Objective Test and Performance Measurement of Automotive Crash Warning Systems

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ABSTRACT[1]

The National Institute of Standards and Technology (NIST), under an interagency agreement with the United States Department of Transportation (DOT), is supporting development of objective test and measurement procedures for vehicle-based warning systems intended to warn an inattentive driver of imminent rear-end, road-departure and lane-change crash scenarios. The work includes development of track and on-road test procedures, and development of an independent measurement system, which together provide data for evaluating warning system performance. This paper will provide an overview of DOT's Integrated Vehicle-Based Safety System (IVBSS) program along with a review of the approach for objectively testing and measuring warning system performance.

Keywords: vehicle-warning system, crash prevention, objective test, performance measurement

1. INTRODUCTION

The National Institute of Standards and Technology (NIST) has worked with the U.S. Department of Transportation (DOT) in a series of cooperative agreements since the mid 1990's. Early work focused on autonomous driving under the Automated Highway System project. Since 2000, NIST has focused on objective test procedures and independent measurement systems for vehicle-based crash warning systems. NIST developed test procedures and an independent measurement system for road-departure warning systems (RDWS) for the DOT RDWS Field Operation Test (FOT) program [1, 2]. NIST is currently participating in the latest DOT program, which involves deployment of an integrated vehicle-based safety system (IVBSS). The IVBSS program is a major initiative within DOT's Intelligent Transportation Systems program [3, 4]. DOT's goal is to accelerate deployment of warning systems that address three major crash scenarios: rear-end, road-departure and lane-change/merge. IVBSS has the potential to address 3.6 M light vehicle and heavy truck crashes annually, of which 27,500 result in one or more fatalities. The IVBSS program will develop warning systems for passenger cars and for heavy trucks in Phase 1. If the systems pass Phase 1 tests, then a fleet of 20 cars and 10 trucks outfitted with warning systems will undergo real-world evaluation using driving volunteers in Phase 2. At the end, IVBSS will produce a report that describes the benefits and potential impact of deploying these systems. The IVBSS team consists of various DOT and other U.S. government agencies, including the National Highway Traffic and Safety Administration (NHTSA), the Volpe National Transportation Systems Center and NIST. The primary industry team partners include the University of Michigan Transportation Research Institute, Visteon Corp., Eaton and Cognex.

NIST's role in the IVBSS program is to assist in the development of objective tests and to develop an independent measurement system for evaluating system performance during the tests. The results of the performance evaluation in Phase 1 will help determine whether to proceed with Phase 2. A follow-on activity in Phase 2 is to characterize system performance in extensive on-road scenarios in order to provide data for benefits estimates. This paper summarizes NIST's (and the IVBSS team's) approach to measurement-based performance evaluation. The approach starts with developing a set of scenarios describing the problem, which in this case evolved from an analysis of the crash database statistics [5]. The scenarios lead to a set of track- and road-based test procedures to determine the system's effectiveness in dealing with the problems. The pass/fail criteria for the tests include metrics that quantify acceptable performance. To promote objectivity further, the tests rely on an independent measurement system (IMS) to provide performance data as opposed to using measurements taken by the system under test. Acceptance of the IMS as the "ground truth" reference

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requires verification of IMS accuracy from results of calibration and characterization tests. The remaining sections describe the three main aspects of measurement-based performance evaluation, objective tests, performance metrics and independent measurement, within the context of the IVBSS. This approach could apply to the objective evaluation of other systems, such as autonomous mobile robots.

2. OBJECTIVE TESTS

The primary function of the IVBSS is to detect and warn the driver of three crash situations: rear-end, road-departure and lane-change/merge. The DOT team conducted a review of test procedures from previous DOT programs and created a set of test scenario guidelines that the industry team is currently using to develop detailed test procedures. In the following descriptions, the term subject vehicle (SV) and principal other vehicle (POV) refer respectively to the IVBSS-equipped vehicle (either light vehicle or heavy truck) and principal other vehicle involved in the crash scenario. The subject vehicle's trajectory includes an "x" that indicates the start of an abort path if no warning occurs by this point. The magnitude of the forward-facing arrow within the vehicle indicates relative speed, and arrows pointing upward or downward indicate acceleration and deceleration, respectively.

Figure 1 illustrates a scenario designed to test the forward collision warning (FCW) function. The IVBSS uses forward radar and forward vision to detect lead vehicles in lane and warn the driver prior to a rear-end collision. In the figure, the POV is initially traveling at a lower speed than the SV and it starts to decelerate. The SV driver waits for a warning until safety considerations dictate slowing down and possibly steering to the side. Variations of the rear-end scenario include a stopped lead vehicle, a lead vehicle on a curve, a vehicle cut-in and a lead vehicle revealed after a cut-out.
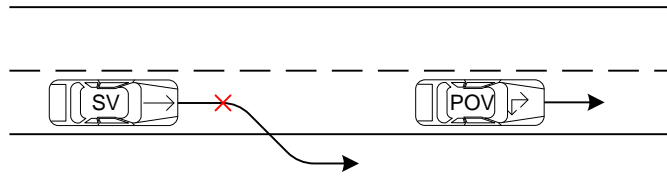

Figure 1. Example rear-end warning test scenario

Figure 2 illustrates a scenario designed to test the road-departure warning (RDW) function. IVBSS uses forward vision to detect road edges and warn the driver prior to the vehicle departing the road. A variation of this scenario is called departure on curve due to excess speed, which tests the curve-speed warning (CSW) function. IVBSS uses GPS and a map to determine safe speed for an approaching curve and warn the driver to slow down. The heavy truck IVBSS will not implement the CSW warning function.
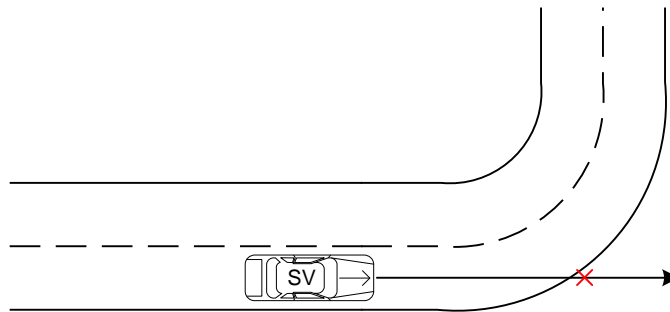

Figure 2. Example road-departure warning test scenario

Figure 3 illustrates a scenario designed to test the lane-change/merge (LCM) warning function. IVBSS uses side radar and possibly side vision to detect vehicles in adjacent lanes and to warn the driver of imminent collision during a lane

change or lane merge. The heavy-truck IVBSS must account for a trailer, which greatly increases the difficulty of sensing potential collisions during lane-changes. A variation of this scenario is the POV in the adjacent lane approaching from the rear at a higher speed.
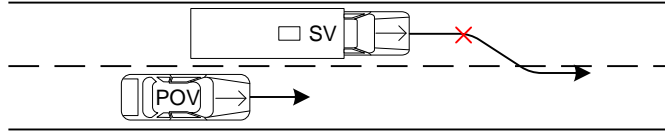

Figure 3. Example lane-change warning test scenario

Figure 4 illustrates a scenario designed to test how the IVBSS handles situations involving multiple threat warnings (MTW). IVBSS implements an arbitration algorithm to resolve instances where multiple warnings may occur. In the "Rear-End and Lane-Change" multiple threat scenario (shown in figure), the SV changes lane into an adjacent vehicle (called P2) after encountering a slower moving POV (called P1). Two other scenarios under consideration include a "Lane-Change and Rear-End" scenario (reverses the order of the encountered threats) and a "Rear-End and Road-Departure" scenario (driver attempts to avoid a rear-end collision by driving off the road). At this time, the IVBSS team has not finalized the behavior of the system in these scenarios.
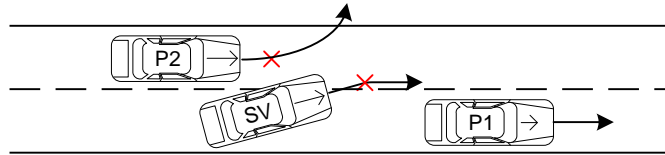

Figure 4. Example multiple-threat warning test scenario

Besides the track-based tests, the IVBSS will undergo on-road tests to examine system performance under a wider array of conditions not easily replicated on a track. These include traffic, roadside objects, lane marking quality, lighting conditions (early morning, nighttime lighting, etc.) and road geometries, to name a few. Warnings will be analyzed to determine whether they are true positive (warn condition) or false positive (no warn condition). Phase 2 will include a more in-depth characterization of the system to examine issues such as percent of time system is available and under what types of conditions the system is unavailable.

The results of the track and on-road tests will feed into the benefits estimate analysis. In the benefits analysis, the system accrues benefit by successfully passing a test scenario. The value of the benefit comes from analyses of the crash statistics associated with scenario.

3. PERFORMANCE MEASURES

Objective evaluation occurs through use of quantitative metrics and independent measurements. An example of a metric is the crash prevention boundary (CPB) that determines the range at which a warning should take place [6]. The following CPB metrics include a driver reaction phase (distance vehicle travels from time of warning until driver initiates a response) and a driver response phase (the distance the vehicle travels during braking or steering). The rear-end version of the CPB is:

$$r_w = v_f t_r + \frac{v_f^2 - v_l^2}{-2(a_f - a_l)} \qquad \textbf{(1)}$$

Where:

v_f = measured following vehicle forward velocity (m/s)
v_l = measured lead vehicle forward velocity (m/s)
t_r = assumed driver reaction time (s)
a_l = measured lead vehicle acceleration (braking is negative) (m/s^2)
a_f = assumed following vehicle acceleration to avoid collision (m/s^2)

The CPB for a roadway departure on a straight road is:

$$r_w = v_{lat}t_r + \frac{v_{lat}^2}{-2a_{lat}}$$ **(2)**

Where:

v_{lat} = measured lateral velocity (positive toward road edge) (m/s)
t_r = assumed driver reaction time (s)
a_{lat} = assumed lateral acceleration to avoid departure (negative away from road edge) (m/s^2)

Warning ranges below a specified range are late while warnings beyond an acceptable range are early. Figure 5 shows results from a road departure toward a barrier test conducted at the Transportation Research Corporation in East Liberty, OH. These tests examined a road-departure warning system developed for DOT. The plot shows distance to the barrier at the time of warning versus the lateral velocity toward the barrier for each test run (shown as small circles). The curve is the CPB for a roadway departure assuming a 1.5 s driver reaction time and a 3.0 m/s^2 lateral acceleration limit. The plot shows that all the tests were "on time" (the early line does not appear in the graph).
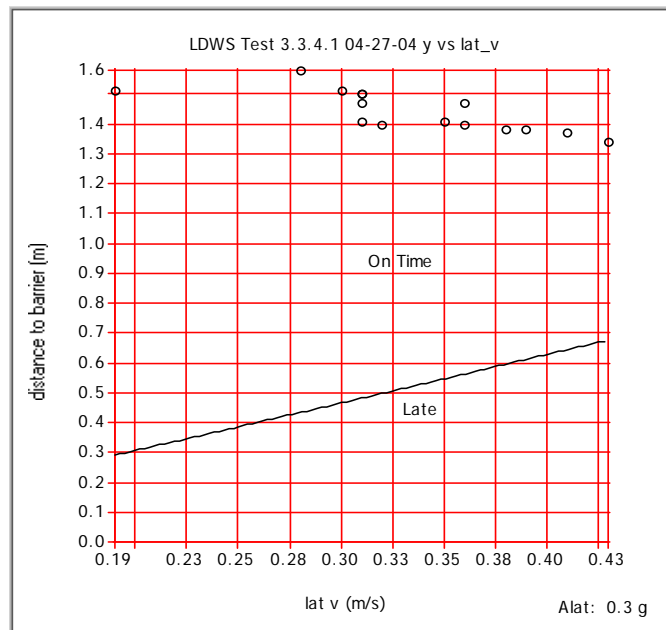

Figure 5. Results from a road-departure toward Jersey barrier test. The plot shows range to the barrier at the time of warning as a function of lateral velocity toward the barrier. All the warnings were on time (i.e., they occurred above the CPB line).

4. INDEPENDENT MEASUREMENT SYSTEM

The performance metrics described above contain variables that an IMS must measure during a test. The IMS NIST developed for the RDWS FOT uses a three-camera calibrated vision system to measure vehicle lateral position and

lateral velocity during a test. A camera and microphone within the vehicle captures the time of a warning. The analysis of a test starts by locating the video frame where a warning first occurs. Figure 6 shows a video frame capturing a road departure warning. The frame is a quad image containing images from four cameras. The lower left quad shows the view from a camera facing the warning display in the dash. The thick arrow indicates a right-side road departure. The top left quad shows the left down-looking camera. An automatic lane-tracking algorithm executed during post-processing tracks lane position and computes lateral velocity. The upper right quad shows the view from a down-facing camera on the vehicle's right side. The lane marker is under the vehicle. The lower right quad shows the view from a camera that points forward and shows the lane-tracking algorithm results over the left and right markers.
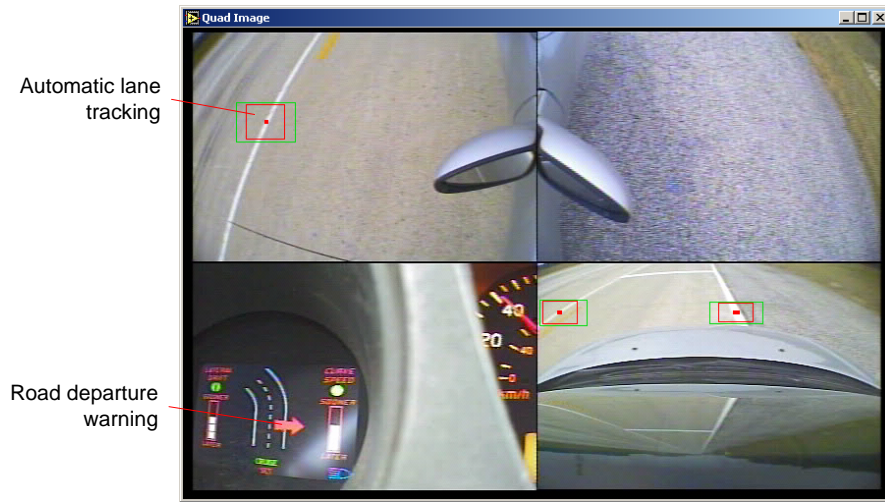

Figure 6. Post-process analysis of video using IMS software.

The vision calibration scheme for the RDW IMS supports range measurement out to 4 m. NIST is near completion in adding a dual-head laser scanner that will provide range measurements out to 70 m and up to 300° around the vehicle. Figure 7 shows the laser-scanner mounted on the NIST/DOT test bed vehicle.

Figure 7. Dual-head laser scanner mounted on NIST/DOT vehicle

According to the accuracy requirements for testing rear-end collision warning systems, range errors should be less than 5% of measured range or 2 m (whichever is greater) [7]. NIST is conducting both static and dynamic tests to verify the accuracy of the laser scanner. The static test determines "best case" system performance from a stationary position. Table 1 summarizes the test conditions, which consist of the factors that affect performance such as target range and target reflectance. Figure 8 shows one laser scanner mounted on a tripod and Figure 9 shows a target. The test involves placing the target at each range and measuring the error (difference between reference range and the mean value of measurements) and the uncertainty (standard deviation of measurements). A summary of the static test results appears in Table 2. The static range uncertainty is approximately 0.1 % of range, which falls within the accuracy requirements of 5 % of range.

Variable Factor	Value Tested
Range to target	1 m, 20 m, 40 m, 60 m, 72 m
Target Reflectance	99 % R, 50 % R, 2 % R
Target Angle of Incidence	0°, 30°, 60°
Field of Regard	-60°, 0°, 60° Sensor Azimuth

Table 1. Static test variables

Figure 8. Laser scanner

Figure 9. Target, 99% reflectivity

Range Error (1)	$(-0.013r + 0.14) \pm (.0016r + 0.001)$ m
Angular Error (2)	$\pm 0.5°$
Maximum range for a 50 % target (3)	72 m
Maximum range for a 2 % target (3) (4)	60 m < r < 72 m

Table 2. Static test results

Notes: (1) r = measured range, uncertainty value is 2σ; (2) estimate from rotation testing (3) 0.6 m x 0.6 m planar target; (5) 2 % target visible at 60 m but not at 72 m.

Static tests provide only a partial assessment of range accuracy. The laser scanner's accuracy should also meet requirements while mounted on a vehicle traveling at highway speeds. Under these conditions, timing and

synchronization errors can produce range errors unseen during static tests. Since it is difficult to take consecutive measurements to a target from a known range while the vehicle is moving, NIST is developing a dynamic test that combines measurements from repeated trips around a surveyed course. The test requires a time measurement system (TMS) to capture the precise time the vehicle crosses over a surveyed point on the track (referred to as event time). Reflective strips at longitudinal distances of 0, 20, 40 and 60 meters from a cylindrical target serve as known reference ranges (see Figure 10). An emitter-detector optical switch mounted on the vehicle's bumper causes the TMS to capture the GPS Universal Time Code when the vehicle crosses a reflector (to within 1 µs). The laser-scanner time stamps all data (video and range) with GPS time as well. The dynamic test consists of at least 10 runs past the target at speeds of 30 m/s (67 mi/h) and 10 m/s (22 mi/h). Computing the range error involves comparing the laser-scanner's measured range to the target against the surveyed range at the appropriate time (when the vehicle crosses the reflector). A linear interpolation of range to target using event time improves accuracy when the event occurs between range scans. Initial results indicate that the laser scanner's dynamic uncertainty also falls within the required 5 % of range.
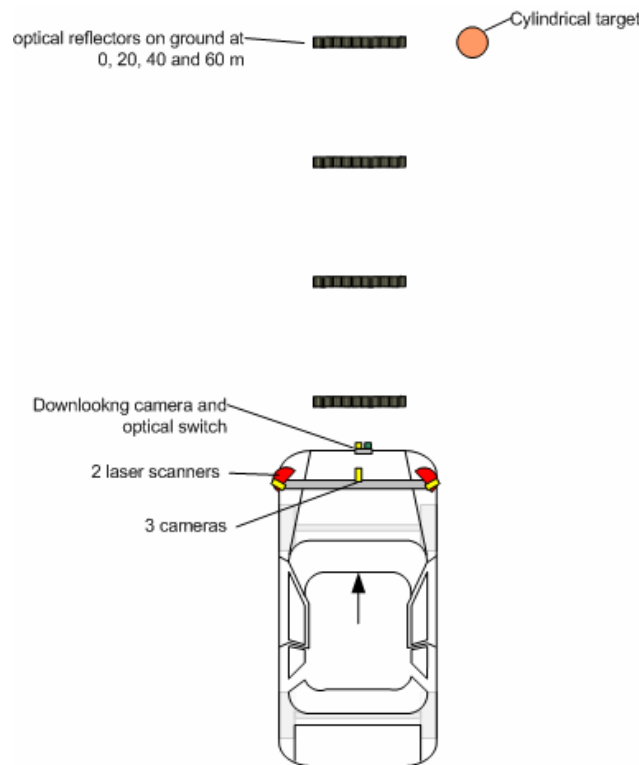
Figure 10. Diagram of dynamic test where vehicle crosses over reflective strips at known distance from target.

5. CONCLUSIONS AND ACKNOWLEDGEMENTS

This paper describes an approach for objectively measuring the performance of automotive crash warning systems. The approach consists of developing track and road tests based upon analysis of crash statistics, developing metrics for quantifying system performance, and using an independent measurement system to measure performance. A new U.S. DOT program on integrated vehicle-based safety systems is using this approach to evaluate an integrated rear-end, road-departure and lane-change/merge warning system. The paper includes example IVBSS tests and metrics. NIST is integrating a dual-head laser scanner into its independent measurement system to provide ground-truth for rear-end tests. The laser scanner is undergoing static and dynamic tests to determine whether its accuracy meets the program's needs.

Administration and the IVBSS Program Manager, and Dr. Wassim Najm of the Volpe National Transportation Systems Center.

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