foot) brake and, in a vehicle manufactured or assembled on or after January 1, 1964, must be visible from a distance of not less than 300 feet to the rear in normal sunlight. In a vehicle manufactured or assembled before January 1, 1964, the stop lamp or lamps must be visible from a distance of not less than 100 feet. The stop lamp may be incorporated with one or more other rear lamps. **(3)** A stop lamp may not project a glaring light. 61-9-219. Additional lighting equipment. **(4)** Any motor vehicle may be equipped with not more than two side cowl or fender lamps which shall emit an amber or white light without glare. **(5)** Any motor vehicle may be equipped with not more than one running board courtesy lamp on each side thereof which shall emit a white or amber light without glare.	Tentatively

	(6) Any motor vehicle may be equipped with not more than two backup lamps either separately or in combination with other lamps, but any such backup lamps shall not be lighted when the motor vehicle is in forward motion. **(7)** Any vehicle may be equipped with lamps which may be used for the purpose of warning the operators of other vehicles of the presence of a vehicular traffic hazard requiring the exercise of unusual care in approaching, overtaking, or passing, and when so equipped may display such warning in addition to any other warning signals required by this chapter. The lamps used to display such warning to the front shall be mounted at the same level and as widely spaced laterally as practicable and shall display simultaneously flashing white or amber lights, or any shade of color between white and amber. The lamps used to display such warning to the rear shall be mounted at the same level and as widely spaced laterally as practicable, and shall show simultaneously flashing amber or red lights, or any shade of color between amber and red. These warning lights shall be visible from a distance of not less than 500 feet under normal atmospheric conditions at night.	
Nebraska [67]	**(1)** Any motor vehicle having four or more wheels which is manufactured or assembled, whether from a kit or otherwise, after January 1, 1954, designed or used for the purpose of carrying passengers or freight, any autocycle, or any trailer, in use on a highway, shall be equipped with brake and turn signal lights in good working order. **(2)** Motorcycles other than autocycles, motor-driven cycles, motor scooters, bicycles, electric personal assistive mobility devices, vehicles used solely for agricultural purposes, vehicles not designed and intended primarily for use on a highway, and, during daylight hours, fertilizer trailers as defined in section 60-326 and implements of husbandry designed primarily or exclusively for use in agricultural operations shall not be required to have or maintain in working order signal lights required by this section, but they may be so equipped. The operator thereof shall comply with the requirements for utilizing hand and arm signals or for utilizing such signal lights if the vehicle is so equipped.	Tentatively
Nevada [68]	Stop Lamps: **(1)** Mounted on the rear of the vehicle	Tentatively

	(2) Display a red, amber or yellow light **(3)** Visible from at least 300 to the rear in normal sunlight **(4)** Be activated upon application of the brake **(5)** May be incorporated with the tail lamp **(6)** *Vehicles manufactured before July 1, 1969 must have at least one stop lamp if they were originally equipped with only one stop lamp	
New Hampshire [69, 70]	**(1)** It shall be unlawful for any person to drive any motor vehicle, including any motorcycle, moped or motor-driven cycle, full trailer, trailer, or semi-trailer in this state unless it is equipped with one or more stop lamps in working order at all times; provided, however, that stop lamps shall not be required on a farm tractor, and further provided that whenever a vehicle is manufactured with multiple stop lamps or stop lamps with multiple bulbs or filaments, each of the lamps, bulbs, or filaments shall be in working order. **(2)** Any motor vehicle may be equipped with back-up lamps either separately or in combination with other lamps. Such back-up lamps shall not be lighted when the motor vehicle is in forward motion.	
New Jersey [71]	**(1)** No vehicle shall be equipped with and no person shall use upon any vehicle any flashing lights except as a means for indicating right or left turns or for the purpose of warning of the presence of a vehicular traffic hazard; provided, however, that a vehicle may be equipped with flashing lights of a type approved by the Chief Administrator if it falls into one of the categories of vehicles set forth in 13:24-2.1(a)1 to 5 or as otherwise provided in this chapter. **(2)** All lights visible from the front of the car must be white or amber. **(3)** All lights visible from the front sides of the car must be amber. **(4)** All lights visible from the back or near back of the car must be red.	Tentatively

	(5) License plate illumination must be white. **(6)** No flashing lights may be used.	
New Mexico [72]	**(1)** Any motor vehicle, trailer, semitrailer and house trailer may be equipped and when required under Sections 66-3-801 through 66-3-887 NMSA 1978 shall be equipped with the following signal lamps or devices: a) Stop lamp or stop lamps on the rear which shall emit a red, amber or yellow light and which shall be actuated upon application of the service brakes and which may but need not be incorporated with one or more other rear lamps; and b) Lamp or lamps or mechanical signal device capable of clearly indicating any intention to turn either to the right or to the left and which shall be visible both from the front and rear. **(2)** Every stop lamp shall be plainly visible and understandable from a distance of one hundred feet to the rear both during normal sunlight and at nighttime and a signal lamp or lamps indicating intention to turn shall be visible and understandable during daytime and nighttime from a distance of one hundred feet both to the front and rear. When a vehicle is equipped with a stop lamp or other signal lamps, such lamp or lamps shall at all times be maintained in good working condition. No stop lamp or signal lamp shall project a glaring or dazzling light. **(3)** All mechanical signal devices shall be self-illuminated when in use at the times mentioned in Section 66-3-802 NMSA 1978.	Tentatively
New York [73]	**(1)** Stop lamps. (a) Every motor vehicle, except a motorcycle, operated or driven upon the public highways of the state, if manufactured prior to January first, nineteen hundred fifty-two, shall be equipped with at least one stop lamp which shall display a red to amber light visible at least five hundred feet from the rear of the vehicle when the brake of such vehicle is applied. **(2)** Colored and flashing lights. The provisions of this subdivision shall govern the affixing and display of lights on vehicles, other than those lights required by law.	Tentatively

	(3) No light, other than a white light, and no revolving, rotating, flashing, oscillating or constantly moving white light shall be affixed to, or displayed on any vehicle except as prescribed herein. **(4)** Red lights and certain white lights. One or more red or combination red and white lights, or one white light which must be a revolving, rotating, flashing, oscillating or constantly moving light, may be affixed to an authorized emergency vehicle, and such lights may be displayed on an authorized emergency vehicle when such vehicle is engaged in an emergency operation, and upon a fire vehicle while returning from an alarm of fire or other emergency. **(5)** Any motor vehicle may be equipped with and every passenger vehicle registered in this state and manufactured or assembled after January first, nineteen hundred sixty-nine, shall be equipped with at least one back-up light. Such light shall display a white light to the rear when the ignition switch is energized and reverse gear is engaged. Such light shall not be lighted when the motor vehicle is in forward motion.	
North Carolina [74, 75]	**(1)** No person shall sell or operate on the highways of the State any motor vehicle manufactured after December 31,1955, and on or before December 31, 1970, unless it shall be equipped with a stop lamp on the rear of the vehicle. No person shall sell or operate on the highways of the State any motor vehicle, manufactured after December 31, 1970,unless it shall be equipped with stop lamps, one on each side of the rear of the vehicle. No person shall sell or operate on the highways of the State any motorcycle or motor-driven cycle, manufactured after December 31, 1955, unless it shall be equipped with a stop lamp on the rear of the motorcycle or motor-driven cycle. The stop lamps shall emit, reflect, or display a red or amber light visible from a distance of not less than 100 feet to the rear in normal sunlight, and shall be actuated upon application of the service (foot) brake. The stop lamps may be incorporated into a unit with one or more other rear lamps. **(2)** Backup Lamps.--Every motor vehicle originally equipped with white backup lamps shall have those lamps in operating condition.	Tentatively

	(3) Use of white or clear lights on rear of vehicles prohibited; exceptions. It shall be unlawful for any person to willfully drive a motor vehicle in forward motion upon the highways of this State displaying white or clear lights on the rear of said vehicle. The provisions of this section shall not apply to the white light required by G.S. 20-129(d) or so-called backup lights lighted only when said vehicle is in reverse gear or backing. Violation of this section does not constitute negligence per se in any Civil action. (1973, c. 1071.)	
North Dakota [76, 77]	**(1)** Any motor vehicle may be equipped and when required under this chapter must be equipped with a stop lamp or lamps on the rear of the vehicle which shall display a red light visible from a distance of not less than three hundred feet [91.44 meters] to the rear in normal sunlight, and which shall be actuated upon application of the service (foot) brake, and which may, but need not, be incorporated with one or more other rear lamps. **(2)** Any motor vehicle may be equipped with one or more backup lamps either separately or in combination with other lamps, but the backup lamp or lamps may not be lighted when the vehicle is in a forward motion. **(3)** Any vehicle may be equipped with one or more side marker lamps which may be flashed in conjunction with turn signals or vehicular hazard warning signals.	Tentatively
Ohio [78]	**(1)** Stop lights shall be mounted on the rear of the vehicle, actuated upon application of the service brake, and may be incorporated with other rear lights. Such stop lights when actuated shall emit a red light visible from a distance of five hundred feet to the rear, provided that in the case of a train of vehicles only the stop lights on the rear-most vehicle need be visible from the distance specified. **(2)** Such stop lights when actuated shall give a steady warning light to the rear of a vehicle or train of vehicles to indicate the intention of the operator to diminish the speed of or stop a vehicle or train of vehicles.	Tentatively
Oklahoma [79]	Stop lamps: **(1)** Every vehicle shall be equipped with at least two stop lamps which shall meet the requirements of this section. **(2)** The stop lamps required by this section:	Tentatively

	a) Shall be mounted on the rear of the vehicle at the same level, as far apart as practicable, and at a height of not more than seventy-two (72) inches nor less than fifteen (15) inches; b) Shall display a red or amber light, or any shade of color between red and amber, visible from a distance of not less than five hundred (500) feet to the rear in normal sunlight; and c) Shall be actuated upon application of the brakes. Back-up and vehicular hazard warning lamps: **(3)** Any motor vehicle shall be equipped with not more than two back-up lamps either separately or in combination with other lamps. **(4)** Any back-up lamp shall not be lighted when the motor vehicle is in forward motion.	
Oregon [80]	**(1)** Except as provided in subsection (11) of this section, brake lights shall emit a steady burning light. **(2)** Brake lights shall be activated upon application of the service brake.	Tentatively
Pennsylvania [81, 82]	**(1)** Back-up lamps. Back-up lamps, if the vehicle is so equipped, shall turn off automatically when the vehicle goes forward. **(2)** Other required lamps. A trailer shall have at least one red stop lamp on each side of the rear of the vehicle, which shall be illuminated immediately upon application of the service brake.	Tentatively
Rhode Island [83, 84]	**(1)** Flashing lights are prohibited, except on an authorized emergency vehicle, school bus, snow removal equipment, or on any vehicle as a means for indicating a right or left turn. **(2)** Tail lamps required. – Every motor vehicle, trailer, semi-trailer, and pole trailer, and any other vehicle which is being drawn at the end of a train of vehicles, shall be equipped with at least one tail lamp mounted on the rear, which when lighted as required in this chapter, shall emit a red light plainly visible from a distance of five hundred feet (500') to the rear, provided that in the case of a train	Tentatively

	of vehicles only the tail lamp on the rearmost vehicle need actually be seen from the distance specified. Violations of this section are subject to fines enumerated in § 31-41.1-4.	
South Carolina [85]	**(1)** Any motor vehicle may be equipped with not more than two back-up lamps either separately or in combination with other lamps, but any such back-up lamp shall not be lighted when the motor vehicle is in forward motion. **(2)** A stop lamp on the rear which shall emit a red or yellow light and which shall be actuated upon application of the service (foot) brake and which may but need not be incorporated with a tail lamp	Tentatively
South Dakota [86]	**(1)** Except for a vehicle equipped with a slow-moving vehicle emblem in compliance with §§ 32-15-20 and 32-15-21, each motor vehicle, trailer, semitrailer, and pole trailer shall be equipped with at least two stop lamps with at least one on each side. The side stop lamps shall be mounted on the same level and as widely spaced laterally as practicable. However, each motor vehicle, trailer, semitrailer, and pole trailer manufactured and assembled before July 1, 1973, and each motorcycle and motor-driven cycle shall be equipped with at least one stop lamp. A stop lamp shall be mounted on the rear of the vehicle at a height of no more than seventy inches nor less than fifteen inches. Each stop lamp shall display a red light visible from a distance of not less than three hundred feet to the rear in normal sunlight, except for a moped, which shall be visible from a distance of not less than one hundred fifty feet. Each stop lamp shall be actuated upon application of the brake which may be incorporated with one or more rear lamps. A violation of this section is a petty offense.	Tentatively
Tennessee [87]	**(1)** A white backup light operates when the motor vehicle is in reverse. **(2)** Every motor vehicle shall be equipped with two (2) red tail lamps and two (2) red stoplights on the rear of the vehicle, and one(1) tail lamp and one (1) stoplight shall be on each side, except that passenger cars manufactured or assembled prior to January1, 1939, trucks manufactured or assembled prior to January 1, 1968, and motorcycles and motor-driven cycles shall have at least one (1) red tail lamp and one (1) red stoplight. No nonemergency vehicle shall operate or install emergency flashing light systems such as strobe, wig-wag, or other flashing lights in tail light lamp, stoplight area, or factory	Tentatively

	installed emergency flasher and backup light area; provided, however, that the foregoing prohibition shall not apply to the utilization of a continuously flashing light system. For the purposes of this part, “continuously flashing light system” means a brake light system in which the brake lamp pulses rapidly for no more than five (5) seconds when the brake is applied, and then converts to a continuous light as a normal brake lamp until the time that the brake is released.	
Texas [88]	Stop Lamp: **(1)** All motor vehicles are required to have functioning stop lamp(s), as applicable to the number of stop lamp(s) equipped on the vehicle at the time the vehicle was originally manufactured. **(2)** A stop lamp must emit a red or amber light, or any shade of color between red and amber. **(3)** A stop lamp must be visible from a distance of not less than 300 feet to the rear in normal sunlight. **(4)** The stop lamp shall be actuated upon application of the service (foot) brake and may be incorporated with one or more other rear lamps. **(5)** Stop lamp lens must be of a type meeting Department of Public Safety standards.	Tentatively
Utah [89]	**(1)** A back-up lamp or lamps may not be lighted when the motor vehicle is in forward motion.	Tentatively
Vermont [90, 91]	**(1)** Backup lamp required to operate when bus, truck, or truck tractor is in reverse.	Tentatively
Virginia [92, 93]	**(1)** Any motor vehicle may be equipped with fog lights, not more than two of which can be illuminated at any time, one or two auxiliary driving lights if so equipped by the manufacturer, two daytime running lights, two side lights of not more than six candlepower, an interior light or lights of not more than 15 candlepower each, and signal lights. The provision of this section limiting interior lights to no more than 15candlepower shall not apply to (i) alternating, blinking, or flashing colored emergency lights mounted inside law-enforcement motor vehicles which may otherwise legally be equipped with such colored emergency lights, or (ii) flashing shielded red or red and white lights, authorized under § 46.2-1024 , mounted inside vehicles owned or used by (a) members	Tentatively

	of volunteer fire companies or volunteer emergency medical services agencies, (b) professional firefighters, or (c) police chaplains. (/46.2-1024/) **(2)** Every motor vehicle, trailer, or semitrailer, except an antique vehicle not originally equipped with a brake light, registered in the Commonwealth and operated on the highways in the Commonwealth shall be equipped with at least two brake lights of a type approved by the Superintendent. Such brake lights shall automatically exhibit a red or amber light plainly visible in clear weather from a distance of 500 feet to the rear of such vehicle when the brake is applied.	
Washington [94]	**(1)** Any motor vehicle may be equipped with one or more backup lamps either separately or in combination with other lamps, but any(any such backup lamp or lamps shall not be lighted when the motor vehicle is in forward motion. **(2)** One green light to be activated when the accelerator of the motor vehicle is depressed;(depressed; **(3)** Not more than two amber lights to be activated when the motor vehicle is moving forward, or standing and idling, but is not under(under the power of the engine. **(4)** Such auxiliary system shall not interfere with the operation of vehicle stop lamps or turn signals, as required by RCW 46.37.07046.37.070..Such system, however, may operate in conjunction with such stop lamps or turn signals. **(5)** Only one color of the system may be illuminated at any one time, and at all times either the green light, or amber light or lights shall(shall be illuminated when the stop lamps of the vehicle are not illuminated.	Tentatively
West Virginia [95]	**(1)** A stop lamp on the rear which shall emit a red or yellow light and which shall be actuated upon application of the service (foot) brake and which may but need not be incorporated with a tail lamp. **(2)** All mechanical signal devices shall be self-illuminated when in use at the times mentioned in section two of this article.	Tentatively
Wisconsin [96]	Stop Lamps:	Tentatively

	(1) No person shall operate a motor vehicle, lightweight utility vehicle as defined in s. 346.94 (21) (a) 2., mobile home, or trailer or semitrailer upon a highway unless such motor vehicle, lightweight utility vehicle, mobile home, or trailer or semitrailer is equipped with at least one stop lamp mounted on the rear and meeting the specifications set forth in this section. The stop lamp on a mobile home or trailer or semitrailer shall be controlled and operated from the driver's seat of the propelling vehicle. A stop lamp may be incorporated with a tail lamp. No vehicle originally equipped at the time of manufacture and sale with 2 stop lamps shall be operated upon a highway unless both such lamps are in good working order. **(2)** A stop lamp shall be so constructed as to be actuated upon application of the service or foot brake or separate trailer brake and shall emit a red or amber light plainly visible and understandable from all distances up to 300 feet to the rear during normal sunlight when viewed from the driver's seat of the vehicle following. Special restrictions on lamps and the use thereof: **(1)** Whenever a motor vehicle equipped with headlamps also is equipped with any adverse weather lamps, spot lamps or auxiliary lamps, or with any other lamp on the front thereof projecting a beam of intensity greater than 300 candlepower, not more than a total of 4 of any such lamps or combinations thereof on the front of the vehicle shall be lighted at any one time when such vehicle is upon a highway. **(2)** Except as provided in sub. (3), or as otherwise expressly authorized or required by this chapter, no person shall operate any vehicle or equipment on a highway which has displayed thereon: a) Any color of light other than white or amber visible from directly in front; or b) Any color of light other than red on the rear; or c) Any flashing light.	

	(3) A motorcycle may be equipped with a lighting device that illuminates the ground directly beneath the motorcycle if all of the following apply: a) The lighting device is not visible to approaching vehicles. b) The lighting device does not display a red, blue, or amber light. c) The lighting device does not display a flashing, oscillating or rotating light. History: 2015 a. 27.	
Wyoming [97]	**(4)** All lighting devices and reflectors mounted on the rear of any vehicle shall display or reflect a red color, except the stop light or other signal device, which may be red or yellow, and except that the light illuminating the license plate shall be white and the light emitted by a backup lamp shall be white. **(5)** Any motor vehicle may be equipped with not more than two (2) backup lamps either separately or in combination with other lamps, but any such backup lamp shall not be lighted when the motor vehicle is in forward motion.	Yes