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Advanced Driver Assistance System (ADAS) Performance Variability with Partial Overlap Targets

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Abstract

While various Advanced Driver Assistance System (ADAS) features have become more prevalent in passenger vehicles, their ability to potentially avoid or mitigate vehicle crashes has limitations. Due to current technological limitations, forward collision mitigation technologies such as Forward Collision Warning (FCW) and Automated Emergency Braking (AEB) lack the ability to consistently perform in many unique and challenging scenarios. These limitations are often outlined in driver manuals for ADAS equipped vehicles. One such scenario is the case of a stationary lead vehicle at the side of the road. This is generally considered to be a challenging scenario for FCW and AEB to address because it can often be difficult for the system to discern this threat accurately and consistently from non-threatening roadway infrastructure without unnecessary or nuisance system activations. This is made more difficult when the stationary lead vehicle is only partially in the driving lane and not directly in the forward path, as is the case in the current FCW and AEB confirmation test protocols used by the National Highway Traffic Safety Administration (NHTSA). Partial overlap tests are carried out by Euro New Car Assessment Program (NCAP), however data has not been published to date showing the effect this has on performance.

A test series was designed to investigate the effect of variable overlap, with stationary lead vehicle targets, on the triggering and timing of warnings presented by forward collision mitigation technology.

Keywords

Forward Collision Warning, Automated Emergency Braking, mitigation, offset, overlap, performance, automotive

Introduction

Forward collision mitigation technologies typically use forward facing radar, cameras, and/or lidar (in any combination) to sometimes detect, warn, and/or react to objects perceived to be in the forward path of the vehicle. In response to objects that represent a potential conflict, FCW systems may issue alerts which are typically activated when a threshold is reached for a time-based measure of criticality called the time-to-collision (TTC). In the event that the driver does not respond to a warning, or their response is inadequate to avoid an impending collision, an AEB system (if present on the vehicle) can, under certain circumstances, automatically apply the brakes in order to avoid or reduce the severity of a collision. The ability to accurately determine in-path vs. out-of-path objects has been an ongoing area of research and improvement for FCW and AEB systems and is an important factor in balancing the rate of true alerts vs. nuisance alerts.

FCW and AEB were introduced on passenger vehicles in the U.S. for model year (MY) 2000 and MY 2006 respectively. [1] Some of the first data published on the potential effectiveness and consumer acceptance of forward collision mitigation technology followed the 1999-2004 Automotive Collision Avoidance System Field Operational Test (or ACAS FOT), led by General Motors under contract with NHTSA. [2] While FCW was found to reduce the prevalence of tailgating among equipped vehicles, only one third of the FCW alerts were found to be in response to imminent hazards in the same lane as the vehicle, as opposed to roadside objects, turning vehicles, or lane changes.

The performance of FCW and AEB have been assessed in common crash scenarios by NHTSA's NCAP, its European equivalent, Euro NCAP, and consumer safety organizations, among others. In order to quantify effectiveness in these scenarios, standardized test protocols were developed by various agencies. Accompanying NHTSA's July 2008 final decision on updating NCAP to include the assessment of FCW systems, [3] NHTSA drafted test protocols to confirm the presence of FCW systems. [4] With updated test protocols published in 2010, [5] NHTSA began conducting confirmatory tests for new vehicles starting in MY 2011, and included three rear-end scenarios at 45 mph. If the vehicle provided an FCW alert before a specified TTC threshold in five out of seven trials in each scenario, the vehicle's Monroney label was permitted to state that the model included the FCW feature. The FCW protocol was updated again in February of 2013. [6]

In February 2016, Mobileye submitted comments to NHTSA's 2015 Request for Comments (RFC) on proposed changes to NCAP. The comments suggested the inclusion of partial overlap test conditions for FCW and AEB confirmation tests wherein the Subject Vehicle (SV) would have 25% to 40% overlap with the target. [7] Euro NCAP introduced partial overlap conditions in its car-to-car AEB test protocol in November 2017. [8] As part of Euro NCAP testing, tests were conducted with varied lateral overlap in several scenarios according to Table 1.

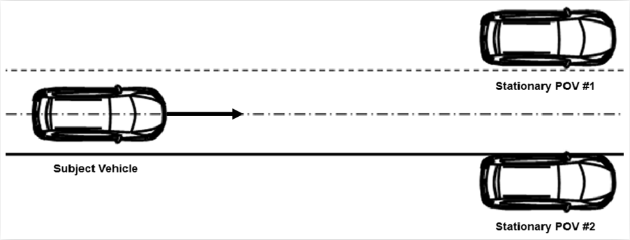
Recognizing the need for accuracy in differentiating between in-path and out-of-path objects, NHTSAs 2023 Notice of Proposed Rulemaking (NPRM) on AEB for light vehicles included a 'Pass-through false activation scenario' in which the SV passes between two stationary vehicles in adjacent lanes. [9] This test is similar to the UNECE R131 [10] and UNECE R152 [11] false reaction tests and is depicted in Figure 1.

It is evident from the various test protocols developed by Euro NCAP and NHTSA that discerning in-path and out-of-path objects is a non-trivial task for current forward collision mitigation technologies. To the authors' knowledge, there is no published research which quantifies the performance of forward collision mitigation systems in response to targets which are partially offset from the forward path. Moreover, Euro NCAP protocols only require testing with a minimum absolute overlap of 50%. It is expected that with less overlap between the SV and target (i.e., increased lateral offset) the performance of the forward collision mitigation system will become degraded.

TABLE 1 Lateral Overlap Conditions outlined in Euro NCAP AEB C2C Test Protocol v2.0.1.

	Lateral Overlap				
Scenario	-50%	-75%	100%	75%	50%
Stationary Lead Vehicle	✓	✓	✓	✓	✓
Moving Lead Vehicle	✓	✓	✓	✓	✓
Decelerating Lead Vehicle			✓		

FIGURE 1 Diagram of Pass-Through False Activation Scenario



Test Vehicles

The test vehicles utilized for the subject test series involved a passenger vehicle equipped with a forward collision mitigation system (FCW and AEB) and the Guided Soft Target (GST) shown in Figure 2. The GST is comprised of the Global Vehicle Target (GVT), assembled atop the Low-Profile Robotic Vehicle (LPRV) which is a robotic platform which can be used to control the motion of the GST. The GVT Revision G, also known as the Soft Car 360®, is manufactured by Dynamic Research, Inc. [12] and is composed of foam support pieces with an outer vinyl skin assembled with Velcro to facilitate breakaway upon a collision, preventing damage to the target and the test vehicle. The GVT has a photo-realistic vinyl skin, Infrared (IR) properties, vehicle dimensions, and radar reflectivity representative of a small passenger vehicle. The GVT falls within the specifications of ISO 19206 –3:2021. [13].

The tested passenger vehicle, referred to herein as the SV, was a late model (2023) battery electric vehicle (BEV) equipped with a forward mounted radar and forward-looking camera. The warning cascade for the vehicle was as follows:

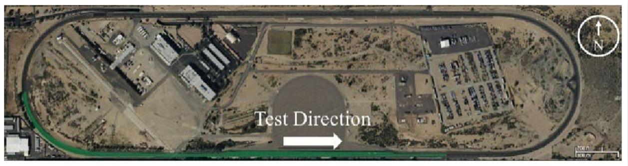
- A red warning light illuminates (FCW)
- The red warning light flashes
- An audible alert is issued
- The brakes apply automatically (AEB)

Test Setup

All tests were conducted on the south straight of Exponent's Test and Engineering Center (TEC) 2-mile test track between 10 am and 6 pm Mountain Standard Time, during the weeks of October 2nd and October 9th, 2023. The TEC is located in Phoenix, Arizona. The SV approached the GST from the west headed eastbound (Figure 3).

FIGURE 2 Graphic depicting GST.

FIGURE 3 Exponent Test and Engineering Center (TEC)



The SV was instrumented with an Oxford Technical Systems' (OXTS) RT3000v3 inertial navigation system (INS). The INS combines an onboard Inertial Measurement Unit (IMU) with a dual-antenna GPS with differential corrections received from a GPS base station to achieve 1 cm positional accuracy. The SV was also instrumented with a light-up LED strip which was triggered by a push-button that simultaneously was logged by the data acquisition system (DAS), in order to sync the video feed with the rest of the data. Onboard cameras monitored the dashboard to observe when the FCW alert was issued, the footwell, and a driver's perspective. A complete detail of all equipment and DAS can be found in Appendix A.

For each of the test scenarios, the SV was nominally centered in the lane and the GST position varied laterally. Tests were conducted with the GST centered in the lane and nominally offset within the lane by 25%, 50% and 75% towards the passenger side of the SV. A test series was also run with the GST offset 25% towards the driver side of the SV (Figure 4). These offsets resulted in 70%, 44%, and 20% nominal overlaps between the vehicles relative to the SV width (Figure 5).

FIGURE 4 Extents of vehicle positions relative to lane

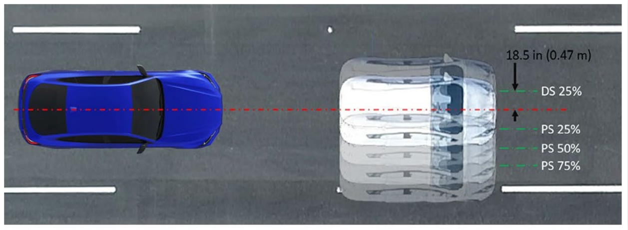


FIGURE 5 Comparison of frontal overlaps for passenger side offsets

TABLE 2 Test matrix

		GST Lateral Offset				
		-25%	0%	25%	50%	75%
Approach Speed (mph)	**25**	7	9	7	3	9
	35	5	9	6	5	6
	45	6	10	6	7	6

Prior to conducting any tests, the SV's FCW system was characterized by performing 7 runs with the SV approaching a stationary GST at a constant 45 mph with no lateral offset between the vehicles. Each test was run until an FCW alert was issued and then the SV operator input steering to avoid the GST. The TTC at the onset of an FCW alert for each run was then calculated.

After any collision between the SV and the GST, the same test procedure was followed and the TTC at FCW alert onset was compared to the observed TTC's in the pre-test FCW system characterization. This was done to verify that there was no damage to any of the FCW/AEB system components and to ensure that the system was still aligned similarly to when the vehicle was received. This is one of several methods that could be used to show a deviation in system performance following an impact with the soft target.

The last step prior to initiating the test series was to orient the vehicles such that they were nose to tail, centered in the lane. A data file was then logged which recorded the local position of the SV at the point of impact. All measurements were determined relative to this zero point.

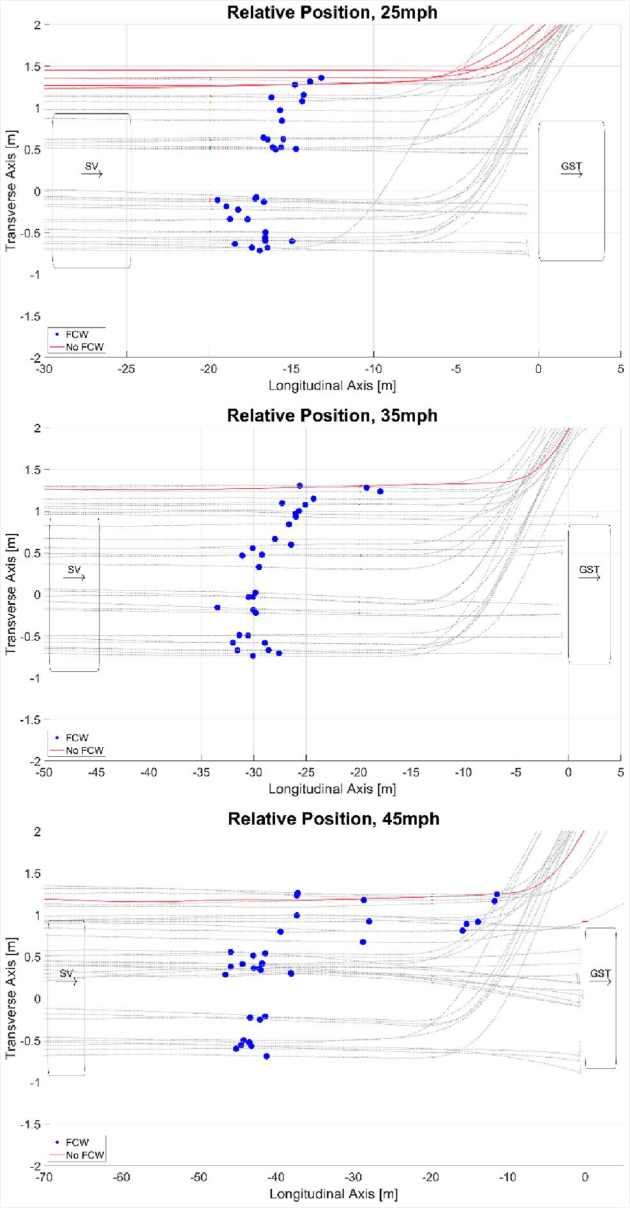
Test Matrix

The testing reported in this paper was part of a larger overall test series conducted over two weeks in October 2023. These tests included approaches where the SV operator steered after receiving a FCW, steered after AEB activation, steered regardless of system response to avoid colliding with the GST, or took no action. The goal of this portion of the test series was to demonstrate system variability and determine if there were any trends between approach speed, overlap, and warning time in the tested ADAS system. Four lateral offsets were tested, at varying speeds (Table 2). The different approach methodologies have not been separated. In total 101 runs were evaluated. Tests where the SV yaw rate exceeded 1°/second in the 50m prior to FCW activation were discarded, consistent with NHTSA confirmatory test protocols.

Test Results

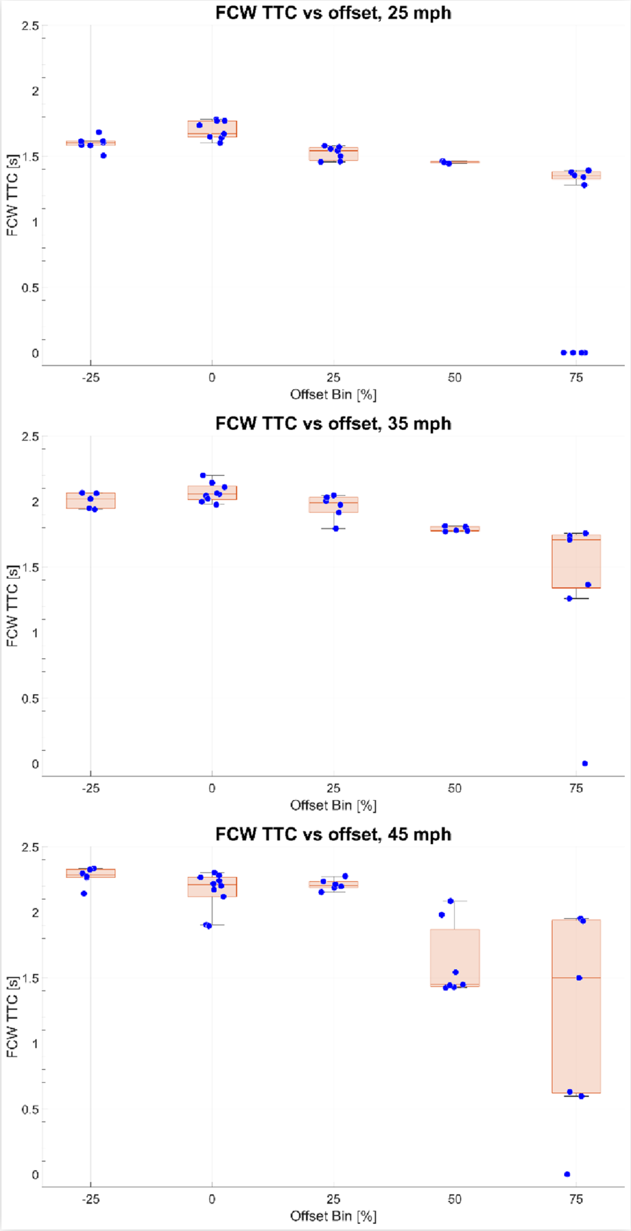
Figure 6 depicts the position of the SV relative to the GST throughout each test run, highlighting the point at which an FCW alert is presented. Test runs which exhibited no FCW alert are highlighted in red. While the operator of the SV attempted to maintain a straight path there was

FIGURE 6 Test runs demonstrating repeatability of vehicle trajectories for (nominal) approach speeds of 25, 35, and 45 mph. The points of FCW activation and collision (if relevant) are marked. SV and GST dimensions are drawn for reference. Note: the unequal scaling on the vertical and horizontal axes alters the aspect ratios for the vehicles. Trajectory lines represent the path of the subject vehicle centerline. Distinction between swerve and no-swerve runs is evident from the trajectory.



some variability in the lateral position of the SV as it approached the stationary GST, as shown in Figure 6. This was deemed to be minimal enough to exclude the effect of weaving as an artifact in the data. The data show a correlation between lateral offset and the timing of FCW alerts with nominal SV speeds of 25 mph and 35 mph. The observed correlation is weaker in the 45 mph runs.

FIGURE 7 Box and scatter plots of TTC at FCW activation versus (nominal) offset for (nominal) subject vehicle approach speeds of 25, 35, and 45 mph. Individual data points received random horizontal displacement to prevent overlap. This displacement is not reflective of true offset value. For runs where FCW did not provide an alert, the TTC value was set to zero. A negative offset corresponds to shifting the target vehicle toward the driver's side.



The tests were binned by actual offset in increments of 25%. For each run, the TTC at FCW alert onset was calculated and compared across other runs in the same bin. Box plots for each bin are generated and displayed in Figure 7. The median of FCW alert timing decreases with higher lateral offset[1] which makes evident the degradation in system performance and reliability with

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[1] Higher/increased lateral offset refers to absolute values

increasing lateral offset. It is noteworthy that the type of observed degradation varies according to speed. At higher closing speeds and higher lateral offsets, the interquartile range (IQR) of the TTC at onset of FCW alert is observed to be greater. This is consistent with increased variability in the timing of FCW alerts. This increased variability is not observed at lower closing speeds (25 mph). Rather, with high lateral offsets, more missed detections occur at lower speeds than at higher speeds (four missed detections in the 25 mph runs vs. one each respectively in the 35 mph and 45 mph runs.)

Conclusions and Future Work

The following conclusions were observed from the test results:

1. There is a correlation between increased lateral offset and FCW alert timings, with later warnings occurring at high lateral offsets.
2. At high lateral offsets, the variability of FCW alert timing increases with higher closing speed.
3. At high lateral offsets, missed detections occurred more frequently at lower closing speeds.

Based on vehicle owner's manuals which describe the performance limitations of forward collision mitigation systems (which rely on a similar sensing architecture to the tested vehicle), it is expected that these technologies perform best at detecting objects directly in or substantially within the forward path. The observed degradation in system performance at increased lateral offset aligns with these expectations. At increased lateral offset, the ability to accurately and consistently detect an object as in-path is more difficult.

At high lateral offset, it is uncertain why missed detections occur more frequently at lower closing speeds. It is possible that there is programmed logic which weighs the potential of a missed detection vs a false positive. The likely variables considered in this decision are the potential risk/criticality (which is proportional to closing speed) and the uncertainty in the prediction (which is increased at high lateral offset).

In conclusion, this study has shed light on the performance variability of radar and camera based forward collision mitigation systems, highlighting their limitations when approaching partial overlap targets. Moving forward, there are several avenues for future research to explore. Firstly, additional studies involving more subject vehicles of varied technology type (stereo vision, Lidar, etc.) could provide insights into how performance variability in this scenario may be reduced. Secondly, carrying out this investigation with a real target vehicle (instead of the GST) could be valuable. Past studies have compared the radar signature of the GST with real vehicles [14], and compared the performance of forward collision mitigation technology in response to the GST and NHTSA's strikable surrogate vehicle (SSV) [15]. However, no publicly available test data exists that compares the effect of target type (GST vs real vehicle) on performance variability of forward collision mitigation technology in response to a partial overlap target. Additionally, further research might examine the effect of target orientation on performance variability.

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Appendix A: Test Equipment

- Oxford Technical Solutions' (OXTS) RT3003
- Free Wave Radio to receive differential corrections from Exponents GPS base station
- DEWESoft's DEWE-43A
- AB Dynamics SYNC-0 system
- USB video cameras (NEXIGO 1080P HD Webcams)
- Synchronization system with digital outputs and LED strips
- 12-volt DC and 120-volt AC power provided by auxiliary battery systems

Test data was recorded by two onboard Data Acquisition Systems (DAS). A DEWESoft DEWE-43A, and an AB Dynamics SYNC-0.

Data recorded on the AB Dynamics SYNC-0 system included:

- Vehicle X Position [m][2]
- Vehicle Y Position [m]
- Vehicle Speed [mph]
- Digital Input Trigger [Boolean]

Data recorded on the DEWESoft DEWE-43A included:

- Frame count of all USB video cameras
- Digital Input Trigger [Boolean]
- Forward looking video
- Video of Dashboard display
- Video of pedal box area
- Brake light signal voltage

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[2] Vehicle position is recorded in a Cartesian format using a local origin placed on the test track at Exponent's Test and Engineering Center. The AB Dynamics SYNC-0 converts the positional data from the RT3000v3 into this local coordinate system.

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