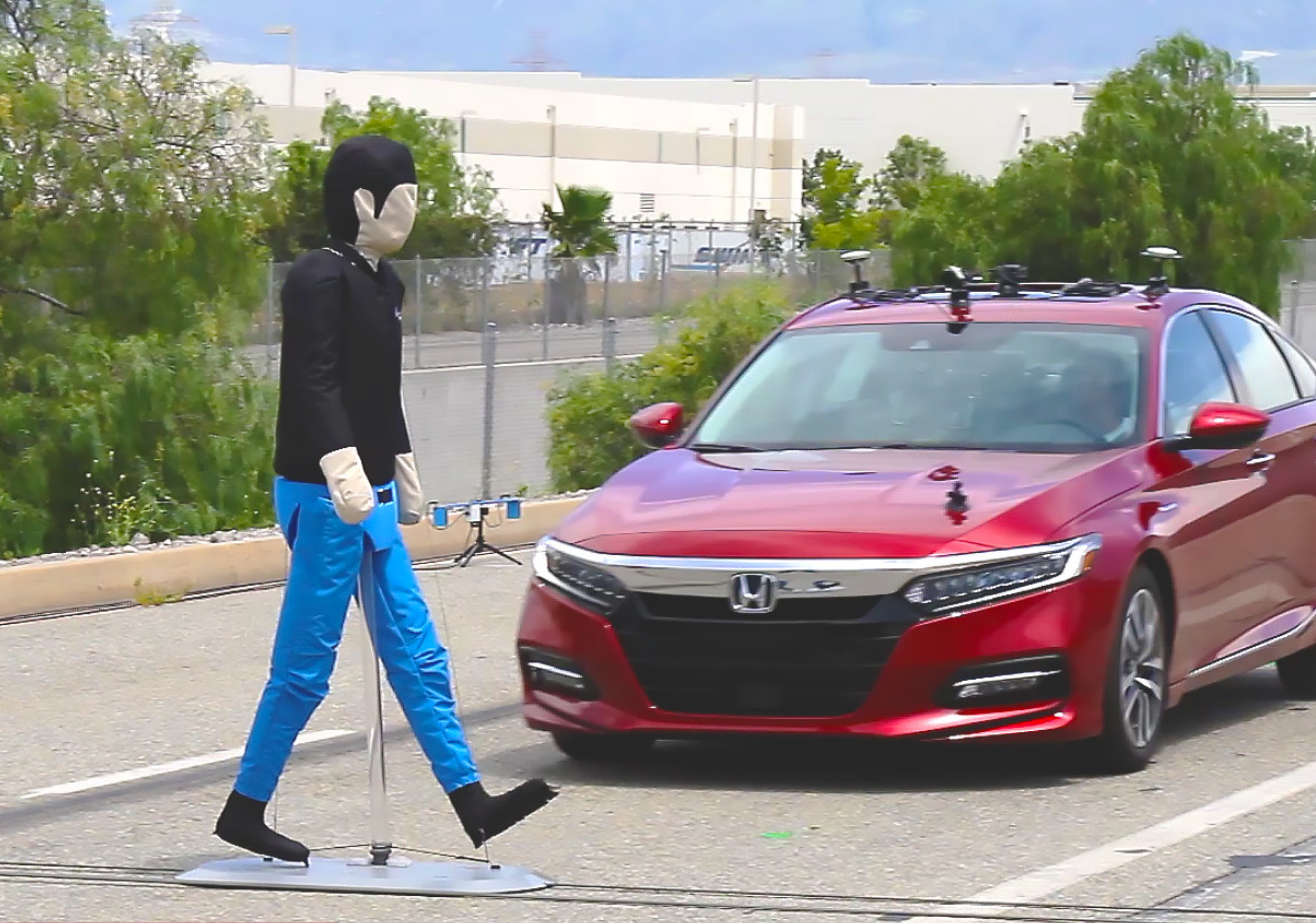

OCTOBER 2019

AUTOMATIC EMERGENCY BRAKING WITH PEDESTRIAN DETECTION

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Abstract

On average, a pedestrian is killed every 88 minutes in traffic crashes in the United States. That is more than 16 people a day, almost 115 people a week. In 2017 that totaled nearly 6,000 pedestrians lives lost and accounted for 16% of all traffic fatalities, a percentage that has steadily increased since 2012 [1].

Pedestrian detection systems with automatic braking functionality have the potential to prevent or reduce the severity of collisions resulting in property damage, personal injury and/or death. The purpose of this work is to detail the performance and limitations of currently available pedestrian detection systems. Only systems with automatic braking functionality were evaluated within this work. It is important to note that these systems are meant to add an additional layer of driver assistance and collision mitigation; they are not intended to serve as a substitute for an engaged driver.

Testing was performed on a closed-course to simulate common dynamic interactions between vehicles and pedestrians.

Research Questions:

1. How do vehicles equipped with pedestrian detection systems perform when encountering an adult pedestrian crossing the roadway?
2. How do vehicles equipped with pedestrian detection systems perform when encountering challenging vehicle/pedestrian interactions?
    a. Child pedestrian darting into traffic from between two parked vehicles
    b. Vehicle turning right on adjacent road with adult pedestrian crossing simultaneously
    c. Vehicle approaching two adult pedestrians alongside the roadway
3. How do pedestrian detection systems function at night?

Key Findings:

The following numbered points pertain to the numbered research questions listed above:

1. When encountering an adult pedestrian in a perpendicular crossing scenario:
    a. Each test vehicle provided visual notification of an impending collision during each test run conducted at 20 mph.
        i. In aggregate, a collision with an adult pedestrian target was avoided 40% of the time
        ii. During an additional 35% of the time, collisions were mitigated by an average speed of 4.4 mph
    b. At 30 mph, three out of four test vehicles failed to reduce the impact speed by at least 5 mph during the initial test run.

2. Evaluated pedestrian detection systems were significantly challenged in the following scenarios:
    a. When encountering a child pedestrian at 20 mph, a collision was avoided 11% of the time in aggregate. An additional 25% of the time, collisions were mitigated by an average speed of 5.9 mph.
    b. When encountering a pedestrian immediately after a right curve, none of the test vehicles mitigated the impact speed during any of the five test runs.
    c. When encountering two pedestrians alongside the roadway at 20 mph, a collision was avoided 20% of the time in aggregate. An additional 35% of the time, collisions were mitigated by an average speed of 3.4 mph.
3. Evaluated pedestrian detection systems were ineffective during nighttime conditions.

Contents

1 Introduction

A casual observation of any American city center will reveal scores of distracted pedestrians crossing busy streets without proper awareness of their surroundings. Compounding this problem are distracted drivers who use their phones to talk, text, access the internet or even play mobile games all while their vehicle is in motion. The National Highway Traffic Safety Administration (NHTSA) conducted a literature review on the effect of electronic device use on pedestrian safety and found that pedestrian distraction is a problem of which the effects can be detected in crash data, naturalistic observations, simulator studies and within the laboratory [2].

According to the National Highway Traffic Safety Administration, there were nearly 6,000 pedestrians killed in vehicle crashes in 2017. Additionally, 75% percent of pedestrian fatalities occurred in the dark as compared to daylight (21%), dusk (2%) and dawn (2%) [1].

Research by the Volpe National Transportation Systems Center suggests that automatic emergency braking systems with pedestrian detection functionality could reduce up to 5,000 annual vehicle/pedestrian crashes and 810 fatal vehicle/pedestrian crashes [3]. This estimate is based on the performance data of three production systems. For crashes that do occur, the severity of injury could be mitigated through reduction of the impact speed.

Figure 1: 1959 Cadillac Cyclone concept car Image Source: General Motors

The idea of a forward collision avoidance system was explored beginning in the 1950s. George Rashid first submitted a patent for a radar-based "automatic vehicle control system" in 1954 [4]. In addition, manufacturers such as Studebaker-Packer and General Motors experimented with similar radar-based systems integrated in concept cars such as the Cadillac Cyclone. At the time, none of the prototype systems were put into production because of issues with object differentiation, reliability, complexity, cost and potential liability.

In 2011, Volvo introduced the first pedestrian detection mitigation system available in the U.S. This system used both radar and image sensors to detect possible collisions with pedestrians as well as rear-end collisions with other vehicles and motorcycles. Current systems typically utilize a radar sensor mounted behind the front grille along with one or two image sensors (cameras) located behind the windshield. Systems that only utilize radar or image sensors are also available; although this configuration is less common. Lidar sensors are beginning to be incorporated into consumer-grade vehicles starting with the Audi A8 for the 2019 model year.

Throughout this work, the term “pedestrian detection system” refers to an automatic emergency braking system with pedestrian detection functionality unless otherwise noted. Primary research was conducted on a closed-course to evaluate the performance of pedestrian detection systems on midsize sedans available for sale throughout the U.S. While crossover utility vehicles have eclipsed sedans in terms of overall market share, midsize sedans still represent the fourth bestselling segment, responsible for 10% of total new vehicle market share in 2018.

2 Background

Current pedestrian detection systems will warn the driver through an audible, visual or haptic alert when it determines a significant collision risk exists. 56% of 2018 model year vehicles come equipped with automatic emergency braking with pedestrian detection functionality as either standard or optional equipment.

It is important for drivers to understand the capabilities of any Advanced Driver Assistance System (ADAS) present in their vehicle. In terms of pedestrian detection, drivers should be aware of the difference between a collision warning and collision mitigation system. Specifically, a warning system will alert the driver to an imminent collision but will take no evasive action such as applying the brakes. A mitigation system will alert the driver and if no action is taken, the system will actively apply the brakes to avoid or lessen the severity of the collision. Mitigation systems were exclusively evaluated within this work.

Depending on the sensor suite, the system can monitor a field of view several yards in front of the vehicle. Inputs from the radar sensor, camera(s) and/or lidar is fed into a central processing unit that classifies objects based on their speed relative to the vehicle and their size. These sensor types are described in Section 2.1. Programming these systems is a complex endeavor because not only does the central processing unit (CPU) have to distinguish pedestrians from other similarly sized objects but false alarms and braking events must be minimized via tracking and predicting a travel path. For example, the system must not brake for pedestrians alongside the vehicle in an adjacent sidewalk.

Despite advances relative to earlier systems, there are still significant limitations. Depending on the vehicle, the owner's manual will specify multiple scenarios in which the system may not recognize a pedestrian(s). Examples include nighttime conditions, inclement weather, two or more pedestrians in close proximity, and lateral offset relative to the centerline of the vehicle. Additionally, it is common for owner's manuals to explicitly state that the system may fail to respond to an imminent collision regardless of the driving environment. **For this reason, it is imperative that drivers recognize that regardless of any pedestrian detection functionality such as warning and/or mitigation, they are always responsible for the safe operation of their vehicle.**

2.1 Sensors Utilized for Pedestrian Detection Systems

ADAS such as pedestrian detection rely on a variety of sensors in order to gather data about the surrounding environment. Every sensor consists of a hardware and software component; the hardware is composed of the physical parts necessary to emit and/or receive electromagnetic radiation as well as signal conditioning and data processing. The software component is responsible for converting raw data into useful information about the dynamic environment around the vehicle as well as determining an appropriate response.

Most ADAS such as forward collision warning/mitigation, adaptive cruise control, dynamic driving assistance (sustained lateral and longitudinal control) and lane keeping assistance utilize the same sensors, regardless of system functionality. For example, current pedestrian detection and dynamic driving assistance systems both predominantly rely on inputs from radar and image sensors. In many cases, the sensors themselves are identical and interchangeable between systems from the same manufacturer. This is primarily done to reduce cost and simplify manufacturing logistics.

Differences between current systems in terms of the sensor package are usually limited to the number, placement and range of radar sensors. Partially automated driving assistance, lane keeping assistance and blind spot monitoring systems require information about the surroundings around the sides of the vehicle. Short-range radar and/or ultrasonic sensors are strategically placed to accomplish this. This is not usually required for other systems; only front facing sensors are present if the aforementioned systems are not included. Additionally, systems such as rear cross traffic alert and parking obstruction warning rely on information about the environment around the rear of the vehicle. Short-range radar and/or ultrasonic sensors are widely integrated within these systems, typically located within and/or behind the rear bumper.

It is important to note that more processing power is required as system functionality becomes more complex. This is especially true if multiple capabilities are integrated into a singular system. In conjunction with processing capability, software algorithms are largely responsible for system performance. Many analysts believe future developments in artificial intelligence and deep learning will accelerate the development of fully autonomous vehicles. A detailed discussion relating to data processing and software design considerations are outside the scope of this work.

Sensors for vehicle systems can be grouped into one of four categories including:

1. Radar (**RA**dio **D**etection **A**nd **R**anging)
2. Image Sensors (Cameras)
3. Lidar (**LI**ght **D**etection **A**nd **R**anging)
4. Ultrasonic Sonar

The intent of this section is to provide a general overview of sensors utilized for ADAS [5]. Ultrasonic sonar is widely incorporated into production vehicles because of their performance relating to short-range object detection and low cost. Since they usually have an effective range of 20 feet or less, they are typically integrated within parking assistance systems and have limited potential for other driver assistance systems such as pedestrian detection. For this reason, ultrasonic sonar will not be discussed further.

2.1.1 Radar (RAdio Detection And Ranging)

A radar system generates radiation within the microwave region of the electromagnetic (EM) spectrum. The generated radar waves are reflected by solid objects back to the sensor. Based on the characteristics of the reflected signal, object attributes such as position, distance, velocity and shape may be determined. Modern automotive radar systems typically generate and receive electromagnetic waves at a frequency of 77 or 79 GHz with a corresponding wavelength in the millimeter range. Within this range, sensors can be designed for optimal use depending on output power, scan angle and other factors.

Short-range radars are optimized to operate about 15 to 20 feet from the vehicle. While this distance overlaps with ultrasonic sonar, short-range radar is usually a better option if the distance of interest exceeds about 15 feet. Mid range radars are useful in the approximate range of 15 to 100 feet and are suitable for applications such as cross-traffic alert, pedestrian detection and blind-spot monitoring. Long-range radars are optimized for distances beyond about 100 feet. While return signals will degrade with increasing distance, there is no distinct cutoff where a return signal can no longer contain useful information. In most cases, long-range radar sensors are functional beyond distances required by the driving environment. Applications served by long-range radar include adaptive cruise control, automatic emergency braking and forward collision warning.

Advantages of radar for automotive applications include functionality through most weather conditions such as rain, snow and fog; radar is also unaffected by ambient lighting conditions. Additionally, radar sensors can usually be integrated behind plastic grills and bumpers because the radiation is able to penetrate most plastics with minimal signal loss; this allows design engineers more flexibility with exterior design elements. Finally, automotive grade radar sensors are robust and able to withstand dirt and dust while being cost-effective compared to lidar.

Radar comes with some inherent limitations based on the region of microwaves within the EM spectrum. Specifically, radar has lower resolution than lidar and is not effective at discerning object detail. For this reason, driver-assistance and autonomous vehicle systems typically include image sensors in conjunction with radar.

2.1.1 Image Sensors (Cameras)

Image sensors (otherwise known as digital cameras) detect visible light within the EM spectrum and convert the input into digital code. Typically, the sensor is based on a charge-coupled device (CCD) or complementary metal oxide semiconductor (CMOS) design.

A CCD sensor is a silicon chip with an array of photosensitive receptors embedded on the chip. Each receptor represents a pixel; when a pixel is impacted by a photon, a charge is generated with a magnitude dependent on the energy of the photon ("color" is dependent on the energy of a photon within the visible range of the EM spectrum). The charge magnitude is converted to a voltage measurement and is finally converted to digital data with an analog-to-digital converter.

The CMOS detector was invented in 1963 but was not widely used in image generation until the 1990s. A primary difference between CCD and CMOS devices relates to the signal format; while CCD devices output an analog signal, CMOS devices are inherently digital because they directly output discrete voltages.

Image sensors used for automotive applications are typically sensitive to EM radiation within the visible range (about 380 to 700 nm). However, image sensors responsive to other regions within the EM spectrum can be useful. Near-infrared radiation (NIR) consists of radiation with frequencies just below the detection threshold for human vision. Most image sensors are moderately sensitive to NIR but are usually configured to filter this region because of its irrelevancy in terms of human perception. By disabling the NIR filtering, useful information can be obtained for driver-assistance and autonomous vehicle systems. Additionally, medium-wave (MWIR) and/or long-wave infrared radiation (LWIR) can be measured by image sensors for thermal imaging. Warm-blooded organisms emit radiation within this part of the EM spectrum; thermal imaging can therefore create images of people and animals regardless of lighting conditions. Additionally, thermal imaging remains effective in adverse weather such as rain, snow and fog.

Cameras are a popular inclusion within sensor suites for driver-assistance and autonomous driving systems due to their relatively low cost, durability and effectiveness. Cameras remain the most reliable way of detecting lane markings; some autonomous vehicle systems utilize radar and cameras to accurately measure distances to objects while collecting detailed visual information about the object. Similar to radar, cameras can evaluate the driving environment at short or long distances; with enough cameras, it is possible to create a complete 360-degree image around the vehicle.

While generally effective, cameras have some limitations. Image sensors in the visible range of the EM spectrum do not work in the dark and are impacted by adverse weather conditions such as snow and rain. While IR sensors are less affected by lighting and weather conditions, they are generally less effective at discerning object detail. Additionally, it can be challenging to incorporate cameras within optimal areas of the vehicle while providing protection from the elements and keeping the impact to vehicle aesthetics to a minimum.

2.1.2 Lidar (LIght Detection And Ranging)

Lidar sensors measure distance to objects by emitting infrared radiation and evaluating the reflected energy. The most common lidar designs emit pulses of infrared light and measure the time-of-flight between emitted and reflected light to elucidate distance. Besides distance evaluation, lidar can also measure object velocity and create high-resolution maps of the environment. While multiple methods with lidar design are possible, the most common methods currently include motor-driven mechanical scanning and microelectromechanical systems (MEMS) scanning lidar.

To date, most approaches to creating 3D maps via lidar have centered on motor-driven mechanical scanning. This allows for digital mapping as well as real-time assessments. Unfortunately, current mechanical scanning lidar designs are bulky and expensive. Another tactic entails utilizing microelectricalmechanical systems (MEMS) devices to steer the laser beams rather than a mechanical motor. Some believe that these devices will allow for a low-cost, high-quality alternative to mechanical beam steering. These devices can also be programmed to produce fast, low-resolution data or slower but high-resolution data depending on the specific driving environment and real-time data input requirements.

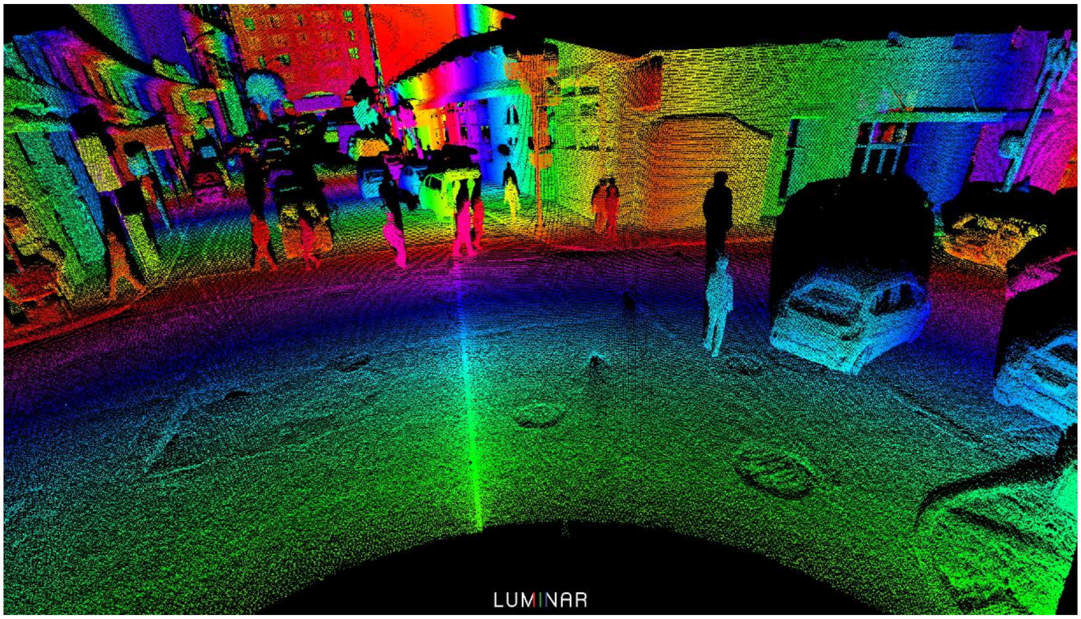

Figure 2: 3D digital point map created by scanning lidar Image Source: Luminar Technologies

Many industry analysts believe that lidar will become an integral part of a sensor suite for autonomous vehicle systems. As a result, significant research is underway within both industry and academia to develop robust, reliable automotive-grade lidar designs that can be produced at a price point enabling integration within commonly available vehicles. The main reason lidar is anticipated to be a primary sensor in future autonomous vehicle systems is because of its superior ability to create high-resolution 3D point maps. These can be used by system software for localization and corresponding navigation tailored to the specific driving environment. In addition to digital 3D mapping, lidar resolution can allow for object classification and lane marker detection with accuracy currently approaching that of high-quality image sensors. Currently, lidar systems are somewhat sensitive to precipitation and fog. An additional potential limitation to lidar is its tendency to be blinded by direct sunlight; however, countermeasures that seek to address this issue are under development.

The 2019 Audi A8 is the first production vehicle to incorporate a mechanical lidar scanner supplied by Valeo. This vehicle was not included for testing and is identified here for informational purposes only.

3 Vehicle Selection Methodology

AAA researchers identified midsize sedans that included a pedestrian detection mitigation system as either standard or optional equipment. For a vehicle to be eligible for testing, the integrated pedestrian detection system must have collision mitigation functionality. Specifically, if only visible, audible, and/or haptic alerts are provided without automatic braking application, the vehicle was excluded from testing.

The following criteria were utilized to select four (4) midsize sedans for testing:

1. Domestic and import original equipment manufacturer must be included for testing
2. Variety of manufacturers (only one vehicle per OEM will be evaluated)
3. Sales data was utilized to select vehicles with respect to popularity
4. If a vehicle was due for a redesign in the next model year, it was excluded for testing
5. Preproduction vehicles were excluded from testing

Based on the preceding criteria, the following vehicles were selected for testing:

1. 2019 Chevrolet Malibu with Front Pedestrian Braking
2. 2019 Honda Accord with Honda Sensing® - Collision Braking System™
3. 2019 Tesla Model 3 with Automatic Emergency Braking
4. 2019 Toyota Camry with Toyota Safety Sense™ - Pre-Collision System with Pedestrian Detection

Test vehicles were procured from manufacturers or specialty rental fleets.

A detailed description of test vehicle preparations is provided in Section 5.

4 Test Equipment and Resources

Figure 3: 2019 Chevrolet Malibu outfitted with measurement equipment Image Source: AAA

4.1 Vehicle Dynamics Equipment

4.1.1 DEWESoft IMU-2 RTK Inertial Measurement Unit

Each vehicle was outfitted with a DEWESoft IMU-2 to capture vehicle dynamics and position data. An inertial measurement unit measures a body's specific force within each spatial axis via a combination of calibrated accelerometers and gyroscopes. The IMU-2 rover interfaced with a base station to incorporate real-time kinematics (RTK) technology. This allows for high-accuracy position measurements down to ≤ 2 cm.

Horizontal Accuracy	**0.01 m**
Vertical Accuracy	**0.02 m**
Velocity Accuracy	**0.01 m/s**
Roll & Pitch Accuracy	**0.15°**
Heading Accuracy	**0.1°**
Slip Angle Accuracy	**0.1°**
Output Data Rate	**500 Hz**

Figure 4: DEWESoft IMU-2 specifications Image Source: AAA

While the maximum update rate of the IMU-2 is 500 Hz, data was captured at a rate of 200 Hz to minimize unnecessary oversampling.

4.1.2 DEWESoft CAM-120 Cameras

Each vehicle was equipped with one front-facing camera and one camera facing the instrument cluster to capture visual notifications originating from the pedestrian detection system. Video from both cameras was captured at a rate of 30 Hz.

Image Sensor	**Sony ICX618**
Sensor Type	**CCD**
FPS	**120 FPS @ 640x480**
Dynamic Range	**32 dB autogain function**
Shutter Time	**58 ns-60 s (autoshutter function)**

Figure 5: DEWESoft CAM-120 specifications Image Source: AAA

4.1.3 DEWESoft CAN-2 Interface

Test vehicles were equipped with a CAN interface to receive position, speed and acceleration data from the dynamic pedestrian target. This data was captured at a rate of 100 Hz and time-synced with vehicle data and video.

4.2 Pedestrian Targets

4.2.1 4activeSB Dynamic Surfboard Platform

The 4activeSB platform is utilized for testing with dynamic pedestrian targets. For perpendicular crossing scenarios, light barriers were utilized to time the movement of the pedestrian target such that the target was located along the centerline of the test vehicle upon contact (assuming the pedestrian detection system does not mitigate or prevent the collision).

For nonorthogonal crossing scenarios i.e., the test vehicle travels along a curved roadway before encountering the pedestrian target, a GPS transmitter was placed on the vehicle and linked to the platform via Wi-Fi. The transmitter broadcast vehicle kinematic data to the platform to compensate for lateral position and speed deviations. This real-time correction allowed for the pedestrian target to be positioned along the vehicle centerline upon impact, regardless of any speed reduction by the pedestrian detection system.

4.2.2 4activePS Static Adult Pedestrian Target

This target is designed to replicate the size and shape of an average sized adult. Additionally, the radar and infrared reflectivity of the target is designed to be representative of a typical adult. Specifically, the IR reflectivity from 850 to 910 nm measured at 45° and 90° is 40-60% for the clothes and skin and 20-60% for the hair on top of the head. The body height and width is 71 inches and 20 inches, respectively.

4.2.3 4activePA Articulated Adult Pedestrian Target

The articulated adult pedestrian target is designed for use in dynamic test scenarios; specifically, the “legs” of the target realistically mimic a walking motion as the dummy moves along the roadway. This closely simulates a typical pedestrian in terms of radar, infrared and camera detection as well as a humanlike Micro Doppler spread. The IR reflectivity, body height and width are identical to the static adult target previously described.

4.2.4 4activePA Articulated Child Pedestrian Target

The articulated child pedestrian target is designed to be representative of a typical 7-year-old and is intended for use in dynamic test scenarios. Like the adult pedestrian target, the “legs” of the target realistically mimic the walking motion of a typical child. The body height and width is 45 inches and 12 inches, respectively.

4.3 Data Processing

All test data was post-processed with DEWESoft X3 SP6 software equipped with the Polygon plugin. Polygon allows kinematic data originating from the test vehicle and the dynamic pedestrian target to be evaluated relative to each other. Additionally, the position of the vehicle centerline relative to the test lane can be quantified.

4.4 Test Facility

All track testing was conducted on closed surface streets on the grounds of Auto Club Speedway in Fontana, California and was rented by AAA for independent testing.

All straight-line testing was conducted on a dry asphalt surface free of visible moisture. The surface was straight and flat, free of potholes and other irregularities that could cause undesired variations in the trajectory of the test vehicle. The testing area consisted of a four-lane roadway divided down the middle by a solid white line. Inner lanes were marked by the solid white line on the medial side and a dashed white line on the lateral side. Outer lanes were bounded by a curb on the lateral side and a dashed white line on the medial side. The width of each lane was 12 feet. One side of the roadway was bounded by a solid wall with a height of approximately 15 feet. To eliminate the possibility of sensor interference, the two lanes closest to this wall were not utilized for any testing activities.

Before testing, the test lane was virtually mapped by DEWESoft Polygon® software.

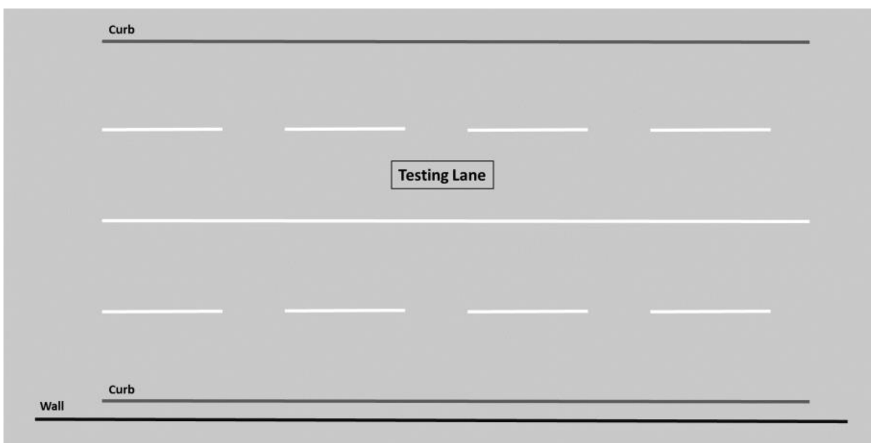

Figure 6: Illustration of testing surface Image Source: AAA

During straight-line testing, no other vehicles, obstructions or objects were within 16 feet lateral distance from the center of the test lane and 75 feet longitudinal distance from the pedestrian target(s).

The test surface utilized for curvilinear testing is described in Section 7.2.2.

5 Vehicle Preparation

All test vehicles were evaluated in the "as received" condition from the manufacturer or specialty rental company. Any vehicles procured from a specialty rental company were sourced directly from the inventory of a new vehicle dealership. Vehicles provided by the manufacturer were verified by that OEM to be suitable for pedestrian detection system testing.

All test vehicles were verified to be equipped with a pedestrian detection system that was enabled, properly functioning, free of modifications and calibrated. The odometer reading of all test vehicles was between 200 and 5,000 miles.

Additionally, vehicles were inspected to verify testing suitability according to the following checklist:

- No warning lights illuminated
- All system components are free of damage and unaffected by any technical service bulletins and/or recalls
- All fluid reservoirs filled to at least the minimum indicated levels

All test vehicles were outfitted with new original fitment tires inflated to the pressure specified on the tire loading placard on the vehicle. Before the start of each testing day, all vehicles were driven in a mix of urban and freeway environments for a minimum of 60 miles in order to condition the tires, burnish the brakes and ensure initialization of the pedestrian detection system.

For test vehicles with driver configurable settings for the timing of collision warning and/or brake application, the system was set to the middle setting. If an even number of settings were available, the next latest setting closest to the midpoint was utilized.

Before the start of each testing day, the areas surrounding the image and radar sensors on all test vehicles were cleaned to ensure proper system operation.

6 Inquiry 1: How do vehicles equipped with pedestrian detection systems perform when encountering an adult pedestrian crossing the roadway?

6.1 Objective

Evaluate pedestrian detection system performance during a common pedestrian crossing scenario simulated on a closed-course.

6.2 Methodology

The most common motor vehicle collision involving a pedestrian involves a vehicle traveling along a straight roadway while a pedestrian crosses the roadway in a perpendicular direction [3]. To evaluate the effectiveness of evaluated pedestrian detection systems in terms of mitigating or preventing this type of collision, the adult pedestrian target previously described in Section 4.2.3 was utilized. The target moved along the roadway atop the dynamic surfboard platform referenced in Section 4.2.1. The steady-state speed of the pedestrian target was controlled by the 4activeSB unit and was set to 3.10

mph; this is considered walking speed for the typical adult [6]. The acceleration of the pedestrian target was selected such that steady-state speed was reached 10 feet from the centerline of the test lane. For each test, the pedestrian dummy moved from right to left across the travel path of the vehicle.

The 4activeSB controller was setup within the outer lane opposite of the wall illustrated in Figure 6. The pedestrian target platform was 13.1 feet from the centerline of the test lane and was activated by four light barriers along the travel path of the test vehicle. The approach speed was pre-defined within the 4active software; this information in conjunction with the timing of the vehicle crossing the light barriers allowed the controller to place the pedestrian target along the lateral centerline of the vehicle (50% offset relative to the front right corner) upon impact. If the impact speed was significantly reduced via automatic braking, the impact point will be greater than 50% offset. This is a consequence of sudden speed reduction and does not constitute an invalid test run.

Figure 7: 4active light barrier for pedestrian target timing Image Source: AAA

At the start of each test run, the test vehicle was stationary in the center of the test lane at a longitudinal distance of 350-450 feet from the pedestrian target. From this point, the test vehicle was gradually accelerated to steady-state speed and kept within the center of the lane. Once the vehicle was within four seconds time-to-collision (TTC) with the pedestrian target, the vehicle speed relative to the evaluated speed and lateral deviation from the center of the lane was required to be ± 0.5 mph and 0.33 feet respectively for the test run to be valid. Additionally, the brake pedal was not touched during the test run until after contact with the pedestrian target occurred or pedal application was required to keep the vehicle stationary after pedestrian target contact was avoided by the pedestrian detection system.

For each test run, the longitudinal distance and TTC from the pedestrian target was recorded upon occurrence of the following events:

- Visual alert that a collision is imminent
- Braking automatically applied by the pedestrian detection system

Within this work, automatic braking was considered to have occurred once longitudinal deceleration ≥ 0.10 G. Additionally, the impact speed or separation distance were recorded if contact with the pedestrian target occurred or the collision was avoided, respectively.

Approach speeds of 20 and 30 mph were evaluated. These speeds were evaluated because they are representative of speed limits on urban and suburban roadways with significant pedestrian traffic. For each test vehicle, five runs were performed at a speed of 20 mph; the approach speed was then increased to 30 mph. One run was performed at this speed; additional runs up to a maximum of five were performed if the impact speed was mitigated by a minimum of 5 mph during the initial test run. This approach was utilized to minimize damage to test vehicles and pedestrian targets. Additionally, testing at this speed was discontinued if significant damage occurred to the test vehicle and/or pedestrian target.

It is important to note that the owner's manual of each test vehicle specifies that the integrated pedestrian detection system is not designed to entirely avoid a collision and/or may not operate depending on several factors including but not limited to those explicitly identified. Therefore, the results provided herein do not necessarily imply poor performance if a collision is not completely avoided. Emphasis should be placed on the degree of speed mitigation relative to the stated approach speed.

Previous research into driver reaction times with collision warnings [7] and in the context of unexpected events [8] suggest that a minimum of 1.50 seconds are required for an undistracted driver to move the foot from the accelerator to the brake pedal for an unanticipated situation if no warning is provided. If a collision warning is provided to a distracted driver, the average response time to the warning is between 0.75-1.15 seconds, depending on the timing of the collision warning. However, this response time only accounts for the driver moving the foot off the accelerator; brake application requires an additional 0.50 second, on average. Depending on vehicle speed, up to several seconds can be required for the vehicle to actually come to a complete stop.

6.3 Test Results

Within Figures 8-15, "N/A" indicates that while the run was completed, notification and/or braking was not provided. "DNT" indicates that a run was not performed. The average of all runs where notification and/or braking was provided was calculated with respect to those runs only. For example, if braking was provided for three out of five runs, the two runs with no braking were not considered within the calculation.

6.3.1 2019 Chevrolet Malibu

20 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
2.480	2.410	2.366	2.31	1.064	**2.126**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
74.12	69.54	71.71	69.50	31.53	**63.28**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	N/A	N/A	N/A	N/A	**N/A**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
N/A	N/A	N/A	N/A	N/A	**N/A**
Impact Speed (mph)					
19.0	19.5	18.3	19.7	19.7	**19.2**
Seperation Distance At End of Test (ft)					
0.00	0.00	0.00	0.00	0.00	**0.00**

Figure 8: Measurements from test runs conducted at 20 mph Image Source: AAA

At 20 mph, a visual notification was provided for each of the five runs with an average TTC of 2.126 seconds and a corresponding standard deviation of 0.534 seconds. On average, the vehicle was 63.28 feet from the pedestrian target when visual notification of a potential collision was provided. However, automatic braking did not significantly mitigate the impact speed in any of the five runs. For run three, slight braking was applied before impact; however, the resulting deceleration was under the 0.10 G threshold which constituted an automatic braking event.

30 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
2.103	DNT	DNT	DNT	DNT	**2.103**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
93.77	DNT	DNT	DNT	DNT	**93.77**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
27.1	DNT	DNT	DNT	DNT	**27.1**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
0.776 @ 18.34	DNT	DNT	DNT	DNT	**0.776 @ 18.34**
Impact Speed (mph)					
25.5	DNT	DNT	DNT	DNT	**25.5**
Seperation Distance At End of Test (ft)					
0.00	DNT	DNT	DNT	DNT	**0.00**

Figure 9: Measurements from test runs conducted at 30 mph Image Source: AAA

One run was conducted at 30 mph because the system did not mitigate the impact speed by at least 5 mph during the initial run. For this run, visual notification was provided with a TTC of 2.013 seconds; the vehicle was located 93.77 feet from the pedestrian target at this time.

6.3.2 2019 Honda Accord

20 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
0.023	1.153	0.865	1.000	0.534	**0.715**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
0.92	33.71	25.48	29.39	16.04	**21.11**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	31.71	24.32	27.62	15.15	**24.70**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
N/A	0.883 @ 5.62	0.999 @ 14.29	1.018 @ 13.90	1.950 @ 4.92	**1.213 @ 9.68**
Impact Speed (mph)					
20.1	0.0	0.0	0.0	0.6	**4.1**
Seperation Distance At End of Test (ft)					
0.00	3.91	3.57	4.10	0.00	**2.32**

Figure 10: Measurements from test runs conducted at 20 mph Image Source: AAA

At 20 mph, a visual notification was provided for each of the five runs with an average TTC of 0.715 seconds and a corresponding standard deviation of 0.402 seconds. On average, the vehicle was 21.11 feet from the pedestrian target when visual notification of a potential collision was provided. Automatic braking significantly mitigated the impact speed in one of the five runs; the impact speed in this case was only 0.6 mph. The system completely avoided impact in three additional runs. In total, the system either mitigated or avoided impact with the pedestrian target for four out of five runs.

30 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
0.834	0.300	0.615	1.018	0.865	**0.726**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
37.71	13.29	26.89	44.52	39.60	**32.40**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
35.53	10.66	26.89	43.65	39.60	**31.27**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
1.771 @ 4.28	1.173 @ 1.56	1.346 @ 19.58	1.066 @ 31.73	1.233 @ 7.46	**1.318 @ 12.92**
Impact Speed (mph)					
1.2	25.2	12.5	0.0	0.0	**7.78**
Seperation Distance At End of Test (ft)					
0.00	0.00	0.00	2.88	5.13	**1.60**

Figure 11: Measurements from test runs conducted at 30 mph Image Source: AAA

Five runs were conducted at 30 mph because the system mitigated the impact speed by 23.8 mph during the first run. Visual notification was provided with an average TTC of 0.726 seconds and a corresponding standard deviation of 0.249 seconds. On average, the vehicle was located 32.40 feet from the pedestrian target at this time when visual notification of a potential collision was provided. Automatic braking significantly mitigated the impact speed in two of the five runs. The system completely avoided impact in two additional runs. In total, the system either mitigated or avoided impact with the pedestrian target for four out of five runs conducted at 30 mph.

6.3.3 2019 Tesla Model 3

20 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
0.807	0.935	3.636	0.792	1.057	**1.445**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
23.41	27.40	105.38	22.91	29.71	**41.76**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
4.96	0.74	1.15	5.62	3.82	**3.26**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
1.083 @ 0.52	0.108 @ 0.74	0.110 @ 1.15	0.991 @ 1.67	0.868 @ 1.10	**0.632 @ 1.04**
Impact Speed (mph)					
17.3	19.6	19.0	16.8	17.5	**18.0**
Seperation Distance At End of Test (ft)					
0.00	0.00	0.00	0.00	0.00	**0.00**

Figure 12: Measurements from test runs conducted at 20 mph Image Source: AAA

At 20 mph, a visual notification was provided for each of the five runs with an average TTC of 1.445 seconds and a corresponding standard deviation of 1.100 seconds. On average, the vehicle was 41.76 feet from the pedestrian target when visual notification of a potential collision was provided. However, automatic braking only slightly mitigated the impact speed in three of the five runs; the impact speed was mitigated by an average of 2.8 mph. The system failed to mitigate the impact speed for the remaining two runs at 20 mph.

30 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
0.220	DNT	DNT	DNT	DNT	**0.220**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
9.22	DNT	DNT	DNT	DNT	**9.22**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
0.86	DNT	DNT	DNT	DNT	**0.86**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
0.106 @ 0.44	DNT	DNT	DNT	DNT	**0.106 @ 0.44**
Impact Speed (mph)					
28.9	DNT	DNT	DNT	DNT	**28.9**
Seperation Distance At End of Test (ft)					
0.00	DNT	DNT	DNT	DNT	**0.00**

Figure 13: Measurements from test runs conducted at 30 mph Image Source: AAA

One run was conducted at 30 mph because the system did not mitigate the impact speed by at least 5 mph during the initial run. Visual notification was provided with a TTC of 0.220 seconds; the vehicle was located 9.22 feet from the pedestrian target at this time.

6.3.4 2019 Toyota Camry

20 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
1.255	1.079	1.229	1.330	1.339	**1.246**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
35.83	30.12	34.89	38.40	38.12	**35.47**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
30.15	26.15	30.88	28.71	29.34	**29.05**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
0.897 @ 23.81	1.024 @ 20.16	1.096 @ 23.14	0.842 @ 21.70	1.053 @ 22.41	**0.982 @ 22.24**
Impact Speed (mph)					
0.0	0.0	0.0	0.0	0.0	**0.0**
Seperation Distance At End of Test (ft)					
4.67	5.25	4.26	4.27	4.54	**4.60**

Figure 14: Measurements from test runs conducted at 20 mph Image Source: AAA

At 20 mph, a visual notification was provided for each of the five runs with an average TTC of 1.246 seconds and a corresponding standard deviation of 0.094 seconds. On average, the vehicle was 35.47 feet from the pedestrian target when visual notification of a potential collision was provided. Additionally, automatic braking completely avoided impact with the pedestrian target for all five runs at 20 mph.

30 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
N/A	DNT	DNT	DNT	DNT	**N/A**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	DNT	DNT	DNT	DNT	**N/A**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	DNT	DNT	DNT	DNT	**N/A**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
N/A	DNT	DNT	DNT	DNT	**N/A**
Impact Speed (mph)					
29.8	DNT	DNT	DNT	DNT	**29.8**
Seperation Distance At End of Test (ft)					
0.00	DNT	DNT	DNT	DNT	**0.00**

Figure 15: Measurements from test runs conducted at 30 mph Image Source: AAA

One run was conducted at 30 mph because the system did not mitigate the impact speed by at least 5 mph during the initial run. No notification or automatic braking was provided during this run.

6.4 Summary of Test Results

At 20 mph, all evaluated pedestrian detection systems provided visual notification of an impending collision for each of the five runs. Two out of four test vehicles completely avoided a collision with the pedestrian target for at least three out of five runs. However, the remaining two test vehicles impacted the pedestrian target for each of the five runs with minimal (if any) reduction in impact speed.

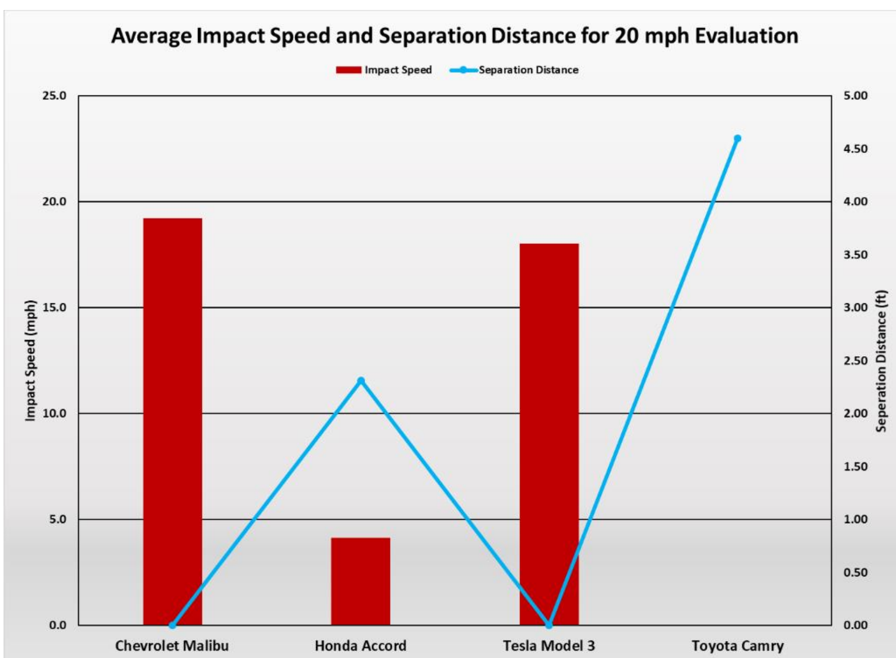

Figure 16: Average Impact Speed (mph) and Separation Distance (ft) at 20 mph Image Source: AAA

Figure 16 illustrates the average impact speed and separation distance for test runs conducted at 20 mph. An effective system will be characterized by a low or nonexistent average impact speed in conjunction with a nonzero average separation distance.
At 30 mph, three out of four test vehicles failed to reduce the impact speed by at least 5 mph during the initial run. A graph depicting average impact speed and separation distance is not provided because a varying number of test runs were performed depending on the vehicle.

These results illustrate that the effectiveness of these systems is largely vehicle specific; variations in performance among test vehicles preclude meaningful conclusions regarding system performance as a whole. In some cases, a significant degree of variability was noted for the performance of the same test vehicle being evaluated within the same scenario. However, all test vehicles impacted the pedestrian target with no automatic braking applied at least once while evaluating approach speeds of 20 and 30 mph. This finding illustrates that drivers must never rely on these systems to prevent a collision with a pedestrian; instead only considering them as a backup of last resort.

7 Inquiry 2: How do vehicles equipped with pedestrian detection systems perform when encountering challenging vehicle/pedestrian interactions?

7.1 Objective

Evaluate pedestrian detection system performance during challenging pedestrian/vehicle encounters simulated on a closed-course.

7.2 Methodology

In order to evaluate performance during common vehicle/pedestrian interactions anticipated to challenge pedestrian detection systems, the following scenarios were evaluated on a closed-course:

1) Child pedestrian darting into traffic from between two parked vehicles
2) Vehicle turning right on adjacent road with adult pedestrian crossing simultaneously
3) Vehicle approaching two adult pedestrians alongside the roadway

It is important to note that the owner’s manual for three of the four test vehicles specify that integrated pedestrian detection systems may not react when presented with one or more scenarios identified above.

The relevant excerpts are provided for reference:

2019 Chevrolet Malibu – pg 213: "Front Pedestrian Braking (FBP) does not provide an alert or automatically brake the vehicle unless it detects a pedestrian. FPB may not detect pedestrians, including children:

- When the pedestrian is not directly ahead, fully visible, or standing upright, or when part of a group.
- Due to poor visibility, including nighttime conditions, fog, rain, or snow…

Be ready to take action and apply the brakes."

2019 Tesla Model 3 – pg 88: "Collision Avoidance features cannot always detect all objects, vehicles, bikes, or pedestrians, and you may experience unnecessary, inaccurate, invalid, or missed warnings for many reasons, particularly if:

- The road has sharp curves.
- Visibility is poor (due to heavy rain, snow, fog, etc.).

… Warning: The limitations previously described do not represent an exhaustive list of situations that may interfere with proper operation of Collision Avoidance Assist features. These features may fail to provide their intended function for many other reasons. It is the driver's responsibility to avoid collisions by staying alert, paying attention, and taking corrective action as early as possible."

2019 Toyota Camry – pg 259: "Some pedestrians such as the following may not be detected by the radar sensor and camera sensor, preventing the system from operating properly:

- … Groups of pedestrians who are close together…
- Pedestrians in the dark, such as at night or while in a tunnel…
- Pedestrians running out from behind a vehicle or a large object"

It is acknowledged that these scenarios evaluate system performance in situations explicitly identified as problematic to the pedestrian detection system. Additionally, these situations could also prove difficult for an attentive human driver. However, it would be beneficial to understand how pedestrian detection systems respond in the context of challenging situations that can be reasonably anticipated during naturalistic driving.

Within Figures 17-37, "N/A" indicates that while the run was completed, notification and/or braking was not provided. "DNT" indicates that a run was not performed. The average of all runs where notification and/or braking was provided was calculated with respect to those runs only. For example, if braking was provided for three out of five runs, the two runs with no braking were not considered within the calculation.

7.2.1 Child Pedestrian Darting From Between Two Parked Vehicles

Children are among the most vulnerable road users, especially without attentive adult supervision. To assess the ability of evaluated pedestrian detection systems to mitigate or prevent a collision with a child pedestrian, a common scenario was simulated. Specifically, two vehicles were parked in the lane to the right of the test lane. As the test vehicle approaches, a child pedestrian target previously described in Section 4.2.4 emerges from between the two parked vehicles into the travel path of the oncoming vehicle at a speed of 3.10 mph; this is considered running speed for a typical child. The parked vehicles were midsize sedans spaced 5 feet apart and allowed for a lateral clearance of approximately 5 feet as the test vehicle passed. The movement of the pedestrian target is controlled by the 4active SB controller described in Section 4.2.1. This scenario is particularly challenging because there is no clear line of sight until the target emerges from between the parked vehicles; this equates to a TTC of 1.5-2.0 seconds for evaluated approach speeds of 20 and 30 mph. The impact point was 50% offset relative to the right front corner of the test vehicle. If the impact speed was significantly reduced via automatic braking, the impact point will be greater than 50% offset.

While challenging, the devised scenario is realistic because children can sometimes be unaware of their surroundings and unexpectedly dart into traffic from behind obstacles. Due to their small size, they can be shielded from view until they are already in the travel path of an oncoming vehicle.

It is assumed that a human driver would undoubtedly be challenged to brake in time to avoid a collision. However, it is important to understand the ability of pedestrian detection systems to assist the driver when critical situations present themselves with little to no warning; especially considering the intent of an ADAS feature such as pedestrian detection.

The test lane previously described in Section 4.4 and illustrated by Figure 6 was utilized. At the start of each test run, the test vehicle was stationary in the center of the test lane at a longitudinal distance of 350-450 feet from the pedestrian target. From this point, the test vehicle was gradually accelerated to steady-state speed and kept within the center of the lane. Once the vehicle was within four (4) seconds time-to-collision (TTC) with the pedestrian target, the vehicle speed relative to the evaluated speed and lateral deviation from the center of the lane was required to be ± 0.5 mph and 0.1 m respectively for the test run to be valid. Additionally, the brake pedal was not touched during the test run until after contact with the pedestrian target occurred or pedal application was required to keep the vehicle stationary after pedestrian target contact was avoided by the pedestrian detection system.

For each test run, the longitudinal distance and TTC from the pedestrian target was recorded upon occurrence of the following events:

- Visual alert that a collision is imminent
- Braking automatically applied by the pedestrian detection system

Within this work, automatic braking was considered to have occurred once longitudinal deceleration ≥ 0.10 G. Additionally, the impact speed or separation distance were recorded if contact with the pedestrian target occurred or the collision was avoided, respectively.

For each test vehicle, a minimum of four runs at an approach speed of 20 mph were conducted. If a visual collision notification was provided for at least one of the four runs, a fifth run at 20 mph was conducted. If braking intervention was provided for at least three runs at 20 mph, the approach speed was increased to 30 mph and five additional runs were performed.

7.2.1.1 2019 Chevrolet Malibu

20 mph					
Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Average**
Notification TTC (s)					
1.303	0.583	1.047	1.225	0.901	**1.012**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
37.10	17.06	29.92	38.89	26.41	**29.88**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
19.01	10.09	20.63	N/A	N/A	**16.58**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
0.391 @ 13.40	0.312 @ 7.22	0.353 @ 13.67	N/A	N/A	**0.352 @ 11.43**
Impact Speed (mph)					
17.1	19.9	16.6	20.5	19.5	**18.7**
Seperation Distance At End of Test (ft)					
0.0	0.0	0.0	0.0	0.0	**0.0**

Figure 17: Measurements from test runs conducted at 20 mph Image Source: AAA

At 20 mph, a visual notification was provided for each of the five runs with an average TTC of 1.012 seconds and a corresponding standard deviation of 0.256 seconds. On average, the vehicle was 29.88 feet from the pedestrian target when visual notification of a potential collision was provided. However, automatic braking did not significantly mitigate the impact speed in any of the five runs. Automatic braking only slightly reduced the impact speed for runs one and three; the average speed reduction for these runs was 3.2 mph.

30 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
0.875	N/A	1.192	0.325	0.542	**0.734**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
37.11	N/A	51.12	14.51	23.97	**31.68**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	N/A	25.79	N/A	N/A	**25.79**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
N/A	N/A	1.010 @ 1.74	N/A	N/A	**1.010 @ 1.74**
Impact Speed (mph)					
29.5	29.5	22.0	30.5	30.1	**28.3**
Seperation Distance At End of Test (ft)					
0.00	0.00	0.00	0.00	0.00	**0.00**

Figure 18: Measurements from test runs conducted at 30 mph Image Source: AAA

Five runs were conducted at 30 mph because the system provided some degree of automatic braking for three runs at 20 mph. Visual notification was provided for four out of five runs; for these runs, the average TTC was 0.734 seconds upon notification. On average, the vehicle was located 31.68 feet from the pedestrian target at this time. Automatic braking reduced the impact speed by 8.0 mph during the third run; automatic braking was not applied during the four additional runs at 30 mph.

7.2.1.2 2019 Honda Accord

20 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
N/A	0.504	0.767	0.756	0.465	**0.623**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	15.27	22.45	22.81	13.37	**18.48**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	13.49	20.39	21.06	11.66	**16.65**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
N/A	1.238 @ 0.37	1.354 @ 1.67	1.645 @ 4.16	1.439 @ 2.37	**1.419 @ 2.143**
Impact Speed (mph)					
20.4	7.2	0.0	0.0	10.7	**7.7**
Seperation Distance At End of Test (ft)					
0.0	0.0	0.8	2.4	0.0	**0.6**

Figure 19: Measurements from test runs conducted at 20 mph Image Source: AAA

At 20 mph, visual notification was provided for four out of five runs; for these runs, the average TTC was 0.623 seconds upon notification. The corresponding standard deviation was 0.139 seconds. On average, the vehicle was 18.48 feet from the pedestrian target when visual notification of a potential collision was provided. However, automatic braking significantly mitigated or avoided impact with the pedestrian target for four out of five runs. The system significantly mitigated the impact speed for two out of five runs with an average speed reduction of 11.1 mph. The system completely avoided impact for two out of five runs.

30 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
0.52	N/A	N/A	0.177	N/A	**0.349**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
22.80	N/A	N/A	7.83	N/A	**15.32**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
22.80	N/A	N/A	7.83	N/A	**15.32**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
1.251 @ 10.03	N/A	N/A	1.056 @ 1.21	N/A	**1.154 @ 5.62**
Impact Speed (mph)					
16.5	29.5	29.5	24.0	30.0	**25.9**
Seperation Distance At End of Test (ft)					
0.00	0.00	0.00	0.00	0.00	**0.00**

Figure 20: Measurements from test runs conducted at 30 mph Image Source: AAA

Five runs were conducted at 30 mph because the system provided some degree of automatic braking for at least three runs at 20 mph. Visual notification was provided for two out of five runs; for these runs, the average TTC was 0.349 seconds upon notification. On average, the vehicle was located 15.32 feet from the pedestrian target at this time. Automatic braking reduced the impact speed by an average of 9.75 mph during these runs; automatic braking was not applied during the three additional runs at 30 mph.

7.2.1.3 2019 Tesla Model 3

20 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
0.04	0.29	0.039	N/A	N/A	**0.123**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
1.32	8.60	1.29	N/A	N/A	**3.74**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	3.65	N/A	N/A	N/A	**3.65**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
N/A	0.830 @ 0.78	N/A	N/A	N/A	**0.830 @ 0.78**
Impact Speed (mph)					
19.9	18.8	19.8	20.0	19.6	**19.6**
Seperation Distance At End of Test (ft)					
0.0	0.0	0.0	0.0	0.0	**0.0**

Figure 21: Measurements from test runs conducted at 20 mph Image Source: AAA

At 20 mph, visual notification was provided for three out of five runs; for these runs, the average TTC was 0.123 seconds upon notification. The corresponding standard deviation was 0.014 seconds. On average, the vehicle was 3.74 feet from the pedestrian target when visual notification of a potential collision was provided. Automatic braking did not significantly mitigate the impact speed in any of the five runs.

30 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
DNT	DNT	DNT	DNT	DNT	**DNT**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
DNT	DNT	DNT	DNT	DNT	**DNT**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
DNT	DNT	DNT	DNT	DNT	**DNT**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
DNT	DNT	DNT	DNT	DNT	**DNT**
Impact Speed (mph)					
DNT	DNT	DNT	DNT	DNT	**DNT**
Seperation Distance At End of Test (ft)					
DNT	DNT	DNT	DNT	DNT	**DNT**

Figure 22: Measurements from test runs conducted at 30 mph Image Source: AAA

No runs were performed at 30 mph because the system failed to provide automatic braking for at least three runs at 20 mph.

7.2.1.4 2019 Toyota Camry

20 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
N/A	N/A	N/A	N/A	DNT	**N/A**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	N/A	N/A	N/A	DNT	**N/A**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	N/A	N/A	N/A	DNT	**N/A**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
N/A	N/A	N/A	N/A	DNT	**N/A**
Impact Speed (mph)					
20.2	20.0	19.8	20.2	DNT	**20.1**
Seperation Distance At End of Test (ft)					
0.0	0.0	0.0	0.0	DNT	**0.0**

Figure 23: Measurements from test runs conducted at 20 mph Image Source: AAA

At 20 mph, no notification or automatic braking was provided for any of the four runs.

30 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
DNT	DNT	DNT	DNT	DNT	**DNT**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
DNT	DNT	DNT	DNT	DNT	**DNT**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
DNT	DNT	DNT	DNT	DNT	**DNT**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
DNT	DNT	DNT	DNT	DNT	**DNT**
Impact Speed (mph)					
DNT	DNT	DNT	DNT	DNT	**DNT**
Seperation Distance At End of Test (ft)					
DNT	DNT	DNT	DNT	DNT	**DNT**

Figure 24: Measurements from test runs conducted at 30 mph Image Source: AAA

No runs were performed at 30 mph because the system failed to provide automatic braking for at least three runs at 20 mph.

7.2.1.4.1 Summary of Results

In regards to the acquisition of a child pedestrian darting out from between two parked vehicles, three out of four test vehicles failed to completely avoid a collision in any of the five runs conducted at 20 mph. Additionally, these vehicles failed to significantly mitigate the impact speed on a consistent basis. Additionally, the two test vehicles evaluated at 30 mph failed to significantly mitigate the impact speed consistently. This illustrates that while these systems can serve as a backup, they do not reliably respond to the sudden appearance of child pedestrians and drivers must maintain situational awareness at all times.

7.2.2 Vehicle Turning Right With Adult Pedestrian Crossing Simultaneously

Previous work by the Volpe Transportation Center identified prominent pre-crash vehicle/pedestrian scenarios in terms of frequency and injury severity [3]. Specifically, a vehicle making a right turn while a pedestrian crosses the road immediately after the turn was the second-most implicated pre-crash scenario, trailing only perpendicular crossing situations. The intuitive nature of this finding could be surmised based on a casual observation of many intersections found in urban and suburban areas.

To replicate this scenario, a right corner within the surface streets of Auto Club Speedway was utilized for testing. The radius of curvature was 57 feet; immediately after the curve was a straight section of roadway. The distance between the end of the curve and the pedestrian target was 11 feet. The corner utilized for this test is illustrated in Figure 8. During testing, the roadway was free of visible moisture.

Additionally, the roadway was free of potholes, bumps and other irregularities that could cause the vehicle trajectory to deviate significantly. No significant obstacles impeded visibility of the pedestrian target as the vehicle entered the curved section of roadway.

To evaluate the effectiveness of evaluated pedestrian detection systems in terms of mitigating or preventing this type of collision, the adult pedestrian target previously described in Section 4.2.3 was utilized. The target moved along the roadway atop the dynamic surfboard platform referenced in Section 4.2.1. The steady-state speed of the pedestrian target was controlled by the 4activeSB unit and was set to 3.10 mph; this is considered walking speed for the typical adult. The acceleration of the pedestrian target was selected such that steady-state speed was reached 8 feet from the centerline of the test lane. For each test, the pedestrian dummy moved from right to left across the travel path of the vehicle.

The 4activeSB controller was setup on the right side of the test lane relative to the vehicle under test. The pedestrian target platform was 10 feet from the centerline of the test lane and was activated by a GPS transmitter placed on the vehicle under test. The approach speed was pre-defined within the 4active software; this information in conjunction with the dimensions of the curved lane and the velocity of the test vehicle allowed the controller to place the pedestrian target accurately along an impact point 50% offset relative to the right front corner of the test vehicle. If the impact speed was significantly reduced via automatic braking, the impact point will be greater than 50% offset. This is a consequence of sudden speed reduction and does not constitute an invalid test run.

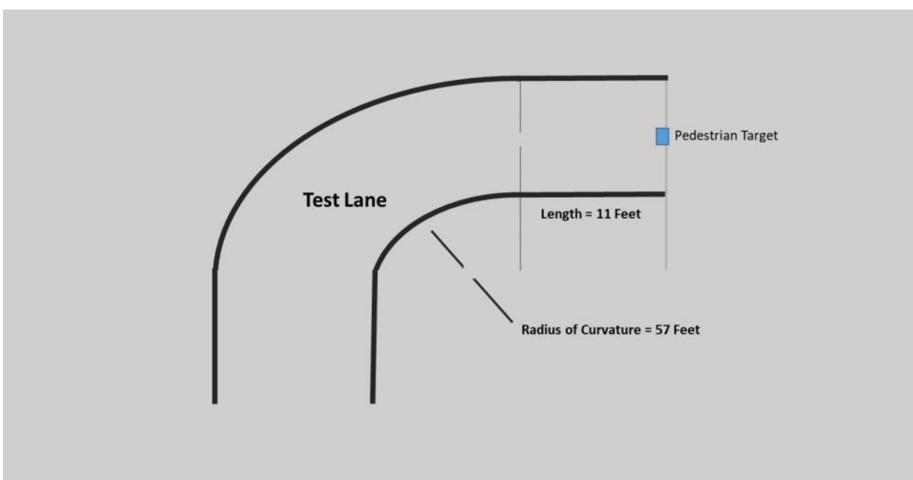

Figure 25: Illustration of test lane (not drawn to scale) Image Source: AAA

At the start of each test run, the test vehicle was stationary in the center of the test lane approximately 100-150 feet from the beginning of the right curve. From this point, the test vehicle was gradually accelerated to steady-state speed and kept within the center of the lane. Once the vehicle entered the right curve, the vehicle speed relative to the evaluated speed and lateral deviation from the center of the lane was required to be ± 1.0 mph and 0.1 m respectively for the test run to be valid. Additionally, the brake pedal was not touched during the test run until after contact with the pedestrian target occurred or pedal application was required to keep the vehicle stationary after pedestrian target contact was avoided by the pedestrian detection system.

For each test run, the longitudinal distance and TTC from the pedestrian target was recorded upon occurrence of the following events:

- Visual alert that a collision is imminent
- Braking automatically applied by the pedestrian detection system

Within this work, automatic braking was considered to have occurred once longitudinal deceleration ≥ 0.10 G. Additionally, the impact speed or separation distance were recorded if contact with the pedestrian target occurred or the collision was avoided, respectively.

A nominal approach speed of 15 mph was maintained throughout the curve and the straight section of roadway immediately preceding the pedestrian target. Five runs were performed for each test vehicle.

7.2.2.1 2019 Chevrolet Malibu

Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
0.180	N/A	0.190	0.660	0.745	**0.444**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
4.06	N/A	4.37	13.54	16.06	**9.51**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	N/A	N/A	N/A	N/A	**N/A**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
N/A	N/A	N/A	N/A	N/A	**N/A**
Impact Speed (mph)					
15.4	15.1	15.8	14.3	14.7	**15.1**
Seperation Distance At End of Test (ft)					
0.00	0.00	0.00	0.00	0.00	**0.00**

Figure 26: Measurements from test runs conducted at 15 mph Image Source: AAA

Visual notification was provided for four out of five runs; for these runs, the average TTC was 0.444 seconds upon notification. The corresponding standard deviation was 0.261 seconds. On average, the vehicle was 9.51 feet from the pedestrian target when visual notification of a potential collision was provided. Automatic braking was not applied in any of the five runs.

7.2.2.2 2019 Honda Accord

Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
N/A	N/A	N/A	N/A	N/A	**N/A**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	N/A	N/A	N/A	N/A	**N/A**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	N/A	N/A	N/A	N/A	**N/A**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
N/A	N/A	N/A	N/A	N/A	**N/A**
Impact Speed (mph)					
14.5	14.6	14.6	14.6	15.5	**14.8**
Seperation Distance At End of Test (ft)					
0.00	0.00	0.00	0.00	0.00	**0.00**

Figure 27: Measurements from test runs conducted at 15 mph Image Source: AAA

No notification or automatic braking was provided for any of the five runs.

7.2.2.3 2019 Tesla Model 3

Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
N/A	N/A	N/A	N/A	N/A	**N/A**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	N/A	N/A	N/A	N/A	**N/A**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	N/A	N/A	N/A	N/A	**N/A**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
N/A	N/A	N/A	N/A	N/A	**N/A**
Impact Speed (mph)					
14.1	14.4	14.1	14.0	14.2	**14.2**
Seperation Distance At End of Test (ft)					
0.00	0.00	0.00	0.00	0.00	**0.00**

Figure 28: Measurements from test runs conducted at 15 mph Image Source: AAA

No notification or automatic braking was provided for any of the five runs.

7.2.2.4 2019 Toyota Camry

Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
N/A	N/A	N/A	N/A	N/A	**N/A**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	N/A	N/A	N/A	N/A	**N/A**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	N/A	N/A	N/A	N/A	**N/A**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
N/A	N/A	N/A	N/A	N/A	**N/A**
Impact Speed (mph)					
14.6	14.9	14.6	14.7	15.0	**14.8**
Seperation Distance At End of Test (ft)					
0.00	0.00	0.00	0.00	0.00	**0.00**

Figure 29: Measurements from test runs conducted at 15 mph Image Source: AAA

No notification or automatic braking was provided for any of the five runs.

7.2.2.4.1 Summary of Test Results

When a pedestrian target was located immediately after a right curve, all test vehicles failed to apply any degree of automatic braking. This demonstrates that evaluated pedestrian detection systems were not designed to react to pedestrians when the vehicle is traveling in a curvilinear motion.

7.2.3 Two Adult Pedestrians Alongside Roadway

A vehicle colliding with a pedestrian walking alongside the roadway with or against traffic was identified as the fourth most common crash scenario involving pedestrians [3]. This type of encounter can prove challenging to pedestrian detection systems because the person's silhouette is less distinguishable to the system when observed from the front or rear and can also blend into the surroundings alongside the roadway. Additionally, a pedestrian walking in a perpendicular direction is easier to identify because of their gait.

In conjunction with the challenges presented by one pedestrian walking alongside the roadway, two or more pedestrians walking together are even more challenging because their combined silhouettes become ambiguous in terms of their appearance to the image sensor(s). This is an important consideration because it is commonplace for pedestrians to walk in close proximity.

To evaluate the ability of tested pedestrian detection systems to respond a group of pedestrians partially in the travel path, the static adult pedestrian target and articulated adult pedestrian target described in Sections 4.2.2 and 4.2.3, respectively, were utilized. The static target was placed in the test lane such that the impact point would be 25% offset from the right front corner of the test vehicle. The articulated target was placed just to the right of the testing lane such that the right front corner of the test vehicle would have a lateral clearance of approximately 1.5 feet at the impact point. Both targets were placed such that their "backs" were turned toward the oncoming test vehicle. While the articulated target was utilized, it was static for this test scenario.

It is acknowledged that two static pedestrians partially in the roadway is not a statistically common pre-crash scenario. However, this is a reasonable simulation of two dynamic pedestrians because from the perspective of the oncoming vehicle, their silhouettes are not likely to appear significantly different from walking pedestrians in terms of discernable gait.

The test lane previously described in Section 4.4 and illustrated by Figure 6 was utilized. Each test run was initialized and subject to tolerances according to the methodology previously described in Section 6.2. For each test vehicle, five runs at an approach speed of 20 mph were performed. If braking was automatically applied for at least one test run, five additional runs at an approach speed of 30 mph were performed.

7.2.3.1 2019 Chevrolet Malibu

20 mph					
Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Average**
Notification TTC (s)					
3.871	2.989	3.323	3.514	3.690	**3.477**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
111.29	87.20	96.49	100.49	112.83	**101.66**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
40.68	34.78	35.47	36.91	28.12	**35.19**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
1.469 @ 6.89	0.829 @ 29.63	0.866 @ 30.35	0.865 @ 31.63	0.805 @ 23.26	**0.967 @ 24.35**
Impact Speed (mph)					
14.3	17.6	17.6	15.5	14.6	**15.9**
Seperation Distance At End of Test (ft)					
0.00	0.00	0.00	0.00	0.00	**0.00**

Figure 30: Measurements from test runs conducted at 20 mph Image Source: AAA

At 20 mph, a visual notification was provided for each of the five runs with an average TTC of 3.477 seconds and a corresponding standard deviation of 0.305 seconds. On average, the vehicle was 101.66 feet from the pedestrian target when visual notification of a potential collision was provided. However, automatic braking only slightly mitigated the impact speed for each of the five runs. The average speed reduction was 4.1 mph.

30 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
3.066	3.617	3.076	4.136	3.478	**3.475**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
134.91	160.02	134.29	183.26	152.74	**153.04**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
51.79	41.48	53.65	43.19	37.06	**45.43**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
0.752 @ 44.04	0.769 @ 34.40	0.714 @ 45.88	0.836 @ 37.11	0.736 @ 30.57	**0.761 @ 38.4**
Impact Speed (mph)					
27.0	28.2	27.0	28.5	29.4	**28.0**
Seperation Distance At End of Test (ft)					
0.00	0.00	0.00	0.00	0.00	**0.00**

Figure 31: Measurements from test runs conducted at 30 mph Image Source: AAA

At 30 mph, a visual notification was provided for each of the five runs with an average TTC of 3.475 seconds and a corresponding standard deviation of 0.396 seconds. On average, the vehicle was 153.04 feet from the pedestrian target when visual notification of a potential collision was provided. However, automatic braking only slightly mitigated the impact speed for each of the five runs. The average speed reduction was 2.0 mph.

7.2.3.2 2019 Honda Accord

20 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
0.088	1.330	0.147	0.504	0.357	**0.485**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
1.80	39.00	4.46	15.12	10.49	**14.17**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	32.58	N/A	11.55	8.14	**17.42**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
N/A	0.873 @ 6.55	N/A	0.175 @ 3.70	0.614 @ 2.43	**0.554 @ 4.23**
Impact Speed (mph)					
20.5	0.0	20.5	19.1	17.2	**15.5**
Seperation Distance At End of Test (ft)					
0.00	4.23	0.00	0.00	0.00	**0.85**

Figure 32: Measurements from test runs conducted at 20 mph Image Source: AAA

At 20 mph, a visual notification was provided for each of the five runs with an average TTC of 0.485 seconds and a corresponding standard deviation of 0.448 seconds. On average, the vehicle was 14.17 feet from the pedestrian target when visual notification of a potential collision was provided.

Automatic braking avoided a collision for one of the five runs and slightly mitigated the impact speed for an additional run; the speed reduction in this case was 2.8 mph. The impact speed was not significantly reduced for the remaining three runs.

30 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
1.053	0.963	1.271	0.807	0.392	**0.897**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
45.86	41.90	56.79	35.89	17.16	**39.52**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
23.13	14.98	51.85	22.67	12.80	**25.09**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
1.048 @ 3.39	0.456 @ 1.04	0.947 @ 10.04	0.600 @ 2.19	0.228 @ 11.51	**0.656 @ 5.63**
Impact Speed (mph)					
19.2	28.3	0.0	27.6	29.2	**20.9**
Seperation Distance At End of Test (ft)					
0.00	0.00	5.28	0.00	0.00	**1.06**

Figure 33: Measurements from test runs conducted at 30 mph Image Source: AAA

At 30 mph, a visual notification was provided for each of the five runs with an average TTC of 0.897 seconds and a corresponding standard deviation of 0.294 seconds. On average, the vehicle was 39.52 feet from the pedestrian target when visual notification of a potential collision was provided. Automatic braking avoided a collision for one of the five runs and mitigated the impact speed for an additional run; the speed reduction in this case was 10.8 mph. The impact speed was slightly reduced for the second and fourth runs; the average speed reduction for these runs was 2.1 mph.

7.2.3.3 2019 Tesla Model 3

20 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
2.330	4.166	4.774	4.861	4.829	**4.192**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
67.90	120.54	139.91	142.64	142.40	**122.68**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
N/A	N/A	N/A	N/A	N/A	**N/A**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
N/A	N/A	N/A	N/A	N/A	**N/A**
Impact Speed (mph)					
20.5	19.9	19.5	20.2	20.1	**20.0**
Seperation Distance At End of Test (ft)					
0.0	0.0	0.0	0.0	0.0	**0.00**

Figure 34: Measurements from test runs conducted at 20 mph Image Source: AAA

At 20 mph, a visual notification was provided for each of the five runs with an average TTC of 4.192 seconds and a corresponding standard deviation of 0.965 seconds. On average, the vehicle was 122.68 feet from the pedestrian target when visual notification of a potential collision was provided. However, automatic braking was not provided for any of the five runs.

30 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
DNT	DNT	DNT	DNT	DNT	**DNT**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
DNT	DNT	DNT	DNT	DNT	**DNT**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
DNT	DNT	DNT	DNT	DNT	**DNT**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
DNT	DNT	DNT	DNT	DNT	**DNT**
Impact Speed (mph)					
DNT	DNT	DNT	DNT	DNT	**DNT**
Seperation Distance At End of Test (ft)					
DNT	DNT	DNT	DNT	DNT	**DNT**

Figure 35: Measurements from test runs conducted at 30 mph Image Source: AAA

No runs were performed at 30 mph because the system failed to provide automatic braking for at least one run at 20 mph.

7.2.3.4 2019 Toyota Camry

20 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
1.911	N/A	1.334	N/A	1.158	**1.468**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
57.33	N/A	39.17	N/A	33.96	**43.49**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
30.43	N/A	29.80	N/A	23.95	**28.06**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
0.761 @ 22.45	N/A	0.769 @ 20.79	N/A	1.418 @ 6.71	**0.982 @ 16.65**
Impact Speed (mph)					
0.0	19.8	0.0	20.1	0.0	**8.0**
Seperation Distance At End of Test (ft)					
2.52	0.00	2.63	0.00	1.48	**1.33**

Figure 36: Measurements from test runs conducted at 20 mph Image Source: AAA

At 20 mph, visual notification was provided for three out of five runs; for these runs, the average TTC was 1.468 seconds upon notification. The corresponding standard deviation was 0.322 seconds. On average, the vehicle was 43.49 feet from the pedestrian target when visual notification of a potential collision was provided. For the three runs where notification was provided, automatic braking avoided impact with the pedestrian targets. No automatic braking was provided for the remaining two runs.

30 mph					
Run 1	Run 2	Run 3	Run 4	Run 5	Average
Notification TTC (s)					
1.304	0.400	N/A	0.664	N/A	**0.789**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)					
57.5	17.76	N/A	14.62	N/A	**29.96**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)					
43.38	8.9	N/A	N/A	N/A	**26.14**
Max Deceleration (G)/Associated Longitudinal Distance (ft)					
1.368 @ 10.29	0.450 @ 0.98	N/A	N/A	N/A	**0.909 @ 5.64**
Impact Speed (mph)					
5.1	29.2	30.3	30.3	29.7	**24.9**
Seperation Distance At End of Test (ft)					
0.00	0.00	0.00	0.00	0.00	**0.00**

Figure 37: Measurements from test runs conducted at 30 mph Image Source: AAA

At 30 mph, visual notification was provided for three out of five runs; for these runs, the average TTC was 0.789 seconds upon notification. The corresponding standard deviation was 0.380 seconds. On average, the vehicle was 29.96 feet from the pedestrian target when visual notification of a potential collision was provided. Automatic braked significantly mitigated the impact speed for one run, the speed reduction in this case was 24.9 mph. The impact speed was not significantly reduced for the remaining four runs.

7.2.3.4.1 Summary of Test Results

When approaching two pedestrian targets alongside the roadway, two out of four test vehicles failed to completely avoid a collision in any of the five runs conducted at 20 mph. When impact occurred, the reduction in impact speed (if any) was minimal. This finding also applies to vehicles that completely avoided a collision during at least one run.

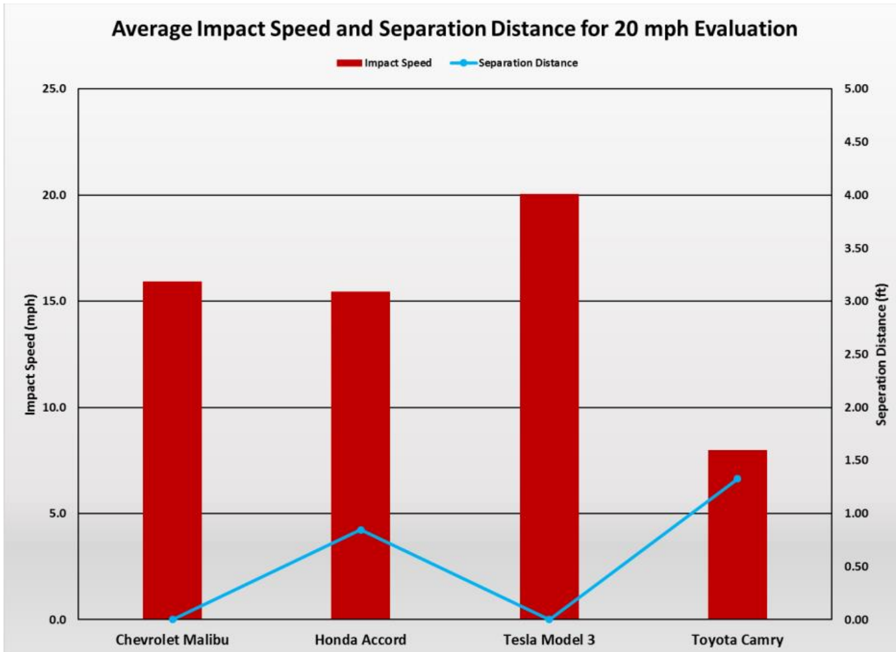

Figure 38: Average Impact Speed (mph) and Separation Distance (ft) at 20 mph Image Source: AAA

When evaluated at 30 mph, all test vehicles failed to significantly mitigate the impact speed on a consistent basis. This test scenario demonstrates that evaluated pedestrian detection systems struggle when approaching more than one pedestrian in a parallel direction alongside the roadway.

7.3 Overall Summary of Test Results

On average, all evaluated pedestrian detection systems were significantly challenged and struggled to consistently mitigate or prevent collisions with pedestrian targets during scenarios described in Sections 7.2.1 through 7.2.3. These findings are largely consistent with system limitations described within the owner's manual of each test vehicle. As such, drivers are strongly urged to familiarize themselves with proper operation and limitations of any ADAS features present within their vehicle.

8 Inquiry 3: How do pedestrian detection systems function at night?

8.1 Objective

Evaluate the ability of tested pedestrian detection systems to mitigate or avoid vehicle/pedestrian conditions within low ambient light environments.

8.2 Methodology

According to the NHTSA, most pedestrian fatalities take place at night away from intersections [1]. Over the past 10 years, nighttime crashes accounted for more than 90% of the total increase in pedestrian deaths [9]. A literature review suggests that there is little to no publicly available information regarding the performance of pedestrian detection systems in low-light conditions. Based on vehicle/pedestrian crash statistics, this environment is especially critical to evaluate. One of the primary purposes of this work is to provide information about how commonly available pedestrian detection systems perform during low-light conditions.

It is acknowledged that the owner's manual of each test vehicle states that the integrated pedestrian detection system may not discern pedestrians at night or in adverse weather such as rain, snow, sleet or fog. However, it is irrefutable that assistance from a pedestrian detection system would be of benefit during nighttime conditions and could possibly be the time of greatest need.

To evaluate the performance of tested pedestrian detection systems in low-light conditions, the methodology described in Section 6.2 was repeated with the exception of evaluated approach speeds. An approach speed of 25 mph was evaluated for this scenario. No ambient street lighting was present; while this parameter is very challenging, it is nonetheless a reasonable test scenario considering the lack of lighting in many naturalistic environments. For each vehicle, four runs were performed. The low-beam headlights were engaged for each test run. Testing commenced one hour after sunset. On the night of testing, a waxing gibbous moon was clearly seen with minimal cloud cover.

8.3 Test Results

Within Figures 39-42, "N/A" indicates that while the run was completed, notification and/or braking was not provided.

8.3.1 2019 Chevrolet Malibu

Run 1	Run 2	Run 3	Run 4	Average
Notification TTC (s)				
N/A	N/A	N/A	N/A	**N/A**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)				
N/A	N/A	N/A	N/A	**N/A**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)				
N/A	N/A	N/A	N/A	**N/A**
Max Deceleration (G)/Associated Longitudinal Distance (ft)				
N/A	N/A	N/A	N/A	**N/A**
Impact Speed (mph)				
24.5	24.5	24.6	24.7	**24.6**
Seperation Distance At End of Test (ft)				
0.00	0.00	0.00	0.00	**0.00**

Figure 39: Measurements from test runs conducted at 25 mph Image Source: AAA

No notification or automatic braking was provided for any of the four (4) runs.

8.3.2 2019 Honda Accord

Run 1	Run 2	Run 3	Run 4	Average
Notification TTC (s)				
N/A	N/A	N/A	N/A	**N/A**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)				
N/A	N/A	N/A	N/A	**N/A**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)				
N/A	N/A	N/A	N/A	**N/A**
Max Deceleration (G)/Associated Longitudinal Distance (ft)				
N/A	N/A	N/A	N/A	**N/A**
Impact Speed (mph)				
24.5	24.5	24.8	24.6	**24.6**
Seperation Distance At End of Test (ft)				
0.00	0.00	0.00	0.00	**0.00**

Figure 40: Measurements from test runs conducted at 25 mph Image Source: AAA

No notification or automatic braking was provided for any of the four (4) runs.

8.3.3 2019 Tesla Model 3

Run 1	Run 2	Run 3	Run 4	Average
Notification TTC (s)				
N/A	N/A	N/A	N/A	**N/A**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)				
N/A	N/A	N/A	N/A	**N/A**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)				
N/A	N/A	N/A	N/A	**N/A**
Max Deceleration (G)/Associated Longitudinal Distance (ft)				
N/A	N/A	N/A	N/A	**N/A**
Impact Speed (mph)				
24.6	24.5	25.0	24.6	**24.7**
Seperation Distance At End of Test (ft)				
0.00	0.00	0.00	0.00	**0.00**

Figure 41: Measurements from test runs conducted at 25 mph Image Source: AAA

No notification or automatic braking was provided for any of the four (4) runs.

8.3.4 2019 Toyota Camry

Run 1	Run 2	Run 3	Run 4	Average
Notification TTC (s)				
N/A	N/A	N/A	N/A	**N/A**
Notification Longitudinal Distance (ft) (Vehicle to Dummy)				
N/A	N/A	N/A	N/A	**N/A**
Braking Longitudinal Distance (ft) (Vehicle to Dummy)				
N/A	N/A	N/A	N/A	**N/A**
Max Deceleration (G)/Associated Longitudinal Distance (ft)				
N/A	N/A	N/A	N/A	**N/A**
Impact Speed (mph)				
24.1	25.3	24.0	24.7	**24.5**
Seperation Distance At End of Test (ft)				
0.00	0.00	0.00	0.00	**0.00**

Figure 42: Measurements from test runs conducted at 25 mph Image Source: AAA

No notification or automatic braking was provided for any of the four (4) runs.

8.4 Summary of Test Results

Evaluated pedestrian detection systems were found to be ineffective within a low-ambient light environment. This finding is consistent with limitations described within the owner's manual of each test vehicle.

It is important to note that test conditions were representative of a roadway with no streetlights; testing was conducted at an approach speed of 25 mph; this is a typical speed limit in many residential areas that may or may not have street lighting. This test illustrates that drivers must not rely on assistance from current pedestrian detection systems during nighttime driving or other environments with reduced visibility.

Previous AAA research found that cloudy or yellowed headlights generate only 20% of the light originally generated when they were new. This finding in conjunction with the results presented in Section 8.3 underscores the need for motorists to check their headlights for signs of deterioration and to be aware of limitations inherent to any ADAS features integrated into their vehicle.

9 Key Findings

1. When encountering an adult pedestrian in a perpendicular crossing scenario:
    a. Each test vehicle provided visual notification of an impending collision during each test run conducted at 20 mph.
        i. In aggregate, a collision with an adult pedestrian target was avoided 40% of the time

        ii. During an additional 35% of the time, collisions were mitigated by an average speed of 4.4 mph
    b. At 30 mph, three out of four test vehicles failed to reduce the impact speed by at least 5 mph during the initial test run.
2. Evaluated pedestrian detection systems were significantly challenged in the following scenarios:
    a. When encountering a child pedestrian at 20 mph, a collision was avoided 11% of the time in aggregate. An additional 25% of the time, collisions were mitigated by an average speed of 5.9 mph.
    b. When encountering a pedestrian immediately after a right curve, none of the test vehicles mitigated the impact speed during any of the five test runs.
    c. When encountering two pedestrians alongside the roadway at 20 mph, a collision was avoided 20% of the time in aggregate. An additional 35% of the time, collisions were mitigated by an average speed of 3.4 mph.
3. Evaluated pedestrian detection systems were ineffective during nighttime conditions.

10 Summary Recommendations

1. Never rely on pedestrian detection systems to avoid a collision. These systems serve as a backup rather than a primary means of collision avoidance.
2. Drivers should familiarize themselves with proper operation of any ADAS features found within their vehicle as well as any system limitations. This information can be found within the owner's manual.
3. Improved effectiveness in nighttime conditions would significantly enhance the functionality of currently available pedestrian detection systems.

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