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AUTOMATIC EMERGENCY BRAKING PERFORMANCE IN THE CONTEXT OF COMMON CRASH SCENARIOS

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ABSTRACT

In collaboration with the National Highway Traffic Safety Administration (NHTSA), twenty automakers have voluntarily agreed to equip their passenger vehicles with Automatic Emergency Braking (AEB) systems as standard equipment by September 1, 2022. As these systems become commonplace on new vehicles, it is important that consumers understand system performance and limitations in a variety of common scenarios. To evaluate the performance of current AEB systems, four popular vehicles equipped with an AEB system as standard equipment were evaluated in a variety of common scenarios within a closed-course environment.

Research Questions:

1. How do evaluated AEB systems perform when encountering a stationary vehicle ahead at speeds of 30 and 40 mph?
2. How do evaluated AEB systems perform when encountering moving vehicles in collision scenarios involving an intersection?
    a. Test and target vehicles in a perpendicular collision scenario (T-bone)
    b. Test vehicle turning left in front of oncoming target vehicle (Unprotected left turn)

Key Findings:

1. How do evaluated AEB systems perform when encountering a stationary vehicle ahead?
    a. At a steady-state approach speed of 30 mph, evaluated AEB systems prevented a collision for 17 of 20 test runs, in aggregate. For test runs that resulted in a collision, the impact speed was reduced by an average of 86 percent.
    b. At a steady-state approach speed of 40 mph, evaluated AEB systems prevented a collision for 6 of 20 test runs, in aggregate. For test runs that resulted in a collision, the impact speed was reduced by an average of 62 percent.
2. How do evaluated AEB systems perform when encountering moving vehicles in collision scenarios involving an intersection?
    a. For a perpendicular collision scenario, an unmitigated collision occurred for 100 percent of test runs, in aggregate.
    b. For a collision scenario involving a left turn in front of an oncoming vehicle, an unmitigated collision occurred for 100 percent of test runs, in aggregate.

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CONTENTS

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I. INTRODUCTION

Automatic Emergency Braking (AEB) systems were first introduced on the Japanese-market Honda Inspire with its Collision Mitigation Brake System and the Mercedes-Benz S-Class with PRE-SAFE®, both in 2003. Since then, AEB has become increasingly common on vehicles across various price points. This progress was escalated on March 17, 2016, when NHTSA and the Insurance Institute for Highway Safety (IIHS) announced a voluntary commitment by twenty automakers, representing more than 99 percent of the U.S. auto market, to make AEB standard across their vehicle lineup by September 1, 2022 [1]. According to Consumer Reports, 83 percent of 2022 model year vehicles sold in the U.S. are equipped with AEB as standard equipment. This figure has substantially grown during recent years; likely a result of preparations required to meet the commitment date. For context, only 31 percent of 2018 model year vehicles came with AEB as standard equipment. In addition to increasing standardization in new vehicles, the prevalence of AEB systems will continue to increase as older vehicles are retired.

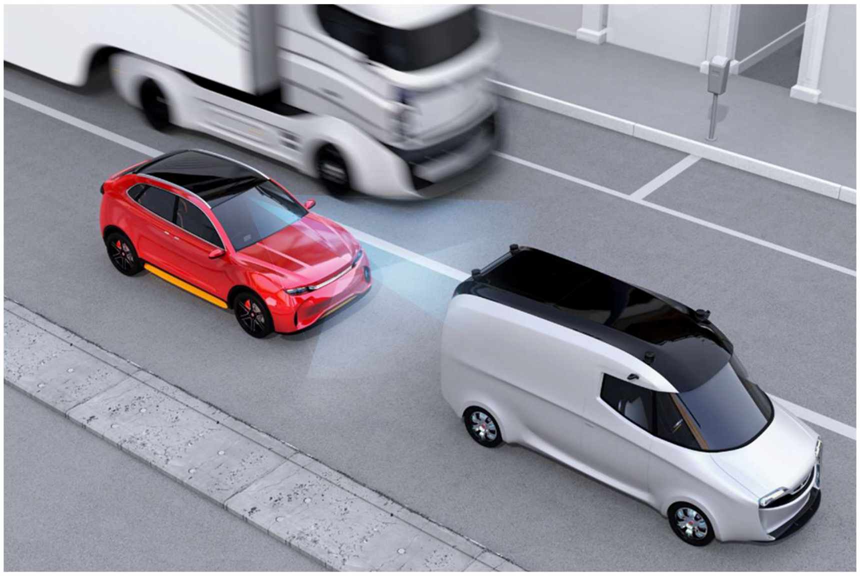

Figure 1: Automatic Emergency Braking systems gaining widespread prevalence Image Source: AAA

Widespread inclusion of AEB across the U.S. vehicle fleet has the potential to prevent a significant number of injuries and fatalities. Previous research by IIHS found that vehicles equipped with AEB exhibited a 50 percent decrease of police-reported rear-end crashes relative to equivalent vehicles without an AEB system [2]. These figures take into account police-reported rear-end crashes with or without injury in twenty-two states during 2010–2015 for six makes.

This documented reduction in rear-end crash rates are specific to considerably earlier forms of AEB in terms of age as well as refined hardware and software design iterations released since. It could be hypothesized that current AEB systems like those characterized in this work would exhibit improved performance relative to their predecessors. This would represent enormous benefit in relation to prevented fatalities, decreased injury occurrence and severity, in addition to decreased economic impact. To better understand the benefits and limitations of current AEB system design, it is essential that system performance be characterized and tested against common scenarios encountered in naturalistic environments.

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II. BACKGROUND

The concept of an automatic braking system was first explored in the 1950s with the technology featured on the 1959 Cadillac Cyclone. While this vehicle was only a concept and not suitable for mass production, the idea of an automatic collision avoidance system was the precursor to AEB systems available today. Resulting from the discovery of civilian applications for radar technology and continued refinement in the ensuing decades, the first production system was introduced on the fourth-generation Honda Inspire with the Collision Mitigation Braking System. Other manufacturers quickly released their own versions of AEB in parallel to other types of advanced driver assistance systems (ADAS). A detailed narrative of hardware and software design considerations in the context of ADAS is outside the scope of this work; for a general overview, refer to Section 2.2 of the Active Driving Assistance research report on the AAA NewsRoom.

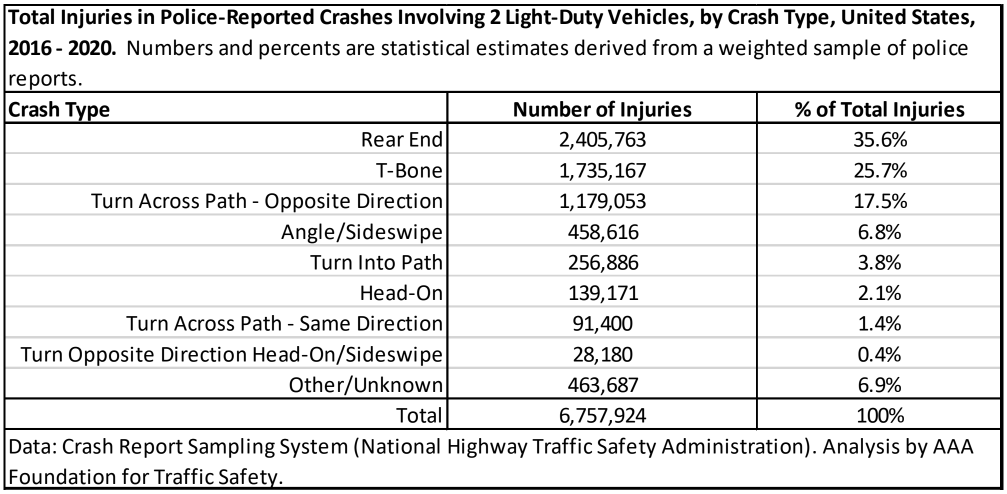
As previously described, 2010–2015 model year AEB systems have demonstrated measurable benefit in terms of reducing the occurrence of police-reported rear-end crashes and resulting fatalities, personal injury, and property damage. Regarding ADAS in totality, AEB systems are among the most effective at preventing or mitigating crashes of varying severity. Compared to a 50 percent reduction in total police-reported rear-end crashes for vehicles equipped with AEB, vehicles equipped with lane departure warning systems exhibited an 11 percent decrease in single-vehicle, sideswipe, and head-on crashes relative to equivalent vehicles without the technology [3].

To understand the performance of current AEB systems within the scope of common crash scenarios that may be reasonably prevented or mitigated by the technology, AAA selected four common vehicles that were equipped with an AEB system as standard equipment for evaluation. Data from NHTSA’s Crash Report Sampling System (CRSS) and Fatality Analysis Reporting System (FARS) were utilized to inform the design of closed-course test scenarios. CRSS obtains its data from a nationally representative probability sample of police-reported crashes involving all types of motor vehicles, pedestrians, and cyclists, ranging from property-damage-only crashes to those that result in fatalities [4]. In contrast, FARS is a nationwide census providing yearly data regarding fatal injuries suffered in motor vehicle traffic crashes [5].

The AAA Foundation for Traffic Safety analyzed 2016–2020 CRSS and FARS data involving crashes that could be reasonably prevented or mitigated by an AEB system. To meet this objective, crashes were required to meet all of the following criteria to be included within analysis:

- Involved vehicles were passenger vehicles i.e., car, light pickup truck, SUV, crossover, vans
- The first impact of the striking vehicle was with another stationary or moving passenger vehicle
- Exactly two passenger vehicles were involved in the first impact
- Striking vehicle was tracking (no traction loss) prior to first impact
- Striking vehicle was on the roadway prior to first impact
- Striking vehicle did not leave and return to the roadway prior to first impact

Injury estimates and fatalities for included crashes with respect to type, speed limit, and lighting condition are provided in Figures 2–7. It is important to note that injury and fatality figures provided herein do not account for crashes outside of the specified analysis criteria.

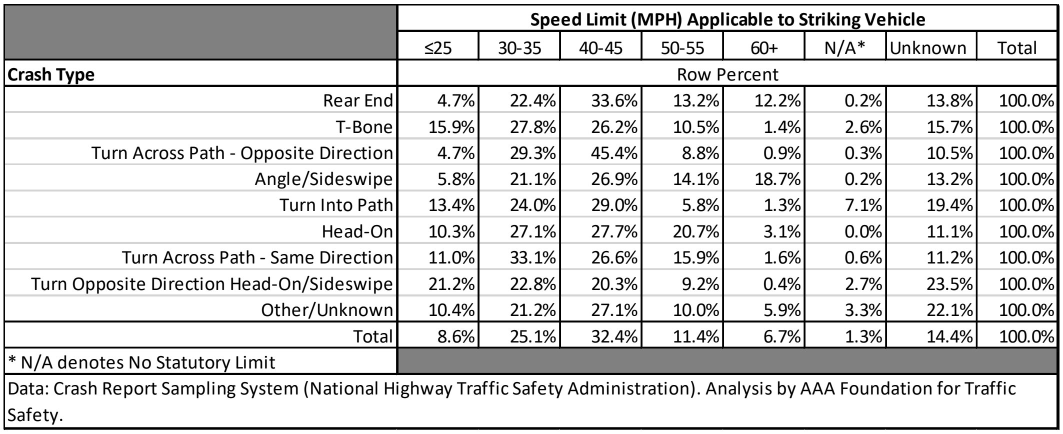


Total Injuries in Police-Reported Crashes Involving 2 Light-Duty Vehicles, by Crash Type, United States, 2016 - 2020. Numbers and percents are statistical estimates derived from a weighted sample of police reports.

Crash Type	Number of Injuries	% of Total Injuries
Rear End	2,405,763	35.6%
T-Bone	1,735,167	25.7%
Turn Across Path - Opposite Direction	1,179,053	17.5%
Angle/Sideswipe	458,616	6.8%
Turn Into Path	256,886	3.8%
Head-On	139,171	2.1%
Turn Across Path - Same Direction	91,400	1.4%
Turn Opposite Direction Head-On/Sideswipe	28,180	0.4%
Other/Unknown	463,687	6.9%
Total	6,757,924	100%

Data: Crash Report Sampling System (National Highway Traffic Safety Administration). Analysis by AAA Foundation for Traffic Safety.

Figure 2: Total injuries with respect to crash type Image Source: AAA

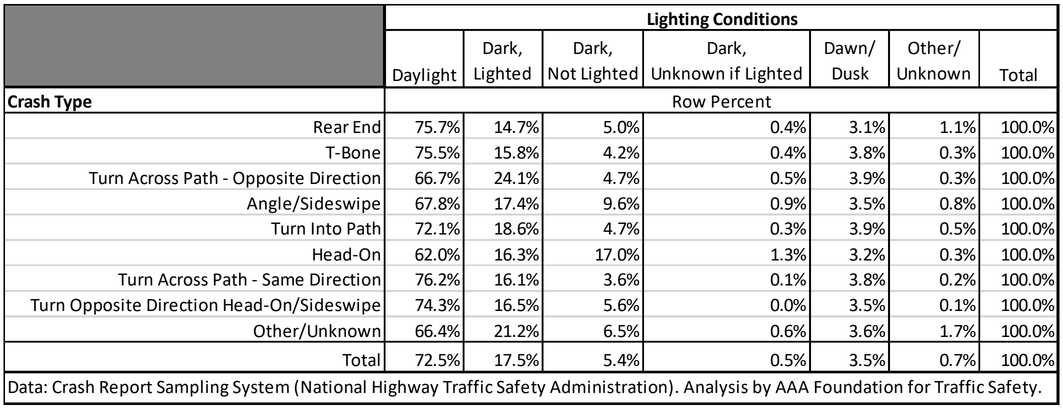


	Speed Limit (MPH) Applicable to Striking Vehicle							
	≤25	30-35	40-45	50-55	60+	N/A*	Unknown	Total
Crash Type	Row Percent							
Rear End	4.7%	22.4%	33.6%	13.2%	12.2%	0.2%	13.8%	100.0%
T-Bone	15.9%	27.8%	26.2%	10.5%	1.4%	2.6%	15.7%	100.0%
Turn Across Path - Opposite Direction	4.7%	29.3%	45.4%	8.8%	0.9%	0.3%	10.5%	100.0%
Angle/Sideswipe	5.8%	21.1%	26.9%	14.1%	18.7%	0.2%	13.2%	100.0%
Turn Into Path	13.4%	24.0%	29.0%	5.8%	1.3%	7.1%	19.4%	100.0%
Head-On	10.3%	27.1%	27.7%	20.7%	3.1%	0.0%	11.1%	100.0%
Turn Across Path - Same Direction	11.0%	33.1%	26.6%	15.9%	1.6%	0.6%	11.2%	100.0%
Turn Opposite Direction Head-On/Sideswipe	21.2%	22.8%	20.3%	9.2%	0.4%	2.7%	23.5%	100.0%
Other/Unknown	10.4%	21.2%	27.1%	10.0%	5.9%	3.3%	22.1%	100.0%
Total	8.6%	25.1%	32.4%	11.4%	6.7%	1.3%	14.4%	100.0%

* N/A denotes No Statutory Limit

Data: Crash Report Sampling System (National Highway Traffic Safety Administration). Analysis by AAA Foundation for Traffic Safety.

Figure 3: Percent distribution of injuries with respect to speed limit Image Source: AAA



	Lighting Conditions						
	Daylight	Dark, Lighted	Dark, Not Lighted	Dark, Unknown if Lighted	Dawn/ Dusk	Other/ Unknown	Total
Crash Type	Row Percent						
Rear End	75.7%	14.7%	5.0%	0.4%	3.1%	1.1%	100.0%
T-Bone	75.5%	15.8%	4.2%	0.4%	3.8%	0.3%	100.0%
Turn Across Path - Opposite Direction	66.7%	24.1%	4.7%	0.5%	3.9%	0.3%	100.0%
Angle/Sideswipe	67.8%	17.4%	9.6%	0.9%	3.5%	0.8%	100.0%
Turn Into Path	72.1%	18.6%	4.7%	0.3%	3.9%	0.5%	100.0%
Head-On	62.0%	16.3%	17.0%	1.3%	3.2%	0.3%	100.0%
Turn Across Path - Same Direction	76.2%	16.1%	3.6%	0.1%	3.8%	0.2%	100.0%
Turn Opposite Direction Head-On/Sideswipe	74.3%	16.5%	5.6%	0.0%	3.5%	0.1%	100.0%
Other/Unknown	66.4%	21.2%	6.5%	0.6%	3.6%	1.7%	100.0%
Total	72.5%	17.5%	5.4%	0.5%	3.5%	0.7%	100.0%

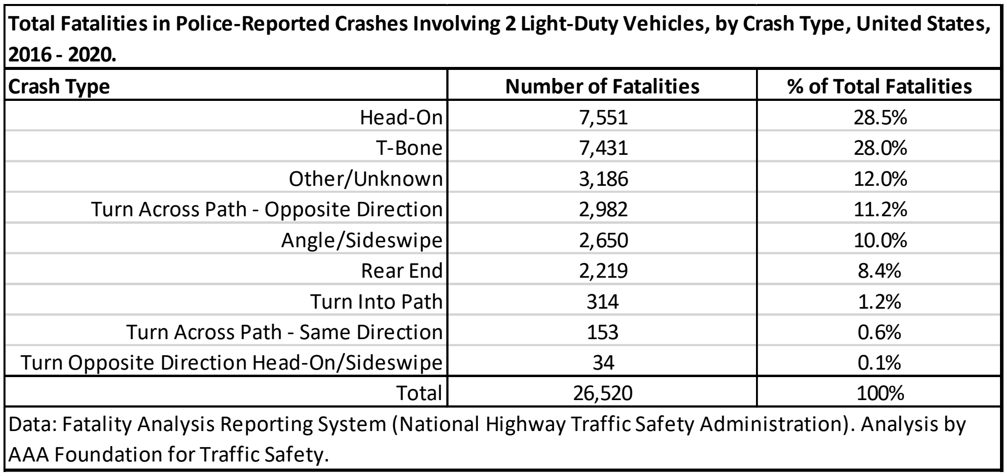
Data: Crash Report Sampling System (National Highway Traffic Safety Administration). Analysis by AAA Foundation for Traffic Safety.

Figure 4: Percent distribution of injuries with respect to lighting condition Image Source: AAA

In aggregate, the following three crash types are responsible for 79 percent of injuries among analyzed crashes:

- Rear-end crashes
- T-Bone (90° incident angle) crashes
- Crashes involving one vehicle turning across the path of an oncoming striking vehicle

Among these crash types involving injury, 60 percent occur on roadways with speed limits of 30-45 mph. AEB performance evaluations have historically focused on lower testing speeds that do not align with posted speed limits at which these incidents commonly occur. AAA strongly advocates for system testing that reasonably accounts for rear-world crash scenarios, rather than exclusively designing test standards around known system capabilities. Lighting condition is another significant consideration for representative system evaluation. Among injury-causing crash types previously identified, 74 percent occur in daylight conditions.

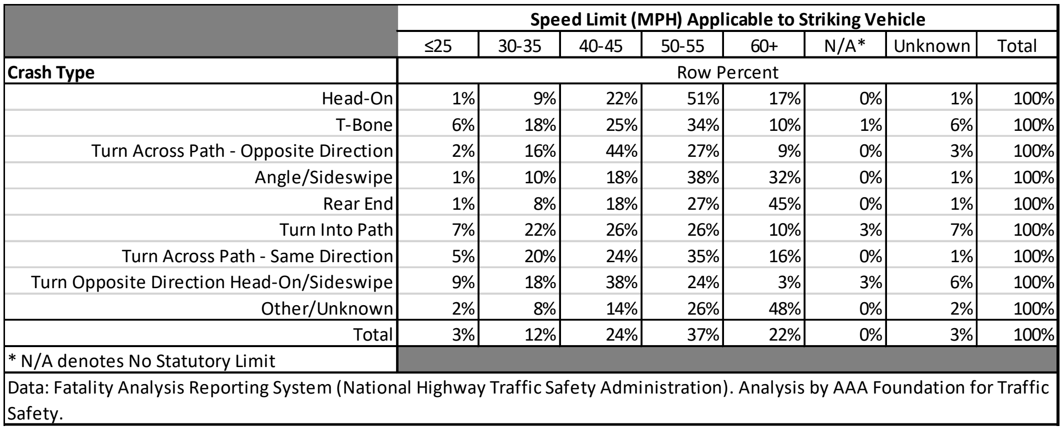


Total Fatalities in Police-Reported Crashes Involving 2 Light-Duty Vehicles, by Crash Type, United States, 2016 - 2020.

Crash Type	Number of Fatalities	% of Total Fatalities
Head-On	7,551	28.5%
T-Bone	7,431	28.0%
Other/Unknown	3,186	12.0%
Turn Across Path - Opposite Direction	2,982	11.2%
Angle/Sideswipe	2,650	10.0%
Rear End	2,219	8.4%
Turn Into Path	314	1.2%
Turn Across Path - Same Direction	153	0.6%
Turn Opposite Direction Head-On/Sideswipe	34	0.1%
Total	26,520	100%

Data: Fatality Analysis Reporting System (National Highway Traffic Safety Administration). Analysis by AAA Foundation for Traffic Safety.

Figure 5: Total fatalities with respect to crash type Image Source: AAA



	Speed Limit (MPH) Applicable to Striking Vehicle							
	≤25	30-35	40-45	50-55	60+	N/A*	Unknown	Total
Crash Type	Row Percent							
Head-On	1%	9%	22%	51%	17%	0%	1%	100%
T-Bone	6%	18%	25%	34%	10%	1%	6%	100%
Turn Across Path - Opposite Direction	2%	16%	44%	27%	9%	0%	3%	100%
Angle/Sideswipe	1%	10%	18%	38%	32%	0%	1%	100%
Rear End	1%	8%	18%	27%	45%	0%	1%	100%
Turn Into Path	7%	22%	26%	26%	10%	3%	7%	100%
Turn Across Path - Same Direction	5%	20%	24%	35%	16%	0%	1%	100%
Turn Opposite Direction Head-On/Sideswipe	9%	18%	38%	24%	3%	3%	6%	100%
Other/Unknown	2%	8%	14%	26%	48%	0%	2%	100%
Total	3%	12%	24%	37%	22%	0%	3%	100%

* N/A denotes No Statutory Limit

Data: Fatality Analysis Reporting System (National Highway Traffic Safety Administration). Analysis by AAA Foundation for Traffic Safety.

Figure 6: Percent distribution of fatalities with respect to speed limit Image Source: AAA

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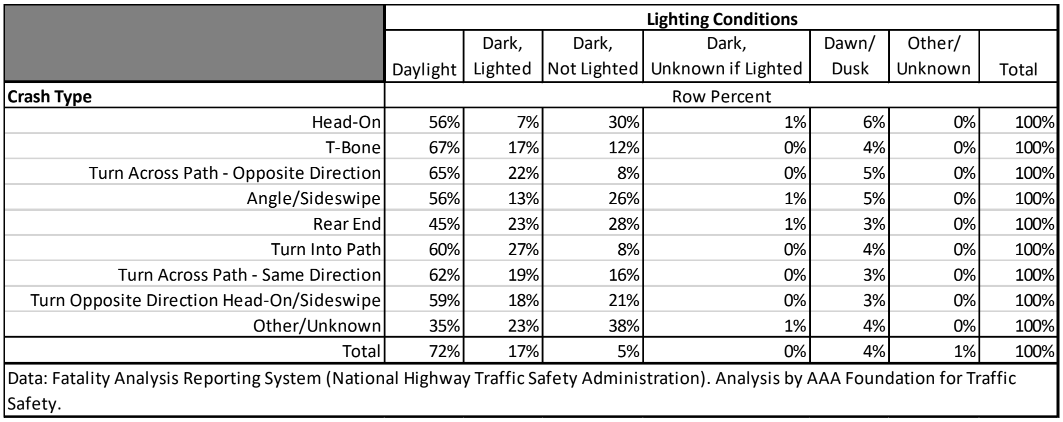


	Lighting Conditions						
	Daylight	Dark, Lighted	Dark, Not Lighted	Dark, Unknown if Lighted	Dawn/ Dusk	Other/ Unknown	Total
Crash Type	Row Percent						
Head-On	56%	7%	30%	1%	6%	0%	100%
T-Bone	67%	17%	12%	0%	4%	0%	100%
Turn Across Path - Opposite Direction	65%	22%	8%	0%	5%	0%	100%
Angle/Sideswipe	56%	13%	26%	1%	5%	0%	100%
Rear End	45%	23%	28%	1%	3%	0%	100%
Turn Into Path	60%	27%	8%	0%	4%	0%	100%
Turn Across Path - Same Direction	62%	19%	16%	0%	3%	0%	100%
Turn Opposite Direction Head-On/Sideswipe	59%	18%	21%	0%	3%	0%	100%
Other/Unknown	35%	23%	38%	1%	4%	0%	100%
Total	72%	17%	5%	0%	4%	1%	100%

Data: Fatality Analysis Reporting System (National Highway Traffic Safety Administration). Analysis by AAA Foundation for Traffic Safety.

Figure 7: Percent distribution of fatalities with respect to lighting condition Image Source: AAA

Between 2016 and 2020, there were a total of 187,293 fatalities on public roadways throughout the United States. Of those fatalities, 99,738 were in single-vehicle crashes and 19,980 were in crashes involving more than two vehicles. For the remaining 67,575 fatalities in two-vehicle crashes, 29,799 fatalities involved vehicles other than passenger vehicles (i.e., motorcycles, heavy trucks, buses, etc). An additional 11,256 fatalities were excluded based on analysis criteria previously identified.

In aggregate, the three crash types responsible for the majority of injuries additionally accounted for 48 percent of the 26,520 fatalities analyzed. As shown in Figure 5, head-on type crashes account for over 28 percent of fatal crashes analyzed. AAA previously evaluated a partial head-on crash scenario with three 2020–2021 model year vehicles equipped with an AEB system; no alerts or braking intervention were noted for any test runs for two of three test vehicles. Due to equipment design limitations and the potential for significant vehicle damage, an artificially low closing speed of 40 mph was evaluated. It is unlikely that current AEB systems will significantly mitigate collisions at speeds where fatalities commonly occur; 90 percent of these fatalities occur on roadways with speed limits at or above 40 mph (potential closing speeds at or above 80 mph). For detailed methodology and test results, refer to the Active Driving Assistance System Performance research report on the AAA NewsRoom.

Besides head-on crashes, T-bone and turn across path – opposite direction crashes are responsible for 39 percent of analyzed fatalities, in aggregate. Angle/sideswipe and rear-end crashes account for 10 and 8 percent of analyzed fatalities, respectively. However, rear-end crashes are responsible for over five times more injuries than angle/sideswipe crashes as shown in Figure 2. Based on this observation, AAA researchers elected to focus on rear-end crashes due to injury prevalence in addition to comparable fatality rates between the two crash types.

Among fatalities associated with rear-end, T-bone, and turn across path crash types, 76 percent occurred on roadways with speed limits of 40 mph or greater. Additionally, 63 percent of total fatalities among these crash types occur in daylight conditions.

Based on injury and fatality characteristics elucidated from 2016–2020 crash data, closed-course test scenarios based on intersection and rear-end crashes are of primary focus within this work. AEB systems have the potential to mitigate or prevent a significant number of these types of injury-causing crashes. Specifically, the following three closed-course test scenarios will be evaluated in daylight conditions to understand the performance of current AEB systems in the context of situations during which injuries and fatalities commonly occur:

- Test vehicle approaching a stationary target vehicle with no lateral offset between vehicles
- Test and target vehicles simultaneously approaching an intersection with an incident angle of 90°
- Test vehicle turns left into approaching target vehicle

Detailed test methodology is provided in Section VI and Section VII.

III. VEHICLE SELECTION METHODOLOGY

AAA researchers utilized industry sources and information from owner's manuals to verify test vehicles were equipped with an AEB system as standard equipment on all trim levels. Passive warning systems that do not actively apply braking force in response to a potential collision are not considered within this research. Sales data was utilized to identify popular vehicles in terms of 2020–2022 model year vehicles in operation (VIO).

The most popular vehicle was selected first; the remaining three test vehicles were selected in sequential order based on the following criteria:

- A variety of domestic and import automakers must be represented (no more than one vehicle per manufacturer group i.e. Buick/Chevrolet will be included)
- A variety of AEB system sensor suppliers will be included (i.e. Continental, Hella, Bosch, etc.)
- The vehicle model was not previously included in 2021 ADA research conducted by AAA

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

- 2022 Chevrolet Equinox LT with "Chevy Safety Assist"
- 2022 Ford Explorer XLT with "Pre-Collison Assist with Automatic Emergency Braking"
- 2022 Honda CR-V Touring with "Honda Sensing®"
- 2022 Toyota RAV4 LE with "Toyota Safety Sense™"

IV. TEST EQUIPMENT AND RESOURCES

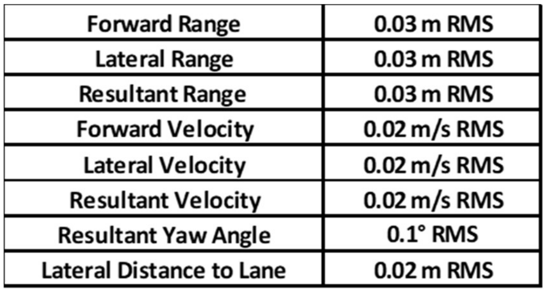
A. Vehicle Dynamics Equipment

1. Oxford Technical Solutions (OxTS) RT3000 V2 with RT-Range Hunter

Each vehicle was outfitted with an OxTS RT3000 v2 with an RT-Range Hunter. These instruments were utilized to capture test and target vehicle kinematic information and process vehicle-to-vehicle measurements relative to the vehicle under test. The RT3000 units interfaced with a site-installed base station to incorporate real-time kinematics (RTK) technology. The RT-Range interfaced with targets via XLAN. All measurements were captured at a rate of 100 Hz.

Position Accuracy	**0.01 m**
Velocity Accuracy	**0.01 m/s**
Roll & Pitch Accuracy	**0.03°**
Heading Accuracy	**0.1°**
Slip Angle Accuracy	**0.15°**
Output Data Rate	**100 Hz**

Figure 8: OxTS RT3000 specifications Image Source: AAA

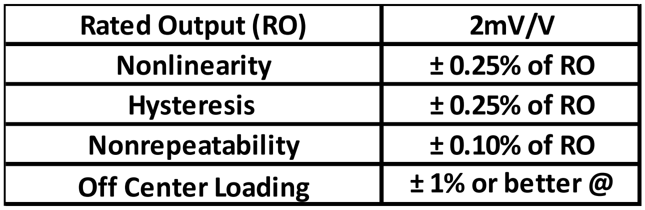


Forward Range	0.03 m RMS
Lateral Range	0.03 m RMS
Resultant Range	0.03 m RMS
Forward Velocity	0.02 m/s RMS
Lateral Velocity	0.02 m/s RMS
Resultant Velocity	0.02 m/s RMS
Resultant Yaw Angle	0.1° RMS
Lateral Distance to Lane	0.02 m RMS

Figure 9: OxTS RT-Range Hunter specifications Image Source: AAA

2. Futek LAU220 Pedal Force Sensor

Each vehicle was equipped with a brake pedal force sensor to verify no braking intervention was applied during closed-course testing.



Rated Output (RO)	2mV/V
Nonlinearity	± 0.25% of RO
Hysteresis	± 0.25% of RO
Nonrepeatability	± 0.10% of RO
Off Center Loading	± 1% or better @

Figure 10: Futek LAU220 specifications Image Source: AAA

3. DEWESoft CAM-120 Cameras with CAM-BOX2 Distribution Box

Each vehicle was equipped with one camera facing the instrument cluster to capture any visual AEB alerts. Additionally, one camera was mounted to each side of the vehicle to monitor positioning relative to lane markers. Video from all cameras was captured at a rate of 45 Hz.

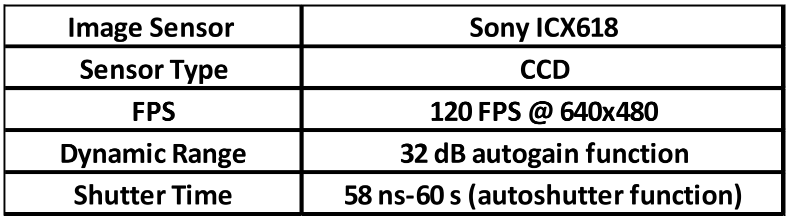


Image Sensor	Sony ICX618
Sensor Type	CCD
FPS	120 FPS @ 640x480
Dynamic Range	32 dB autogain function
Shutter Time	58 ns-60 s (autoshutter function)

Figure 11: DEWESoft CAM-120 specifications Image Source: AAA

4. DEWESoft CAN-2 Interface

Test vehicles were equipped with a CAN interface to capture data from OxTS instrumentation. Vehicle kinematics and range data were captured at a rate of 100 Hz and time-synced with pedal force measurements and video.

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5. Data Logging Equipment

Test vehicles were either equipped with a DEWESoft DEWE-43 or SIRIUS® slice data logger to log pedal force measurements at a rate of 2000 Hz. Each data logger was equipped with anti-aliasing filters to attenuate frequencies above the Nyquist frequency.

6. DRI Low Profile Robotic Vehicle (LPRV) with DRI Soft Car 360®

The robotic vehicle is a hardened, satellite guided, self-propelled, low-profile vehicle, which serves as a dynamic platform for the DRI Soft Car. The LPRV has a top speed of 50 mph and a maximum deceleration rate of 0.8 G. The positions of the vehicle under test and LPRV are measured continually using differential GPS with RTK correction. Kinematic data relating to the vehicle under test is broadcast to the LPRV via wireless LAN. This information, in conjunction with pre-loaded time-space trajectories (one each for the vehicle under test and LPRV), allows the LPRV to arrive at predefined locations relative to the vehicle under test in a repeatable manner.

Additionally, data from the LPRV was processed by the OxTS RT-Range Hunter to calculate LRPV kinematics relative to the vehicle under test (vehicle under test acts as a non-Newtonian reference frame).

Longitudinal Acceleration	**+0.11 G, -0.8 G**
Lateral Acceleration	**± 0.8 G**
Path Following Accuracy	**0.05 m**
Position Measurement Accuracy	**0.02 m**

Figure 12: DRI Low Profile Robotic Vehicle specifications Image Source: AAA

Figure 13: DRI Low Profile Robotic Vehicle Image Source: AAA

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The Soft Car 360® is calibrated to be representative of a small passenger vehicle relevant to automotive sensors including radar and cameras. The hatchback model was utilized for testing; its length, width and height are 158 in, 67 in, and 56 in, respectively.

B. *Test Facility*

All closed-course testing was conducted on roadways specifically designed for standardized ADAS testing on the grounds of Minter Field Airport in Shafter, California.

All 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 significant variations in the trajectory of the test vehicle.

For rear-end AEB test scenarios, the testing lane was approximately 0.7 miles long and consisted of a two-lane roadway divided down the middle by a dashed yellow line. The width and length of each dashed yellow line segment was 4 inches and 10 feet 4 inches, respectively. The separation distance between line segments was 29 feet; this distance remained constant throughout the test lane.

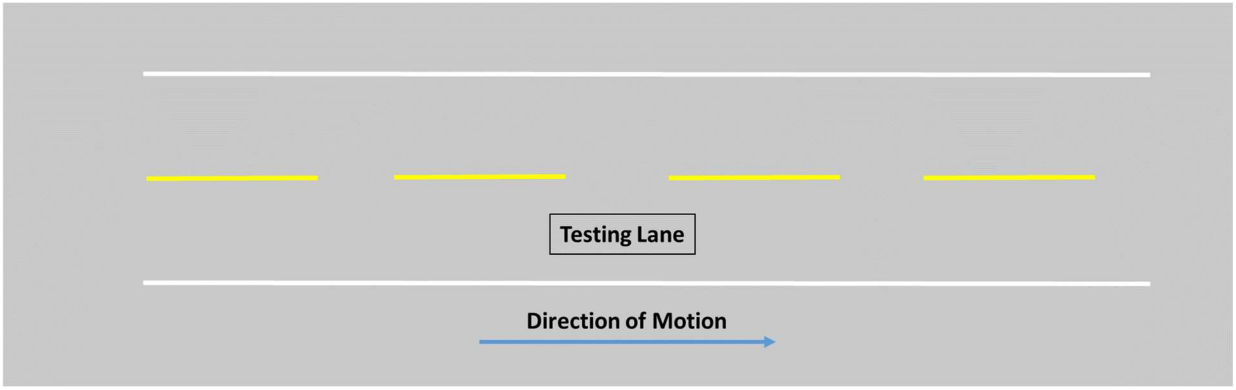

Figure 14: Illustration of testing surface for rear-end AEB test scenarios Image Source: AAA

Each individual lane was marked by a solid white line on the lateral side and the previously described dashed yellow line on the medial side with a nominal lane width of 12 feet. This lane width is representative of typical roadways including interstates and limited-access expressways in both urban and rural areas within the United States.

For intersection-based test scenarios, an intersection specifically designed for ADAS evaluation was utilized. There were no obstructions present that could impede visibility of vehicles approaching the intersection. The testing lane was approximately 0.7 miles long and consisted of a two-lane roadway divided down the middle by a dashed yellow line. The width and length of each dashed yellow line segment was 4 inches and 10 feet 4 inches, respectively. The separation distance between line segments was 29 feet; this distance remained constant throughout the test lane. Each individual lane was marked by a solid white line on the lateral side and the previously described dashed yellow line on the medial side with a nominal lane width of 12 feet. Two identical roadways with width and lane marking dimensions intersected at 90° to form the intersection utilized for testing; a graphical illustration is provided within Figure 15 (not to scale).

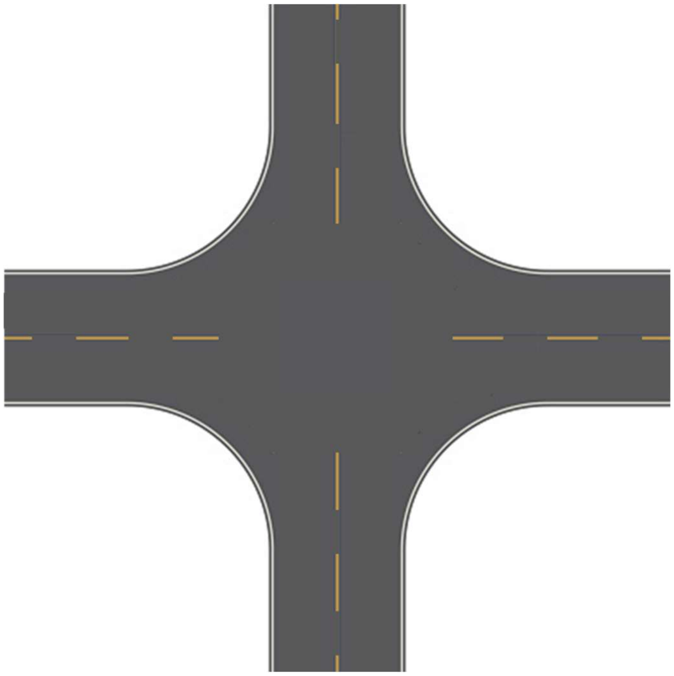

Figure 15: Illustration of testing surface for intersection-based AEB test scenarios Image Source: AAA

V. VEHICLE PREPARATION

All vehicles were procured directly from manufacturers or specialty rental fleets. Vehicles provided by the manufacturer were verified by the OEM to be suitable for testing. To ensure the proper functioning of the AEB system, all test vehicles were serviced at Los Angeles–area dealerships to include a four-wheel alignment and if necessary, recalibration of the AEB system before commencing closed-course testing. Each dealership provided documentation to ensure AEB systems were calibrated according to manufacturer specifications and updated to the latest software version (as of May 2022).

AEB systems were verified to be enabled and free of modifications. The odometer reading of all test vehicles was between 200 and 3,700 miles at the start of testing.

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

- No warning lights illuminated
- All system components free of damage and unaffected by any technical service bulletins and/or recalls
- Any stored diagnostic trouble codes were resolved and cleared
- All fluid reservoirs filled to at least the minimum indicated levels
- Tires inflated to placard pressure following stabilization at ambient temperature in a shaded environment

Before the start of each testing day, the areas surrounding the image sensors on all test vehicles were cleaned to ensure optimal system operation. A calibration drive of varying speeds was performed prior to testing for each key cycle. All instrumentation was powered via dedicated 12V batteries and completely isolated from the vehicle electrical system.

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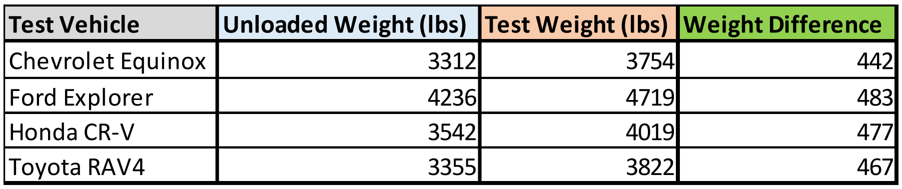
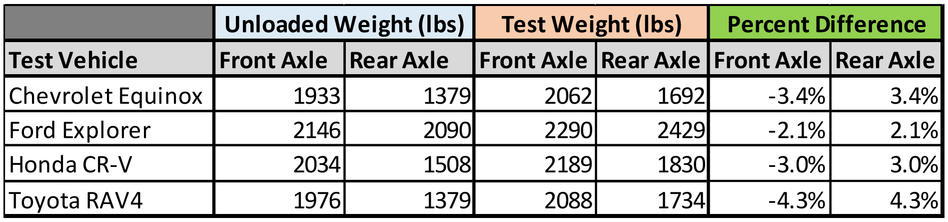
The unloaded curb weight of all vehicles (with a full tank of gas) was measured; this weight was utilized to derive the test weight for each vehicle to include the test driver, instrumentation operator, all instrumentation and additional ballast weight (if necessary) according to Sections 7.4.5 and 7.4.6 of the Euro NCAP AEB C2C Test Protocol v.3.0.3 [6]. Unloaded and tested vehicle weights and axle distributions are provided in Figures 16 and 17. Test weights were verified prior to the start of testing; the fuel tank was kept at least three-quarters full throughout the entirety of testing.



Test Vehicle	Unloaded Weight (lbs)	Test Weight (lbs)	Weight Difference
Chevrolet Equinox	3312	3754	442
Ford Explorer	4236	4719	483
Honda CR-V	3542	4019	477
Toyota RAV4	3355	3822	467

Figure 16: Unloaded and tested vehicle weight Image Source: AAA



	Unloaded Weight (lbs)		Test Weight (lbs)		Percent Difference	
Test Vehicle	Front Axle	Rear Axle	Front Axle	Rear Axle	Front Axle	Rear Axle
Chevrolet Equinox	1933	1379	2062	1692	-3.4%	3.4%
Ford Explorer	2146	2090	2290	2429	-2.1%	2.1%
Honda CR-V	2034	1508	2189	1830	-3.0%	3.0%
Toyota RAV4	1976	1379	2088	1734	-4.3%	4.3%

Figure 17: Unloaded and tested vehicle weight distribution Image Source: AAA

VI. INQUIRY 1: HOW DO COMMON AEB SYSTEMS PERFORM WHEN ENCOUNTERING A STATIONARY VEHICLE AHEAD?

A. Objective

Evaluate the performance of common AEB systems in the context of situations involving a potential collision with a stationary passenger vehicle ahead.

B. Methodology

In sections herein, “target vehicle” refers to the simulated stationary vehicle. To allow for full characterization of AEB system performance, the LPRV previously described in Section IV.A.6 was utilized.

For each of the test scenarios, the following data were collected and utilized to characterize system performance according to parameters within Figure 18:

- AEB warning indicators (via video recording)
- Longitudinal velocity and acceleration for test and target vehicles
- Longitudinal and lateral position of target vehicle relative to test vehicle
- Calculated time-to-collision (TTC)

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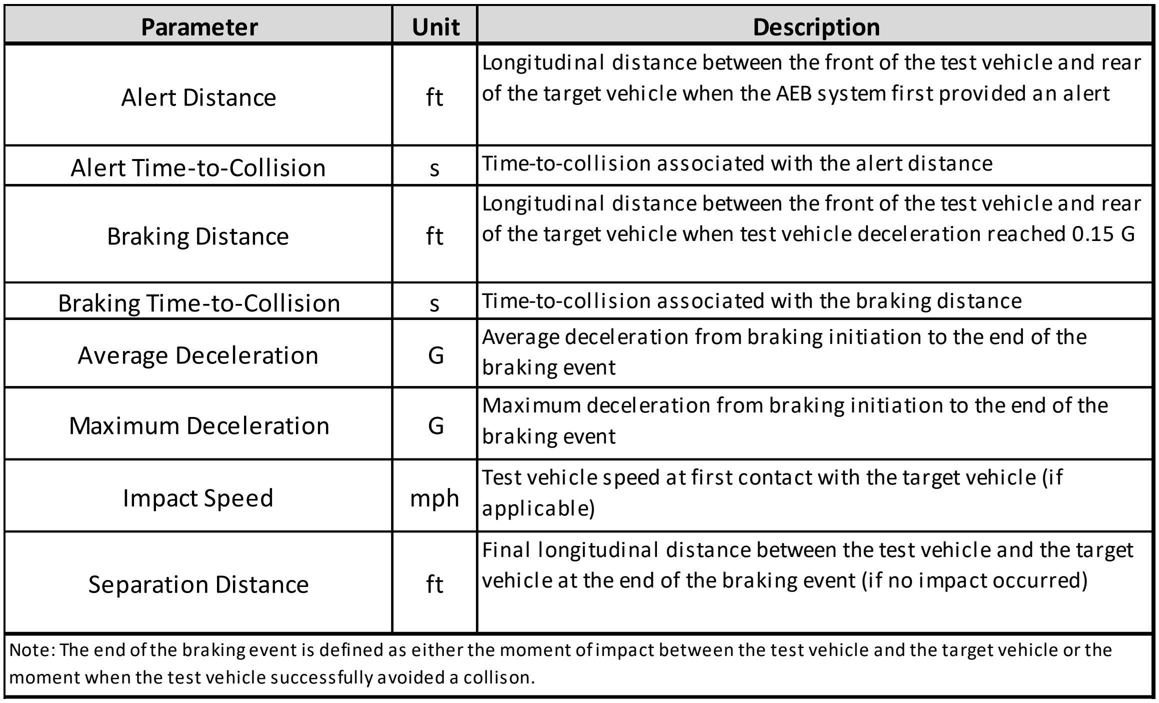

Parameter	Unit	Description
Alert Distance	ft	Longitudinal distance between the front of the test vehicle and rear of the target vehicle when the AEB system first provided an alert
Alert Time-to-Collision	s	Time-to-collision associated with the alert distance
Braking Distance	ft	Longitudinal distance between the front of the test vehicle and rear of the target vehicle when test vehicle deceleration reached 0.15 G
Braking Time-to-Collision	s	Time-to-collision associated with the braking distance
Average Deceleration	G	Average deceleration from braking initiation to the end of the braking event
Maximum Deceleration	G	Maximum deceleration from braking initiation to the end of the braking event
Impact Speed	mph	Test vehicle speed at first contact with the target vehicle (if applicable)
Separation Distance	ft	Final longitudinal distance between the test vehicle and the target vehicle at the end of the braking event (if no impact occurred)

Note: The end of the braking event is defined as either the moment of impact between the test vehicle and the target vehicle or the moment when the test vehicle successfully avoided a collison.

Figure 18: Performance parameters for rear AEB scenario Image Source: AAA

Alert distances are provided at the instant that a notification of a vehicle ahead is visible on the test vehicle's instrument cluster. Automatic braking is considered to have occurred once the test vehicle's longitudinal deceleration exceeds 0.15 G. For test vehicles with adjustable AEB sensitivity settings, the midpoint setting was utilized for all test runs. If an even number of settings were available, the next latest setting (i.e. the timing of the collision warning and/or braking application) relative to the midpoint setting was utilized.

$$TTCa = \frac{-v_r - \sqrt{v_r^2 - 2a_{TV}r}}{a_{TV}}$$

Figure 19: TTC with test vehicle acceleration Image Source: AAA

Figure 19 provides the TTC equation utilized within the following sections, where v_r is the test vehicle velocity, a_{TV} is the test vehicle acceleration, and r is the longitudinal separation distance.

A rear-end collision scenario with no lateral offset between vehicles is within design capabilities of modern AEB systems including those evaluated with this research. As described in Section II, a majority of injuries caused by rear-end collisions occur on roadways with posted speed limits of 30–45 mph. Based on this finding, test vehicle speeds of 30 mph and 40 mph were evaluated. While the granularity of the data precludes insight into typical closing speeds, a stationary vehicle ahead presents the largest possible speed differential between involved vehicles.

The lateral centerline of the stationary target vehicle was positioned over the lateral centerline of the testing lane as shown in Figure 14. To initiate a test run, the lead vehicle accelerated to the test speed within the center of the test lane; for the run to be valid, the test vehicle was required to maintain the target speed within ± 1 mph once the front of the test vehicle was within 600 feet of the rear of the stationary target vehicle.

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Steady-state speed was maintained until impact with the target vehicle occurred or the AEB system provided an alert. If an alert was provided, the test driver immediately removed their foot from the accelerator and provided no intervention until the test vehicle either successfully avoided a collision or impact with the target vehicle occurred. After each run, data was reviewed to ensure the test driver did not inadvertently apply pressure to the brake pedal until one of these two conditions were met. For each test vehicle, five test runs for each test speed were performed.

C. *Test Results*

1. *30 mph Rear AEB Test Scenario*

30 mph Rear-End AEB Test Scenario			
Test Vehicle	**Provided an Alert**	**Applied Brakes**	**Impacted Simulated Vehicle**
Chevrolet Equinox	5/5	5/5	1/5
Ford Explorer	5/5	5/5	0/5
Honda CR-V	5/5	5/5	2/5
Toyota RAV4	5/5	5/5	0/5
Note: The results are presented as the number of occurences out of five total test runs per vehicle per scenario.			

Figure 20: High-level performance observations for each test vehicle Image Source: AAA

All test vehicles provided an alert and initiated braking in response to the stationary target vehicle for each of the five test runs. Two of four test vehicles successfully avoided an impact for each of the five test runs. Figure 20 provides overall results pertaining to alert, braking, and impact phases.

a) *Chevrolet Equinox*

	Chevrolet Equinox							
	Alert Distance (ft)	Alert TTC (s)	Braking Distance (ft)	Braking TTC (s)	Avg Deceleration (G)	Max Deceleration (G)	Impact Speed (mph)	Separation Distance (ft)
Run 1	128.5	2.885	38.7	0.900	0.765	1.025	0.0	0.2
Run 2	130.6	2.894	38.4	0.887	0.780	1.075	0.0	0.2
Run 3	125.7	2.877	38.9	0.934	0.766	1.072	0.0	2.2
Run 4	126.1	2.827	37.1	0.873	0.770	1.037	6.4	0.0
Run 5	123.9	2.867	37.0	0.901	0.790	1.123	0.0	2.2
Average	**126.9**	**2.870**	**38.0**	**0.899**	**0.774**	**1.067**	**1.3**	**1.0**
Standard Deviation	**2.4**	**0.023**	**0.8**	**0.020**	**0.010**	**0.034**	**2.6**	**1.0**

Figure 21: Run level test data for the Chevrolet Equinox Image Source: AAA

For each of the five test runs, the Chevrolet Equinox detected the target vehicle and initiated braking in response to the stationary target vehicle. In aggregate, an impact was avoided for four of five test runs. An impact occurred for the fourth test run; the impact speed was significantly reduced by 23.6 mph or 79 percent relative to the 30 mph test speed. For two of four test runs characterized by no impact, the test vehicle came to a stop inside the cumulative positioning resolution of vehicle dynamics instrumentation within test and target vehicles.

Alert and braking distances as well as deceleration characteristics were consistent for each of the five test runs. On average, braking was initiated 38 feet from the rear of the target vehicle, corresponding to an average TTC of 0.899 seconds. The deceleration rate was abrupt for each of the five test runs with an average and maximum deceleration magnitude of 0.774 and 1.067 G, respectively.

b) Ford Explorer

	Ford Explorer							
	Alert Distance (ft)	Alert TTC (s)	Braking Distance (ft)	Braking TTC (s)	Avg Deceleration (G)	Max Deceleration (G)	Impact Speed (mph)	Separation Distance (ft)
Run 1	N/A*	N/A*	43.0	1.019	0.816	1.330	0.0	4.9
Run 2	80.8	1.878	45.7	1.084	0.823	1.245	0.0	7.5
Run 3	85.5	1.945	45.2	1.058	0.818	1.221	0.0	6.4
Run 4	75.9	1.817	41.6	1.046	0.828	1.127	0.0	7.3
Run 5	73.1	1.739	44.2	1.074	0.829	1.215	0.0	8.7
Average	**78.9**	**1.845**	**43.9**	**1.056**	**0.823**	**1.228**	**0.0**	**7.0**
Standard Deviation	**4.7**	**0.076**	**1.5**	**0.023**	**0.005**	**0.065**	**0.0**	**1.3**

Figure 22: Run level test data for the Ford Explorer Image Source: AAA

For each of the five test runs, the Ford Explorer detected the target vehicle and initiated braking in response to the stationary target vehicle. An issue with the instrument cluster camera for the first test run was discovered in post-processing which precluded recording of the separation distance associated with the visual alert. However, the instrument operator noted a visual alert was provided during this test run. In aggregate, an impact was avoided for each of five test runs. Additionally, final separation distances provided a buffer between the two vehicles.

Alert and braking distances as well as deceleration characteristics were consistent for each of the five test runs. On average, braking was initiated 43.9 feet from the rear of the target vehicle, corresponding to an average TTC of 1.056 seconds. The deceleration rate was abrupt for each of the five test runs with average and maximum deceleration magnitudes of 0.823 and 1.228 G, respectively.

c) Honda CR-V

	Honda CR-V							
	Alert Distance (ft)	Alert TTC (s)	Braking Distance (ft)	Braking TTC (s)	Avg Deceleration (G)	Max Deceleration (G)	Impact Speed (mph)	Separation Distance (ft)
Run 1	94.6	2.143	57.2	1.308	0.654	0.834	0.0	7.7
Run 2	100.4	2.203	56.2	1.251	0.329	0.857	3.3	0.0
Run 3	104.4	2.293	49.0	1.122	0.741	0.918	0.0	6.7
Run 4	96.7	2.201	52.9	1.229	0.274	0.839	2.8	0.0
Run 5	100.3	2.201	49.6	1.140	0.709	0.892	0.0	6.9
Average	**99.3**	**2.208**	**53.0**	**1.210**	**0.541**	**0.868**	**1.2**	**4.3**
Standard Deviation	**3.4**	**0.048**	**3.3**	**0.070**	**0.199**	**0.032**	**1.5**	**3.5**

Figure 23: Run level test data for the Honda CR-V Image Source: AAA

For each of the five test runs, the Honda CR-V detected the target vehicle and initiated braking in response to the stationary target vehicle. In aggregate, an impact was avoided for three of five test runs. For the remaining two test runs, the impact speed was significantly reduced by an average of 27 mph or 90 percent relative to the 30 mph test speed. For both test runs, it was noted that braking was discontinued approximately 6.5 feet from the rear of the target vehicle, resulting in a minor impact.

Alert and braking distances were consistent for each of the five test runs. On average, braking was initiated 53 feet from the rear of the target vehicle, corresponding to an average TTC of 1.210 seconds. In terms of deceleration rate, there is a notable decrease in average and maximum deceleration magnitudes for test runs that resulted in minor impact vs. test runs that resulted in no impact.

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d) Toyota RAV4

	Toyota RAV4							
	Alert Distance (ft)	Alert TTC (s)	Braking Distance (ft)	Braking TTC (s)	Avg Deceleration (G)	Max Deceleration (G)	Impact Speed (mph)	Separation Distance (ft)
Run 1	115.5	2.571	52.5	1.214	0.559	0.920	0.0	7.7
Run 2	112.3	2.568	51.3	1.228	0.517	0.745	0.0	3.7
Run 3	115.8	2.607	51.4	1.205	0.532	0.781	0.0	3.8
Run 4	111.9	2.557	55.0	1.292	0.504	0.750	0.0	3.7
Run 5	111.7	2.558	55.4	1.309	0.499	0.825	0.0	3.7
Average	**113.4**	**2.572**	**53.1**	**1.250**	**0.522**	**0.804**	**0.0**	**4.5**
Standard Deviation	**1.8**	**0.018**	**1.8**	**0.043**	**0.022**	**0.065**	**0.0**	**1.6**

Figure 24: Run level test data for the Toyota RAV4 Image Source: AAA

For each of the five test runs, the Toyota RAV4 detected the target vehicle and initiated braking in response to the stationary target vehicle. In aggregate, an impact was avoided for each of five test runs. Additionally, final separation distances provided a buffer between the two vehicles.

Alert and braking distances, as well as deceleration characteristics, were consistent for each of the five test runs. On average, braking was initiated 53.1 feet from the rear of the target vehicle, corresponding to an average TTC of 1.250 seconds. The deceleration rate was abrupt for each of the five test runs with average and maximum deceleration magnitudes of 0.522 and 0.804 G, respectively.

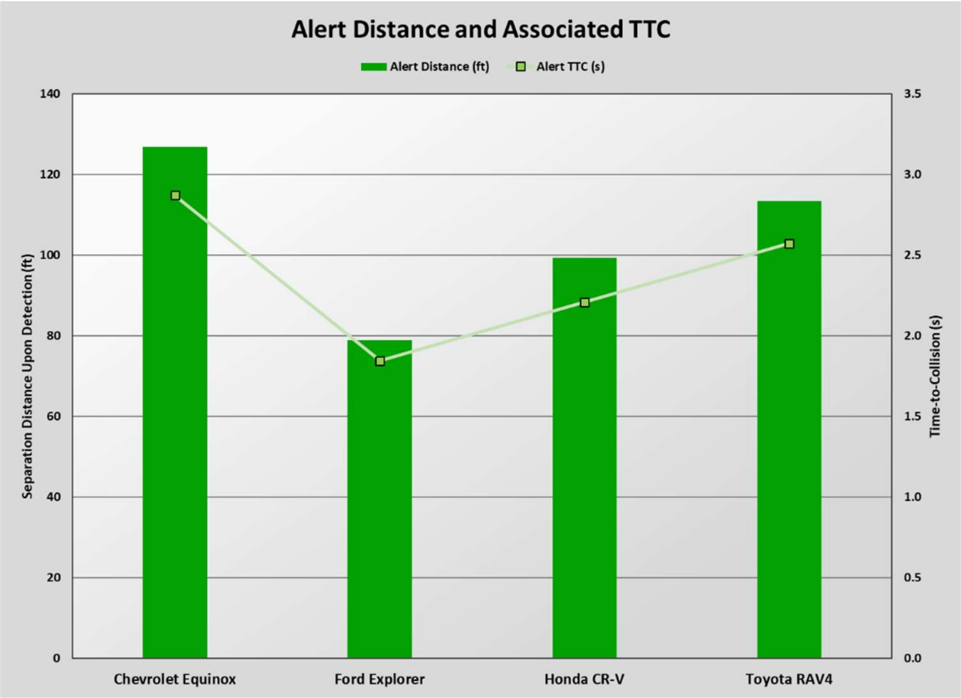

Figure 25: Average alert distance and associated TTC for each test vehicle Image Source: AAA

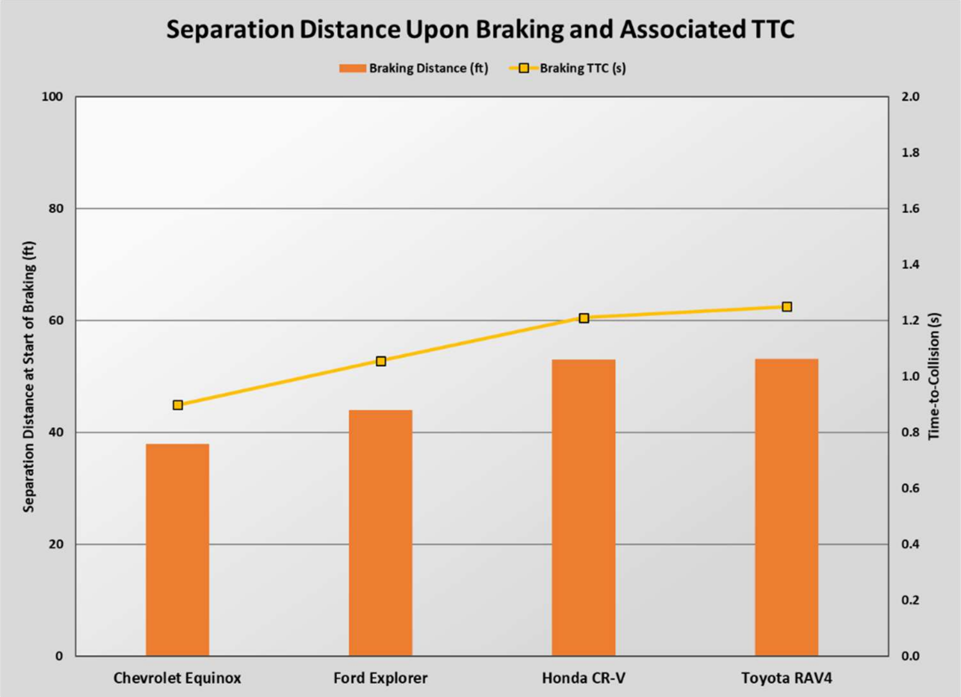

Figure 26: Average braking distance and associated TTC for each test vehicle Image Source: AAA

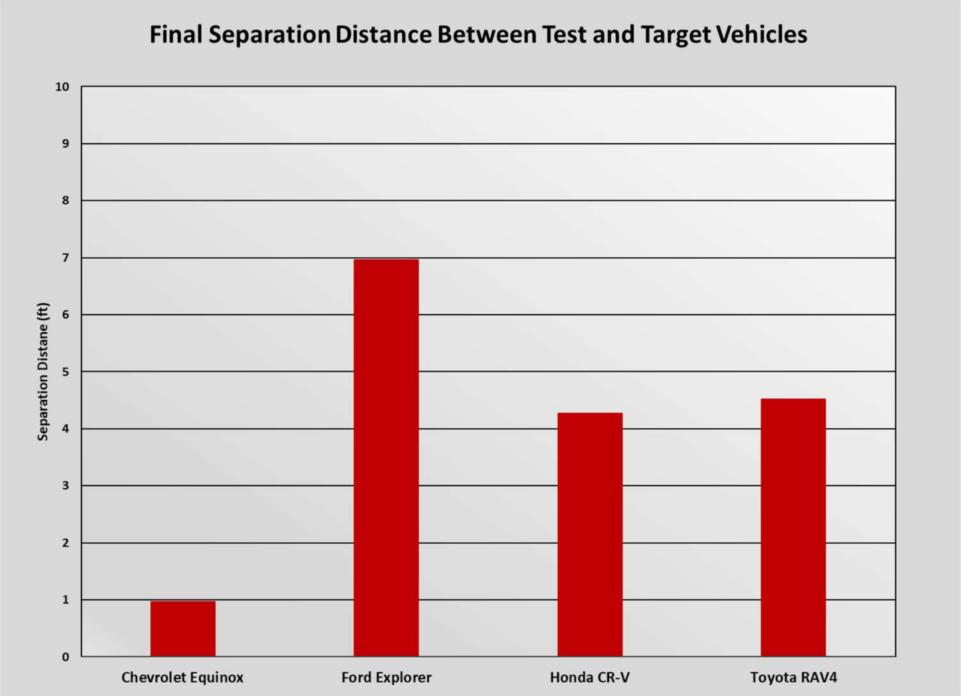

Figure 27: Average separation distance between test and target vehicles Image Source: AAA

Figures 25–27 illustrate the average alert, braking, and final separation distances for each test vehicle. It is noted that the relative timing of alerts among test vehicles do not directly correlate to the timing of braking

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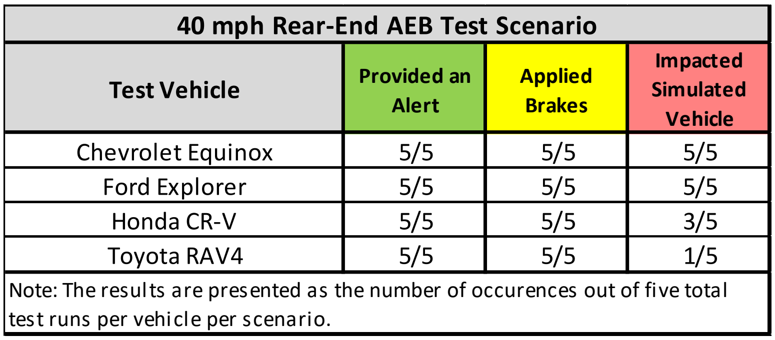
initiation or final separation distances among test vehicles. Within Figure 27, all test runs including those resulting in impact (no separation distance) were included within provided averages.

2. 40 mph Rear AEB Test Scenario



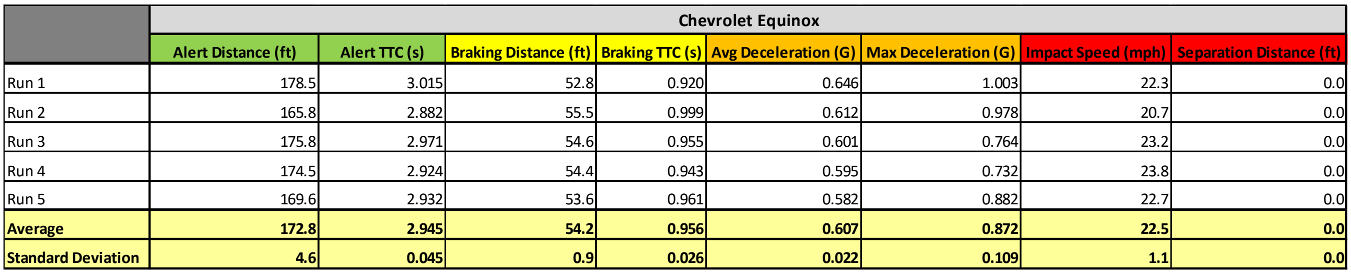
40 mph Rear-End AEB Test Scenario			
Test Vehicle	**Provided an Alert**	**Applied Brakes**	**Impacted Simulated Vehicle**
Chevrolet Equinox	5/5	5/5	5/5
Ford Explorer	5/5	5/5	5/5
Honda CR-V	5/5	5/5	3/5
Toyota RAV4	5/5	5/5	1/5

Note: The results are presented as the number of occurences out of five total test runs per vehicle per scenario.

Figure 28: High-level performance observations for each test vehicle Image Source: AAA

All test vehicles provided an alert and initiated braking in response to the stationary target vehicle for each of the five test runs. Each test vehicle impacted the target vehicle during at least one of five test runs; two of four test vehicles impacted the target vehicle during each of the five test runs. Figure 28 provides overall results pertaining to alert, braking, and impact phases.

a) Chevrolet Equinox



	Chevrolet Equinox							
	Alert Distance (ft)	Alert TTC (s)	Braking Distance (ft)	Braking TTC (s)	Avg Deceleration (G)	Max Deceleration (G)	Impact Speed (mph)	Separation Distance (ft)
Run 1	178.5	3.015	52.8	0.920	0.646	1.003	22.3	0.0
Run 2	165.8	2.882	55.5	0.999	0.612	0.978	20.7	0.0
Run 3	175.8	2.971	54.6	0.955	0.601	0.764	23.2	0.0
Run 4	174.5	2.924	54.4	0.943	0.595	0.732	23.8	0.0
Run 5	169.6	2.932	53.6	0.961	0.582	0.882	22.7	0.0
Average	**172.8**	**2.945**	**54.2**	**0.956**	**0.607**	**0.872**	**22.5**	**0.0**
Standard Deviation	**4.6**	**0.045**	**0.9**	**0.026**	**0.022**	**0.109**	**1.1**	**0.0**

Figure 29: Run level test data for the Chevrolet Equinox Image Source: AAA

For each of the five test runs, the Chevrolet Equinox detected the target vehicle and initiated braking in response to the stationary target vehicle. In aggregate, an impact occurred for each of the five test runs. On average, the impact speed was reduced by 17.5 mph or 44 percent relative to the 40-mph test speed. This speed mitigation was less than the average 23.6 mph or 79 percent speed mitigation noted for 30 mph test runs characterized by target vehicle impact, suggesting that a closing speed of 40 mph is significantly more challenging for the AEB system relative to 30 mph.

Alert and braking distances as well as impact speed were consistent for each of the five test runs. On average, braking was initiated 54.2 feet from the rear of the target vehicle, corresponding to an average TTC of 0.956 seconds. The deceleration rate was abrupt for each of the five test runs with average and maximum deceleration magnitudes of 0.604 and 0.872 G, respectively.

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b) Ford Explorer

	Ford Explorer							
	Alert Distance (ft)	Alert TTC (s)	Braking Distance (ft)	Braking TTC (s)	Avg Deceleration (G)	Max Deceleration (G)	Impact Speed (mph)	Separation Distance (ft)
Run 1	122.0	2.118	60.6	1.065	0.835	1.064	9.3	0.0
Run 2	121.6	2.078	60.1	1.045	0.836	1.090	10.7	0.0
Run 3	110.6	1.962	61.2	1.103	0.851	1.086	3.3	0.0
Run 4	123.6	2.073	64.6	1.097	0.854	1.165	7.3	0.0
Run 5	116.3	1.984	59.9	1.037	0.850	1.085	10.5	0.0
Average	**118.9**	**2.043**	**61.3**	**1.069**	**0.845**	**1.098**	**8.2**	**0.0**
Standard Deviation	**4.8**	**0.060**	**1.7**	**0.027**	**0.008**	**0.035**	**2.7**	**0.0**

Figure 30: Run level test data for the Ford Explorer Image Source: AAA

For each of the five test runs, the Ford Explorer detected the target vehicle and initiated braking in response to the stationary target vehicle. In aggregate, an impact occurred for each of the five test runs. On average, the impact speed was significantly reduced by 31.8 mph or 80 percent relative to the 40-mph test speed. However, the observation that an impact occurred for each test run suggests that a closing speed of 40 mph is significantly more challenging for the AEB system relative to 30 mph.

Alert and braking distances were consistent for each of the five test runs. On average, braking was initiated 61.3 feet from the rear of the target vehicle, corresponding to an average TTC of 1.069 seconds. The deceleration rate was abrupt for each of the five test runs with average and maximum deceleration magnitudes of 0.845 and 1.098 G, respectively.

c) Honda CR-V

	Honda CR-V							
	Alert Distance (ft)	Alert TTC (s)	Braking Distance (ft)	Braking TTC (s)	Avg Deceleration (G)	Max Deceleration (G)	Impact Speed (mph)	Separation Distance (ft)
Run 1	142.1	2.371	87.3	1.479	0.694	0.928	0.0	8.8
Run 2	147.2	2.522	83.2	1.450	0.471	0.950	9.8	0.0
Run 3	146.2	2.528	81.1	1.433	0.476	0.898	9.3	0.0
Run 4	137.9	2.421	83.5	1.476	0.470	0.910	9.3	0.0
Run 5	154.2	2.592	86.3	1.467	0.709	0.965	0.0	9.7
Average	**145.5**	**2.487**	**84.3**	**1.461**	**0.564**	**0.930**	**5.7**	**3.7**
Standard Deviation	**5.4**	**0.080**	**2.2**	**0.017**	**0.112**	**0.025**	**4.6**	**4.5**

Figure 31: Run level test data for the Honda CR-V Image Source: AAA

For each of the five test runs, the Honda CR-V detected the target vehicle and initiated braking in response to the stationary target vehicle. In aggregate, an impact occurred for three of five test runs. For these test runs, the impact speed was significantly reduced by 30.5 mph or 76 percent relative to the 40-mph test speed. For runs characterized by no impact, the final separation distance provided a buffer between the two vehicles.

Alert and braking distances were consistent for each of the five test runs. On average, braking was initiated 84.3 feet from the rear of the target vehicle, corresponding to an average TTC of 1.461 seconds. In terms of deceleration rate, there is a notable decrease in average and maximum deceleration magnitudes for test runs that resulted in impact vs. test runs that resulted in no impact.

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d) Toyota RAV4

	Toyota RAV4							
	Alert Distance (ft)	Alert TTC (s)	Braking Distance (ft)	Braking TTC (s)	Avg Deceleration (G)	Max Deceleration (G)	Impact Speed (mph)	Separation Distance (ft)
Run 1	154.6	2.627	78.6	1.367	0.621	0.888	0.0	3.3
Run 2	151.9	2.609	78.9	1.388	0.583	0.933	0.0	3.0
Run 3	150.0	2.594	75.8	1.345	0.197	0.917	32.1	0.0
Run 4	149.6	2.566	80.0	1.403	0.587	0.857	0.0	3.3
Run 5	150.9	2.595	80.8	1.421	0.581	0.846	0.0	3.1
Average	**151.4**	**2.598**	**78.8**	**1.385**	**0.514**	**0.888**	**6.4**	**2.5**
Standard Deviation	**1.8**	**0.020**	**1.7**	**0.027**	**0.159**	**0.033**	**12.8**	**1.3**

Figure 32: Run level test data for the Toyota RAV4 Image Source: AAA

For each of the five test runs, the Toyota RAV4 detected the target vehicle and initiated braking in response to the stationary target vehicle. In aggregate, an impact occurred for one of five test runs. For this test run, the impact speed was reduced by 7.9 mph or 20 percent relative to the 40-mph test speed, resulting in a major impact. While impact was avoided for four of five test runs, this largely unmitigated impact with the target vehicle suggests a closing speed of 40 mph presents a challenge in terms of consistent AEB system performance. For test runs characterized by no impact, the final separation distance provided a buffer between the two vehicles.

Alert and braking distances were consistent for each of the five test runs. On average, braking was initiated 78.8 feet from the rear of the target vehicle, corresponding to an average TTC of 1.385 seconds. In terms of deceleration rate, there is a notable decrease in average deceleration magnitude for the test run that resulted in major impact vs. test runs that resulted in no impact.

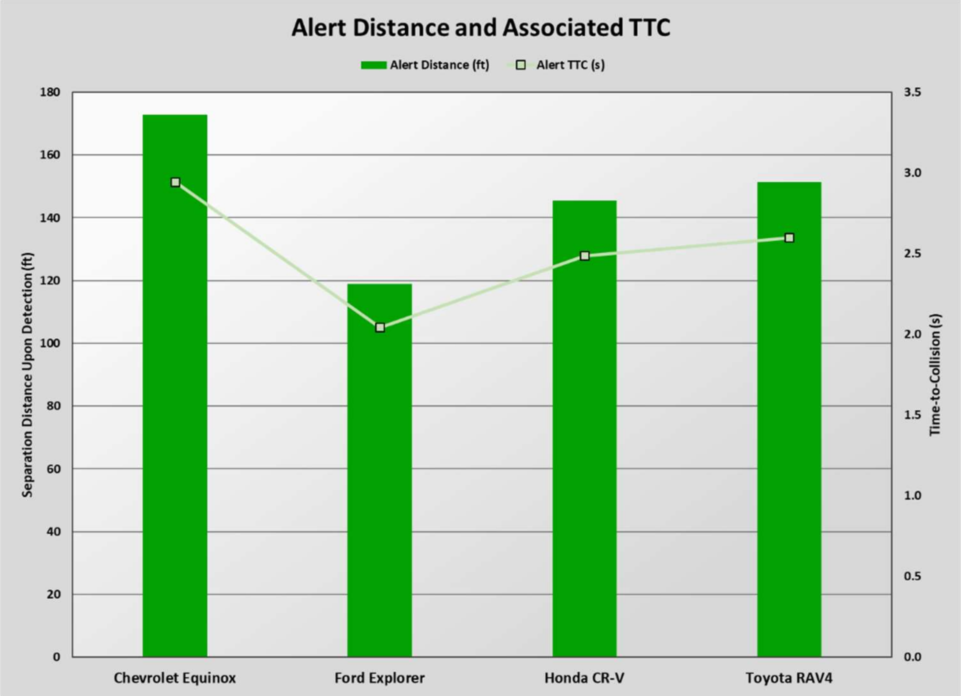

Figure 33: Average alert distance and associated TTC for each test vehicle Image Source: AAA

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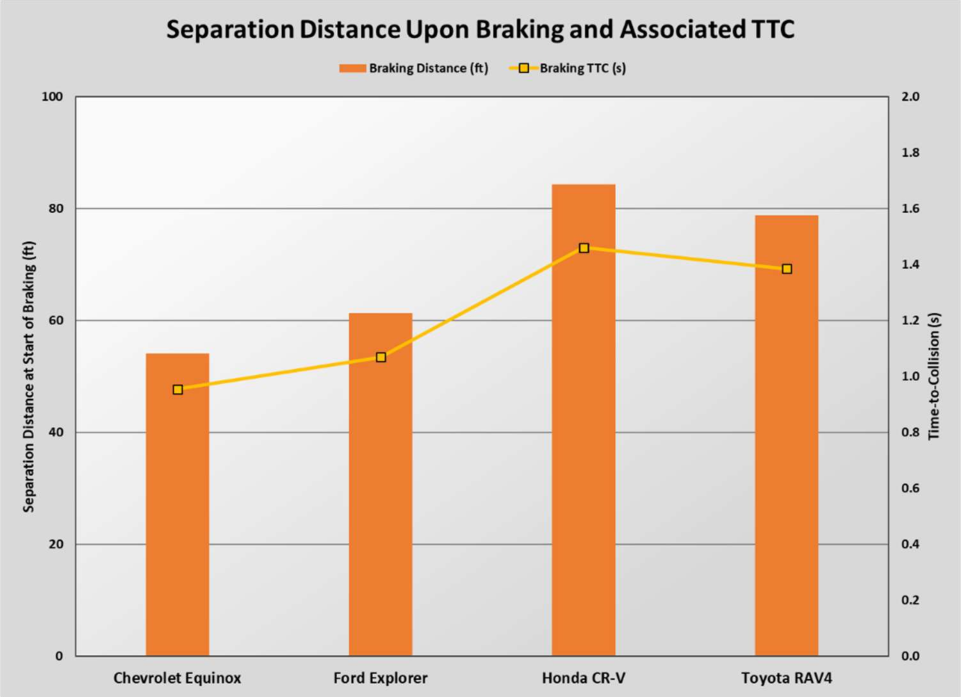

Figure 34: Associated braking distance and associated TTC for each test vehicle Image Source: AAA

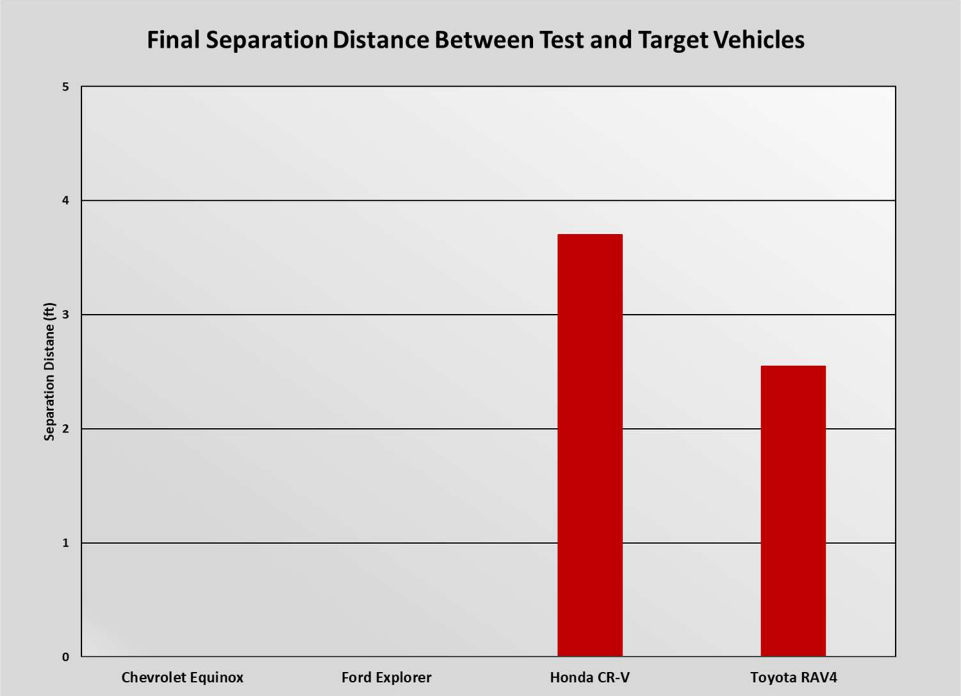

Figure 35: Average separation distance between test and target vehicles Image Source: AAA

Figures 33–35 illustrate the average alert, braking, and final separation distances for each test vehicle. It is noted that the relative timing of alerts among test vehicles do not directly correlate to the timing of braking

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initiation or final separation distances among test vehicles. Within Figure 35, all test runs including those resulting in impact (no separation distance) were included within provided averages.

D. Discussion

With a closing speed of 30 mph, all test vehicles consistently detected the stationary target vehicle ahead and initiated braking for each of the five test runs. In aggregate, 17 of 20 total test runs resulted in no impact with the target vehicle. For impacts that occurred, the average speed mitigation was 25.8 mph or 86 percent relative to the 30-mph closing speed. These results are encouraging and suggest that evaluated AEB systems are capable of consistently avoiding or significantly mitigating rear-end impacts at the lower bound of posted speed limits observed when injuries caused by rear-end collisions commonly occur.

At a 40-mph closing speed, performance observations suggest that evaluated AEB systems are more challenged to consistently avoid rear-end collisions relative to a closing speed of 30 mph. While all test vehicles detected the stationary target ahead and initiated braking for each of the five test runs, an impact occurred for 14 of 20 test runs in aggregate. For impacts that occurred, the average speed mitigation was 24.7 mph or 62 percent relative to the 40-mph closing speed. It is important to note that 59 percent of injuries caused by rear-end collisions occur on roadways with posted speed limits at or above 40 mph. While collision avoidance would undoubtedly be ideal, consistent impact speed mitigation as demonstrated by this research could potentially reduce injury severity and in some cases, occurrence.

VII. INQUIRY 2: HOW DO COMMON AEB SYSTEMS PERFORM WHEN ENCOUNTERING MOVING VEHICLES IN COLLISION SCENARIOS INVOLVING AN INTERSECTION?

A. Objective

Evaluate the performance of common AEB systems in the context of typical intersection-based collision scenarios frequently resulting in injury.

B. Methodology

In sections herein, “target vehicle” refers to the simulated dynamic vehicle utilized to create a collision scenario. To allow for full characterization of AEB system performance, the LPRV previously described in Section IV.A.6 was utilized.

For each of the test scenarios, the following data were collected and utilized to characterize system performance according to parameters within Figure 36:

- AEB warning indicators (via video recording),
- Longitudinal and lateral velocity and acceleration for test and target vehicles
- Longitudinal and lateral position of target vehicle relative to test vehicle
- Calculated time-to-collision (TTC)

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Parameter	Unit	Description
Alert Distance	ft	Separation distance during which AEB system first provided an alert. For perpendicular collision scenario, this is defined as the longitudinal distance between the front of the test vehicle and left side of the target vehicle. For turning collision scenario, this is defined as the resultant distance between the left front corner of the test vehicle and closest point of the target vehicle.
Alert Time-to-Collision	s	Time-to-collision associated with the alert distance
Braking Distance	ft	Separation distance between test vehicle and target vehicle when test vehicle deceleration reached 0.15 G. Separation distances are defined within "Alert Distance" parameter.
Braking Time-to-Collision	s	Time-to-collision associated with the braking distance
Average Deceleration	G	Average deceleration from braking initiation to the end of the braking event
Maximum Deceleration	G	Maximum deceleration from braking initiation to the end of the braking event
Impact Speed	mph	Test vehicle speed at first contact with the target vehicle (if applicable)
Separation Distance	ft	Final longitudinal distance between the test vehicle and the target vehicle at the end of the braking event (if no impact occurred). Separation distances are defined within "Alert Distance" parameter.
Note: The end of the braking event is defined as either the moment of impact between the test vehicle and the target vehicle or the moment when the test vehicle successfully avoided a collison.		

Figure 36: Performance parameters for intersection-based AEB scenarios Image Source: AAA

Alert distances are provided at the instant that a notification of a vehicle ahead is visible on the test vehicle's instrument cluster. Automatic braking is considered to have occurred once the test vehicle's resultant deceleration exceeds 0.15 G. For test vehicles with adjustable AEB sensitivity settings, the midpoint setting was utilized for all test runs. If an even number of settings were available, the next latest setting (i.e. the timing of the collision warning and/or braking application) relative to the midpoint setting was utilized.

$$TTCa = \frac{-v_r - \sqrt{v_r^2 - 2a_{TV}r}}{a_{TV}}$$

Figure 37: TTC for perpendicular collision scenario Image Source: AAA

$$TTCa = \frac{-v_r - \sqrt{v_r^2 - 2a_{TV}r}}{a_{TV}}$$

Figure 38: TTC for turning collision scenario Image Source: AAA

Figures 37 and 38 provide the TTC equations utilized for perpendicular and turning collision scenarios, respectively. Within Figure 37, v_r is the longitudinal test vehicle velocity, a_{TV} is the longitudinal test vehicle acceleration, and r is the longitudinal separation distance. Within Figure 38, v_r is the relative longitudinal test and target vehicle velocity, a_{TV} is the relative longitudinal test and target vehicle acceleration, and r is the resultant separation distance.

It is acknowledged that collisions involving vehicles moving in a different direction and situations in which the test vehicle is actively turning are more challenging for AEB systems relative to rear-end collision scenarios. However, intersection-based collisions between two vehicles account for a significant number of injuries. As described within Section II, T-bone and turn across oncoming vehicle path type collisions account for 43 percent of analyzed injuries.

Regardless of challenges inherent to intersection-based collision scenarios, AEB system performance in the context of these scenarios should be evaluated; consistent impact speed mitigation or collision prevention could significantly reduce injury severity and/or occurrence. Additionally, a majority of fatalities associated with these collision scenarios occur on roadways with speed limits at or above 40 mph; it is likely that impact speed mitigation would reduce the occurrence of fatalities associated with these collision scenarios.

1. Perpendicular (T-bone) collision scenario

For each test vehicle, the intersection previously described within Section IV.B was utilized. The lateral centerline of the target vehicle was oriented above the right lane centerline within a perpendicular roadway relative to the test vehicle. The lateral centerline of the test vehicle was oriented above the right lane centerline of the intersecting roadway. This lateral positioning was maintained by both vehicles through the entirety of the test run. Both test and target vehicles approached the intersection at a steady-state test speed of 30 mph. For this collision type, the test speed represents the lower bound of posted speed limits on roadways where injuries and fatalities commonly occur.

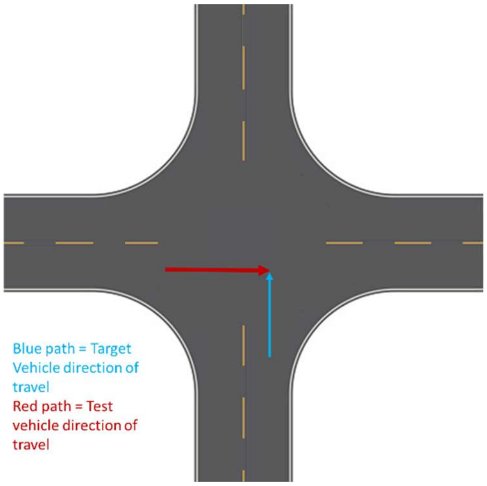


Figure 39: Perpendicular collision scenario trajectory and impact point Image Source: AAA

To initiate a test run, the test vehicle accelerated to the test speed from a starting point approximately 1000 feet from the potential collision point. For the test run to be valid, the test speed must have been reached and maintained within ± 1 mph once the front of the test vehicle was within 600 feet of the potential collision point.

At the start of the test run, the front of the target vehicle was located approximately 300 feet from the lateral centerline of the lane occupied by the test vehicle. The target vehicle accelerated to a steady-state speed of 30 mph automatically in synchronization with the test vehicle. The target vehicle was programmed to adjust its trajectory such that the front center point of the test vehicle would impact the target vehicle's left side center point (50 percent offset relative to the front left corner) if no braking intervention was applied. If the test vehicle rapidly decelerated before impact, the impact point will be greater than 50 percent offset.

The test vehicle maintained steady-state speed until impact with the target vehicle occurred or the AEB system provided an alert. If an alert was provided, the test driver immediately removed their foot from the accelerator and provided no intervention until the test vehicle either successfully avoided a collision or impact with the target vehicle occurred. After each run, data was reviewed to ensure the test driver did not inadvertently apply pressure to the brake pedal until one of these two conditions were met. For each test vehicle, five test runs were performed.

2. Test vehicle turning left in front of oncoming target vehicle

For each test vehicle, the intersection previously described within Section IV.B was utilized. The lateral centerline of the target vehicle was oriented above the right lane centerline. The lateral centerline of the test vehicle was oriented above the centerline of the oncoming lane relative to the target vehicle; this lateral position was maintained until the left turn was initiated. The test vehicle approached the intersection and initiated turning at a steady-state speed of 10 mph. The target vehicle approached the intersection at a steady-state speed of 25 mph.

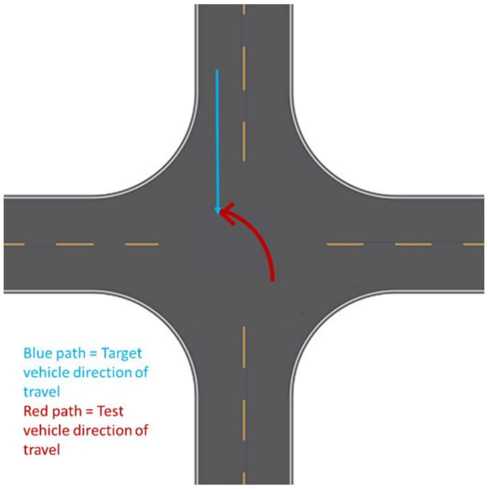


Figure 40: Turning collision scenario trajectory and impact point Image Source: AAA

It is acknowledged that target and test vehicle speeds are significantly slower relative to posted speed limits on roadways where injuries and fatalities commonly occur as a result of this collision scenario. However, testing constraints relating to potential vehicle damage, test repeatability, and limitations of evaluated AEB systems necessitate a slower testing speed.

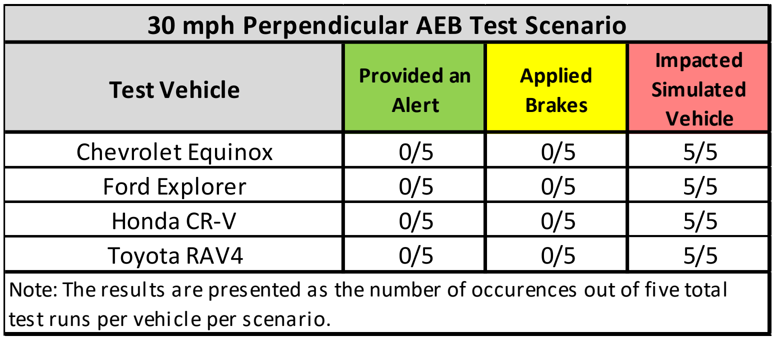
At the start of the test run, the front of the target vehicle was located approximately 400 feet from the potential collision point in the middle of the intersection. The target vehicle accelerated to a steady-state speed of 25 mph automatically in synchronization with the test vehicle. The target vehicle was programmed to adjust its longitudinal velocity such that the front center point of the test vehicle would impact the target vehicle's front left corner if no braking intervention was applied.

To initiate a test run, the test vehicle accelerated to the test speed from a starting point approximately 600 feet from the potential collision point; the left turn signal was engaged throughout the test run. For the test run to be valid, the test speed must have been reached and maintained within ± 1 mph once the test driver initiated the left turn. For consistency between test runs, a traffic cone approximately 6 feet to the right of the roadway edge was utilized to signal the driver to begin turning; chalk was used to mark the turning radius followed by the test driver.

The test vehicle maintained steady-state speed throughout the turn until impact with the target vehicle occurred or the AEB system provided an alert. If an alert was provided, the test driver immediately removed their foot from the accelerator and provided no intervention until the test vehicle either successfully avoided a collision or impact with the target vehicle occurred. After each run, data was reviewed to ensure the test driver did not inadvertently apply pressure to the brake pedal until one of these two conditions were met. For each test vehicle, five test runs were performed.

C. Test Results

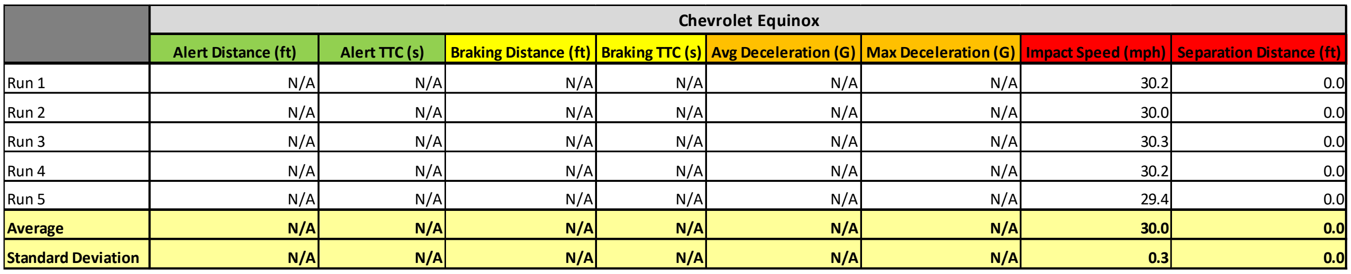
1. Perpendicular (T-bone) collision scenario



30 mph Perpendicular AEB Test Scenario			
Test Vehicle	Provided an Alert	Applied Brakes	Impacted Simulated Vehicle
Chevrolet Equinox	0/5	0/5	5/5
Ford Explorer	0/5	0/5	5/5
Honda CR-V	0/5	0/5	5/5
Toyota RAV4	0/5	0/5	5/5
Note: The results are presented as the number of occurences out of five total test runs per vehicle per scenario.			

Figure 41: High-level performance observations for each test vehicle Image Source: AAA

All test vehicles failed to detect the imminent perpendicular collision with the target vehicle resulting in unmitigated impact for each of the five test runs. Figure 41 provides overall results pertaining to alert, braking, and impact phases. Figures 42–45 provide run-level data for each test vehicle; impact speed is the only reported parameter as neither alerts nor braking mitigation were provided for any test runs.



	Chevrolet Equinox							
	Alert Distance (ft)	Alert TTC (s)	Braking Distance (ft)	Braking TTC (s)	Avg Deceleration (G)	Max Deceleration (G)	Impact Speed (mph)	Separation Distance (ft)
Run 1	N/A	N/A	N/A	N/A	N/A	N/A	30.2	0.0
Run 2	N/A	N/A	N/A	N/A	N/A	N/A	30.0	0.0
Run 3	N/A	N/A	N/A	N/A	N/A	N/A	30.3	0.0
Run 4	N/A	N/A	N/A	N/A	N/A	N/A	30.2	0.0
Run 5	N/A	N/A	N/A	N/A	N/A	N/A	29.4	0.0
Average	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**30.0**	**0.0**
Standard Deviation	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**0.3**	**0.0**

Figure 42: Run-level test data for the Chevrolet Equinox Image Source: AAA

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	Ford Explorer							
	Alert Distance (ft)	Alert TTC (s)	Braking Distance (ft)	Braking TTC (s)	Avg Deceleration (G)	Max Deceleration (G)	Impact Speed (mph)	Separation Distance (ft)
Run 1	N/A	N/A	N/A	N/A	N/A	N/A	29.7	0.0
Run 2	N/A	N/A	N/A	N/A	N/A	N/A	29.8	0.0
Run 3	N/A	N/A	N/A	N/A	N/A	N/A	30.3	0.0
Run 4	N/A	N/A	N/A	N/A	N/A	N/A	29.8	0.0
Run 5	N/A	N/A	N/A	N/A	N/A	N/A	29.3	0.0
Average	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**29.8**	**0.0**
Standard Deviation	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**0.3**	**0.0**

Figure 43: Run-level test data for the Ford Explorer Image Source: AAA

	Honda CR-V							
	Alert Distance (ft)	Alert TTC (s)	Braking Distance (ft)	Braking TTC (s)	Avg Deceleration (G)	Max Deceleration (G)	Impact Speed (mph)	Separation Distance (ft)
Run 1	N/A	N/A	N/A	N/A	N/A	N/A	30.7	0.0
Run 2	N/A	N/A	N/A	N/A	N/A	N/A	30.4	0.0
Run 3	N/A	N/A	N/A	N/A	N/A	N/A	30.3	0.0
Run 4	N/A	N/A	N/A	N/A	N/A	N/A	30.0	0.0
Run 5	N/A	N/A	N/A	N/A	N/A	N/A	30.3	0.0
Average	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**30.3**	**0.0**
Standard Deviation	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**0.2**	**0.0**

Figure 44: Run-level test data for the Honda CR-V Image Source: AAA

	Toyota RAV4							
	Alert Distance (ft)	Alert TTC (s)	Braking Distance (ft)	Braking TTC (s)	Avg Deceleration (G)	Max Deceleration (G)	Impact Speed (mph)	Separation Distance (ft)
Run 1	N/A	N/A	N/A	N/A	N/A	N/A	29.5	0.0
Run 2	N/A	N/A	N/A	N/A	N/A	N/A	30.8	0.0
Run 3	N/A	N/A	N/A	N/A	N/A	N/A	30.1	0.0
Run 4	N/A	N/A	N/A	N/A	N/A	N/A	30.8	0.0
Run 5	N/A	N/A	N/A	N/A	N/A	N/A	29.8	0.0
Average	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**30.2**	**0.0**
Standard Deviation	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**0.5**	**0.0**

Figure 45: Run-level test data for the Toyota RAV4 Image Source: AAA

2. *Test vehicle turning in front of oncoming target vehicle*

10 mph Turn-In AEB Test Scenario			
Test Vehicle	**Provided an Alert**	**Applied Brakes**	**Impacted Simulated Vehicle**
Chevrolet Equinox	0/5	0/5	5/5
Ford Explorer	0/5	0/5	5/5
Honda CR-V	0/5	0/5	5/5
Toyota RAV4	0/5	0/5	5/5
Note: The results are presented as the number of occurences out of five total test runs per vehicle per scenario.			

Figure 46: High-level performance observations for each test vehicle Image Source: AAA

As the left turn was initiated, all test vehicles failed to detect the imminent collision with the target vehicle resulting in unmitigated impact for each of the five test runs. Figure 46 provides overall results pertaining to alert, braking, and impact phases. Figures 47–50 provide run-level data for each test vehicle; impact speed is the only reported parameter as neither alerts nor braking mitigation were provided for any test runs.

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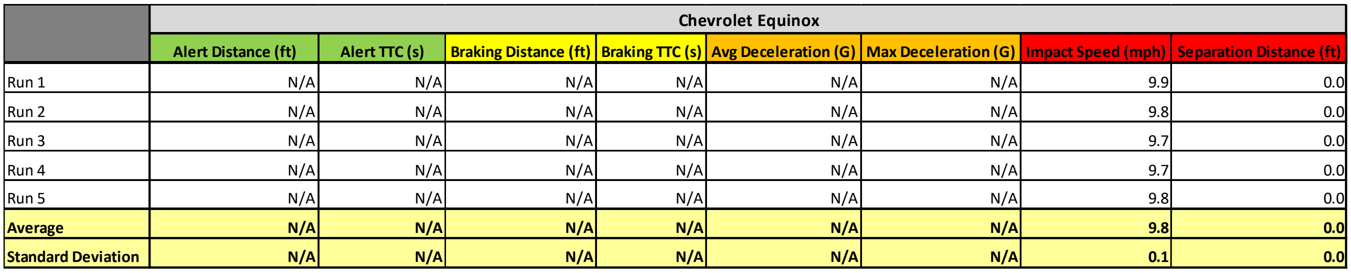
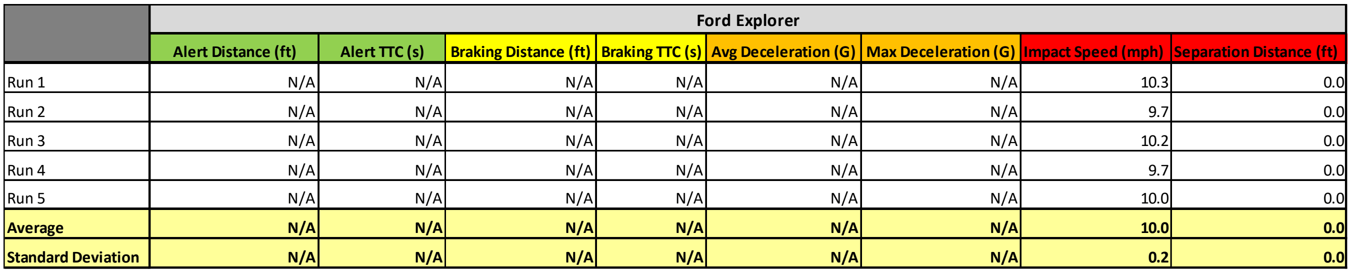


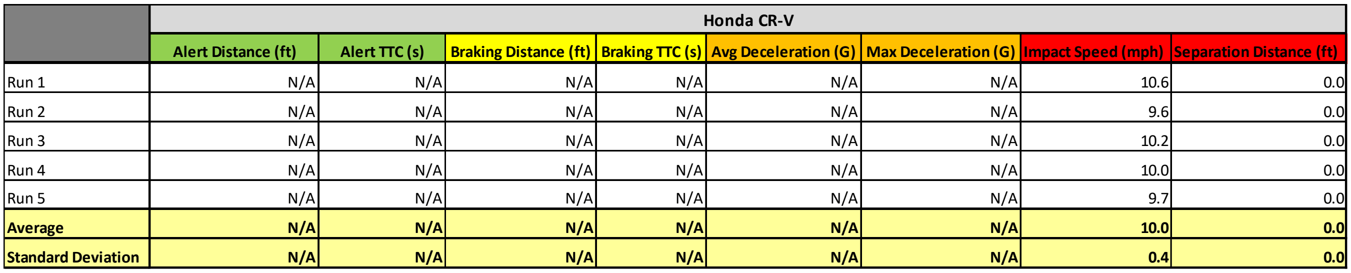
	Chevrolet Equinox							
	Alert Distance (ft)	Alert TTC (s)	Braking Distance (ft)	Braking TTC (s)	Avg Deceleration (G)	Max Deceleration (G)	Impact Speed (mph)	Separation Distance (ft)
Run 1	N/A	N/A	N/A	N/A	N/A	N/A	9.9	0.0
Run 2	N/A	N/A	N/A	N/A	N/A	N/A	9.8	0.0
Run 3	N/A	N/A	N/A	N/A	N/A	N/A	9.7	0.0
Run 4	N/A	N/A	N/A	N/A	N/A	N/A	9.7	0.0
Run 5	N/A	N/A	N/A	N/A	N/A	N/A	9.8	0.0
Average	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**9.8**	**0.0**
Standard Deviation	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**0.1**	**0.0**

Figure 47: Run-level test data for the Chevrolet Equinox Image Source: AAA



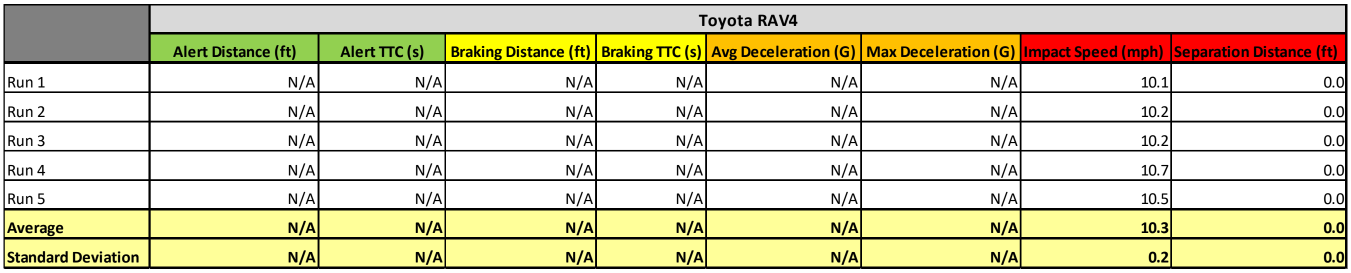
	Ford Explorer							
	Alert Distance (ft)	Alert TTC (s)	Braking Distance (ft)	Braking TTC (s)	Avg Deceleration (G)	Max Deceleration (G)	Impact Speed (mph)	Separation Distance (ft)
Run 1	N/A	N/A	N/A	N/A	N/A	N/A	10.3	0.0
Run 2	N/A	N/A	N/A	N/A	N/A	N/A	9.7	0.0
Run 3	N/A	N/A	N/A	N/A	N/A	N/A	10.2	0.0
Run 4	N/A	N/A	N/A	N/A	N/A	N/A	9.7	0.0
Run 5	N/A	N/A	N/A	N/A	N/A	N/A	10.0	0.0
Average	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**10.0**	**0.0**
Standard Deviation	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**0.2**	**0.0**

Figure 48: Run-level test data for the Ford Explorer Image Source: AAA



	Honda CR-V							
	Alert Distance (ft)	Alert TTC (s)	Braking Distance (ft)	Braking TTC (s)	Avg Deceleration (G)	Max Deceleration (G)	Impact Speed (mph)	Separation Distance (ft)
Run 1	N/A	N/A	N/A	N/A	N/A	N/A	10.6	0.0
Run 2	N/A	N/A	N/A	N/A	N/A	N/A	9.6	0.0
Run 3	N/A	N/A	N/A	N/A	N/A	N/A	10.2	0.0
Run 4	N/A	N/A	N/A	N/A	N/A	N/A	10.0	0.0
Run 5	N/A	N/A	N/A	N/A	N/A	N/A	9.7	0.0
Average	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**10.0**	**0.0**
Standard Deviation	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**0.4**	**0.0**

Figure 49: Run-level test data for the Honda CR-V Image Source: AAA



	Toyota RAV4							
	Alert Distance (ft)	Alert TTC (s)	Braking Distance (ft)	Braking TTC (s)	Avg Deceleration (G)	Max Deceleration (G)	Impact Speed (mph)	Separation Distance (ft)
Run 1	N/A	N/A	N/A	N/A	N/A	N/A	10.1	0.0
Run 2	N/A	N/A	N/A	N/A	N/A	N/A	10.2	0.0
Run 3	N/A	N/A	N/A	N/A	N/A	N/A	10.2	0.0
Run 4	N/A	N/A	N/A	N/A	N/A	N/A	10.7	0.0
Run 5	N/A	N/A	N/A	N/A	N/A	N/A	10.5	0.0
Average	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**10.3**	**0.0**
Standard Deviation	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**0.2**	**0.0**

Figure 50: Run-level test data for the Toyota RAV4 Image Source: AAA

D. Discussion

Each evaluated AEB system failed to issue an alert or provide any braking mitigation for any of the five test runs for each test scenario. In aggregate, 40 of 40 test runs involving common intersection-based scenarios resulted in impact with no speed mitigation. This finding illustrates the reality that current AEB systems are ineffective at mitigating or preventing intersection-based collision scenarios, which accounted for 2,914,220 police-reported injuries and 10,413 fatalities in the United States between 2016 and 2020. It is additionally

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important to note that evaluated test speeds were representative of the lower bound of posted speed limits observed when injuries and fatalities caused by intersection-based collisions typically occur.

VIII. CONCLUSIONS

In general, evaluated AEB systems were effective in consistently avoiding or mitigating rear-end collisions with a stationary vehicle ahead at speeds of 30 and 40 mph. This finding is encouraging due to the associated potential of AEB systems to reduce injuries and fatalities caused by this common collision scenario. As the collective vehicle fleet continues turnover with the introduction of more vehicles equipped with AEB, it is anticipated that injury occurrence and severity as well as fatalities associated with rear-end collisions will gradually decrease over time.

For common intersection-based collision scenarios included within this work, all evaluated AEB systems were ineffective at providing an alert or braking mitigation. Specifically, 100 percent of test runs involving an intersection-based collision scenario (T-bone and turn across path–opposite direction) resulted in an impact with no speed mitigation. While system performance results could be viewed as discouraging, it is important to note that standardized testing by research and regulatory agencies focus on front-to-rear collisions (i.e., rear-end collision scenarios). Performance observations within this work highlight an opportunity for further system refinement in the context of challenging collision scenarios. AAA recommends that automakers and technology companies continue to invest in ADAS development for scenarios that can offer the greatest safety benefit. As the industry continues down the path of driving automation, continual enhancement of established ADAS in the interim will help save lives, reduce the occurrence of serious injury, and promote public acceptance of future iterations of vehicle automation.

IX. KEY FINDINGS

1. How do evaluated AEB systems perform when encountering a stationary vehicle ahead?
    a. At a steady-state approach speed of 30 mph, evaluated AEB systems prevented a collision for 17 of 20 test runs, in aggregate. For test runs that resulted in a collision, the impact speed was reduced by an average of 86 percent.
    b. At a steady-state approach speed of 40 mph, evaluated AEB systems prevented a collision for 6 of 20 test runs, in aggregate. For test runs that resulted in a collision, the impact speed was reduced by an average of 62 percent.
2. How do evaluated AEB systems perform when encountering moving vehicles in collision scenarios involving an intersection?
    a. For a perpendicular collision scenario, an unmitigated collision occurred for 100 percent of test runs, in aggregate.
    b. For a collision scenario involving a left turn in front of an oncoming vehicle, an unmitigated collision occurred for 100 percent of test runs, in aggregate.

X. RECOMMENDATIONS

1. Automakers should continue to refine AEB systems with the objective of incorporating collision mitigation capability for common intersection-based crash scenarios.

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2. Automakers and regulatory agencies should prioritize focus on system design and test protocols around collision attributes observed when injuries and fatalities commonly occur.

3. Regardless of current system limitations, automakers should continue efforts to include AEB systems as standard equipment throughout their product portfolio.

XI. REFERENCES

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