Performance Evaluation of Integrated Vehicle-Based Safety Systems

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Abstract—[1]This paper describes a program to develop and test an integrated crash warning system that addresses rear-end, lane change, and roadway departure crashes for passenger cars and heavy commercial trucks. One of the goals of this program is to facilitate the deployment of integrated crash warning systems by creating performance specifications and objective test procedures, and estimating potential safety benefits for integrated safety systems. In support of this goal, equations for the safety benefits estimation methodology are introduced and test scenarios derived from national crash database statistics are delineated. The approach, performance metrics and independent measurement system used to conduct objective tests are also discussed.

Keywords*: warning system, crash prevention, objective test, performance measurement*

I. INTRODUCTION

Rear-end, lane change, and roadway departure crashes account for approximately 3.6 million police-reported crashes each year on U.S. roadways. These three crash types result in about 27,500 of the Nation's 42,000 annual traffic fatalities and contribute to a considerable economic loss due to injuries, property damage, and decreased productivity. Studies conducted by the U.S. Department of Transportation (U.S. DOT) indicate that a substantial percentage of the 3.6 million target crashes could be prevented annually by widespread deployment of integrated crash warning systems that would warn drivers of imminent crash situations and prompt them to take corrective action [1 – 3].

In November of 2005, the U.S. DOT entered into a cooperative research agreement with an industry team to develop and test an integrated, vehicle-based, crash warning system that addresses rear-end, lane change and roadway departure crashes [4]. The four-year, two-phase program that will be carried out under this agreement is known as the Integrated Vehicle-Based Safety System (IVBSS) program.

During Phase I of the program, individual crash warning subsystems will be enhanced; the integrated system will be designed, and component subsystems will be combined with a driver-vehicle interface (DVI) into a prototype vehicle. The prototype vehicle will undergo a series of tests aimed at verifying that the integrated system meets the performance requirements and is safe for use by unescorted volunteer drivers for extended periods.

In Phase II, the deployment fleets will be constructed; volunteer drivers and truck fleets will be recruited, and the field operational test (FOT) will be implemented. Volunteer drivers and employees of the truck fleets will use the project vehicles as their own personal vehicle to drive as they normally would for a period of approximately one month. The field test will last approximately one year. Data will be collected on the driver/vehicle/system performance and the driving environment using on-board data acquisition systems (DASs).

Objective tests will be developed to verify the performance of the integrated system installed on the fleet of passenger cars and heavy commercial trucks during Phase I. These verification tests consist of controlled scenarios and procedures, typically conducted on test tracks or pre-defined routes on public roads. Results from these tests will help refine the design and construction of the prototype vehicles, and ensure deployment readiness for the field test.

As part of the IVBSS program, an independent evaluation will be performed to estimate potential safety benefits, determine driver and truck fleet acceptance, and characterize the capability and performance of the integrated system used in the field test. In addition to numerical and video data collected from the on-board DASs, subjective data will be gathered from field participants through surveys and focus groups.

II. BENEFITS ESTIMATION

IVBSS technologies have the potential to reduce the number of motor vehicle crashes and severity of crash-related injury. Prior to wide-scale deployment in the U.S. vehicle fleet, these safety benefits can be estimated using data collected from field tests of deployment-ready systems. Safety is ideally measured from actual crash data; however, such data are rare or non-existent during the conduct of field tests since a wide

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exposure is required to ensure adequate crash data. The scope of field tests is typically limited to a few instrumented vehicles driven by volunteer subjects for a relatively short period. A methodology has been formulated to predict safety benefits utilizing non-crash, driver/vehicle/system performance data collected from encounters with various driving conflicts during the FOT [5].

Safety benefits are measured by estimating the number of crashes that might be avoided and the total harm that might be reduced due to full deployment of integrated systems. These two measures of safety benefits can be translated into monetary savings in terms of crash economic cost [6]. The number of crashes avoided is used to project monetary savings in crash economic cost due to property-damage only. Savings in injury-related economic costs are estimated by multiplying the total harm reduction factor with the cost of all injuries. The total harm reduction factor encompasses reductions in injuries due to crashes avoided and lower-severity of injuries from crashes not avoided.

The annual number of target crashes that might be avoided with full deployment of an integrated system, N_a, is:

$$N_a = \sum_{i=1}^{n} N_{wo}(S_i) \times E(S_i) \tag{1}$$

$n \equiv$ Number of applicable pre-crash scenarios, S_i

$N_{wo}(S_i) \equiv$ Annual number of target crashes preceded by S_i prior to full deployment

$E(S_i) \equiv$ System effectiveness in avoiding target crashes preceded by S_i

Target crashes consist of vehicular dynamic scenarios and crash contributing factors that the system is designed to address. Pre-crash scenarios refer to vehicle orientations, dynamics, and movements that happen immediately prior to a target crash, as well as the critical event that makes the crash imminent [7]. $N_{wo}(S_i)$ can be obtained from national crash databases such as the National Automotive Sampling System/ General Estimates System (GES) and Crashworthiness Data System (CDS) databases. $E(S_i)$ is expressed as:

$$E(S_i) = 1 - \frac{P_w(C \mid S_i)}{P_{wo}(C \mid S_i)} \times \frac{P_w(S_i)}{P_{wo}(S_i)} \tag{2}$$

$P_w(C|S_i) \equiv$ Probability of a crash with IVBSS assistance given that S_i has been encountered

$P_{wo}(C|S_i) \equiv$ Probability of a crash without IVBSS assistance given that S_i has been encountered

$P_w(S_i) \equiv$ Probability of an S_i encounter with IVBSS assistance

$P_{wo}(S_i) \equiv$ Probability of an S_i encounter without IVBSS

The ratios $\frac{P_w(C \mid S_i)}{P_{wo}(C \mid S_i)}$ and $\frac{P_w(S_i)}{P_{wo}(S_i)}$ are known respectively as the crash prevention ratio and scenario exposure ratio. The prevention ratio can be obtained from computer simulations of kinematical models with representative random variables (e.g., Monte Carlo simulation), using naturalistic driving data from the FOT and experimental data from the system design phase. The exposure ratio can be obtained from FOT data by counting the number of conflicts encountered and normalizing by the number of vehicle miles traveled with and without the integrated warning system engaged.

The methodology described above depends on the identification of driving conflicts from driving situations recorded during the conduct of field tests. These conflicts are defined in a similar way as pre-crash scenarios. It should be noted that these driving conflicts, S_i, must be quantified [8]. Some encounters with driving conflicts might be of benign nature, which typically occur in normal driving conditions where immediate and intense driver response to prevent a potential collision may not be required. Thus, boundaries need to be established between benign encounters with driving conflicts (i.e., normal driving situations) and safety-critical encounters with driving conflicts (i.e., near-crashes). Such boundary quantification allows accurate and consistent data reduction by retaining pertinent information on encounters with true critical conflicts obtained in FOTs.

A second benefit estimate is the annual reduction in total harm with full system deployment, H_r, which is obtained as follows:

$$H_r = \sum_{i=1}^{n} H_{wo}(S_i) \times R(S_i) \tag{3}$$

$H_{wo}(S_i) \equiv$ Annual total harm from target crashes preceded by S_i prior to full deployment

$R(S_i) \equiv$ System effectiveness in reducing total harm from target crashes preceded S_i

$H_{wo}(S_i)$ is determined from the following total harm equation:

$$H = \sum_{m=0}^{6} w(m) \times O(m) \tag{4}$$

$m \equiv$ Injury severity level

$w(m) \equiv$ Unit cost of injury severity level m

$O(m) \equiv$ Number of occupants with injury severity level m

Injury severity level, m, is based on the Abbreviated Injury Scale (AIS) used by the medical community. Level 0 refers to an uninjured person while level 6 denotes a fatal injury. Levels 1 through 5 indicate respectively a minor, moderate, serious, severe, or critical injury. The U.S. DOT has estimated the unit cost of each injury severity level, $w(m)$, in terms of economic cost based on year 2000 dollar value [6]. $R(S_i)$ in Equation (**3**) is determined from:

$$R(S_i) = 1 - E'(S_i) \times \frac{\overline{H}_w(S_i)}{\overline{H}_{wo}(S_i)} \tag{5}$$

The variables $E'(S_i)$, $\overline{H}_w(S_i)$ and $\overline{H}_{wo}(S_i)$ are computed from the following equations:

$$E'(S_i) = 1 - E(S_i) \tag{6}$$

$$\frac{\overline{H}_w(S_i)}{\overline{H}_{wo}(S_i)} = \frac{\sum_{k=1}^{\ell} P_w(\Delta v_k \mid S_i) \times \overline{H}(\Delta v_k)}{\sum_{k=1}^{\ell} P_{wo}(\Delta v_k \mid S_i) \times \overline{H}(\Delta v_k)} \tag{7}$$

$\Delta v_k \equiv$ Change in speed in bin k that a vehicle undergoes as a consequence of crashing

$P_{wo}(\Delta v_k|S_i) \equiv$ Probability of Δv_k given that a crash has occurred during an S_i encounter without IVBSS assistance

$\overline{H}(\Delta v_k) \equiv$ Average harm per crash (harm unit) with Δv_k

Equation (**7**) assumes that vehicle crashworthiness (e.g., crash protection offered by vehicles), distribution of vehicle weights, and vehicle occupancy remain the same with and without IVBSS assistance. Therefore, the reduction of injury severity would occur due to lower closing speeds at impact (smaller Δv) if drivers were assisted by IVBSS technologies. The values of $\overline{H}(\Delta v_k)$ can be derived from national crash databases such as the CDS [5]. The parameters $P_w(\Delta v_k|S_i)$ and $P_{wo}(\Delta v_k|S_i)$ can be obtained from the same process used to estimate $P_{wo}(C|S_i)$ and $P_w(C|S_i)$. For instance, Monte Carlo simulations yield a number of crashes along with vehicle speeds at impact that can then be converted to values of Δv using simple models.

III. TEST SCENARIOS

Test scenarios are based on the most frequent pre-crash scenarios and most prevalent driving conditions at the time of the crash. Individual test scenarios are presented for rear-end, lane change, and roadway departure crashes based on 2003 GES statistics. Moreover, scenarios are suggested for integrated system applications.

A. Rear-End Scenarios

The following four scenarios are proposed as a basis for testing the rear-end crash warning function:

1. Host vehicle (vehicle equipped with an integrated warning system) changes lanes and approaches a stopped lead vehicle.
2. Host vehicle is moving at constant speed and approaches a lead vehicle moving at lower constant speed.
3. Host vehicle is closely following a lead vehicle at constant speed and then lead vehicle suddenly decelerates.
4. Host vehicle is moving at constant speed and approaches a stopped lead vehicle.

These scenarios mainly occur in daylight, clear weather, and on straight and level roadways. The most frequent speed limit is 35 mph.

B. Lane-Change Scenarios

The following four scenarios are proposed as a basis for testing the lane change crash warning function:

1. Host vehicle changes lanes (constant longitudinal speed) to the right and encroaches on another vehicle in the adjacent lane.
2. Host vehicle passes (changing lanes with longitudinal acceleration) to the left and encroaches on another vehicle in the adjacent lane.
3. Host vehicle turns to the left and encroaches on another vehicle in the adjacent lane.
4. Host vehicle drifts (changing lanes with small lateral speed) to the right and encroaches on another vehicle in the adjacent lane.

C. Roadway Departure Scenarios

The following five scenarios are proposed as a basis for testing the roadway departure crash warning function:

1. Host vehicle is going straight and departs road edge to the right.
2. Host vehicle is going straight and departs road edge to the left.
3. Host vehicle is negotiating a curve and departs road edge to the right.
4. Host vehicle is negotiating a curve and loses control due to excessive speed on the curve.
5. Host vehicle is turning left at an intersection and departs road edge to the right.

D. Integrated Scenarios

Using the sets of test scenarios from individual crash types listed above, the following integrated scenarios are suggested:

1. Host vehicle is moving at constant speed and approaches a lead vehicle moving at lower constant speed. Host vehicle then attempts to pass to the left adjacent lane that is occupied by another vehicle.
2. Host vehicle is moving at constant speed and approaches a stopped lead vehicle. Host vehicle then attempts to change lanes to the right adjacent lane that is occupied by another vehicle.
3. Host vehicle drifts and is about to depart to the right adjacent lane that is occupied by another vehicle.
4. Host vehicle drifts and is about to depart to the left adjacent lane that is occupied by another vehicle.
5. Host vehicle is closely following a lead vehicle on a straight road, both driving too fast for the upcoming curve. Lead vehicle then suddenly decelerates.

IV. OBJECTIVE TEST PROGRAM

The U.S. DOT has planned an extensive program for testing the integrated system with the following purposes in mind:

- Verifying warning system performance prior to building a fleet of equipped vehicles and conducting the field test
- Determining how well the integrated system addresses each crash scenario
- Conducting preliminary research for possible safety rating programs to be used by the public for buying safer cars

The majority of the test activities take place during Phase I of the IVBSS program. The program will test the four warning functions: rear-end, road departure, lane change and integrated, on passenger and heavy commercial vehicles, and on test track and on-road environments. Track-based tests focus on correctness and timing performance in controlled, ideal conditions. Road-based tests examine performance in real-world conditions and primarily focus on measuring false alarm rates.

V. OBJECTIVE TESTS AND PERFORMANCE METRICS

Objective tests should, as much as possible, remove subjective analysis from the evaluation of system performance. The tests strive toward objectivity by:

- Defining metrics for measuring performance
- Conducting tests under controlled conditions
- Measuring conditions and performance variables using an independent measurement system

Metrics are the ruler, or scale, for objectively evaluating performance. Metrics typically consist of equations of several variables which, when evaluated, produce the performance measurement. Values for the variables may come from assumptions about the driver's response, from previous experiments and from measurements taken in real-time during a test run. Objective tests generate data to evaluate the correctness and timing of warnings. The response of the system for a given test is classified true positive (TP), false positive (FP) and false negative (FN) according to criteria listed in Table 1. The functional requirements dictate when the system should and should not issue a warning.

Table 1 Warning classifications.

Functional Requirement:	**System shall warn**	**System shall not warn**
System warned	TP	FP
System did not warn	FN	TN

The following equations define various effectiveness metrics used to summarize the warning system response ($\sum TP$ means the sum of all true positive warnings for a particular test or set of tests):

$$\text{True\%} = \frac{\sum TP}{\sum (TP + FN)} \times 100$$
$$\text{False\%} = \frac{\sum FP}{\sum (TP + FP)} \times 100 \qquad (8)$$
$$\text{Missed\%} = \frac{\sum FN}{\sum (TP + FN)} \times 100$$

Metrics such as crash prevention boundaries (CPB) are used to determine if a warning provides sufficient time or distance for the driver to react to the warning, and to respond by either braking or steering. A CPB for the forward collision scenario specifies the minimum longitudinal range for a warning:

$$r_w = v_f t_r + \frac{v_f^2 - v_l^2}{-2(a_f - a_l)} \qquad (9)$$

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)

Similarly for a roadway departure on a straight road, the minimum lateral range for a warning is:

$$r_w = v_{lat} t_r + \frac{v_{lat}^2}{-2a_{lat}} \qquad (10)$$

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)

An example application of the CPB metric for evaluating the performance of a road departure crash warning system appears in [9].

VI. PERFORMANCE MEASUREMENT SYSTEM

During system testing, evaluators will use an independent measurement system (IMS) developed by the National Institute of Standards and Technology (NIST) to:

- Support detailed analysis of conditions surrounding a warning or lack of warning
- Provide ground truth reference for measuring system performance
- Provide data and sensor redundancy for test verification purposes

The IMS developed for the roadway departure crash warning system (RDCWS) FOT includes calibrated cameras that enable evaluators to measure ranges to adjacent obstacles and to the road edge at distances up to 4 m [10]. NIST plans to extend the IMS in order to measure range and range-rate to forward-collision obstacles. The minimum requirements for the range measurement system include (desirable capability in parentheses):

- Range out to at least 60 m (100 m)
- 180° (360°) horizontal field of view (FOV) at 0.5° (0.25°) resolution
- 10 Hz (30 Hz) FOV update

A dual-head, laser-range scanner system that meets these requirements is currently being evaluated. The evaluation includes static characterization (stationary sensor and targets) and dynamic characterization (moving sensor and moving targets).

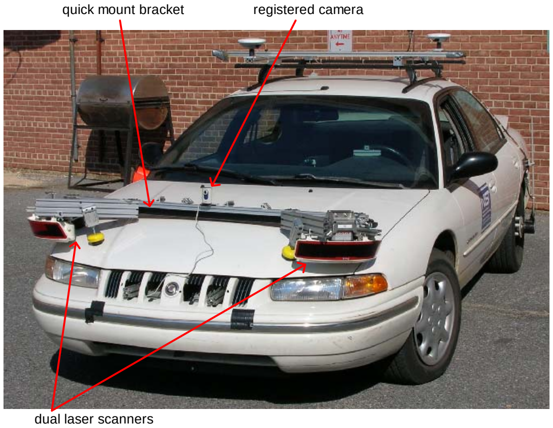

Figure 1 NIST/DOT test bed vehicle with dual-head laser-range scanner mounted on front hood.

VII. SUMMARY

This paper introduced the IVBSS program, a new U.S. DOT safety initiative to build and field test integrated crash warning systems designed to prevent rear-end, lane change, and roadway departure crashes for passenger cars and heavy commercial trucks. The goal of this program is to accelerate the deployment of integrated crash warning technologies by providing government and industry stakeholders' relevant information regarding system performance specifications, objective test procedures, potential safety benefits, and driver acceptance.

In support of the program goals and objectives, a methodology to estimate safety benefits using non-crash, driver/vehicle/system performance data gathered from a field test conducted in a naturalistic driving environment was developed. A set of crash scenarios, which serve multiple activities ranging from system design, objective testing, to safety benefits estimation, were also defined. Objective tests used to ensure that the IVBSS prototype vehicles meet performance requirements and are ready for use by laypersons in the field test were described.

Over the next four years, the IVBSS program will produce integrated system functional requirements, performance specifications, objective test procedures, and a fleet of passenger cars and heavy commercial trucks fitted with IVBSS technologies. In addition, a large database that will characterize driver/vehicle performance on public roads with and without the integrated safety system will be created. This database will be mined to estimate potential safety benefits, driver and truck fleet acceptance, and performance capability and maturity of the technologies. Interim and final program results will be published in public reports that will be available on NHTSA's website, http://www.nhtsa.dot.gov.

REFERENCES

[1] National Highway Traffic Safety Administration, “Preliminary Assessment of Crash Avoidance Systems Benefits”, Version II, Chapter 3, NHTSA Benefits Working Group, Washington, DC, December 1996.

[2] D. Pomerleau and J. Everson, “Run-Off-Road Collision Avoidance Using IVHS Countermeasures – Final Report”, DOT HS 809 170, December 1999.

[3] S. Talmadge, R. Chu, C. Eberhard, K. Jordan, and P. Moffa, “Development of Performance Specifications for Collision Avoidance Systems for Lane Change Crashes”, DOT HS 809 414, August 2001.

[4] http://www.its.dot.gov/ivbss/index.htm

[5] W.G. Najm, M.P. daSilva, and C.J. Wiacek, “Estimation of Crash Injury Severity Reduction for Intelligent Vehicle Safety Systems”, Paper No. 2000-01-1354, SAE 2000 World Congress, Detroit, MI, March 2000.

[6] L. Blincoe, A. Seay, E. Zaloshnja, T. Miller, E. Romano, S. Luchter, and R. Spicer, “The Economic Impact of Motor Vehicle Crashes, 2000”. DOT HS 809 446, May 2002.

[7] W.G. Najm, B. Sen, J.D. Smith, and B.N. Campbell, “Analysis of Light Vehicle Crashes and Pre-Crash Scenarios Based on the 2000 General Estimates System”. DOT-VNTSC-NHTSA 02 04, DOT HS 809 573, February 2003.

[8] D.L. Smith, W.G. Najm, and R.A. Glassco, “The Feasibility of Driver Judgment as a Basis for Crash Avoidance Database Development”. Paper No. 02-3695, Transportation Research Record 1784, TRB 2002 Annual Meeting, Washington, D.C., January 2002.

[9] S. Szabo and B. Wilson, “Application of a Crash Prevention Boundary Metric to a Road Departure Warning System”, Proceedings of the Performance Metrics for Intelligent Systems (PerMIS) Workshop, National Institute of Standards and Technology, Gaithersburg, MD, August 24 - 26, 2004. http://www.isd.mel.nist.gov/documents/szabo/PerMIS04.pdf

[10] S. Szabo and R. Norcross, “An Independent Measurement System for Performance Evaluation of Road Departure Crash Warning Systems”. National Institute of Standards and Technology Internal Report 7287, January 3, 2006