Performance Measurement of Vehicle Crash Imminent Braking Systems

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Abstract—As active safety system features are being introduced to the passenger vehicle market segment, there is an immediate need to develop a standardized testing protocol and scoring mechanism which enables an objective comparison of similar active safety system performance as implemented across various vehicle platforms. It is desirable that this standard is adopted by the entire automotive industry to further advance active safety technologies. This paper describes a proposal for the establishment of such a standard to evaluate and compare the performance of Crash Imminent Braking (CIB) systems. The operation of CIB system is described as a three-state state machine. A standardized scoring matrix is proposed to assess the performance of the system in each state. This standard ensures that every CIB system operates in one and only one state of the state machine at any given time. Subjective and arguable test scenarios are avoided as much as possible in this standard. The proposed scoring system is implemented based on track test data in the evaluation of a 2011 model year passenger vehicle equipped with a CIB system.

Keywords-imminent braking systems; performance measurement

I. INTRODUCTION

With the advancements in computation power, sensory technology, and data analysis techniques, the application of active safety systems to passenger vehicles becomes feasible. At the present time, some advanced active safety systems are equipped on medium and higher-priced vehicles [1-5]. Various sensory technologies, sensory fusion techniques, and data analysis techniques have been used in active safety systems to provide accurate predictions of potential collisions. These predictions can be used to: (i) provide alerts/warnings (e.g., audible, visual, or haptic) to encourage the driver to take preventive actions, and (ii) prepare the vehicle systems to 1) enhance the driver’s ability to avoid the collision (e.g., reducing braking system reaction delays), 2) override the control of the driver (e.g.: autonomous braking) to avoid vehicle collisions or reduce the crash energy of the collision.

The suite of active safety features on different vehicle platforms can vary significantly in feature offering, feature functionality, and performance. Some systems provide a Forward Collision Warning (FCW) feature that only provides warnings to alert the driver to a potential collision. Other systems support an Adaptive Cruise Control (ACC) feature which enables the vehicle to autonomously slow down when a slower vehicle is encountered ahead and then resume the original driver-selected speed once the obstruction clears. Still other systems support autonomous braking capabilities, such as a Crash Imminent Braking (CIB) system feature [6].

Here we define a CIB feature that may provide FCW warnings to the driver and then will initiate an autonomous braking action when the frontal collision is predicted to be unavoidable if braking is not applied immediately. Some of these autonomous braking active safety systems have exhibited operational limitations due to various sensory and data analysis issues. For instance, some systems may offer different levels of maximum braking deceleration capability in response to the assessed potential collision event. Others may not provide autonomous braking capability in response to stationary reference objects in front of the vehicle.

Active safety system manufacturers currently test their systems according to their own defined validation specifications. There is not a common measurement method to objectively compare active safety feature performance levels on different vehicle platforms [5, 7-12]. This paper describes a performance measurement method for evaluating and comparing the capabilities of CIB systems on various vehicles. The design of the method emphasizes the measurement of the vehicle system-level performance results and does not consider the methodologies associated with the decision to engage the autonomous braking functionality. The developed scoring method considers all four possible CIB actions: true positive (system activates in presence of “true” threat objects), true negative (system does not activate in presence of “true” threat objects), false positive (system activates on objects (e.g.: clutter) not considered “true” threat targets), and false negative (system does not activate in presence of “true” threat objects).

Section II of this paper describes a state machine that defines the active safety system braking/warning cycles. This state machine enables the proper definition of the performance measurement matrix. Section III defines the performance measurement matrix for each state. Section IV discusses the...
II. PROBLEM FORMULATION

CIB systems can be applied to both autonomous vehicles and human-driven vehicles. In autonomous vehicles, these systems can attempt to optimize the braking activations. In a human-driven vehicle, the CIB system provides assistance to the human driver. It may override the human driver’s operation decisions only when imminent danger of a collision is predicted. These CIB systems may provide various levels of assistance to driver. The first level provides warning signals; the second level applies autonomous braking. During vehicle operation, the CIB system can operate according to the following state machine.

![State Machine Diagram]

State 1: Safe

State 2: Forward Collision Warning

State 3: Collision Imminent Braking

State 1: No potential collision is predicted. In this state, the active safety system does not take any action.

State 2: A potentially hazardous condition is predicted, but a collision can be avoided if the driver intervenes to slow the vehicle. In this state, the forward collision warning signal is deployed to alert the driver of the potential danger.

State 3: A potentially hazardous condition is predicted and a collision is likely to occur because the current vehicle dynamics do not allow sufficient time for the average driver to react and slow the vehicle sufficiently to avoid the collision. In this state, the CIB system should autonomously activate the brakes.

A CIB system can transition from any one state to any other state. From a system implementation point of view, all CIB systems will transition from state 1 to state 3 via state 2. However, in highly dynamic situations, the onset of the state 2 warning signal may provide insufficient time for the user to react and significantly affect the outcome of the potential collision. In such situations, the CIB system transition to state 3 can be considered as the direct transition from state 1 to state 3. This state transition definition makes it easier to design the procedures for separate testing of FCW and CIB systems.

The decision-making conditions that drive the CIB system to transition from one state to another can vary by different manufacturers and implementation in different vehicles. The state transitions decisions are based on sensory input and data analysis techniques. CIB systems may include radar, lidar, and/or vision technologies [3, 5, 9, 13-16]. The state transition decision process is based upon either single sensor or sensory fusion methodologies. Each of these technologies has potential limitations that could adversely affect the decision-making transition process. In one example, a radar-based CIB system may incorrectly select a manhole cover (resulting from relatively high radar return) as a reference object with which the vehicle might collide and provide a false CIB activation. As such, the scoring method and the associated CIB performance test methodologies must be necessarily technology-agnostics. It cannot be designed to favor one sensor implementation approach over another. However, these sensor limitations should be collectively considered when developing technology-agnostics test scenarios that check the performance of the CIB system.

The designs of the CIB system for human-driven vehicles and autonomous vehicles are quite different. This paper describes the evaluation method of a CIB system for human-driven vehicles. Therefore, all braking actions taken by the CIB system are considered essential for avoiding a collision or reducing the collision energy. This braking action is achieved through activation of the Anti-Lock Braking Systems (ABS).

III. PERFORMANCE MEASUREMENT MATRIX

Here we describe the measuring matrix for the CIB performance. Since the actions taken by the CIB system vary significantly in different states, performance measuring scores are defined for each state. The measuring score reflects the ability of the system to correctly recognize the proper state, initiate warning signals, and/or achieve collision avoidance or a reduction of relative kinetic energy if control actions are taken. In general, the active safety system scores higher if the state transition is correct. A correct state transition is one where the result of action taken is better than that of no action or false action.

To make the description in this paper consistent and easy to follow, we call the CIB-equipped vehicle to be evaluated the “test vehicle”, and call the object or other vehicles in front of the test vehicle the “reference object”.

To objectively compare the performance of all CIB systems, a series of unambiguous test conditions were developed to test the performance of the vehicle for all CIB states. The test suite is conducted on a test track (e.g.: large parking lot with no clutter) in order to ensure a consistent and repeatable test environment. Each of these tests is conducted with different traffic scenarios for various road shapes (e.g.: straight, left-curved, and right-curved) at different specific vehicle speeds. The curved road-shape condition was selected with a 125 meter radius of curvature as measured at the centerline of the test vehicle lane. The reference objects are either a vehicle or pedestrian, as represented by a “balloon vehicle” and “mannequin”. The “balloon vehicle” provides both radar and vision characteristics similar to a mid-size vehicle. The mannequin provides radar and vision characteristics similar to a 50th percentile adult male.
A. State 1 Performance Measurements

When the CIB system is operating in state 1, the vehicle is in a situation which is predicted to be safe. In this state, we define the performance of the CIB system by the number of false actions that the CIB system takes in a set of predefined conditions.

The system should not transition out of state 1 under the following non-threatening, technology-agnostic conditions:

1. Presence of non-threatening targets (e.g. manhole cover, soda cans, debris such as paper and plastic bags, etc.) on the road surface and in the path of the test vehicle.
2. Passing parked and moving cars in an adjacent lane: This tests the abilities of the sensors to discriminate between in-path and out-of-path objects.
3. Environmental conditions (e.g., rain, fog, low sun conditions, etc.): This tests the abilities of the sensors to sense the roadway properly in inclement weather situations.

Relative to each set of test conditions (see Table 1), the CIB performance score of the vehicle in state 1 (SSI) can be defined as

\[
SSI = \frac{1}{2} SSI_a + \frac{1}{2} SSI_b
\]

where:

\[
SSI_a = \frac{1 - (FST2 / TS1)}{100}
\]

\[
SSI_b = \frac{1 - (FST3 / TS1)}{100}
\]

In these calculations, FST2 represents the number of all false state transitions to state 2, FST3 represents the number of all false state transitions to state 3, and TS1 is the number of all state 1 test situations.

The tested system receives a low score for a test scenario when the CIB system inappropriately transitions from state 1 to state 2 or state 3 (e.g.: false positive events that incorrectly activate a warning or braking). If the CIB system does not give any action while in a safe situation (e.g.: true negative events that correctly do not activate a warning or braking), it receives the highest score. The best possible score for each of SSIa and SSIb is 100 and the worst possible score is 0.

It should be noted that the vehicles should be compared within defined sets of test situations. To objectively compare the performance of all CIB systems, we choose the following list of unambiguous test conditions (see Table 1) to test the performance of the vehicle in state 1. In this table, Vt is the speed of the test vehicle, Vr is the speed of the reference object, Do is the distance to start testing the CIB system, and various “non-threatening objects” will be used for different sensor technologies. In this example, radar-based systems are considered; for other sensor technologies, a different set of non-threatening objects would be assigned. SSI does consider false positive and true negative cases but does not consider false negative or true positive events. These later two cases are included in other measurement scores to be described later.

### Table 1. Set of test scenarios for scoring the CIB system in state 1.

<table>
<thead>
<tr>
<th>Scenario Descriptions</th>
<th>Path Types</th>
<th>Test Conditions (5 test runs for each case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 Test vehicle approaching a non-threatening reference object.</td>
<td>Straight Curve Left (125m radius) Curve Right (125m radius)</td>
<td>(Vt km/h, Vr km/h, Do m, reference object type)= (16, 0, 50, manhole cover), (32, 0, 50, manhole cover), (48, 0, 50, manhole cover), (16, 0, 50, corner reflector), (32, 0, 50, corner reflector), (48, 0, 50, corner reflector)</td>
</tr>
<tr>
<td>1.2 Test vehicle passing on the left of a moving reference object.</td>
<td>Straight Curve Left (125m radius) Curve Right (125m radius)</td>
<td>(Vt km/h, Vr km/h, Do m, Yoffset m)= (32,16, 50, 0.5), (48, 16, 50, 0.5), (64, 32, 50, 0.5), (32,16, 50, 0.25), (48, 16, 50, 0.25), (64, 32, 50, 0.25)</td>
</tr>
<tr>
<td>1.2 Test vehicle passing on the right of a moving reference object.</td>
<td>Straight Curve Left (125m radius) Curve Right (125m radius)</td>
<td>(Vt km/h, Vr km/h, Do m, Yoffset m)= (32,16, 50, 0.5), (48, 16, 50, 0.5), (64, 32, 50, 0.5), (32,16, 50, 0.25), (48, 16, 50, 0.25), (64, 32, 50, 0.25)</td>
</tr>
<tr>
<td>1.3 Test vehicle passing on the left of three stationary reference objects.</td>
<td>Straight Curve Left (125m radius) Curve Right (125m radius)</td>
<td>(Vt km/h, Vr km/h, Da car lengths, Do m, Yoffset m)= (16, 6, 50, 0.5), (32,6, 50, 0.5), (64, 32, 50, 0.25), (16, 6, 50, 0.5), (32,6, 50, 0.25), (64, 32, 50, 0.25)</td>
</tr>
</tbody>
</table>
1.3 B Test vehicle passing on the right of three stationary reference objects.

\[ \text{Straight Curve Left (125m radius)} \]
\[ (V_t \text{ km/h}, D_a \text{ car lengths}, D_o \text{ m}, Y_{offset} \text{ m}) = (16, 6, 50, 0.5), (32, 6, 50, 0.5), (64, 6, 50, 0.25), (32, 6, 50, 0.25), (64, 6, 50, 0.25) \]

1.4 A Test vehicle evasively maneuvers into the left lane from behind the moving reference object and proceeds to pass the moving reference object.

\[ \text{Straight Curve Left (125m radius)} \]
\[ (V_t \text{ km/h}, V_r \text{ km/h}, D_m \text{ m}) = (32, 0, 27), (48, 0, 27), (64, 0, 27), (48, 20, 27), (64, 20, 27), (80, 20, 27), (32, 0, 18), (48, 0, 18), (64, 0, 18), (48, 20, 18), (64, 20, 18), (80, 20, 18) \]

1.4 B Test vehicle evasively maneuvers into the right lane from behind the moving reference object and proceeds to pass the moving reference object.

\[ \text{Straight Curve Left (125m radius)} \]
\[ (V_t \text{ km/h}, V_r \text{ km/h}, D_m \text{ m}) = (32, 0, 27), (48, 0, 27), (64, 0, 27), (48, 20, 27), (64, 20, 27), (80, 20, 27), (32, 0, 18), (48, 0, 18), (64, 0, 18), (48, 20, 18), (64, 20, 18), (80, 20, 18) \]

B. State 2 Performance Measurements

The performance score of the CIB system in state 2 (SS2) can be measured by noting when the vehicle appropriately provides warning signals when there is a hazardous condition in front of the test vehicle (true positive action). This measure should not include situations wherein the vehicle provides warning signals when there is not a hazardous condition (false positive action). Those conditions are already included in SS1. There are variations within the performance characteristics of different CIB systems. A more sensitive CIB system may provide an earlier warning signal to the driver, but may be more likely to provide false warning signals. The appropriate level of active safety system sensitivity may be subjective. In this study all measurements attempt to objectively measure the performance. A set of unambiguous situations for warning generating conditions are defined (see Table 2). The performance measurement score for state 2 is defined as

\[ SS2 = (AWS/TS2) \times 100 \]

In this calculation, \( AWS \) is the number of appropriate warning signals, and \( TS2 \) is the number of all state 2 test situations. Therefore, SS2 includes both true positive and false negative cases. The best SS2 score is 100 and worst SS2 score is 0.

The details of these test scenarios are listed in the following table. Since it is subjective to determine if and when a warning signal to the driver should be generated, we use the following criteria to make the state 2 evaluation unambiguous: A warning signal should occur with no less than 2 seconds time-to-collision for the system to be considered in state 2.

Table 2. Set of test scenarios for scoring the CIB system in states 2 and 3.

<table>
<thead>
<tr>
<th>Scenario Descriptions</th>
<th>Path Types</th>
<th>Test Conditions (5 test runs for each case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Test vehicle approaches a stationary reference object vehicle from behind.</td>
<td>Straight Curve Left (125m radius)</td>
<td>(V_t \text{ km/h}, V_r \text{ km/h}, D_o \text{ m}) = (16, 0, 50); (32, 0, 50); (48, 0, 50)</td>
</tr>
<tr>
<td>2.2 Test vehicle approaches a moving reference object vehicle from behind.</td>
<td>Straight Curve Left (125m radius)</td>
<td>(V_t \text{ km/h}, V_r \text{ km/h}, D_o \text{ m}) = (48, 16, 50); (64, 16, 50); (64, 32, 50)</td>
</tr>
<tr>
<td>2.3 Test vehicle follows the moving reference object and the reference object decelerates.</td>
<td>Straight Curve Left (125m radius)</td>
<td>(V_t \text{ km/h}, V_r \text{ km/h}, A_r \text{ g}, D_o \text{ m}) = (32, 32, -0.3, 9.), (32, 32, -0.3, 18), (32, 32, -0.6, 9), (32, 32, -0.6, 18)</td>
</tr>
</tbody>
</table>
C. State 3 Performance Measurements

State 3 represents the situation wherein a potentially hazardous condition is detected and a collision is likely to occur because the dynamics of the test vehicle and reference object do not allow sufficient time for the average driver to react and slow the vehicle sufficiently. In this state, the CIB system should automatically activate the brakes. The performance measurement score, SS3, is defined as the percentage reduction of the kinetic energy of the test vehicle as

$$SS3 \text{=} \%KER \text{=} 100\% \times \frac{[v_t(t_f)^2 - v_t(t_i)^2]}{[v_t(t_f)^2 - v_r(t_f)^2]} \quad (6)$$

where

- $v_t(t)$ is the velocity of the test vehicle at time $t$;
- $v_r(t)$ is the velocity of the reference object at time $t$;
- $p_t(t)$ is the position of the reference object at time $t$;
- $p_r(t)$ is the position of the test vehicle at time $t$;
- $t_i$ is the time when (i) $v_t(t_i) - v_r(t_i) = 0$ (e.g.: no collision event), or (ii) $p_t(t_i) - p_r(t_i) = 0$ (e.g.: collision event);
- $t_f$ is the time when the test vehicle begins autonomous braking (if the test vehicle does not brake prior to collision with the reference object, $t_i = t_f$);
- $[m_r v_r(t_i)^2 - m_r v_r(t_f)^2]$ is the total kinetic energy reduction during the autonomous braking;
- $[m_t v_t(t_i)^2 - m_t v_t(t_f)^2]$ is the autonomous braking energy reduction necessary to avoid a collision if the reference object’s kinetic energy were to remain constant during the test vehicle autonomous braking;
- $[m_r v_r(t_i)^2 - m_r v_r(t_f)^2]$ is the kinetic energy change of the reference object during the period of test vehicle autonomous braking.

The terms in the above equation are analyzed as follows:

- The numerator of the equation $[m_r v_r(t_i)^2 - m_r v_r(t_f)^2]$ is always greater than 0 because $v_t(t_i) > v_r(t_i)$.
- $[m_t v_t(t_i)^2 - m_t v_t(t_f)^2]$ is always greater than 0 because $v_t(t_i) > v_r(t_f)$ for all conditions where the test vehicle can operate in state 3.
- If $[m_r v_r(t_i)^2 - m_r v_r(t_f)^2] > 0$, then $v_t(t_i) > v_r(t_f)$. This means that the reference vehicle is decelerating during the period of test vehicle autonomous braking, and therefore the reference vehicle increases the kinetic energy reduction necessary during the autonomous braking. If $[m_r v_r(t_i)^2 - m_r v_r(t_f)^2] < 0$, then $v_t(t_i) < v_r(t_f)$ and the reference vehicle is accelerating during the period of test vehicle autonomous braking. In this situation, the kinetic energy reduction necessary to avoid a potential collision is decreased during the period of test vehicle autonomous braking. Therefore, the behavior of the reference vehicle affects the test vehicle autonomous braking decision and the value of $t_f$.

Since the autonomous braking performance measurement does not attempt to address to collision characteristics of disparate vehicles, we can assume that $m_r = m_t$. Therefore, equation (5) can be simplified as

$$SS3 \text{=} \%KER \text{=} 100\% \times \frac{[v_t(t_f)^2 - v_t(t_i)^2]}{[v_t(t_f)^2 - v_r(t_f)^2]} \quad (6)$$

SS3 handles both the true positive cases (correctly activated brakes) and false negative (incorrectly not activated brakes) cases. Theoretically, the denominator of equation (6) can range from $-\infty$ to $+\infty$. Therefore, %KER also ranges from $-\infty$ to $+\infty$. The most desirable %KER for an autonomous braking operation is 100% because this represents a situation where the potential collision is avoided without exposing the
occupants to excessive braking and the increased potential of a rear-end collision with a following vehicle. Depending upon the value of %KER, four possible outcomes can be described:

- $0\% \leq \%\text{KER} < 100\%$ -- This indicates that the test vehicle collided with the reference object with a reduced percentage of kinetic energy.
- $\%\text{KER} = 100\%$ -- This indicates that the test vehicle autonomous braking system stopped the vehicle at the precise rate necessary to narrowly avoid a collision with the reference object.
- $100\% < \%\text{KER} < +\infty\%$ -- This indicates that the autonomous braking system has applied the brakes more aggressively than necessary to avoid the collision.
- $-\infty\% < \%\text{KER} < 0\%$ -- This occurs when the denominator of the equation is less than 0 and therefore $v_f(t_f) < v_i(t_i)$. In this situation, the test vehicle cannot collide with the reference object before $t_f$ and the autonomous braking system did not need to be activated.

IV. DISCUSSIONS

The scenarios for the performance measurement of state 3 are more challenging for the CIB system. Some of these tests result in collisions with the reference object. This is especially more common when the test vehicle initial velocity is relatively high. Under these circumstances, the test vehicle CIB system must sense, classify, and react properly to reference objects which are much farther ahead of the test vehicle. For this reason, the performance of the systems will typically degrade with increased initial test vehicle speeds. However, it should be noted that the kinetic energy differential between the test vehicle and the reference object was reduced even in situations in which collisions occurred. Therefore, benefits would be realized (reduction in damage and injuries) even in these collision conditions. It is possible that additional, more difficult testing scenarios can be developed, such that the performance differences among different vehicles and the future system improvements can be more readily identified.

In some situations (such as slippery road surfaces), certain collisions can be unavoidable due to sliding of the vehicle or reduction in effective braking forces as controlled by the anti-lock braking system. This condition would inappropriately degrade the performance measurements of the CIB system as compared to testing performed on surfaces that were not slippery. For this reason, we tested our systems on consistent road surface conditions for each scenario. The braking performance can also be slightly affected by variations from one run to the next in the available braking that can be achieved with the current brake, tire, and road conditions. These variations in performance should be relatively minor, but it should be noted that this limitation in our performance measurements is recognized.

V. CONCLUSIONS

This paper describes a performance matrix for the evaluation of the CIB systems in various passenger vehicles. The performance matrix is defined in three categories according to the CIB operation states. The performance matrix covers the most common true positive, true negative, false positive and false negative test scenarios. The performance matrix has been applied to the CIB road testing results of a 2011 vehicle. Testing of other vehicles of different makes and models is ongoing.

The next step is to formulate a star rating mechanism based on the three CIB scoring systems that could be used by consumers to compare CIB systems objectively as implemented on different vehicle platforms.

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