

Tradeoffs in the Evaluation of Light Vehicle Pre-Collision Systems

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ABSTRACT

Pre-collision systems (PCS) use forward-looking sensors to detect the location and motion of vehicles ahead and provide a sequence of actions to help the driver either avoid striking the rear-end of another vehicle or mitigate the severity of the crash. The actions include driver alerts, amplification of driver braking as distance decreases (dynamic brake support, DBS), and automatic braking if the driver has not acted or has not acted sufficiently (crash imminent braking, CIB).

Recent efforts by various organizations have sought to define PCS objective test procedures and test equipment in support of consumer information programs and potential certification. This paper presents results and insights from conducting DBS and CIB tests on two production vehicles sold in the US. Eleven scenarios are used to assess the systems' performance. The two systems' performance shows that commercial systems can be quite different. Also demonstrated is the experience with test equipment, including a towable target that has been designed for resiliency and radar signature, a braking robot, and bumper guard.

While improvements continue in evaluation procedures, the community may still be a distance away from an ability to test these systems with realistic surrogate targets in speed conditions similar to those that lead to serious injury and fatalities. Recommendations are offered to help improve PCS evaluation.

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INTRODUCTION

Rear-end crashes are the most common crash type in the US. Between 2003 and 2008, the average number of US police-reported, rear-end crashes involving a light vehicle striking the rear of another vehicle in the US was 855,000 [1]. (Light vehicles encompass passenger vehicles, minivans, SUVs, and light trucks.) Pre-collision systems (PCS) use forward-looking sensors to detect the location and motion of vehicles ahead, in order to help drivers avoid or mitigate the severity of an imminent crash with a vehicle ahead. The PCS features of interest in this paper include: driver alert, dynamic brake support (DBS) that amplifies driver braking when sensing indicates a potential crash ahead, and crash-imminent braking (CIB) which is automatic braking to avoid the crash or reduce its severity. (CIB is often called autonomous emergency braking (AEB) in Europe.)

EVALUATION APPROACH

Objective testing of active safety systems is conducted for many reasons including verification during development, OEM benchmarking to compare supplier offerings, standards testing, consumer information programs, and potentially certification. The most common approach is to equip a vehicle with the technology and conduct scripted maneuvers on the test track to expose the system to situations intended to represent a targeted set of real-world crashes.

For PCS, the role of test procedures and equipment poses unique challenges. First, while the driver alert element of PCS may prompt a driver to avoid a pending collision, it is necessary in testing to allow the conflict to develop further. The DBS and CIB elements of PCS often do not avoid a crash alone, but rather mitigate its severity. Therefore the PCS vehicle must be allowed to repeatedly approach something closely resembling a vehicle, and to strike that object at significant relative speeds. A "surrogate target" is required, which is an object that resembles a vehicle (from the sensors' perspective) and yet can be struck without

endangering the safety of test engineers or the integrity of the PCS vehicle. Ideally, dozens if not hundreds of trials are performed while testing the system in various test scenarios.

A second challenge of PCS evaluation is that the active braking function of PCS occurs over very short time periods. Typically these events begin at less than 1.5 sec of time to collision (TTC), defined as distance divided by relative closing speed. The braking interventions may last for less than a second, and yet reach over 0.8 g. Thus instrumentation must be very accurate and run at high speeds, with accurate synchronization in logging. This short duration and the fact that PCS does not always avoid a crash is due to the typical design approach of acting only after it is very unlikely that the driver intends to move laterally around the vehicle ahead. The consequences of a false action of braking are potentially very high.

Third, a challenge of PCS is that the target must appear to its sensors in the same way as a real vehicle. Because critical decisions are made at short distances, with such high potential consequences, the PCS may require a sustained high confidence in its interpretation of forward-looking sensor data because the potential consequence of a false activation of braking is so undesirable. This has implications for surrogate target design. Together these are three of the major challenges of evaluating PCS.

The next sections describe the modification of test procedures based on pilot testing, the test equipment used, the choice of braking profiles to simulate drivers who sometimes apply braking insufficient to avoid crashes, and finally the test results.

OVERVIEW OF PROCEDURES AND TESTING

Test Scenarios: Crash-Imminent Cases

A previous analysis of General Estimates System (GES) and Crashworthiness Data System (CDS) data by our research team indicated that 80 % of the light vehicle-striking crashes can be associated with a set of 10 test scenarios [1]. The test scenarios were chosen to address as many of the most common severe-injury and fatal crashes as possible, and to use 80th percentile speeds for the two vehicles. In that paper, the test scenarios were defined and the description of a new surrogate target that is towed was described. Other test procedures, such as a draft set of tests from the US National Highway Traffic Safety Administration (NHTSA) [2], [3] have been published as well as ones from CAMP [4], IIHS [9] and from several European projects [10]. Many of those tests may be more focused on pass/fail outcomes, while our view is that tests that discriminate more finely between systems are valuable. Therefore most tests are designed to result in impacts with PCS, so that performance differences are clearer.

Since then, extensive testing has been done by the authors of this paper with two factory-installed, commercially-available PCS systems. Such testing involves a PCS-equipped "subject

vehicle" (SV) performing a scripted maneuver in order to approach a "principal other vehicle" (POV) in a very specific manner (see [Figure 1](#)). This testing experience led to revisions in the test procedures from [1] with these changes:

- Stopped-POV scenarios are now conducted at 25 mph and not at 35 mph as suggested in [1]. This is to protect the equipment, especially if the test equipment or the driver fails to engage CIB or DBS (as discussed later). A 25 mph impact is allowable, but 30+ mph will often damage the SV and perhaps the target.
- Slower-POV scenarios are unchanged.
- Decelerating-POV scenarios are run with smaller initial headways and with less POV deceleration. This also reduces the potential impact speeds to not much more than 20 mph, in the case of CIB or DBS not triggering, due to test execution issues.
- The stopped-POV test on a curve was discarded because curvature is not an issue at the short ranges where DBS and CIB act.

The final set of crash-imminent procedures is in [Table 1](#). For each scenario, a CIB trial set is performed with no "driver" braking in the SV so that only PCS prevents the vehicle from simply running into the POV. A second trial set is performed for DBS by emulating SV driver braking with automatic braking application via a "robot." The procedures developed in this project call for the braking robot to begin ramping up deceleration beginning at TTC of two seconds and reaching 0.15 g. This is to simulate inadequate driver braking which is known to be a contributor to rear-end crashes as found from analysis of CDS and event data recorder (EDR) data [5], [6]. Another reason for the low 0.15 g level is to help finesse the tradeoffs between matching actual severe-injury crash kinematics and also ensuring that even if the robot does not activate, the impact is safe for drivers and equipment incurs only minor or negligible damage. Therefore we require that if the robot and accompanying DBS do not activate in a trial, the impact is less than 25 mph (for moving targets) or 30 mph (stationary targets). There is value in re-visiting these tradeoffs in test scenario parameter choices.

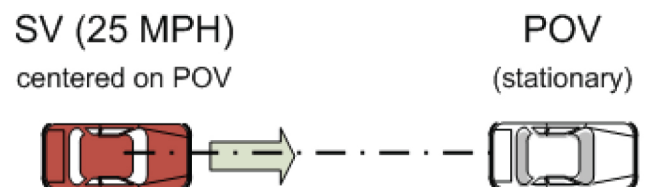


Figure 1. Subject Vehicle (SV) Approaches Principal Other Vehicle (POV)

Two to four trials were conducted for each type (CIB and DBS). In some cases, trials of tests the draft NHTSA documents [2], [3] were also performed. These tests are shown in [Table 1](#). For draft NHTSA tests, the DBS robot is to begin at TTC of 1.0 or

1.1 sec and reach 0.3 g. Eighty-two trials with subject vehicle #1 (SV1) are reported (50 CIB and 32 DBS), along with 54 subject vehicle #2 (SV2) trials (28 CIB and 26 DBS).

Table 1. Crash-imminent test scenarios

Test Scenario	SV (mph)	POV (mph)	Initial headway (sec)	POV (g)	SV (g)
Fixed stopped POV	25	0	--	0	0
Fixed stopped POV, lateral offset	25	0	--	0	0
Fixed stopped POV, decelerating SV	30	0	--	0	0.15
Slower POV	50	25	--	0	0
Slower POV	35	10	--	0	0
Slower POV	25	5	--	0	0
Decelerating POV	30	30	1.0	0.3	0
Decelerating POV	30	30	1.6	0.15	0
Decelerating POV, lateral offset	30	30	1.6	0.15	0
NHTSA draft tests					
Fixed stopped POV	25	0	--	0	0
Slower POV	45	20	--	0	0
Slower POV	25	10	--	0	0

Test Scenarios: False-Positive Cases

A set of four false-positive scenarios were also conducted, summarized in Table 2. For the last scenario in Table 2, the SV remains at constant speed and does not change lanes until it goes around a cone that is 23.5 meters from the rear of the POV, and aligned laterally with the edge of the POV.

The false-positive scenarios are based on engineering judgment and not upon empirical data from actual PCS systems. PCS false positives may be related to misperceptions of same-direction traffic, roadside objects, ghost targets associated with roadway features such as metal features on the surface (e.g., manhole covers or grates on bridges), or more. The scenarios here address PCS vehicles passing adjacent-lane vehicles because this is a very common occurrence in driving. False positives that may occur due to encountering rare and very specific roadway features are very hard to propose as useful tests. For those rare cases, the false positive is likely to be specific to a particular system (sensor and processing algorithms) as well as the particular vehicle motion and environment, making test design very challenging. This research team did not have empirical data to identify meaningful situations of this type, so that proposing such tests did not appear to be a contribution to the field.

These tests are only run for CIB cases (i.e., no SV driver braking is used) with the assumption that we are testing the classification of targets as being in path or not. Therefore results for CIB and DBS are expected to be identical.

Table 2. False-Positive Tests

Test	SV speed (mph)	POV speed (mph)
SV passes between two slower POVs	50	25
SV passes between two stopped POVs	50	0
SV passes stopped POV in adjacent lane	35	0
SV changes lanes to avoid stopped POV ahead	35	0

Comments on Scenario Kinematic Parameters

Consider four issues of kinematics: travel speeds during tests, lead vehicle decelerations, lateral offsets between the lead vehicle and the following PCS-equipped vehicle, and the case of the striking vehicle already braking mildly during approach to another vehicle.

Table 11 below shows the mean and 80th percentile speeds and speed differences for injury and fatal crashes with light vehicles striking other vehicles. Testing at the 80th percentile would ensure that most crashes could be addressed by a test. The table shows the average and 80th percentile travel speeds from GES data before the first critical event (80th percentile is in parentheses). We note that GES travel speed is often missing and may be inaccurate at times, e.g., some police may cite posted speed limit as a default. The rightmost column in the table shows the PCS tests performed that have the highest speeds. This table shows that the tested speeds are close to the mean travel speeds in GES, although 80th percentile speeds are even higher.

Table 3. Travel speeds and speed differences for injury and fatal crashes. Values are mean (and 80th percentile in parentheses) (mph)

Crash type	Travel speeds before first critical event: GES crash data			Tested: SV / POV / difference
	SV speed	POV speed	Difference	
LV stopped	23.9 (35)	0.1 (0)	23.7 (35)	25 / 0 / 25
LV slower	42 (65)	26.9 (50)	15.4 (25)	50 / 25 / 25
LV decel'ing	33.7 (45)	16.7 (30)	17 (30)	30 / 30 / 0

Second, it is noted that approximately 22% of crashes involving light vehicles striking other vehicles occur with the lead vehicle decelerating [1]. This is likely a low estimate because it can be assumed that during many stopped vehicle crashes the PCS

could have observed the lead vehicle still moving just before it came to rest. Therefore testing decelerating lead vehicle scenarios is important and those tests have been included in the test procedures described here. The lead vehicle decelerations include 0.15g and 0.30g which are within the range of common decelerations. Since we wish to avoid impacts which are more than about 20-25 mph, and we do not want short headways which might prevent the SV robot from completing its ramp up before DBS, we select these moderate lead vehicle values.

Third, a review of CDS data shows that there is often less than full overlap between bumpers in rear-end crashes [1]. Approximately one in three crashes involves less than 65% of the bumper on the striking car contacting the struck vehicle. This is significant because oftentimes PCS sensors are mounted on the center of the vehicle, and as there is less perceived target ahead, testing the system's ability to maintain protection is useful.

Fourth, the GES analysis points to an estimate of 10% of the crashes involve the following vehicle already slowing before the first critical event occurs. An example of this may be a driver who is braking mildly turns to look away just before the lead vehicle applies its brakes. The approach taken to address these four kinematic challenges is to include these situations in the PCS procedures.

PCS VEHICLES AND TEST FACILITIES

Testing was done using two production vehicles sold in the US by different manufacturers. Because this paper addresses evaluation procedures, and because there were significant difficulties with accurately executing some of the tests, let us call them SV1 and SV2 but not reveal the make and model. The testing did not use signals from the vehicles nor was proprietary information from the manufacturers used in the design of tests or in the analysis. The tests were done at two locations: some early trials were done at a drag strip in Milan, Michigan, but almost all trials are from a full-scale test track, the FT Techno Fowlerville (Michigan) Proving Ground. The test procedures, test equipment, and conduct and analysis of data were done by UMTRI team members as part of a Toyota Collaborative Safety Research Center project. The sponsor of this work, Toyota Collaborative Safety Research Center, did not participate in the selection of test condition parameters, nor were they involved in testing or analysis.

Surrogate Target

During the project, the rear ends of 25 vehicles were scanned with instrumentation-grade radar by the Michigan Tech Research Institute (MTRI), and the results were used by MTRI to propose a small set of radar-scattering elements to be located strategically within a radar-neutral target [1], [7]. The target itself is made of various foam materials selected for energy absorption, stiffness, and radar properties [1]. The

target is placed on the track for stopped-POV tests and is towed behind a towing vehicle for testing moving-POV scenarios. The surrogate target is shown in Figure 2 below.

Reference [1] presented the design of the target and [7] addressed how radar signature was designed to mimic actual vehicle signatures. The uniqueness of this target is its ability to (a) be radar- and vision-representative of actual vehicles, (b) be impactable at high relative speeds and with lateral-offset impacts, and (c) be low-cost and practical to use in relatively high closing speed impacts (20+ mph with the target moving and 25 mph with the target at rest). Disadvantages are described in a later section, and relate primarily to lateral drifting of the target since it is towed with a rope.

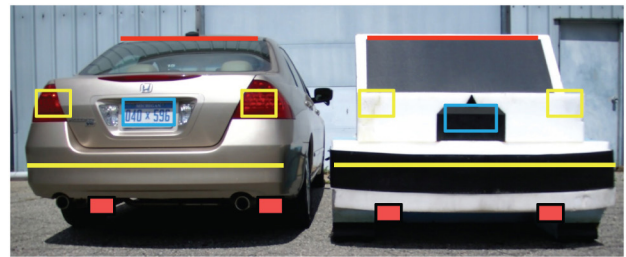


Figure 2. Surrogate Target with Radar Scattering Elements to Match Actual Vehicle Radar Signatures

Simulating Driver Braking

The DBS trials require exposing the system to simulated SV driver braking. This is done with a braking robot designed and built by UMTRI for this effort. The robot is a system to mechanically apply the brake pedal to provide a given profile of vehicle deceleration (Figure 3). A linear actuator is attached to the brake pedal mechanism. A servo controller drives the actuator first using a pre-set stroke rate to simulate initial application and then the loop is closed on deceleration, using an accelerometer signal and, of course, a signal which triggers the closing of this loop. Please note that the robot will stop active control once the deceleration comes within a certain error bound of the target deceleration, or once deceleration exceeds that value. The trigger to begin closing the loop signal can come from a vision-based subsystem that estimates TTC, or from a manual button. The robot design allows the test driver to freely and immediately depress the pedal further.

The choice of using deceleration for closing the loop is not obvious - e.g., triggering based on pedal application rate or pedal force might also be considered. Deceleration was selected because, unlike braking force or pedal displacement rate, deceleration is independent of the specific vehicle model and so, without PCS, the non-PCS impact speed would be the same across all vehicles. Closing the loop on deceleration also simplifies testing since variation due to temperature, tires, and system heat build-up are avoided.

The initial stroke rate is 7.5 cm/s for the first 1.5 cm of travel and then the loop closes on deceleration. The test scenarios in this paper are designed so that simulated SV driver braking