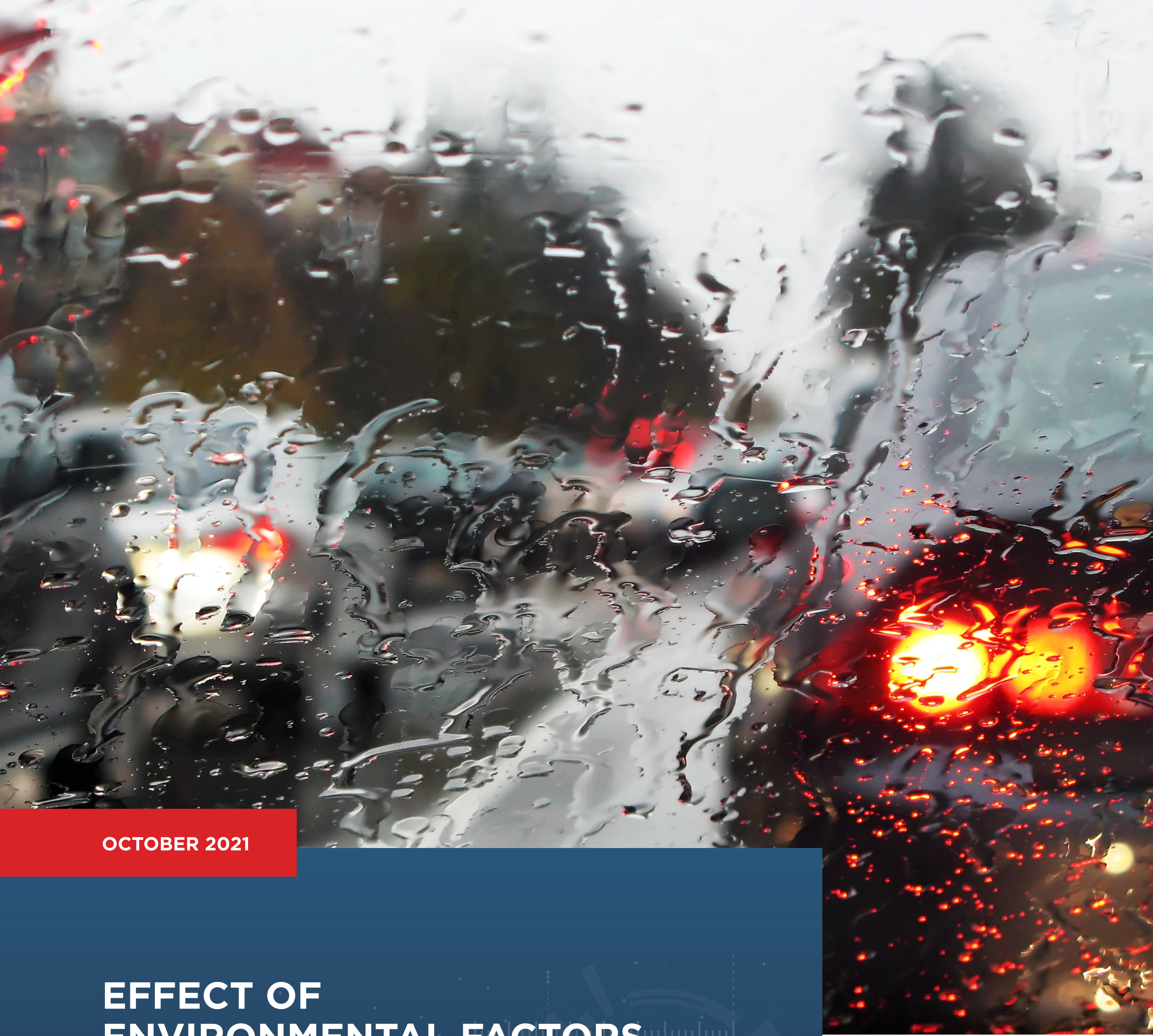

OCTOBER 2021

EFFECT OF ENVIRONMENTAL FACTORS ON ADAS SENSOR PERFORMANCE

NewsRoom.AAA.com

(this page intentionally left blank)

ABSTRACT

Advanced driver assistance systems (ADAS) are becoming increasingly integrated within new vehicles sold in the United States. However, the majority of publicly available performance evaluations occur within idealized operating conditions in terms of weather, time of day, and sensor status, which are typically unrepresentative of naturalistic environments. To evaluate the performance of ADAS in suboptimal conditions, four popular crossover vehicles equipped with lane keeping assist and automatic emergency braking systems were tested in a number of simulated environmental scenarios.

Research Questions:

1. How do vehicles equipped with lane keeping assist and automatic emergency braking systems perform during scenarios with simulated rainfall relative to baseline conditions?
    a. Lane keeping on a roadway with well-defined lane markers
    b. Reacting to a simulated stationary vehicle in the travel lane
2. How do vehicles equipped with lane keeping assist and automatic emergency braking systems perform during scenarios with a dirty windshield (i.e., bugs and dirt) relative to baseline conditions?
    a. Lane keeping on a roadway with well-defined lane markers
    b. Reacting to a simulated stationary vehicle in the travel lane

Key Findings:

1. In general, evaluated lane keeping assist and automatic emergency braking systems were influenced by simulated rainfall.
    a. In terms of lane keeping performance, 69 percent of test runs conducted with simulated rainfall resulted in the test vehicle crossing the lane marker on the roadway.
    b. In aggregate, 17 and 33 percent of test runs conducted with simulated rainfall resulted in a collision for test speeds of 25 and 35 mph, respectively.
2. In general, evaluated lane keeping assist and automatic emergency braking systems were minimally influenced by a dirty windshield.
    a. While minor differences were noted with respect to baseline conditions, lane keeping performance was not negatively influenced by a dirty windshield.
    b. No test runs conducted with a dirty windshield resulted in a collision for either 25mph or 35mph test speeds.

CONTENTS

FIGURES

I. INTRODUCTION

Inclusion of various types of advanced driver assistance systems (ADAS) in the majority of new vehicles sold in the United States could result in significant reductions in fatalities, personal injury, and property damage. A 2018 AAA Foundation analysis estimated that if driver assistance technologies were installed on all vehicles, they would have had the potential to help prevent or mitigate roughly 40 percent of all crashes involving passenger vehicles [1]. Additionally, the Insurance Institute of Highway Safety reported that vehicles equipped with forward collision warning with automatic emergency braking were involved in 50 percent fewer police-reported front-to-rear collisions compared to vehicles without the technology [2]. With the demonstrated effectiveness of ADAS, it is imperative that further development and refinement of existing systems receive sustained emphasis.

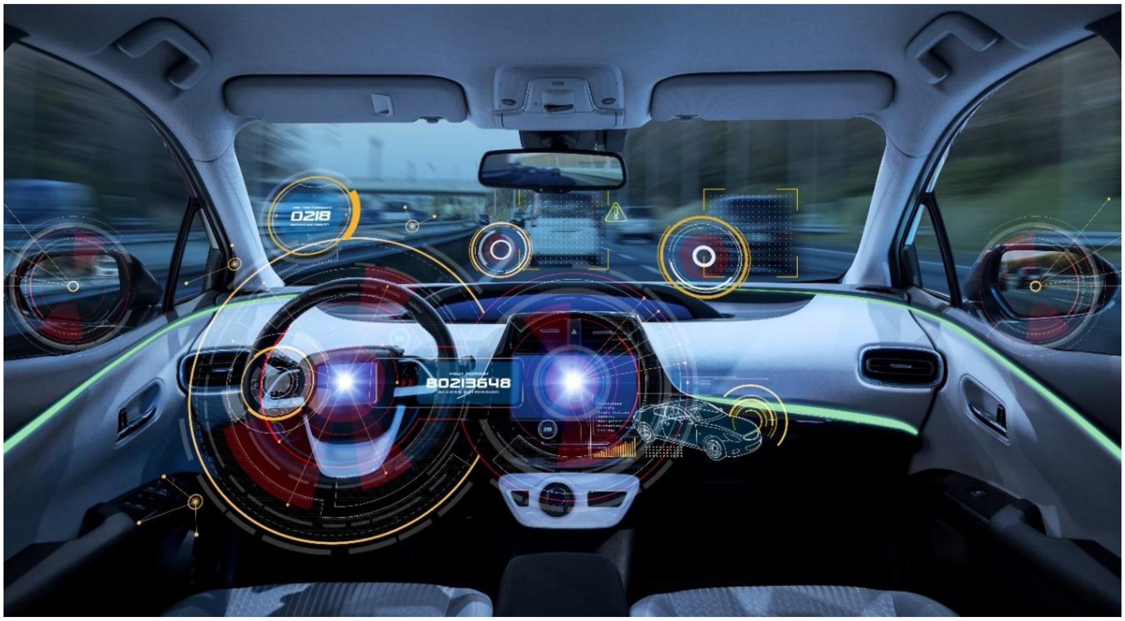

Figure 1: Fully autonomous vehicles will be required to analyze and react to highly dynamic environments Image Source: AAA

The ADAS test procedures utilized by most automakers and vehicle safety organizations specify idealized environmental test conditions. This specification is beneficial in terms of maximum test repeatability by limiting the inclusion of additional independent variables. However, it must be noted that naturalistic environments do not exist in a vacuum; rain, fog, sleet, and snow are frequently encountered by drivers, and vehicle sensors are in various states of cleanliness depending on individual ownership habits.

The purpose of this research is to provide insight into ADAS performance in the context of conditions frequently encountered in naturalistic environments. Within this work, crossover vehicles with both lane keeping assistance and automatic emergency braking systems were selected for evaluation in environments consisting of simulated rain and image sensors occluded by bugs and dirt. All testing activities were conducted on a closed-course and included various lane keeping and braking scenarios.

AAA recommends that testing initiatives utilized by the automotive industry incorporate suboptimal conditions within a comprehensive set of evaluation criteria related to ADAS.

II. BACKGROUND

ADAS comes in many forms and can be broadly characterized as an *active* or *passive* system. Active ADAS refers to a system that provides lateral and/or longitudinal vehicle control in a sustained or temporary manner. Examples include active driving assistance, automatic emergency braking, lane keeping assistance, and adaptive cruise control. In contrast, passive ADAS notifies the driver of an impending collision but does not intervene with lateral or longitudinal vehicle motion. Examples include blind spot warning, forward collision warning, rear cross traffic warning, and lane departure warning.

ADAS relies on a variety of sensors in order to gather information related to the surrounding environment. Sensors consist of a hardware and a software component. The hardware component is composed of the physical components necessary to convert information related to the surrounding environment into a digital signal. The software component is responsible for converting raw analog data into useful information about the dynamic environment surrounding the vehicle as well as determining an appropriate vehicle response.

Depending on the type of sensor, external influences such as weather and sensor cleanliness can have various effects on operation. Specifically, radar[1] sensors are minimally affected by rain, snow, and fog relative to other sensor types and function equally well in lighting conditions ranging from complete darkness to blinding sun. Additionally, radar sensors tend to be less affected by bugs and dirt because they are frequently placed behind plastic bumper covers. In cases where radar sensors are exposed, emitted radio energy can penetrate these particles with minimal attenuation. However, systems such as lane keeping assistance or lane departure warning systems require integration of additional sensors because radar is not effective at discerning object detail and cannot detect variations on a flat surface, such as lane markings. Image sensors (cameras) are currently utilized for object classification and to track lane markings. Depending on the type of electromagnetic radiation (visible, near-infrared, medium wave infrared, etc.) detected by the camera, the sensitivity to weather and dirt varies. Cameras that detect energy in the visible spectrum are most affected by weather, lighting conditions, and bugs/dirt relative to cameras specific to the infrared spectrum.

Automatic emergency braking systems utilize front-facing radar and/or camera(s) to obtain kinematic data pertaining to surrounding vehicles and objects. Lane keeping assistance systems currently rely on one or more cameras to track the position of lane markers. Lane keeping assistance and automatic emergency braking systems effect sustained lateral and temporary longitudinal motion control, respectively.

Currently, lidar[2] sensors are not commonly utilized for lane keeping assistance and lane departure warning systems; however, many analysts believe these sensors will become more widespread within ADAS and eventual autonomous driving systems with further refinement. Some remaining challenges include the aesthetic integration of lidar modules within the vehicle design, complexity, dependability, and cost.

[1] The origin of the word radar is as an acronym for **RA**dio **D**etection **A**nd **R**anging.

[2] The origin of the word lidar is as an acronym for **LI**ght **D**etection **A**nd **R**anging.

III. VEHICLE SELECTION METHODOLOGY

AAA researchers utilized SBD Automotive's ADAS and Autonomy Database and information from owner's manuals to verify test vehicles were equipped with both lane keeping assistance and automatic emergency braking systems. In order to be eligible for testing, vehicles were required to be equipped with a lane keeping assistance system capable of sustained operation and an automatic emergency braking system that provides active intervention upon detection of an impending collision. Crossover vehicles were selected for evaluation because of their continuing popularity in the United States. In 2020, sales of crossovers and utility vehicles accounted for 50 percent of the new vehicle market share [3].

Additionally, the following criteria were utilized for vehicle selection:

- Inclusion of domestic and import OEMs including European and Asian manufacturers
- Variety of manufacturers (only one vehicle per manufacturer will be tested)

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

- 2020 Buick Enclave Avenir with Automatic Emergency Braking and Lane Keep Assist
- 2020 Hyundai Santa Fe with Forward Collision Avoidance Assist and Lane Keeping Assist
- 2020 Toyota RAV4 with Pre-Collision System and Lane Tracing Assist
- 2020 Volkswagen Tiguan[3] with Front Assist and Lane Assist

Additional information related to vehicle identification numbers, setup pictures, and measurements can be found within the appendix of this report.

IV. TEST EQUIPMENT AND RESOURCES

Equipment specifications and illustrations are referenced in Figures 2–6.

A. Vehicle Dynamics Equipment

a) Oxford Technical Solutions (OxTS) RT3000 v2 and RT-Range Hunter

Each vehicle was outfitted with an OxTS RT3000 v2 to capture vehicle kinematic information and an OxTS RT-Range Hunter to process vehicle-to-lane and vehicle-to-vehicle measurements relative to the vehicle under test. The RT3000 interfaced with a site-installed base station to incorporate real-time kinematics (RTK) technology. The RT-Range Hunter interfaced with targets via XLAN.

[3] Upon conclusion of testing, it was determined the VW Tiguan does not use the ADAS camera for automatic emergency braking (AEB) as is relies solely on the forward mounted radar. As a result, the VW Tiguan tests results for automatic emergency braking are not included within this test report.

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 2: OxTS RT3000 v2 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 3: OxTS RT-Range Hunter specifications Image Source: AAA

2) Data Acquisition System—dSPACE MicroAutoBox (MABX)

Sensor inputs and data from the OxTS instrumentation were logged and time synced. Vehicle kinematics and range data were captured at a rate of 100 Hz; the visual and audible alert data were logged at a rate of 100 Hz and 10 000 Hz, respectively. The data acquisition system was equipped with anti-aliasing filters to attenuate frequencies above the Nyquist frequency.

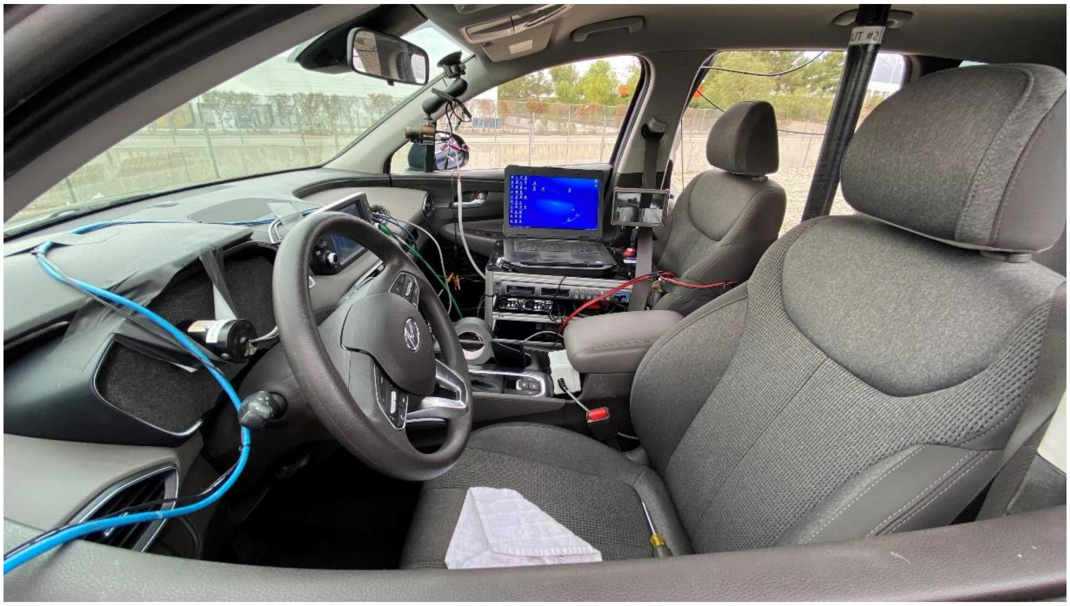

Figure 4: Data acquisition system and sensors installed in test vehicle Image Source: AAA

3) Visual/Audible Sensors

Each test vehicle was equipped with a light sensor and a microphone to capture visual and audible warnings provided by the lane keeping assistance or automatic emergency braking system.

Figure 5: Light sensor for characterization of visual system alerts Image Source: AAA

4) DRI Soft Car 360

Figure 6: DRI Low Profile Robotic Vehicle (Static Base) Image Source: AAA

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.

5) Simulated Rain System

To simulate the effect of rainfall on advanced driver assistance cameras mounted behind the windshield, a custom fabricated system was mounted in the vehicle.

Figure 7: Simulated Rain System Image Source: AAA

This system was designed to be a stand-alone component that could be secured in the cargo area and not move under decelerations exhibited in a typical automatic emergency braking event. To minimize variations in water volume and spray pattern, a precision injector nozzle and water/methanol high-pressure injection pump was utilized to ensure a consistent flowrate of 1L/min. A 5-gallon reservoir was integrated to allow for continuous execution of all test runs for each vehicle. The nozzle was positioned such that the spray pattern covered the entire windshield.

Figure 8: Rain system injector nozzle and mount. Image source: AAA

For all test vehicles, radar sensors were not targeted with simulated rainfall due to variations in sensor placement in addition to the theorized minimal effect of rainfall on sensor performance.

B. Test Facility

All track testing was conducted on closed surface streets on the grounds of the Auto Club Speedway in Fontana, CA. All testing was conducted on a dry asphalt surface free of visible moisture. The test lane was characterized by a width of 12 feet and a testing length of approximately 1900 feet. The lane marker on the right consisted of a solid white line while the lane marker on the left consisted of a broken white line divided into portions of equal length. The lane was generally straight with the exception of a slight right curve at the end of the testing portion. The pavement was in good condition with some minor ruts; this is representative of most well-maintained public roadways.

Figure 9: Test lane for closed-course evaluation Image Source: AAA

Before testing, the test lane was mapped using OxTS Lane Survey and Map Creation software.

V. VEHICLE PREPARATION

All vehicles were procured directly from manufacturers or specialty rental fleets. ***Any vehicles procured from a specialty rental company were sourced directly from the inventory of a new vehicle dealership.*** All test vehicles were evaluated in the "as received" condition from the manufacturer or specialty rental company.

All test vehicles were verified to be equipped with lane keeping assistance and automatic emergency braking systems that were enabled and free of modifications. The odometer reading of all test vehicles was between 500 and 15,000 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 resolved and cleared
- All fluid reservoirs filled to at least the minimum indicated levels

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.

VI. INQUIRY 1: HOW DO VEHICLES EQUIPPED WITH LANE KEEPING ASSISTANCE AND AUTOMATIC EMERGENCY BRAKING SYSTEMS PERFORM DURING SCENARIOS WITH SIMULATED RAINFALL RELATIVE TO BASELINE CONDITIONS?

A. Objective

Evaluate the effect of rainfall on lane keeping assistance and automatic emergency braking system performance relative to baseline conditions.

B. Methodology

In order to evaluate system performance with sufficient repeatability, closed-course testing was utilized to ensure a controlled environment with consistent testing conditions.

1) Lane Placement

Lane keeping assistance systems are designed to assist the driver by providing lateral vehicle control on straight and slightly curved sections of roadway. Depending on the system, either sustained or corrective control is provided. To evaluate the impact of rainfall on these systems, researchers evaluated system performance under baseline conditions and repeated testing with simulated rainfall. Within this work, the baseline is defined as daylight with no rain or fog. Additionally, testing was not conducted in low sun-angle conditions (i.e., sunrise or sunset) under any circumstance. To minimize the impact of varying sun angles and other environmental considerations, test runs with simulated rainfall were conducted immediately after completion of baseline test runs. For all test runs with simulated rainfall, the windshield wipers were engaged at the mid-range continuous speed setting.

For each vehicle, four test runs were performed for both baseline and simulated rainfall conditions. For a test run to be considered valid, the test driver was required to accelerate the vehicle to a steady-state speed of 45 mph and ensure the lane keeping assistance system was engaged prior to entering the mapped portion of the test lane. To ensure steady-state speed throughout the test run, adaptive cruise control was engaged. The test driver loosened their grip on the steering wheel once the vehicle was up to target speed and reached virtual starting gate for the test. The released grip / light touch of the steering wheel enabled the driver to maintain control of the vehicle while allowing the vehicle to steer without external inputs. If the test vehicle laterally deviated outside of the lane markers prior to reaching the end of the mapped testing lane, the test run was terminated and counted as a valid run.

The raw data from each test run consisted of the lateral offset of the vehicle center relative to the right shoulder of the mapped test lane. This metric was calculated with respect to the longitudinal vehicle position relative to the beginning of the mapped test lane. Bessel spline interpolation was performed on each run to calculate the lateral lane position at 50 cm increments. For each test condition, the resulting four interpolations from baseline and simulated rainfall conditions were combined to determine the average lateral lane placement throughout the entirety of the mapped test lane. For interpretation purposes, the average of individual baseline test runs is considered the “characteristic” run. The standard error associated with each run of interpolated data points was graphed as an upper and lower bound of the averaged measurement. This represents a quantitative measure of consistency between individual test runs.

For each vehicle, the average graphs for baseline and simulated rainfall conditions were graphed to illustrate general differences in lane placement and/or consistency along the mapped test lane. Additionally, the Spearman correlation between individual runs with simulated rainfall and the characteristic baseline run was calculated; positive values close to one indicate a strong correlation, negative values close to one indicate an opposite correlation and values near zero indicate no correlation.

2) Automatic Emergency Braking

It is common to encounter stopped or slow-moving vehicles in a variety of driving environments. Automatic emergency braking systems can prevent or mitigate the severity of a collision if the driver does not sufficiently react. To evaluate the impact of rainfall on these systems, researchers evaluated system performance under baseline conditions and repeated testing with the simulated rainfall system activated. Within this work, the baseline is defined as daylight with no rain or fog. Additionally, testing was not conducted in low sun-angle conditions under any circumstance. To minimize the impact of varying sun angles and other environmental considerations, test runs with simulated rainfall were conducted immediately after completion of baseline test runs. For all test runs with simulated rainfall, the windshield wipers were engaged at the mid-range continuous speed. For vehicles with multiple continuous settings, the setting below the fastest speed was utilized.

The DRI Soft Car 360® was utilized to simulate a stationary vehicle centered in the testing lane (herein referred to as the “target vehicle”). For each test vehicle, speeds of 25 mph and 35 mph were evaluated. For each speed, four runs were performed for both baseline and occluded camera conditions unless significant impact occurred for the first two runs. In this case, additional runs were not performed to minimize vehicle damage.

For the test run to be valid, the test driver was required to reach a steady-state target speed (25mph or 35mph) with adaptive cruise control engaged a minimum of 1,500 feet behind the target vehicle. As the test vehicle approached the target vehicle, no driver intervention was applied until contact was made with the target vehicle (if applicable). For each run, the following parameters were captured:

- Detection distance (ft)
- Detection time-to-collision (s)

- Separation distance at start of automatic braking (ft)
- Braking time-to-collision (s)
- Impact speed (mph)
- Final separation distance (ft)

Detection is considered to have occurred at the instant when a notification of an impending collision is provided by the system (audible or visual). Automatic braking is considered to have occurred once longitudinal deceleration exceeds 0.1 G. The test was considered complete once the test vehicle contacted the target vehicle or the test vehicle came to a complete stop.

C. Test Results

1) Lane Placement

a) 2020 Buick Enclave

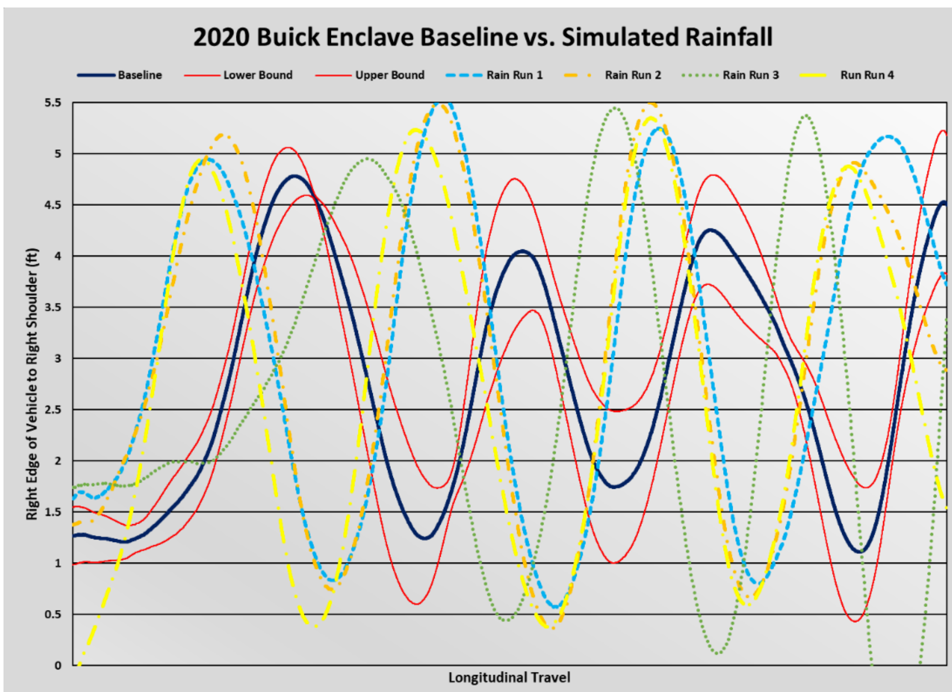

Figure 10: 2020 Buick Enclave averaged baseline lane placement and individual runs with simulated rainfall
Image Source: AAA

Figure 10 illustrates a graphical representation of the test vehicle lateral placement for the characteristic baseline run in comparison to the four individual test runs conducted with simulated rainfall. Quasiperiodicity is exhibited for baseline and simulated rainfall conditions analogous in appearance to an irregular sinusoidal wave. Specifically, this indicates significant "ping-ponging" throughout the entirety of the testing lane for both conditions. It is important to note that this is not characteristic of a system flaw in isolation.

Run 1	Run 2	Run 3	Run 4
-0.357	-0.416	-0.116	-0.463

Figure 11: Spearman correlation coefficients for individual runs with respect to characteristic baseline run
Image Source: AAA

Figure 11 provides the Spearman correlation coefficient for test runs with simulated rainfall with respect to the characteristic baseline run. From a mathematical perspective, the resulting moderate to weak Spearman correlations are due to irregular wave characteristics such as varying peak-to-peak amplitude and frequency. The resulting disorder in phase shifts can "cancel" a strong correlational coefficient despite the clear visual consistency between individual simulated rainfall test runs and the characteristic baseline run. Additionally, phase shifts exhibited between characteristic and simulated rainfall runs can weaken correlation coefficients.

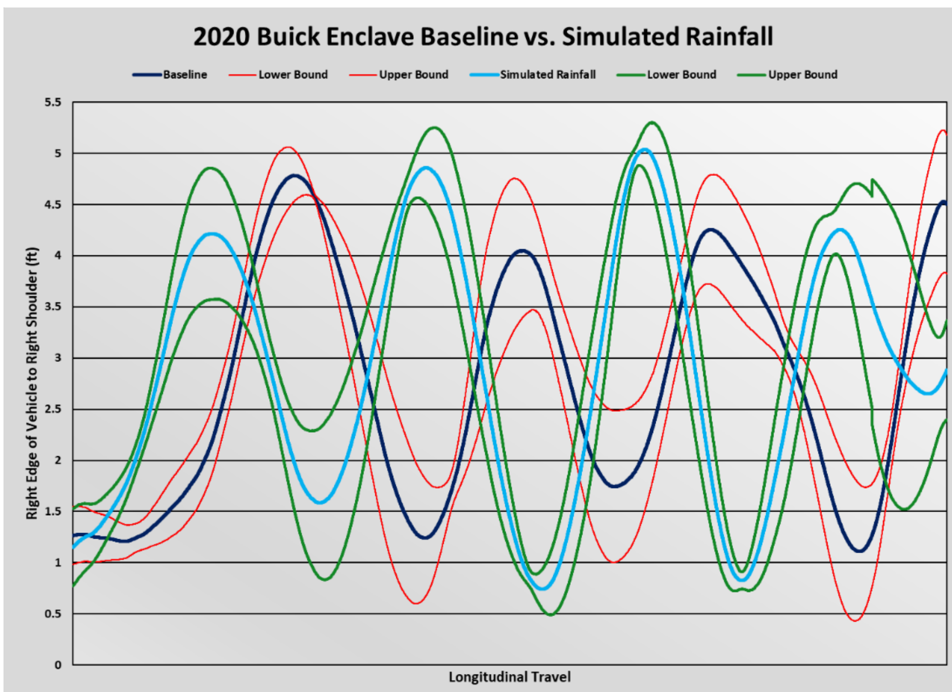

Figure 12: 2020 Buick Enclave averaged baseline and simulated rainfall lane placement
Image Source: AAA

Two differences relate to the increased lateral deviation (peak-to-peak amplitude) and increased occurrence of "ping-ponging" (peak-to-peak frequency) of test runs conducted with simulated rainfall relative to baseline conditions. These differences persist when simulated rainfall test runs are averaged as shown in Figure 12. These variations imply that lane keeping assistance system performance is influenced by significant rainfall. Specifically, significant rainfall may result in larger and more frequent lateral deviations within the travel lane if the driver fails to provide steering input.

b) 2020 Hyundai Santa Fe

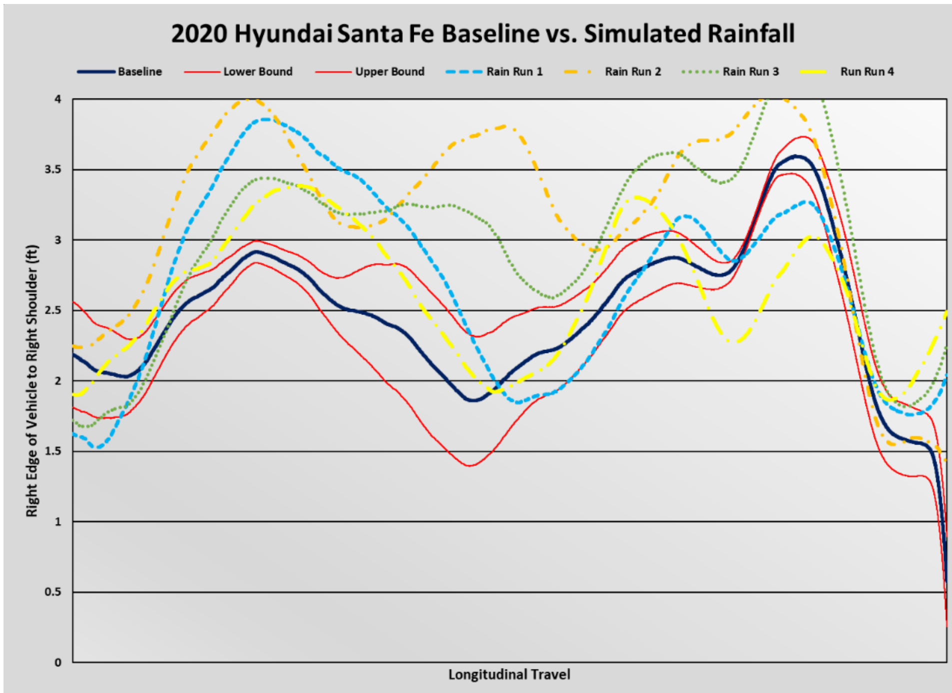

Figure 13: 2020 Hyundai Santa Fe average baseline lane placement and individual runs with simulated rainfall
Image Source: AAA

Figure 13 illustrates a graphical representation of the test vehicle lateral placement for the characteristic baseline run in comparison to the four individual test runs conducted with simulated rainfall. Quasiperiodicity is exhibited for baseline and simulated rainfall conditions not similar in appearance to any common mathematical functions. While the lane placement is generally similar between baseline and simulated rainfall conditions, the lateral lane placement for simulated rainfall conditions is generally biased to the left of the testing lane throughout the test until the end of the run.

Run 1	Run 2	Run 3	Run 4
0.742	0.593	0.847	0.733

Figure 14: Spearman correlation coefficients for individual runs with respect to characteristic baseline run
Image Source: AAA

Figure 14 provides the Spearman correlation coefficient for test runs with simulated rainfall with respect to the characteristic baseline run. The general similarity in system behavior between the characteristic baseline run and individual test runs with simulated rainfall is reflected in moderately strong Spearman coefficients above 0.590.

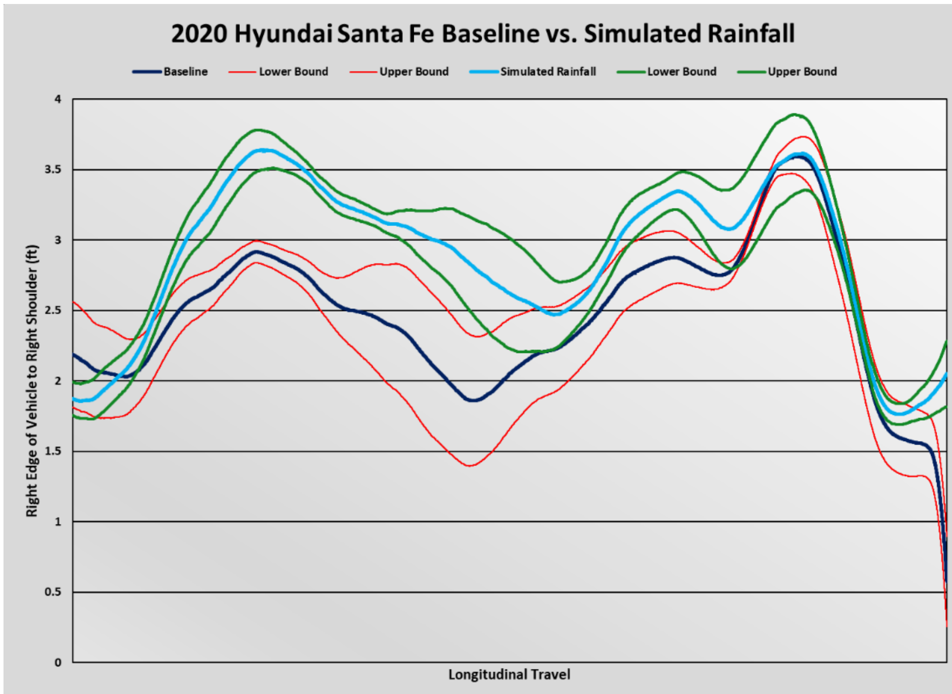

Figure 15: 2020 Hyundai Santa Fe averaged baseline and simulated rainfall lane placement
Image Source: AAA

As previously noted in Figure 13, test runs conducted with simulated rainfall have a persistent bias to the left of the testing lane throughout the test run until the end. This is illustrated by the average of simulated rainfall test runs in Figure 15. However, lane keeping assistance system performance is generally similar in the second half of the run indicating either a corrective and/or adaptive response to simulated rainfall. In combination, these observations suggest that while system performance may be initially influenced, the system is also capable of corrective and/or adaptive actions in response to significant rainfall.

c) 2020 Toyota RAV4

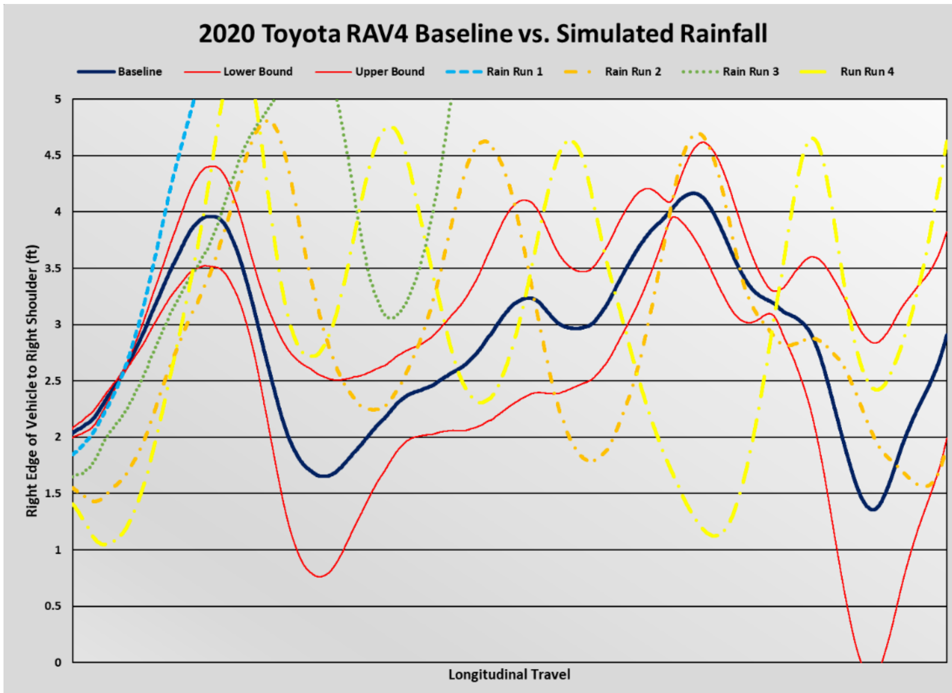

Figure 16: 2020 Toyota RAV4 average baseline lane placement and individual runs with simulated rainfall Image Source: AAA

Figure 16 illustrates a graphical representation of the test vehicle lateral placement for the characteristic baseline run in comparison to the four individual test runs conducted with simulated rainfall. It is important to note that the characteristic baseline run is only comprised of three individual baseline test runs because the test vehicle left the roadway for one of the four baseline runs. To ensure parity between baseline and simulated rainfall scenarios, an additional baseline test run was not performed because test runs conducted with simulated rainfall were counted as valid even if the test vehicle left the roadway prior to completion of the test run.

Quasiperiodicity is exhibited for baseline and simulated rainfall conditions; however, the general appearance between the characteristic averaged run and individual test runs with simulated rainfall is significantly different. The characteristic baseline run does not resemble any common mathematic function whereas the second and fourth test runs are analogous in appearance to an irregular sinusoidal wave. The test vehicle left the testing lane during the first and third test runs. Specifically, test runs conducted with simulated rainfall exhibited significantly more "ping-ponging" than the characteristic baseline run. Significant differences between all individual simulated rainfall test runs with respect to the characteristic baseline run imply that the lane keeping assistance system is influenced by significant rainfall.

Run 1	Run 2	Run 3	Run 4
0.987	0.444	-0.166	-0.092

Figure 17: Spearman correlation coefficients for individual runs with respect to characteristic baseline run
Image Source: AAA

Figure 17 provides the Spearman correlation coefficient for test runs with simulated rainfall with respect to the characteristic baseline run. For simulated rainfall test runs characterized by the test vehicle leaving the roadway prior to completion of the test, the Spearman coefficient only accounts for lateral lane placement of the characteristic baseline run to the longitudinal point at which the test vehicle left the roadway.

The Spearman coefficient for the first test run indicates a strong correlation because the lateral lane placement deviated to the left in general resemblance to the characteristic baseline run before leaving the roadway. Since the test vehicle left the roadway early in the test, this strong correlation value provides limited quantitative insight. The remaining simulated rainfall test runs are characterized by weak correlation coefficients signifying that system behavior with simulated rainfall does not generally resemble system behavior under baseline conditions.

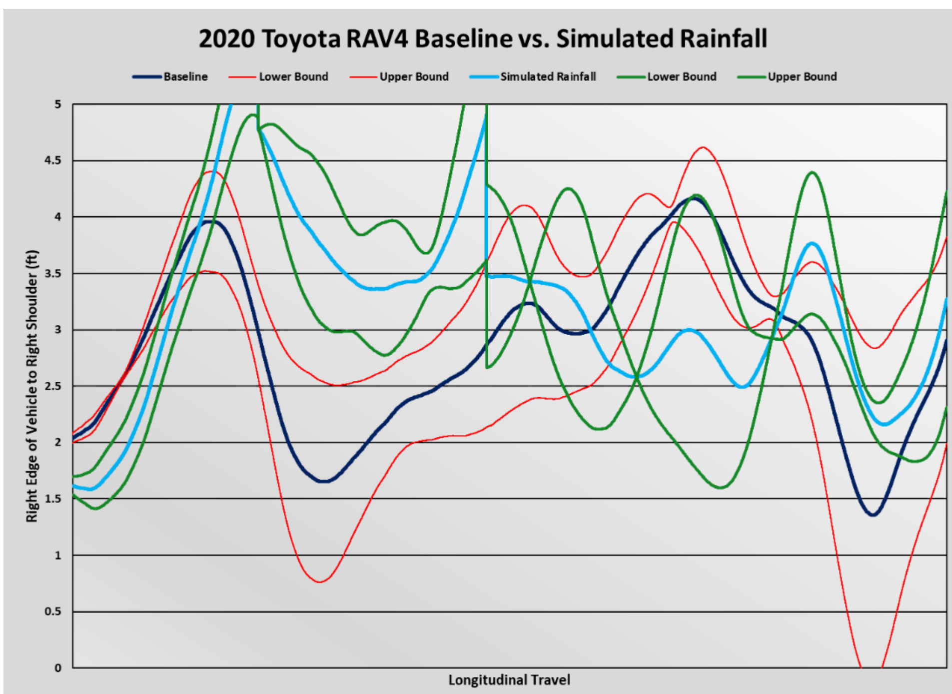

Figure 18: 2020 Toyota RAV4 averaged baseline and simulated rainfall lane placement Image Source: AAA

The average baseline and simulated rainfall test runs are illustrated in Figure 18. If the test vehicle leaves the roadway prior to completion of the test run, lateral lane placement from that run is only averaged to the longitudinal point at which the test vehicle leaves the roadway. In other words, lateral lane placement from the only second and fourth test runs are averaged in the second half of Figure 18 (the point where the test vehicle leaves the roadway on the third test run).

The standard error bounds intersect at multiple points due to the out of phase and irregular sinusoidal waves that characterize the lateral lane placement for the second and fourth test runs. Figure 18 illustrates that system behavior is significantly different for baseline and simulated rainfall conditions. Specifically, significant rainfall may result in the test vehicle leaving the roadway and/or "ping-ponging" within the travel lane if the driver fails to provide steering input.

d) 2020 Volkswagen Tiguan

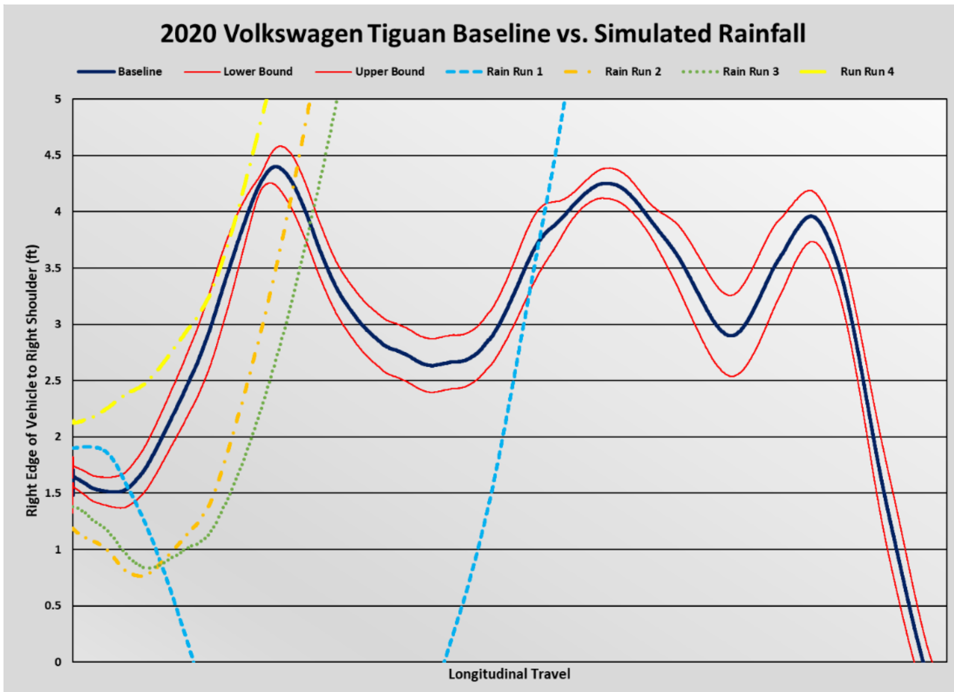

Figure 19: 2020 Volkswagen Tiguan average baseline lane placement and individual runs with simulated rainfall

Image Source: AAA

Figure 19 illustrates a graphical representation of the test vehicle lateral placement for the characteristic baseline run in comparison to the four individual test runs conducted with simulated rainfall. The test vehicle left the roadway prior to test completion for each of the four test runs conducted with simulated rainfall. For this reason, Spearman coefficients are not calculated and test runs with simulated rainfall were not averaged for comparison purposes.

The finding that the test vehicle left the roadway for all individual simulated rainfall test runs prior to test completion imply that the lane keeping assistance system is influenced by significant rainfall. Specifically, significant rainfall may result in the test vehicle leaving the roadway if the driver fails to provide steering input.

2) Automatic Emergency Braking

For narrative purposes, impact speeds are defined as follows within this report:

- 0 mph < Impact Speed ≤ 5 mph = Minor Impact
- 5 mph < Impact Speed ≤ 10 mph = Moderate Impact
- 10 mph < Impact Speed = Significant Impact

a) 2020 Buick Enclave

Buick Enclave 25 mph						
Baseline						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	148.24	4.006	39.37	1.086	0.0	5.80
Run 2	147.63	4.047	39.11	1.076	0.0	5.61
Run 3	149.72	4.010	41.03	1.117	0.0	4.45
Run 4	150.16	4.108	37.86	1.058	0.0	4.13
Average	**148.94**	**4.043**	**39.34**	**1.084**	**0.0**	**5.00**
Standard Deviation	**1.03**	**0.041**	**1.13**	**0.021**	**0.0**	**0.72**
Simulated Rain						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	149.11	4.054	39.68	1.101	0.0	4.31
Run 2	147.32	3.974	41.11	1.117	0.0	4.13
Run 3	148.69	4.057	41.20	1.139	0.0	4.80
Run 4	149.62	4.090	40.69	1.119	0.0	2.15
Average	**148.69**	**4.044**	**40.67**	**1.119**	**0.0**	**3.85**
Standard Deviation	**0.86**	**0.043**	**0.60**	**0.014**	**0.0**	**1.01**

Figure 20: 2020 Buick Enclave individual run data at 25 mph with simulated rainfall
Image Source: AAA

Individual test run data for baseline and occluded camera conditions at 25 mph are provided in Figure 20. For all parameters, the baseline and occluded camera mean values do not significantly differ at the 95 percent confidence level. For both conditions, no contact between the test vehicle and target vehicle occurred for any test runs conducted. Specifically, automatic emergency braking system performance is not significantly influenced by simulated rainfall at 25 mph.

Buick Enclave 35 mph						
Baseline						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	148.73	2.869	70.88	1.381	4.5	0.00
Run 2	146.47	2.853	70.79	1.385	0.0	0.78
Run 3	147.83	2.875	73.14	1.431	0.7	0.00
Run 4	149.72	2.897	75.00	1.470	0.0	1.69
Average	**148.19**	**2.874**	**72.46**	**1.417**	**1.3**	**0.62**
Standard Deviation	**1.20**	**0.016**	**1.75**	**0.036**	**1.9**	**0.69**
Simulated Rain						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	149.79	2.917	73.10	1.425	3.8	0.00
Run 2	148.09	2.901	75.45	1.478	0.0	0.66
Run 3	148.53	2.900	72.71	1.430	0.0	1.58
Run 4	146.89	2.877	71.33	1.407	0.0	1.36
Average	**148.32**	**2.899**	**73.15**	**1.435**	**1.0**	**0.90**
Standard Deviation	**1.04**	**0.014**	**1.48**	**0.026**	**1.7**	**0.62**

Figure 21: 2020 Buick Enclave individual run data at 35 mph with simulated rainfall
Image Source: AAA

Individual test run data for baseline and occluded camera conditions at 35 mph are provided in Figure 21. For all parameters, the baseline and simulated rainfall mean values do not significantly differ at the 95 percent confidence level. However, minor impact occurred for one of four test runs conducted with simulated rainfall. This contrasts with the baseline condition in which minor impact occurred with the target vehicle for two of four runs. Specifically, automatic emergency braking system performance was not negatively influenced by significant rainfall at 35 mph.

b) 2020 Hyundai Santa Fe

Hyundai Santa Fe 25 mph						
Baseline						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	71.48	1.983	40.72	1.163	0.0	8.82
Run 2	72.87	1.971	42.49	1.186	0.0	9.09
Run 3	72.67	1.970	42.09	1.181	0.0	9.80
Run 4	71.25	1.953	42.62	1.185	0.0	8.27
Average	**72.07**	**1.97**	**41.98**	**1.18**	**0.0**	**8.99**
Standard Deviation	**0.71**	**0.01**	**0.75**	**0.01**	**0.0**	**0.55**
Simulated Rain						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	71.28	1.948	45.27	1.281	0.0	4.89
Run 2	72.97	1.988	45.35	1.275	0.0	9.99
Run 3	73.63	1.981	42.74	1.187	0.0	8.02
Run 4	72.27	1.988	44.60	1.269	0.0	9.83
Average	**72.54**	**1.976**	**44.49**	**1.253**	**0.0**	**8.18**
Standard Deviation	**0.87**	**0.016**	**1.05**	**0.038**	**0.0**	**2.05**

Figure 22: 2020 Hyundai Santa Fe individual run data at 25 mph with simulated rainfall
Image Source: AAA

Individual test run data for baseline and occluded camera conditions at 25 mph are provided in Figure 22. For all parameters, the baseline and occluded camera mean values do not significantly differ at the 95 percent confidence level. For both conditions, no contact between the test vehicle and target vehicle occurred for any test runs conducted. Specifically, automatic emergency braking system performance is not significantly influenced by simulated rainfall at 25 mph.

Hyundai Santa Fe 35 mph						
Baseline						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	117.12	2.312	80.93	1.631	0.0	6.22
Run 2	121.72	2.380	76.20	1.537	0.0	3.31
Run 3	122.50	2.380	80.67	1.608	0.0	6.47
Run 4	121.38	2.361	80.67	1.611	0.0	4.90
Average	**120.68**	**2.358**	**79.62**	**1.597**	**0.0**	**5.23**
Standard Deviation	**2.09**	**0.028**	**1.97**	**0.036**	**0.0**	**1.26**
Simulated Rain						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	118.11	2.309	83.07	1.658	0.0	4.61
Run 2	120.88	2.368	82.90	1.661	0.0	4.62
Run 3	120.35	2.359	81.90	1.643	0.0	5.35
Run 4	121.55	2.389	81.24	1.641	0.0	5.63
Average	**120.22**	**2.356**	**82.28**	**1.651**	**0.00**	**5.05**
Standard Deviation	**1.29**	**0.029**	**0.75**	**0.009**	**0.00**	**0.45**

Figure 23: 2020 Hyundai Santa Fe individual run data at 35 mph with simulated rainfall

Image Source: AAA

Individual test run data for baseline and occluded camera conditions at 35 mph are provided in Figure 23. For all parameters, the baseline and occluded camera mean values do not significantly differ at the 95 percent confidence level. For both conditions, no contact between the test vehicle and target vehicle occurred for any test runs conducted. Specifically, automatic emergency braking system performance is not significantly influenced by simulated rainfall at 35 mph.

c) 2020 Toyota RAV4

Toyota RAV4 25 mph						
Baseline						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	77.65	2.132	58.40	1.621	0.0	2.65
Run 2	73.94	2.027	55.41	1.542	0.0	1.94
Run 3	76.95	2.119	58.50	1.633	0.0	2.84
Run 4	73.46	2.003	59.19	1.630	0.0	1.92
Average	**75.50**	**2.070**	**57.87**	**1.606**	**0.0**	**2.34**
Standard Deviation	**1.82**	**0.056**	**1.46**	**0.037**	**0.0**	**0.42**
Simulated Rain						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	77.96	2.137	58.32	1.616	11.7	0.00
Run 2	77.27	2.129	23.68	0.686	7.6	0.00
Run 3	NA	NA	NA	NA	NA	NA
Run 4	NA	NA	NA	NA	NA	NA
Average	**77.61**	**2.133**	**41.00**	**1.151**	**9.7**	**0.00**
Standard Deviation	**0.35**	**0.004**	**17.32**	**0.465**	**2.1**	**0.00**

Figure 24: 2020 Toyota RAV4 individual run data at 25 mph with simulated rainfall
Image Source: AAA

Individual test run data for baseline and simulated rainfall conditions at 25 mph are provided in Figure 24. Since the first two test runs with simulated rainfall were characterized by significant and moderate impact, no additional test runs were performed. As a result, statistical comparisons are not applicable for this dataset. However, it can be inferred that automatic emergency braking system performance is influenced at 25 mph because no impact occurred for any four test runs under baseline conditions in contrast to both test runs conducted with simulated rainfall.

Toyota RAV4 35 mph						
Baseline						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	133.85	2.615	75.79	1.533	0.0	0.77
Run 2	129.83	2.535	76.63	1.541	0.0	0.58
Run 3	126.22	2.446	79.80	1.590	0.0	0.76
Run 4	126.24	2.478	75.84	1.532	0.0	0.32
Average	**129.04**	**2.518**	**77.01**	**1.549**	**0.0**	**0.61**
Standard Deviation	**3.14**	**0.064**	**1.64**	**0.024**	**0.0**	**0.18**
Simulated Rain						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	117.06	2.292	75.07	1.608	0.0	2.27
Run 2	133.56	2.591	77.55	1.555	2.9	0.00
Run 3	126.15	2.473	77.76	1.571	4.0	0.00
Run 4	131.65	2.580	76.60	1.545	22.1	0.00
Average	**127.10**	**2.484**	**76.74**	**1.570**	**7.2**	**0.57**
Standard Deviation	**6.40**	**0.120**	**1.06**	**0.024**	**8.7**	**0.98**

Figure 25: 2020 Toyota RAV4 individual run data at 35 mph with simulated rainfall
Image Source: AAA

Individual test run data for baseline and simulated rainfall conditions at 35 mph are provided in Figure 25. For all parameters, the baseline and simulated rainfall mean values do not significantly differ at the 95 percent confidence level. However, this conclusion by a paired t-test for the impact speed is of limited value due to the disparity in variance between the test conditions.

For the baseline condition, no contact occurred for any four runs in contrast to the simulated rainfall condition in which minor contact occurred for two of four runs and significant impact occurred for an additional run. This would imply automatic emergency braking system performance is influenced by rainfall at 35 mph.

D. Summary of Test Results

1) Lane Placement

Overall, the lane keeping assistance system in three out of four test vehicles was influenced by simulated rainfall. Depending on the test vehicle, characteristics such as increased “ping-ponging” frequency/amplitude and inconsistency in lateral lane placement from run to run were observed. Additionally, when reviewing raw lane placement data, 11 of 16 (68.7%) tests runs with simulated rain resulted in the test vehicle crossing the lane marker on the roadway.

2) Automatic Emergency Braking

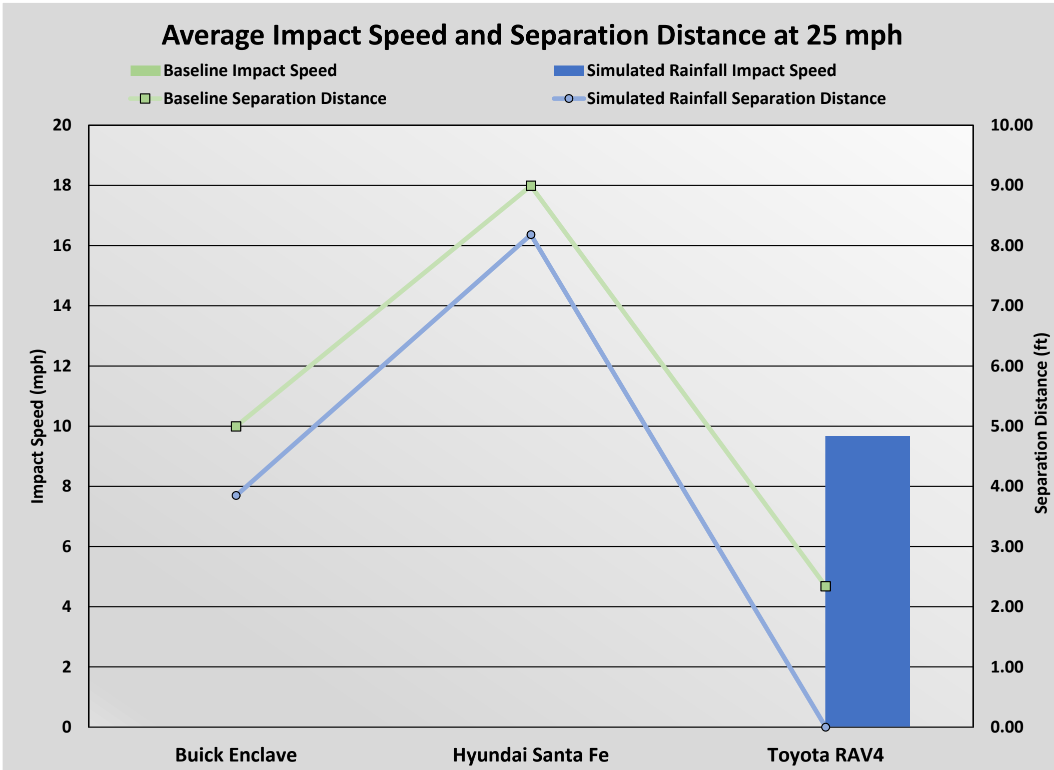

Figure 26: Average impact speed and final separation distance for each test vehicle at 25 mph
Image Source: AAA

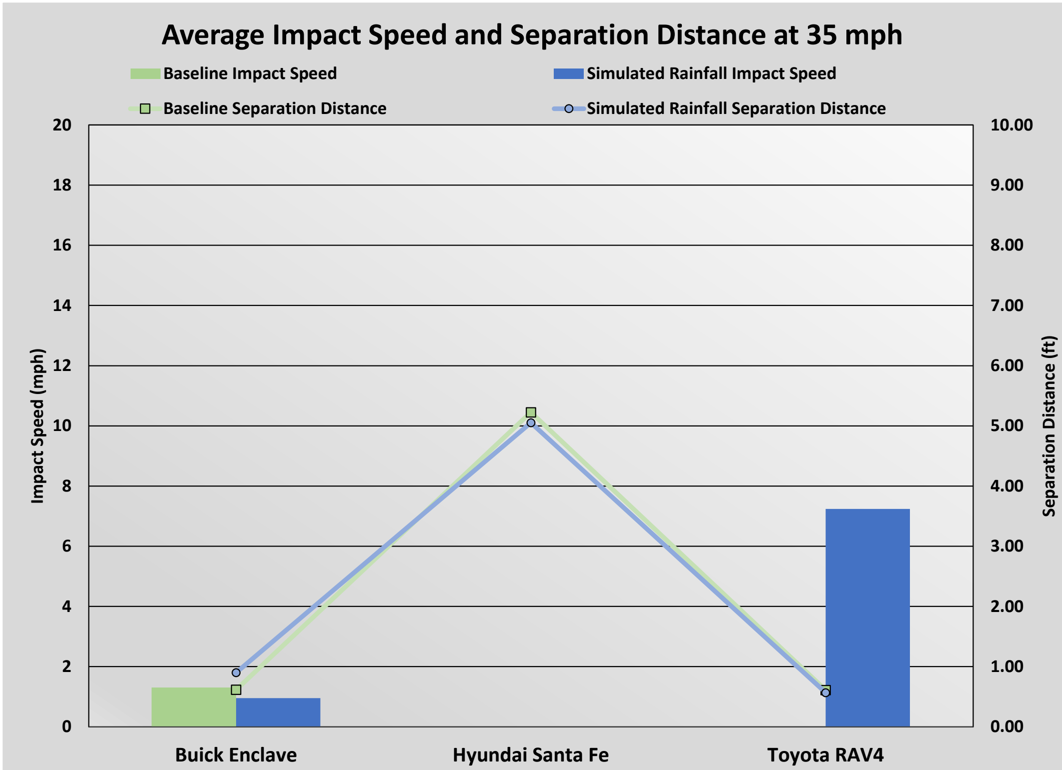

Figure 27: Average impact speed and final separation distance for each test vehicle at 35 mph
Image Source: AAA

Figures 26 and 27 illustrate the average impact speed and associated separation distance for baseline and simulated rainfall conditions for each test vehicle at 25 mph and 35 mph, respectively.

	Simulated Rain 25 mph					
	Buick Enclave					
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Baseline Average	148.94	4.043	39.34	1.084	0.0	5.00
Rainfall Average	148.69	4.044	40.67	1.119	0.0	3.85
Group Average	**148.81**	**4.043**	**40.01**	**1.101**	**0.0**	**4.42**
Std. Deviation	**0.13**	**0.001**	**0.67**	**0.017**	**0.0**	**0.57**
	Hyundai Santa Fe					
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Baseline Average	72.07	1.969	41.98	1.179	0.0	8.99
Rainfall Average	72.54	1.976	44.49	1.253	0.0	8.18
Group Average	**72.30**	**1.973**	**43.23**	**1.216**	**0.0**	**8.59**
Std. Deviation	**0.23**	**0.003**	**1.26**	**0.037**	**0.0**	**0.41**
	Toyota RAV4					
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Baseline Average	75.50	2.070	57.87	1.606	0.0	2.34
Rainfall Average	77.61	2.133	41.00	1.151	9.7	0.00
Group Average	**76.56**	**2.102**	**49.44**	**1.379**	**4.8**	**1.17**
Std. Deviation	**1.06**	**0.032**	**8.44**	**0.228**	**4.8**	**1.17**

Figure 28: Averaged data for each test vehicle at 25 mph Image Source: AAA

Figure 28 provides averaged test run data for baseline and simulated rainfall conditions at 25 mph. Two out of three test vehicles were not negatively influenced by simulated rainfall. The remaining test vehicle impacted the target vehicle twice, which resulted in the researchers moving on to the next test scenario to prevent damage to the vehicle.

Among all test vehicles, 17 percent of all test runs conducted with simulated rainfall at a speed of 25 mph resulted in a collision, whereas no collisions were observed during the baseline testing for the same vehicles.

	Simulated Rain 35 mph					
	Buick Enclave					
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Baseline Average	148.19	2.874	72.46	1.417	1.3	0.62
Rainfall Average	148.32	2.899	73.15	1.435	1.0	0.90
Group Average	**148.26**	**2.886**	**72.80**	**1.426**	**1.1**	**0.76**
Std. Deviation	**0.07**	**0.013**	**0.35**	**0.009**	**0.2**	**0.14**
	Hyundai Santa Fe					
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Baseline Average	120.95	2.373	73.36	1.486	0.0	5.29
Rainfall Average	120.22	2.356	82.28	1.651	0.0	5.05
Group Average	**120.59**	**2.364**	**77.82**	**1.568**	**0.0**	**5.17**
Std. Deviation	**0.37**	**0.008**	**4.46**	**0.083**	**0.0**	**0.12**
	Toyota RAV4					
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Baseline Average	129.04	2.518	77.01	1.549	0.0	0.61
Rainfall Average	127.10	2.484	76.74	1.570	7.2	0.57
Group Average	**128.07**	**2.501**	**76.88**	**1.559**	**3.6**	**0.59**
Std. Deviation	**0.97**	**0.017**	**0.14**	**0.010**	**3.6**	**0.02**

Figure 29: Averaged data for each test vehicle at 35 mph Image Source: AAA

Figure 29 provides averaged test run data for baseline and simulated rainfall conditions at 35 mph. Two out of three test vehicles were not negatively influenced by simulated rainfall. The remaining vehicle impacted the target vehicle on all three trials when evaluated with simulated rainfall.

Among all test vehicles, 33 percent of all test runs conducted with simulated rainfall at a speed of 35 mph resulted in a collision. This contrasts with the baseline condition during which a collision occurred for 17 percent of all test runs.

VII. INQUIRY 2: HOW DO VEHICLES EQUIPPED WITH LANE KEEPING ASSISTANCE AND AUTOMATIC EMERGENCY BRAKING SYSTEMS PERFORM DURING SCENARIOS CONDUCTED WITH A DIRTY WINDSHIELD RELATIVE TO BASELINE CONDITIONS?

A. Objective

Evaluate the effect of a dirty windshield on lane keeping assistance and automatic emergency braking system performance relative to baseline conditions.

B. Methodology

In order to evaluate system performance with sufficient repeatability, closed-course testing was utilized to ensure a controlled environment with consistent testing conditions. To simulate occluded cameras caused by a dirty windshield, a concentrated solution of dirt and bug particles was applied to the glass around system cameras in a consistent pattern. Specifically, a custom fabricated stamp applicator was utilized to apply the solution to the glass in a repeatable manner. The stamp applicator consisted of a square plate six inches in length and width with a protruding random spot pattern. The applicator was dipped in solution and applied to the windshield to produce a consistent pattern of dirt and bug particles in front of and around system cameras located behind the windshield.

Figure 30: Spot pattern of stamp applicator Image Source: AAA

1) Lane Placement

To evaluate the impact of occluded system cameras on lane-keeping performance, researchers evaluated system performance under baseline conditions and repeated testing after applying a solution of dirt and bug particles to the windshield with the stamp applicator, thus occluding the cameras.

Within this work, the baseline is defined as daylight with no rain or fog. Additionally, testing was not conducted in low sun-angle conditions under any circumstance. To minimize the impact of varying sun angles and other environmental considerations, test runs with occluded cameras were conducted immediately after completion of baseline test runs.

For each vehicle, four test runs were performed for both baseline and occluded camera conditions. For a test run to be considered valid, the test driver was required to accelerate the vehicle to a steady-state speed of 45 mph and ensure the lane keeping assistance system was engaged prior to entering the mapped portion of the test lane. To ensure steady-state speed throughout the test run, adaptive cruise control was engaged. The test driver released the grip on the steering wheel once the vehicle was up to target speed and reached virtual starting gate for the test. The released grip/light touch of the steering wheel enabled the driver to maintain control of the vehicle while allowing the vehicle to steer without external inputs. If the test vehicle laterally deviated outside of the lane markers prior to reaching the end of the mapped testing lane, the test run was terminated and counted as a valid run.

The raw data from each test run consisted of the lateral offset of the vehicle center relative to the right shoulder of the mapped test lane. This metric was calculated with respect to the longitudinal vehicle position relative to the beginning of the mapped test lane. Bessel spline interpolation was performed on each run to calculate the lateral lane position at 50 cm increments. For each test condition, the resulting four interpolations from baseline and occluded camera conditions were combined to determine the average lateral lane placement throughout the entirety of the mapped test lane. For interpretation purposes, the average of individual baseline test runs is considered the “characteristic” run. The standard error associated with each run of interpolated data points was graphed as an upper and lower bound of the averaged measurement. This represents a quantitative measure of consistency between individual test runs.

For each vehicle, the average graphs for baseline and occluded camera conditions were graphed to illustrate general differences in lane placement and/or consistency along the mapped test lane. Additionally, the Spearman correlation between individual runs with occluded cameras and the characteristic baseline run was calculated; positive values close to one indicate a strong correlation, negative values close to one indicate an opposite correlation and values near zero indicate no correlation.

2) Automatic Emergency Braking

To evaluate the impact of occluded system cameras on automatic emergency braking performance, researchers evaluated system performance under baseline conditions and repeated testing after applying a solution of dirt and bug particles to the windshield with the stamp applicator.

Within this work, the baseline is defined as daylight with no rain or fog. Additionally, testing was not conducted in low sun-angle conditions under any circumstance. To minimize the impact of varying sun angles and other environmental considerations, test runs with occluded cameras were conducted immediately after completion of baseline test runs.

The DRI Soft Car 360® was utilized to simulate a stationary vehicle centered in the testing lane (herein referred to as the “target vehicle”). For each test vehicle, speeds of 25 mph and 35 mph were evaluated. For each speed, four runs were performed for both baseline and occluded camera conditions unless significant impact occurred for the first two runs. In this case, additional runs were not performed to minimize vehicle damage.

For the test run to be valid, the test driver was required to reach steady-state speed with adaptive cruise control engaged a minimum of 1500 feet behind the target vehicle. As the test vehicle approached the target vehicle, no driver intervention was applied until contact was made with the target vehicle (if applicable). For each run, the following parameters were captured:

- Detection distance (ft)
- Detection time-to-collision (s)
- Separation distance at start of automatic braking (ft)
- Braking time-to-collision (s)
- Impact speed (mph)
- Final separation distance (ft)

Detection is considered to have occurred at the instant when a notification of an impending collision is provided by the system (audible or visual). Automatic braking is considered to have occurred once longitudinal deceleration exceeds 0.1 G. The test was considered complete once the test vehicle contacted the target vehicle or the test vehicle came to a complete stop.

C. Test Results

1) Lane Placement

a) 2020 Buick Enclave

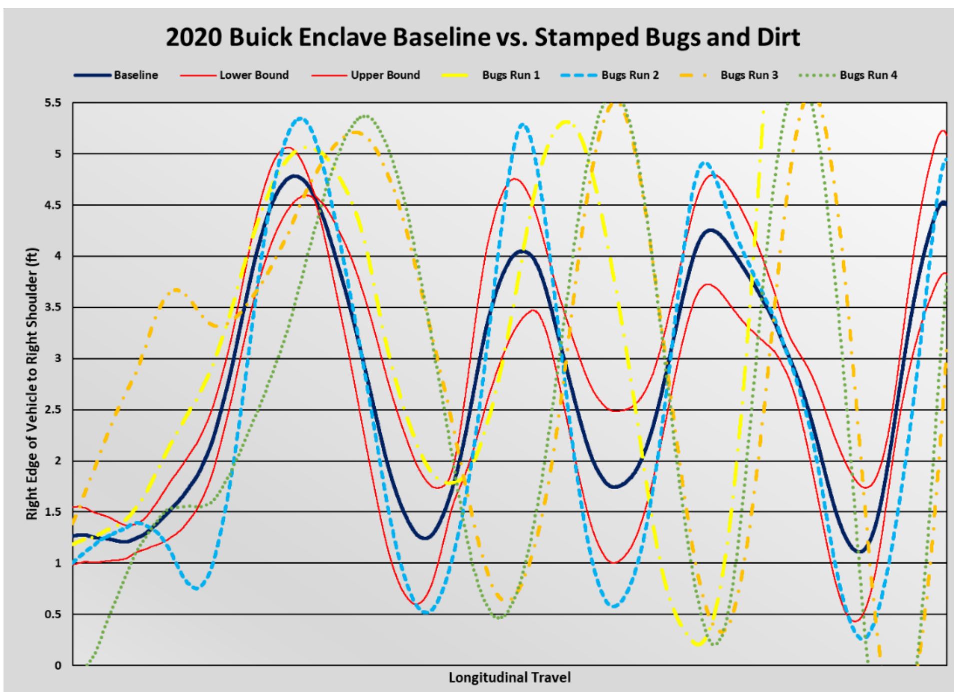

Figure 31: 2020 Buick Enclave average baseline lane placement and individual runs with occluded cameras Image Source: AAA

Figure 31 illustrates a graphical representation of the test vehicle lateral placement for the characteristic baseline run in comparison to the four individual test runs conducted with occluded system cameras. Quasiperiodicity is exhibited for baseline and occluded camera conditions analogous in appearance to an irregular sinusoidal wave. Specifically, this indicates significant “ping-ponging” throughout the entirety of the testing lane for both conditions. It is important to note that this is not characteristic of a system flaw in isolation.

Run 1	Run 2	Run 3	Run 4
0.422	0.922	-0.131	0.066

Figure 32: Spearman correlation coefficients for individual runs with respect to characteristic baseline run
Image Source: AAA

Figure 32 provides the Spearman correlation coefficient for test runs with occluded cameras with respect to the characteristic baseline run. For test run one, the Spearman coefficient only accounts for lateral lane placement of the characteristic baseline run to the longitudinal point at which the test vehicle left the roadway. Test run two indicates a strong correlation because this run is largely in phase with the characteristic baseline run. Test runs three and four exhibit a weak correlation because they are significantly out of phase with the characteristic baseline run. In general, all individual test runs with occluded cameras are similar to the characteristic baseline run in terms of “ping-ponging” frequency.

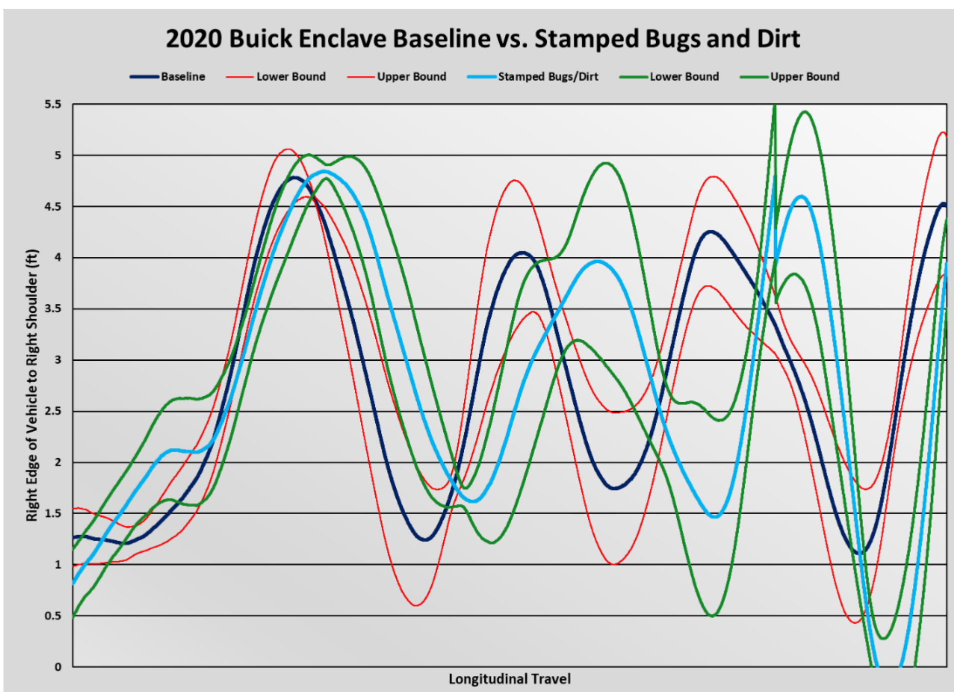

Figure 33: 2020 Buick Enclave averaged baseline and occluded camera placement
Image Source: AAA

The average baseline and occluded camera test runs are illustrated in Figure 33. If the test vehicle leaves the roadway prior to completion of the test run, lateral lane placement from that particular run is only averaged to the longitudinal point at which the test vehicle leaves the roadway. In other words, lateral lane placement from the first test run is averaged up to the point where the test vehicle leaves the roadway.

Based on a comparison of averaged runs, the lane keeping assistance system performance is generally similar in terms of “ping-ponging” lateral deviation and frequency with the exception of one test run leaving the roadway prior to test completion. This implies that system performance is minimally influenced by system cameras occluded with bug and dirt particles.

b) 2020 Hyundai Santa Fe

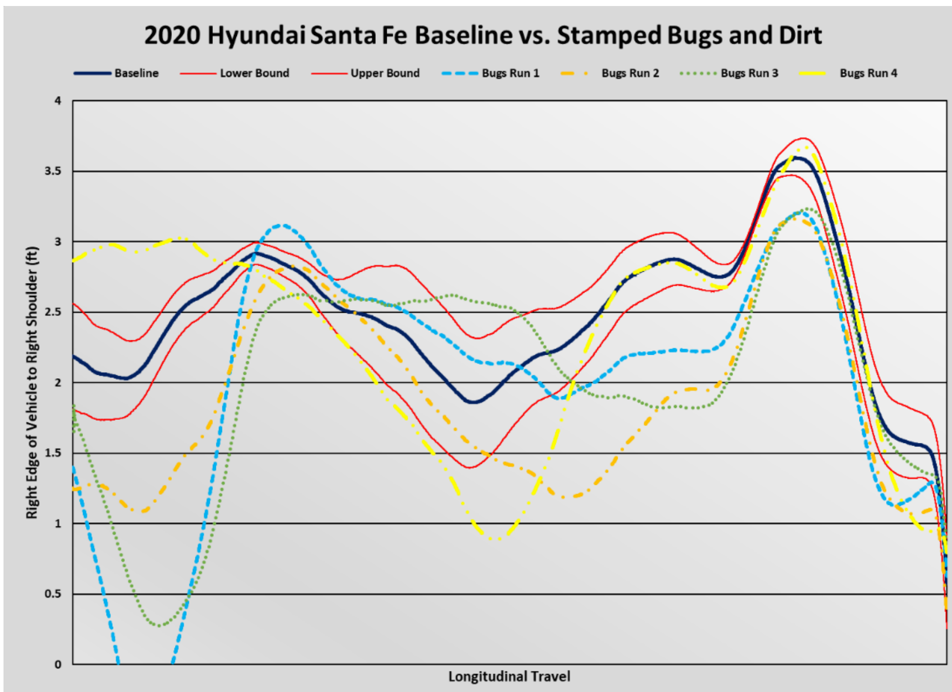

Figure 34: 2020 Hyundai Santa Fe average baseline lane placement and individual runs with occluded cameras Image Source: AAA

Figure 34 illustrates a graphical representation of the test vehicle lateral placement for the characteristic baseline run in comparison to the four individual test runs conducted with occluded cameras. Quasiperiodicity is exhibited for baseline and occluded camera conditions not similar in appearance to any common mathematical functions. While the lane placement is generally similar between baseline and occluded camera conditions, the lateral lane placement is more towards the right of the testing lane in the first half of the run.

Run 1	Run 2	Run 3	Run 4
0.680	0.791	0.366	0.675

Figure 35: Spearman correlation coefficients for individual runs with respect to characteristic baseline run
Image Source: AAA

Figure 35 provides the Spearman correlation coefficient for test runs with occluded cameras with respect to the characteristic baseline run. The general similarity in system behavior between the characteristic baseline run and individual test runs with occluded cameras is reflected in strong Spearman coefficients for test runs one, two, and four.

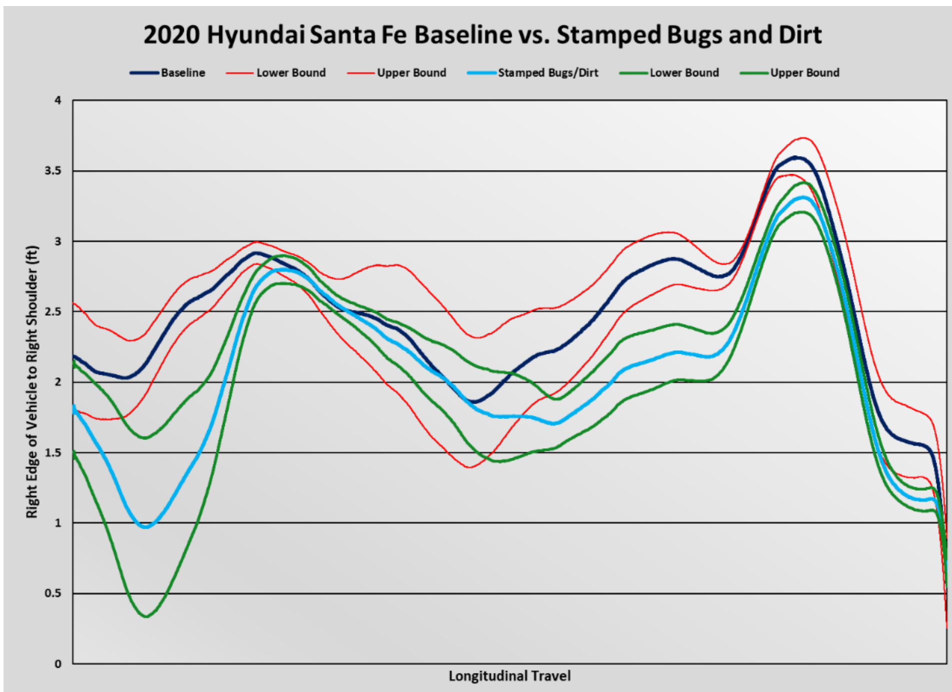

Figure 36: 2020 Hyundai Santa Fe averaged baseline and occluded camera placement
Image Source: AAA

As previously noted in Figure 34, test runs conducted with occluded cameras have a bias to the right of the testing lane in the beginning of the run. This is illustrated by the average of occluded camera test runs in Figure 36. However, the lane keeping assistance system performance is similar for the remainder of the test run indicating either a corrective and/or adaptive response to occluded cameras. In combination, these observations suggest that while system performance may be initially influenced, the system may also be capable of corrective and/or adaptive actions in response to occluded cameras.

c) 2020 Toyota RAV4

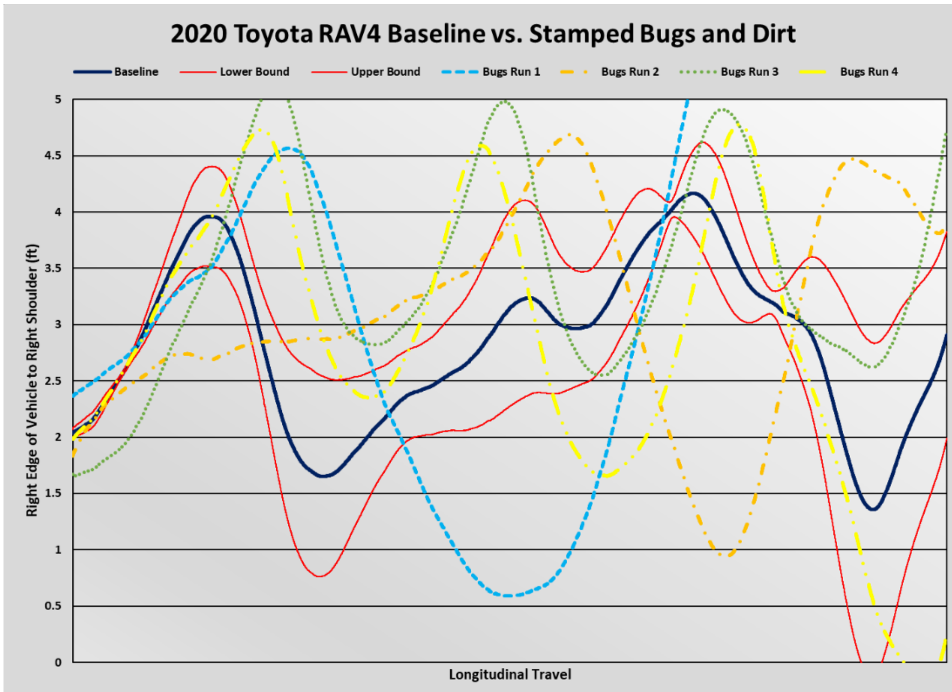

Figure 37: 2020 Toyota RAV4 average baseline lane placement and individual runs with occluded cameras Image Source: AAA

Figure 37 illustrates a graphical representation of the test vehicle lateral placement for the characteristic baseline run in comparison to the four individual test runs conducted with occluded cameras. As previously described in Section VI-C1c, the characteristic baseline run is comprised of three individual baseline test runs because as in the previous test, the test vehicle left the roadway for one of the four baseline runs.

Quasiperiodicity is exhibited for baseline and occluded camera conditions; however, the general appearance between the characteristic averaged run and individual test runs with occluded cameras is significantly different. The characteristic baseline run does not resemble any common mathematic function whereas the third and fourth test runs are similar in appearance to an irregular sinusoidal wave. The test vehicle left the testing lane during the first test run. Specifically, test runs conducted with occluded cameras exhibited more “ping-ponging” than the characteristic baseline run.

Run 1	Run 2	Run 3	Run 4
0.164	-0.433	0.328	0.413

Figure 38: Spearman correlation coefficients for individual runs with respect to characteristic baseline run
Image Source: AAA

Figure 38 provides the Spearman correlation coefficient for test runs with occluded cameras with respect to the characteristic baseline run. For the first test run, the Spearman coefficient only accounts for lateral lane placement of the characteristic baseline run to the longitudinal point at which the test vehicle left the roadway.

The remaining occluded camera test runs are characterized by moderate to weak correlation coefficients signifying that system behavior with occluded cameras does not strongly resemble the characteristic baseline test run.

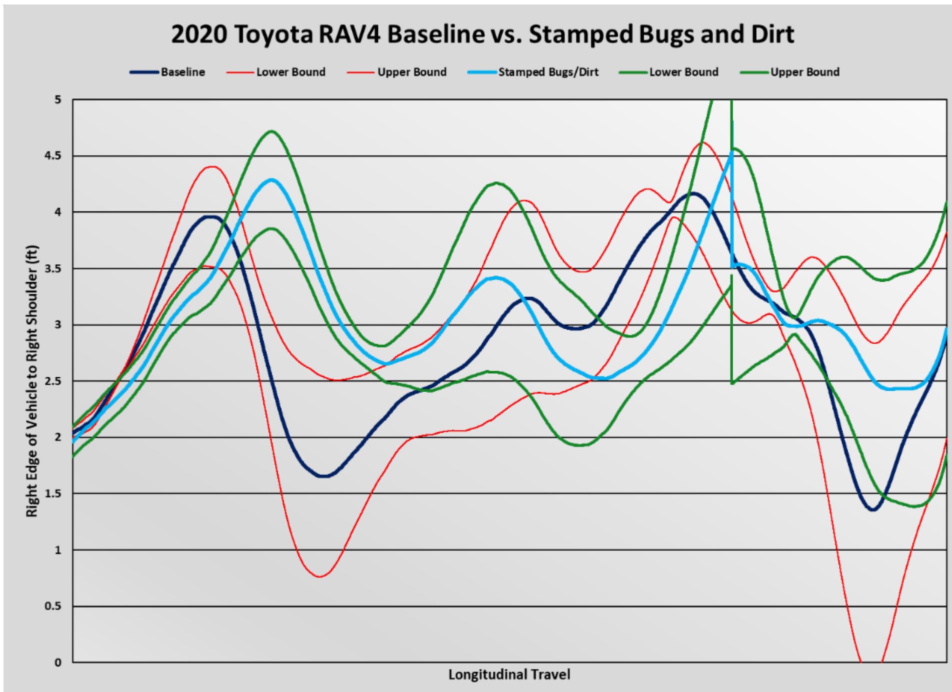

Figure 39: 2020 Toyota RAV4 averaged baseline and occluded cameras placement
Image Source: AAA

The average baseline and occluded camera test runs are illustrated in Figure 39. If the test vehicle leaves the roadway prior to completion of the test run, lateral lane placement from that particular run is only averaged to the longitudinal point at which the test vehicle leaves the roadway. In other words, lateral lane placement from the first occluded camera test run is averaged in the first half of Figure 39 (up to the point where the test vehicle leaves the roadway on the first test run).

The averaged baseline and occluded camera runs are characterized by significantly large standard error indicating variability between individual test runs for both conditions. In this sense, system behavior is implied to be inconsistent in terms of lateral lane placement between test runs for both conditions. It is important to note that this is not characteristic of a system flaw in isolation.

While individual test runs conducted with occluded cameras do not generally resemble the representative baseline run, the inconsistency of individual baseline runs imply that inconsistency in lateral lane placement is not a function of the simulated bugs and dirt mixture. Additionally, the absolute deviation in lateral lane placement for both conditions is of similar magnitude.

d) 2020 Volkswagen Tiguan

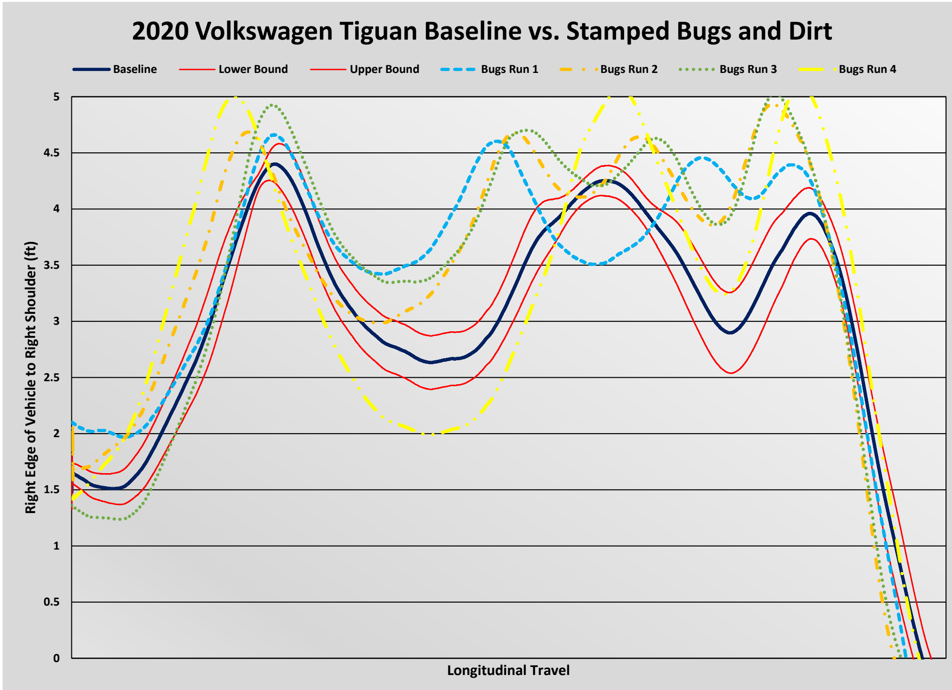

Figure 40: 2020 Volkswagen Tiguan average baseline lane placement and individual runs with occluded cameras
Image Source: AAA

Figure 40 illustrates a graphical representation of the test vehicle lateral placement for the characteristic baseline run in comparison to the four individual test runs conducted with occluded cameras. Quasiperiodicity is exhibited for baseline and occluded camera conditions not similar in appearance to any common mathematical functions. While the lane placement is generally similar between baseline and occluded camera conditions, the lateral lane placement for occluded camera conditions generally exhibit a minor degree of weaving towards the end of the test run.

Run 1	Run 2	Run 3	Run 4
0.649	0.782	0.854	0.838

Figure 41: Spearman correlation coefficients for individual runs with respect to characteristic baseline run
Image Source: AAA

Figure 41 provides the Spearman correlation coefficient for test runs with occluded cameras with respect to the characteristic baseline run. The general similarity in system behavior between the characteristic baseline run and individual test runs with occluded cameras is reflected in moderately strong Spearman coefficients above 0.649.

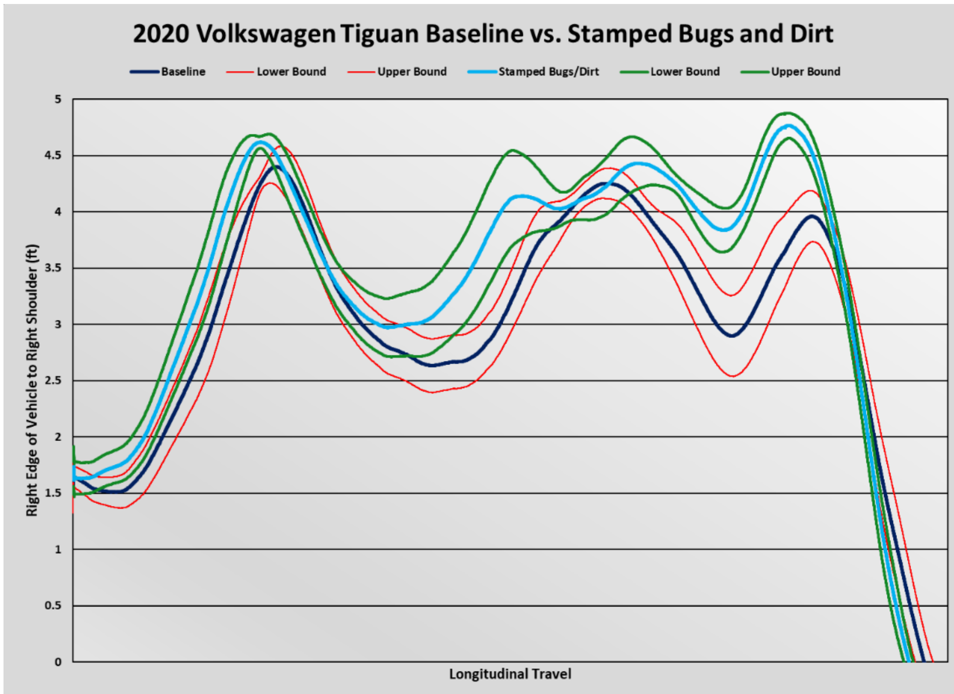

Figure 42: 2020 Volkswagen Tiguan averaged baseline and occluded cameras placement
Image Source: AAA

The average baseline and occluded camera test runs are illustrated in Figure 42. The lane keeping assistance system performance is notably similar throughout the test run indicating that system performance is not significantly influenced by cameras occluded with bug and dirt particles.

2) Automatic Emergency Braking (AEB)

For narrative purposes, impact speeds are defined as follows within this report:

- 0 mph < Impact Speed ≤ 5 mph = Minor Impact
- 5 mph < Impact Speed ≤ 10 mph = Moderate Impact
- 10 mph < Impact Speed = Significant Impact

a) *2020 Buick Enclave*

Buick Enclave 25 mph						
Baseline						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	148.24	4.006	39.37	1.086	0.0	5.80
Run 2	147.63	4.047	39.11	1.076	0.0	5.61
Run 3	149.72	4.010	41.03	1.117	0.0	4.45
Run 4	150.16	4.108	37.86	1.058	0.0	4.13
Average	**148.94**	**4.043**	**39.34**	**1.084**	**0.0**	**5.00**
Standard Deviation	**1.03**	**0.041**	**1.13**	**0.021**	**0.0**	**0.72**
Stamped Bugs/Dirt						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	149.12	4.110	38.92	1.079	0.0	4.54
Run 2	148.83	4.011	40.52	1.111	0.0	4.74
Run 3	149.97	4.096	38.53	1.073	0.0	4.96
Run 4	150.30	4.101	41.43	1.140	0.0	4.55
Average	**149.56**	**4.079**	**39.85**	**1.101**	**0.0**	**4.70**
Standard Deviation	**0.60**	**0.040**	**1.18**	**0.027**	**0.0**	**0.17**

Figure 43: 2020 Buick Enclave individual run data at 25 mph with occluded cameras
Image Source: AAA

Individual test run data for baseline and occluded camera conditions at 25 mph are provided in Figure 43. For all parameters, the baseline and occluded camera mean values do not significantly differ at the 95 percent confidence level. For both conditions, no contact between the test vehicle and target vehicle occurred for any test runs conducted. Specifically, automatic emergency braking system performance is not significantly influenced by cameras occluded with dirt and bug particles at 25 mph.

Buick Enclave 35 mph						
Baseline						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	148.73	2.869	70.88	1.381	4.5	0.00
Run 2	146.47	2.853	70.79	1.385	0.0	0.78
Run 3	147.83	2.875	73.14	1.431	0.7	0.00
Run 4	149.72	2.897	75.00	1.470	0.0	1.69
Average	**148.19**	**2.874**	**72.46**	**1.417**	**1.3**	**0.62**
Standard Deviation	**1.20**	**0.016**	**1.75**	**0.036**	**1.9**	**0.69**
Stamped Bugs/Dirt						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	149.08	2.903	74.58	1.458	0.0	1.44
Run 2	147.88	2.889	71.39	1.394	0.0	0.36
Run 3	146.43	2.874	71.23	1.392	0.0	0.71
Run 4	148.13	2.900	72.82	1.426	0.0	1.19
Average	**147.88**	**2.892**	**72.50**	**1.417**	**0.0**	**0.93**
Standard Deviation	**0.95**	**0.011**	**1.35**	**0.027**	**0.0**	**0.42**

Figure 44: 2020 Buick Enclave individual run data at 35 mph with occluded cameras
Image Source: AAA

Individual test run data for baseline and occluded camera conditions at 35 mph are provided in Figure 44. For all parameters, the baseline and occluded camera mean values do not significantly differ at the 95 percent confidence level. However, the test vehicle did not impact the target vehicle for any test runs conducted with occluded cameras. This contrasts with the baseline condition in which minor impact occurred with the target vehicle for two of four runs. Specifically, automatic emergency braking system performance was not negatively influenced by cameras occluded with bug and dirt particles at 35 mph.

b) 2020 Hyundai Santa Fe

Hyundai Santa Fe 25 mph						
Baseline						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	71.48	1.983	40.72	1.163	0.0	8.82
Run 2	72.87	1.971	42.49	1.186	0.0	9.09
Run 3	72.67	1.970	42.09	1.181	0.0	9.80
Run 4	71.25	1.953	42.62	1.185	0.0	8.27
Average	**72.07**	**1.97**	**41.98**	**1.18**	**0.0**	**8.99**
Standard Deviation	**0.71**	**0.01**	**0.75**	**0.01**	**0.0**	**0.55**
Stamped Bugs/Dirt						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	72.83	1.963	43.13	1.200	0.0	10.51
Run 2	72.69	1.969	42.07	1.180	0.0	6.61
Run 3	73.72	1.990	41.52	1.161	0.0	9.42
Run 4	72.16	1.978	40.09	1.141	0.0	9.78
Average	**72.85**	**1.975**	**41.70**	**1.170**	**0.0**	**9.08**
Standard Deviation	**0.56**	**0.010**	**1.09**	**0.022**	**0.0**	**1.48**

Figure 45: 2020 Hyundai Santa Fe individual run data at 25 mph with occluded cameras
Image Source: AAA

Individual test run data for baseline and occluded camera conditions at 25 mph are provided in Figure 45. For all parameters, the baseline and occluded camera mean values do not significantly differ at the 95 percent confidence level. For both conditions, no contact between the test vehicle and target vehicle occurred for any test runs conducted. Specifically, automatic emergency braking system performance is not significantly influenced by cameras occluded with dirt and bug particles at 25 mph.

Hyundai Santa Fe 35 mph						
Baseline						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	117.12	2.312	80.93	1.631	0.0	6.22
Run 2	121.72	2.380	76.20	1.537	0.0	3.31
Run 3	122.50	2.380	80.67	1.608	0.0	6.47
Run 4	121.38	2.361	80.67	1.611	0.0	4.90
Average	**120.68**	**2.358**	**79.62**	**1.597**	**0.0**	**5.23**
Standard Deviation	**2.09**	**0.028**	**1.97**	**0.036**	**0.0**	**1.26**
Stamped Bugs/Dirt						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	120.34	2.359	72.91	1.472	0.0	4.00
Run 2	119.48	2.339	71.56	1.447	0.0	5.87
Run 3	122.63	2.404	71.85	1.461	0.0	5.07
Run 4	121.36	2.390	77.11	1.563	0.0	6.20
Average	**120.95**	**2.373**	**73.36**	**1.486**	**0.0**	**5.29**
Standard Deviation	**1.17**	**0.025**	**2.22**	**0.045**	**0.0**	**0.85**

Figure 46: 2020 Hyundai Santa Fe individual run data at 35 mph with occluded cameras
Image Source: AAA

Individual test run data for baseline and occluded camera conditions at 35 mph are provided in Figure 46. For all parameters, the baseline and occluded camera mean values do not significantly differ at the 95 percent confidence level. For both conditions, no contact between the test vehicle and target vehicle occurred for any test runs conducted. Specifically, automatic emergency braking system performance is not significantly influenced by cameras occluded with dirt and bug particles at 35 mph.

c) *2020 Toyota RAV4*

Toyota RAV4 25 mph						
Baseline						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	77.65	2.132	58.40	1.621	0.0	2.65
Run 2	73.94	2.027	55.41	1.542	0.0	1.94
Run 3	76.95	2.119	58.50	1.633	0.0	2.84
Run 4	73.46	2.003	59.19	1.630	0.0	1.92
Average	**75.50**	**2.070**	**57.87**	**1.606**	**0.0**	**2.34**
Standard Deviation	**1.82**	**0.056**	**1.46**	**0.037**	**0.0**	**0.42**
Stamped Bugs/Dirt						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	75.40	2.059	58.25	1.611	0.0	3.25
Run 2	74.57	2.029	58.45	1.608	0.0	1.97
Run 3	79.80	2.154	58.43	1.601	0.0	2.68
Run 4	77.50	2.134	53.96	1.510	0.0	3.32
Average	**76.82**	**2.094**	**57.27**	**1.583**	**0.0**	**2.81**
Standard Deviation	**2.03**	**0.052**	**1.91**	**0.042**	**0.0**	**0.54**

Figure 47: 2020 Toyota RAV4 individual run data at 25 mph with occluded cameras
Image Source: AAA

Individual test run data for baseline and occluded camera conditions at 25 mph are provided in Figure 47. For all parameters, the baseline and occluded camera mean values do not significantly differ at the 95 percent confidence level. For both conditions, no contact between the test vehicle and target vehicle occurred for any test runs conducted. Specifically, automatic emergency braking system performance is not significantly influenced by cameras occluded with dirt and bug particles at 25 mph.

Toyota RAV4 35 mph						
Baseline						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	133.85	2.615	75.79	1.533	0.0	0.77
Run 2	129.83	2.535	76.63	1.541	0.0	0.58
Run 3	126.22	2.446	79.80	1.590	0.0	0.76
Run 4	126.24	2.478	75.84	1.532	0.0	0.32
Average	**129.04**	**2.518**	**77.01**	**1.549**	**0.0**	**0.61**
Standard Deviation	**3.14**	**0.064**	**1.64**	**0.024**	**0.0**	**0.18**
Stamped Bugs/Dirt						
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Run 1	131.01	2.565	73.07	1.483	0.0	2.11
Run 2	124.58	2.456	80.36	1.623	0.0	0.97
Run 3	130.02	2.552	77.08	1.557	0.0	2.77
Run 4	134.30	2.624	77.07	1.553	0.0	1.46
Average	**129.98**	**2.549**	**76.90**	**1.554**	**0.0**	**1.83**
Standard Deviation	**3.50**	**0.060**	**2.58**	**0.050**	**0.0**	**0.68**

Figure 48: 2020 Toyota RAV4 individual run data at 35 mph with occluded cameras
Image Source: AAA

Individual test run data for baseline and occluded camera conditions at 35 mph are provided in Figure 48. For all parameters, the baseline and occluded camera mean values do not significantly differ at the 95 percent confidence level. For both conditions, no contact between the test vehicle and target vehicle occurred for any test runs conducted. Specifically, automatic emergency braking system performance is not significantly influenced by cameras occluded with dirt and bug particles at 35 mph.

D. Summary of Test Results

1) Lane Placement

While minor differences in lateral lane placement between baseline and occluded camera conditions were generally noted, test vehicle performance was not significantly influenced by cameras occluded by bugs and dirt in terms of lane keeping assistance performance. It should be noted that this research did not evaluate the impact of higher density patterns (bugs-per-inch) of bugs and dirt, which could potentially influence test results.

2) Automatic Emergency Braking (AEB)

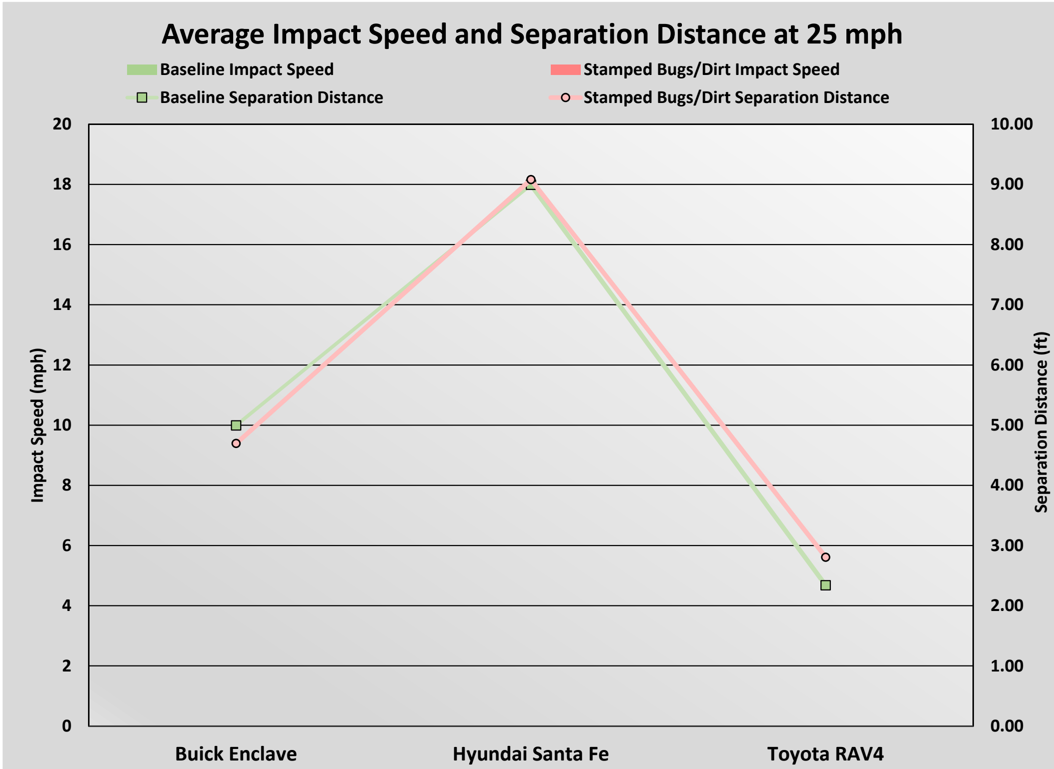

Figure 49: Average impact speed and final separation distance at 25 mph Image Source: AAA

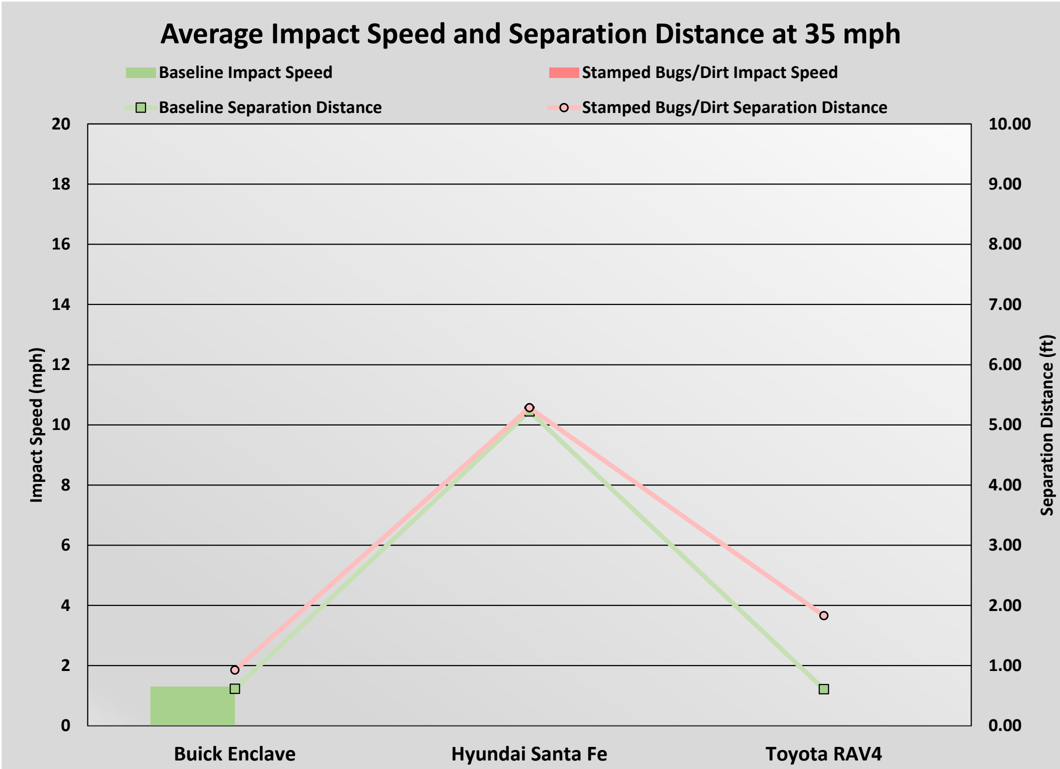

Figure 50: Average impact speed and final separation distance at 35 mph Image Source: AAA

Figures 49 and 50 illustrate the average impact speed and associated separation distance for baseline and occluded camera conditions for each test vehicle at 25 mph and 35 mph, respectively.

	Stamped Bugs/Dirt 25 mph					
	Buick Enclave					
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Baseline Average	148.94	4.043	39.34	1.084	0.0	5.00
Bugs/Dirt Average	149.56	4.079	39.85	1.101	0.0	4.70
Group Average	**149.25**	**4.061**	**39.60**	**1.092**	**0.0**	**4.85**
Std. Deviation	**0.31**	**0.018**	**0.25**	**0.008**	**0.0**	**0.15**
	Hyundai Santa Fe					
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Baseline Average	72.07	1.969	41.98	1.179	0.0	8.99
Bugs/Dirt Average	72.85	1.975	41.70	1.170	0.0	9.08
Group Average	**72.46**	**1.972**	**41.84**	**1.175**	**0.0**	**9.04**
Std. Deviation	**0.39**	**0.003**	**0.14**	**0.004**	**0.0**	**0.04**
	Toyota RAV4					
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Baseline Average	75.50	2.070	57.87	1.606	0.0	2.34
Bugs/Dirt Average	76.82	2.094	57.27	1.583	0.0	2.81
Group Average	**76.16**	**2.082**	**57.57**	**1.595**	**0.0**	**2.57**
Std. Deviation	**0.66**	**0.012**	**0.30**	**0.012**	**0.0**	**0.23**

Figure 51: Averaged data for each test vehicle at 25 mph Image Source: AAA

Figure 51 provides averaged test run data for baseline and occluded camera conditions at 25 mph. The three test vehicles used for automatic emergency braking were not influenced by cameras occluded with bug and dirt particles.

No collisions were observed on any test vehicles during the baseline or simulated bugs and dirt tests for automatic emergency braking at 25mph.

	Stamped Bugs/Dirt 35 mph					
	Buick Enclave					
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Baseline Average	148.19	2.874	72.46	1.417	1.3	0.62
Bugs/Dirt Average	147.88	2.892	72.50	1.417	0.0	0.93
Group Average	**148.03**	**2.883**	**72.48**	**1.417**	**0.6**	**0.77**
Std. Deviation	**0.15**	**0.009**	**0.02**	**0.000**	**0.6**	**0.15**
	Hyundai Santa Fe					
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Baseline Average	120.95	2.373	73.36	1.486	0.0	5.29
Bugs/Dirt Average	120.68	2.358	79.62	1.597	0.0	5.23
Group Average	**120.82**	**2.365**	**76.49**	**1.541**	**0.0**	**5.26**
Std. Deviation	**0.14**	**0.007**	**3.13**	**0.056**	**0.0**	**0.03**
	Toyota RAV4					
	Detection Distance (ft)	Detection TTC (s)	Braking Distance (ft)	Braking TTC (s)	Impact Speed (mph)	Separation Distance (ft)
Baseline Average	129.04	2.518	77.01	1.549	0.0	0.61
Bugs/Dirt Average	129.98	2.549	76.90	1.554	0.0	1.83
Group Average	**129.51**	**2.534**	**76.95**	**1.551**	**0.0**	**1.22**
Std. Deviation	**0.47**	**0.015**	**0.06**	**0.003**	**0.0**	**0.61**

Figure 52: Averaged data for each test vehicle at 35 mph Image Source: AAA

Figure 52 provides averaged test run data for baseline and occluded camera conditions at 35 mph. All test vehicles were not negatively influenced by cameras occluded by bug and dirt particles.

Among all test vehicles, no test runs conducted with occluded cameras at a speed of 35 mph resulted in a collision. This contrasts with the baseline condition during which a collision occurred for 17 percent of all test runs. Tests speeds of 35 mph are thought to be near the upper limit of automatic emergency braking system braking capability to avoid a collision, so this may account for the impacts during the baseline runs.

VIII. OVERALL CONCLUSIONS

The findings of this work illustrate that lane keeping assistance and automatic emergency braking systems can be influenced by environmental conditions such as rainfall and to a lesser extent, system cameras occluded by a dirty windshield. It is important to note that within this work, simulation of rainfall and occluded cameras are representative of moderate conditions and research did not evaluate all potential scenarios of degradation. Depending on individual driving environments and vehicle maintenance habits, the severity of rainfall and camera occlusion simulated in this work will not approach conditions encountered in the naturalistic environment. In other words, lane keeping assistance and automatic emergency braking systems may be influenced to a greater extent in more severe conditions encountered outside of standardized testing.

Drivers must exercise additional caution when utilizing lane keeping assistance and automatic emergency braking systems in inclement weather as performance may be adversely affected. Additionally, drivers should account for additional stopping distance that may be required depending on rainfall intensity, speed, vehicle condition, etc.

In total, lane keeping assistance and automatic emergency braking systems can significantly enhance safety when utilized properly. Drivers must understand system limitations in adverse conditions and regularly clean areas around sensors to ensure optimal performance.

IX. KEY FINDINGS

1. In general, evaluated lane keeping assistance and automatic emergency braking systems were influenced by simulated rainfall.
    a. In terms of lane keeping performance, 69 percent of test runs conducted with simulated rainfall resulted in the test vehicle crossing the lane marker on the roadway.
    b. In aggregate, 17 and 33 percent of test runs conducted with simulated rainfall resulted in a collision for test speeds of 25 and 35 mph, respectively.
2. In general, evaluated lane keeping assistance and automatic emergency braking systems were minimally influenced by a dirty windshield.
    a. While minor differences were noted with respect to baseline conditions, lane keeping assistance performance was not negatively influenced by a dirty windshield.
    b. No test runs conducted with a dirty windshield resulted in a collision for either 25mph or 35mph test speeds.

X. SUMMARY RECOMMENDATIONS

1. Drivers should understand the limitations of ADAS and remain engaged behind the wheel as these systems are an aide, not a replacement for an engaged driver.
2. Drivers must use extra caution and avoid system overreliance, particularly in adverse weather conditions.
3. To ensure optimal system performance, keep areas around cameras and radar sensors clean. The owner’s manual will describe the location of sensors and recommended cleaning procedures.

XI. REFERENCES

[1] A. Benson, B. Tefft, A. M. Svancara and W. Horrey, "Potential Reduction in Crashes, Injuries, and Deaths from Large-Scale Deployment of Advanced Driver Assistance Systems," *AAA Foundation for Traffic Safety,* 2018.

[2] Insurance Institute of Highway Safety, "Real-world benefits of crash avoidance technologies," December 2020. [Online]. Available: https://www.iihs.org/media/259e5bbd-f859-42a7-bd54-3888f7a2d3ef/shuYZQ/Topics/ADVANCED%20DRIVER%20ASSISTANCE/IIHS-real-world-CA-benefits.pdf. [Accessed 3 March 2021].

[3] B. Hurd, "2020 sales wrap-up: The good and the bad of an ugly year," Autoblog, 5 January 2021. [Online]. Available: https://www.autoblog.com/2021/01/05/2020-year-end-auto-sales/. [Accessed 10 March 2021].

[4] SAE International, "Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles," *2018-06.*

APPENDIX

Test Vehicle Information		**Test Information**			
VIN	5NMS2CAD0KH117098	Location	Autoclub Speedway	Date	12/7/2020
Make	Hyundai	Vehicle Width	74in	Weather	Overcast
Model	Santa Fe	Vehicle Length	188in	Temp	61 deg F
Trim		Mileage	11,686	Notes	
Tire Information		**Tire Tread Depth**			
Tire Size	235/55/R17	Left Front	6.5mm		
Manufacturer	Hankook	Right Front	6.0mm		
Perf. Code	104H	Left Rear	7.2mm		
Dot Number	0419	Right Rear	7.3mm		

Test Vehicle Information		**Test Information**			
VIN	5GAERDKW7MJ100019	Location	Autoclub Speedway	Date	12/8/2020
Make	Buick	Vehicle Width	79in	Weather	Sunny
Model	Enclave Avenir	Vehicle Length	204in	Temp	77 deg F
Trim	FWD 1SP	Mileage	2,051		
Tire Information		**Tire Tread Depth**			
Tire Size	255/55/R20	Left Front	8mm		
Manufacturer	Continental	Right Front	8mm		
Perf. Code	107H	Left Rear	9.6mm		
Dot Number	3820	Right Rear	9.6mm		

Test Vehicle Information		**Test Information**			
VIN	4T3D6RFVMU009000	Location	Autoclub Speedway	Date	12/9/2020
Make	Toyota	Vehicle Width	73in	Weather	Sunny
Model	Rav4 Hybrid	Vehicle Length	181in	Temp	64 deg F
Trim	Limited AWD	Mileage	548	Notes	
Tire Information		**Tire Tread Depth**			
Tire Size	225/60/R18	Left Front	7.5mm		
Manufacturer	Michelin	Right Front	7.6mm		
Perf. Code	100H	Left Rear	7.7mm		
Dot Number	3620	Right Rear	7.8mm		

Test Vehicle Information		**Test Information**			
VIN	3VV2B7AX5MM00313	Location	Autoclub Speedway	Date	12/10/2020
Make	Volkswagen	Vehicle Width	72in	Weather	Sunny
Model	Tiguan	Vehicle Length	185in	Temp	63 deg F
Trim	4motion	Mileage	623	Notes	
Tire Information		**Tire Tread Depth**			
Tire Size	235/50/R19	Left Front	8.5mm		
Manufacturer	Pirelli	Right Front	8.4mm		
Perf. Code	99H	Left Rear	8.6mm		
Dot Number	3320	Right Rear	8.4mm		