ADVANCED SURROGATE TARGET DEVELOPMENT FOR EVALUATING PRE-COLLISION SYSTEMS

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ABSTRACT

This paper presents the requirements, design, and resulting performance of a new surrogate target for evaluating pre-collision systems (PCS) that include crash imminent braking and dynamic brake support. The design addresses several criteria for rear-end crash scenarios, including three critical and conflicting criteria: enabling high relative impact speed, maintaining a radar signature that is representative of real vehicles, and minimizing expenses and complexity of fabrication and usage. Test scenarios for evaluating PCS are developed using analyses of US crash data sets, including General Estimates Systems and the Crashworthiness Data System (including its electronic data recording data). Test procedures were developed, leveraging previous work in this area. Surrogate target design requirements were developed, notably new requirements for "impactability," or the ability to be struck repeatedly without damage or safety risks, and 77 GHz radar scattering characteristics. Robustness to higher impact speeds allow testing in severe crash scenarios. Radar characteristics were addressed using a new data set generated using instrumentation-grade radar to scan the rear ends of 25 actual vehicles at numerous angles. The radar scan data was used to create a recommended set of scattering elements to be applied to a radar-neutral structure. A novel approach to the structure was used, emphasizing low cost, weight, resilience, and, safety in higher speed impacts. This approach is intended to present a radar-representative vehicle target to the PCS under test, while allowing the target to be fabricated easily and inexpensively. The target is intended for PCS development as well as formal testing. Work continues to refine the target's signature for vision- and LIDAR-based systems, and an instrumentation system is being fitted to test PCS vehicles in extended use. This work is significant for its contribution to surrogate target work in the emerging area of PCS with crash-imminent braking and dynamic brake support systems. Higher impact speeds and improved radar signatures will improve the correlation between pre-crash system performance in the real world and the outcome of performance testing on the track. Simpler and lower-cost targets allow wider use and perhaps better PCS designs.

INTRODUCTION

Rear-end crashes are the most common crash type in the US. An average of 855,000 rear-end crashes occurred annually in the US between 2003 and 2008, when considering crashes in which a light vehicle struck the rear-end of another motor vehicle, using the General Estimates System (GES) data set. Pre-collision systems are safety systems that use forward-looking remote sensing 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 forward collision warning (FCW), dynamic brake support (DBS), and crash-imminent braking (CIB). When a forward crash is perceived to be imminent, and the driver is braking but not hard enough to avoid impact, DBS automatically provides additional braking to lessen or perhaps avoid the impact. CIB is often called advanced emergency braking (AEB) in Europe, and automatically applies hard braking in the last moments before a crash in order to reduce the severity of, and in some instances, avoid the crash.

The US New Car Assessment Program (NCAP) defines FCW using a set of objective tests in which alerts must be issued no later than a given threshold for scenarios that include the equipped vehicle approaching a stopped vehicle, a slower but moving vehicle, and a decelerating vehicle. US NCAP is considering adding both DBS and CIB to the set of crash avoidance technologies that it addresses, and has released a set of draft test procedures and a strikeable surrogate target. (A surrogate target is a device which is used in objective testing to represent a vehicle, but can be struck by the equipped vehicle without significant damage to the striking vehicle.) There have also been a series of US Department of Transportation (DOT) and European Union (EU) funded projects, as well as privately funded projects.

The question of surrogate target design has been a major theme in the work on evaluation approaches to DBS and CIB. Such targets need to meet several conflicting criteria, including the need for appearing to PCS sensors as actual vehicle appear; the need to be repeatably and safely struck at significant impact speeds, and to be affordable and usable. Most published work has focused on NCAP-like evaluation work, and not focused much on the heavy use required for automaker and supplier development and benchmarking work.

This paper describes a surrogate target design developed jointly by the University of Michigan Transportation Research Institute (UMTRI) and the Michigan Tech Research Institute (MTRI), in conjunction with the Toyota Collaborative Safety Research Center (CSRC). A major goal was that the surrogate target would appear to automative radars and other sensors as a real automobile would appear; another goal was that the system would be impactable at high relative speeds that are seen in actual US crashes, and that the system is usable as an everyday working system by everyday engineers.

TEST SCENARIOS

The surrogate target design must support test scenarios that are to be executed on the test track. Test scenarios were developed based on analysis of the GES as well as the US Crashworthiness Data System (CDES) were conducted, including examination of Event Data Recorder (EDR) data that is available in CDS for those crashes in which drivers approve the sharing of EDR data. GES 2003-2008 data were used, with only light vehicle striking cases considered, with striking vehicle model year required to be 1998 or newer. The focus was on crashes with injuries and fatalaties.

Existing analyses of US rear-end crashes were reviewed, and further analyses of GES data and CDS were conducted. Of particular interest were the pre-crash scenarios, and these were examined using the pre-crash maneuver variables. The pre-crash maneuvers for the vehicle pairs associated with the crash (or first impact, for crashes with more than two vehicles) are shown in Table 1 (only the top ten pairs are shown).

When all pre-crash maneuver pairs are considered and aggregated, the percent of these rear-end crashes are shown in Table 2 as a function of the types of motions that precede the crash sequence. This table shows that rear-end crashes are usually simple in their kinematics: Approximately 77% involve the striking vehicle simply remaining in its travel lane, without maneuvering laterally or changing speed prior to the initiation of the crash sequence. Only 2.6% of these crashes involve any lateral maneuver by the striking vehicle. The struck vehicle is maneuvering laterally only 2.6% of the time as well. Thus these crashes are typically single lane crashes. Furthermore, crashes in which the equipped subject vehicle (SV) is “starting” are typically low-speed crashes, with low chance of injury, and these are not of particular interest for the evaluation that is discussed here. Turning SV cases are likewise not of high interest in evaluation because of the substantial challenge of using vehicle-based sensors to confidently detect threats and predict paths, while yawing at large angles and rates.

Therefore a set of test scenarios are selected which represent 80.4% of the rear-end crashes involving a model year 1998 or later light vehicle striking another vehicle. The speeds of these events are based on the GES travel speed variables, which are associated with the speed before the crash’s precipitating event occurred. These speeds are shown in Table 3. GES data shows that the 80th percentile for the difference in travel speeds between the two vehicles, for injury and fatal crashes, is between 25 and 35 mph, depending on the scenario. (Here, travel speed is the speed prior to the event leading to the crash). These numbers are starting points for determining the initial conditions for objective test speeds and closing speeds. The scenarios that are proposed are shown in Table 4.

Notice these scenarios include cases of “lateral offset.” These are tests in which the SV approaches the target with an offset, so that the center of the SV front bumper strikes the rear bumper off-center, toward one edge at a specified distance. This is

because the CDS data shows that the overlap between the bumpers at impact is less than 50% in about one in three crashes. Another interesting finding from the data (Table 1) is that approximately 10% of crashes are associated with SVs that are decelerating before the precipitating event happens – that is, that although the SV is slowing, it is not slowing enough. At the time of these analyses, the EDR data included only 172 crashes, with EDR data from only one of the vehicles in all but six crashes.

Table1. Rank of rear-end striking scenarios in GES, as described by pre-crash maneuvers

Rank	Pre-crash maneuver		Pct %	Cumul. Pct %
	Subject Vehicle	Struck vehicle		
1	Going Straight	Stopped in lane	41.7	41.7
2	Going Straight	Decel in lane	19.2	60.9
3	Going Straight	Going Straight	10.9	71.8
4	Decelerating in lane	Stopped in lane	7.4	79.2
5	Starting in lane	Stopped in lane	5.7	84.9
6	Decelerating in lane	Decel in lane	2.5	87.4
7	Turning right	Stopped in lane	1.4	88.8
8	Negotiating a curve	Stopped in lane	1.4	90.1
9	Going Straight	Turning right	0.8	91
10	Changing lanes	Stopped in lane	0.7	91.7

Table 2. Rear-end striking pre-crash maneuvers

Pre-crash maneuvers	Stopped	Decel/ accel	Lane-keeping	Turning	Start	Change lanes	Total
Lane-keeping	43.3%	19.7%	11.1%	1.3%	0.7%	0.7%	76.8%
Decel/ accel	7.7%	2.6%					10.2%
Starting	5.7%				0.6%		6.4%
Turning	1.6%						1.6%
Changing lanes	1.0%						1.0%
Total	59.2%	22.3%	11.1%	1.3%	1.3%	0.7%	95.9%

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

Crash type	SV speed	LV speed	Difference
LV stopped	23.9 (35)	0.1 (0)	23.7 (35)
LV slower	42 (65)	26.9 (50)	15.4 (25)
LV decel'ing	33.7 (45)	16.7 (30)	17 (30)
LV cut-in	46 (60)	33.6 (55)	12.8 (25)

Table 4. Crash-imminent test scenarios

Test Scenario	SV (mph)	POV (mph)	Initial headway (sec)	POV (g)	SV (g)
Fixed stopped POV	35	0	n/a	0	0
Fixed stopped POV, lateral offset	35	0	n/a	0	0
Fixed stopped POV, decelerating SV	45	0	n/a	0	0.15
Fixed stopped POV, in curve	35	0	n/a	0	0
Slower POV	50	25	n/a	0	0
Slower POV	35	10	n/a	0	0
Slower POV	25	5	n/a	0	0
Decelerating POV	30	30	2	0.4	0
Decelerating POV	30	30	2	0.2	0
Decelerating POV, lateral offset	30	30	2	0.4	0

TARGET REQUIREMENTS

A set of requirements were developed for the surrogate target. They may be presented in six categories:

Impactability – for impacts from the rear (plus or minus 5 degrees), the target shall

- Be safe for impacts at relative speeds of 35 mph (stopped target) and 25 mph (moving target), possibly with minor damage that can be repaired within hours.
- Survive in good condition for 100 impacts of 15 to 20 mph relative speed.
- Be impactable while traveling 25 mph.

Speeds and decelerations – the target shall:

- Be capable of moving at 30 mph, with a tolerance of 0.5 mph,
- Be capable of decelerations of up to 0.5g, with a tolerance of 0.015g (averaging over 2.5 sec).

Low cost and ease of use. The target shall:

- Be reasonably-priced (less than $US 8000) to support widespread use
- Be suitable for use in both NCAP-level testing as well as development testing with a broader set of testing conditions.
- Be reasonably straightforward to repair and use in test track environments by experienced but not expert staff. After an impact, the target should be usable within a few minutes.

Reflectance – the target shall:

- Appear similar to real vehicles when measured using radar (24 and 77 GHz), as viewed from the rear (and up to 5 deg off-axis, to both the left and right). Soft-covered targets are considered to be unlike real vehicles due to the temporal fluctuations that exceed radar wavelengths.
- Have visual features so that it appears as a vehicle to a vision-based system.

Impacts with lateral offset - the target shall Be impactable when the striking vehicle bumper overlaps only 50% with the target (which occurs in one in three rear-end crashes).

Localization – the target shall support the ability to locate the target within 0.25 m longitudinally and 0.15 m laterally at the moment of impact.

Radar scattering requirements

More detail is warranted on the radar scattering issues. Within this project, Michigan Tech Research Institute used an instrumentation-grade radar at 90 to 98 GHz to scan the rear ends of 25 vehicles including sedans, wagons, SUVs, crossovers, hatchbacks, pickup trucks, and small and large vans. These scans were made from directly behind the vehicles, as well as 1.5 and 3.0 deg away from directly behind; at each of these three locations, scans were made at 0.0 and 1.5 deg elevation.

Analysis of the returns showed that the primary scattering elements of the vehicles were tail-lights, muffler/tailpipes, rear-suspension components (especially when they are visible), license plate shelters (often a convex area), and bumpers. Secondary elements include chassis supports, the joint of the roof and rear-window, side-view mirrors, roof racks, and even rear spoilers. Calibrated high-resolution range-profiles for a vehicle and the surrogate may be compared in Figures 2 and 3, respectively. The scattering characteristics of the surrogates was compared statistically to the vehicles under the same measurement conditions, and a scatterplot comparing real vehicle and surrogate target scattering model parameters is shown in Figure 3. Details of the scanning and the evaluation of the surrogate can be found in [2].

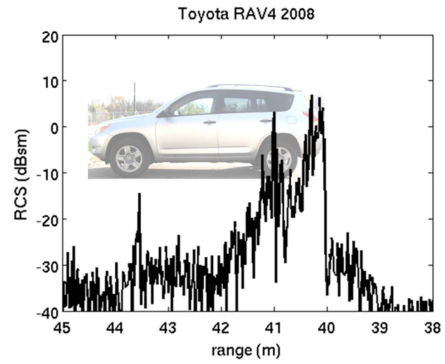

Figure 1. High-resolution, range-profile of one of the sampled vehicles, a 2008 Toyota RAV4.

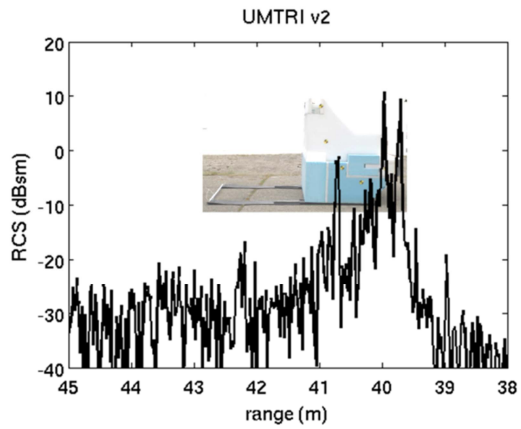

Figure 2. High-resolution, range-profile of the UMTRI surrogate target.

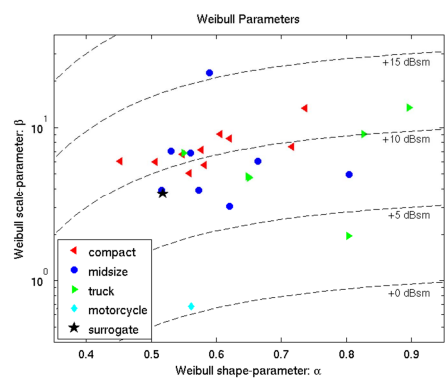

Figure 3. Scattering model parameter values: real vehicles and surrogate target

Table 5 shows a comparison of surrogate target concepts and their ability to support some of the key

requirements. Shaded cells show a problem for various systems, including the towed target concept.

Table 5. Design approaches and requirements

Target Type	Impactability	Speeds & Decels	Cost/Ease	Reflectance	Offsets	Localization
Towed Balloon car	✓	✓	✓	×	✓	O
Towed rail-guided	✓	O	O	✓	×	✓
Drive-over with shell	✓	✓	×	O	✓	✓
Gantry	✓	O	✓	O	✓	✓
Towed sled	✓	✓	✓	✓	✓	O
Go-cart	O	✓	✓	O	O	✓

Table 5 shows six types of surrogate targets that have been constructed and demonstrated for PCS evaluation, and *generically* whether they are clearly able to satisfy each requirement category (check mark); whether they cannot ("*X*"); or whether it is not clear and may depend on the situation ("O"). This table is intended to highlight the basic strengths and challenges that led the UMTRI-MTRI team to its selected approach. Table 5 represents the knowledge of the authors, based on publications as well as visits in 2011, and readers are aware that innovative developments continue and that the requirements in this paper may not be appropriate for all uses. For instance, NHTSA has published a draft set of test procedures as a potential consumer information aid for DBS and CIB, and the tests do not include lateral offsets or decelerating lead vehicles. The table shows that the towed, rail-guided approach they have shown recently would satisfy those needs, but that for testing with impacts at lateral offsets, that selection may present problems.

Balloon cars do not have appropriate radar reflections due to their shape, wind-driven fluctuations, and at least one model is semi-transparent to radar. The towed, rail-guided approach shown early by ADAC in Germany and also used recently by NHTSA provides many advantages, but is not friendly to lateral offset hits. The drive-over approach (e.g., Dynamic Research Inc.) is a very flexible system that addresses several crash types, but it is expensive and the upper "shell" must still be impactable and representative (which is possible). The popular approach of cantilevering a target sideways from a large pickup truck is a straightforward way to begin work and to localize the target very well. Sometimes a radar system will struggle to discriminate the target from the supports, however, and it requires sophisticated "flip up" or "release" mechanisms to allow sizable impacts that do not endanger the drivers, and it is challenging to allow significant target decelerations without triggering these mechanisms. BASt in Germany was one of the early users of a go-cart approach, which is ingenious for its simplicity and target maneuverability. However the challenge of offset impacts and the mass of a system that hosts onboard GPS and computing systems may preclude testing with impacts of 20 mph or more.

For our particular requirements set, we selected a towed sled approach, first suggested to our team by the NHTSA Vehicle Research Test Center staff during an earlier project.

TARGET DESIGN

The surrogate target design concept is a towed, low-weight and impactable target, which carries a discrete set of radar scattering elements that together present the same radar signatures as the real vehicles that were scanned (see Figure 3). The shape of the target, as viewed from the rear, emulates a sedan, with shapes that simulate a trunk, rear window, bumber, rear wheels, and an underbody section. The main body of the target is composed of three types of foam joined with hot glue. The foam includes a rigid polystyrene with moderately reflective radar scattering properties (blue in Figure 3). This provides rigidity and also masks the towing mechanisms from radar. Two types of polyethylene foam that are relatively transparent to radar and lightweight provide energy absorption and flexibility. A polyurethane sheet covers the bumper surface, giving toughness and a slippery reflective surface that mimics real bumpers.

From the radar analysis, a set of eight reflectors were recommended by the radar team: a 4 cm flat metal strip behind the bumper polyurethane covering; a 2 cm flat metal strip at the window-roof join; a license plate imbedded in a concave shelter, with a 3 cm trihedral reflector immediately above the shelter; 3cm trihedrals located at the two tail light locations, as well as two more to represent rear suspension elements. Details of these scatterers were revised based on a radar scanning of the target, in order to better match the parameters of the actual vehicles' scatterer model. The target is 32 Kg.

Figure 3. **Towable surrogate target.**

skids, so that for tests that simulate approaches toward a stationary vehicle, the target slides away easily after impacts. Impacts of 35 mph are safe and results in minor damage to the target; the bumper is detachable and can be replaced within a minute after such high impacts. Impacts of 15 to 20 mph can be repeatedly performed; a target that has seen more than 100 of such hits is still operating without significant deformation. The bumper foam compresses substantially during impact, such that the target springs away from the striking vehicle. Note that the striking vehicle does not need significant protection for testing. After well over 100 hits at speeds up to 35 mph, the team did have to replace a plastic grill on a 2011 Lexus GS350, but a thin plastic film was placed on the hood and bumper area, preventing abrasions.

For moving target tests, the low-friction skids are placed on a simple sled (Figure 4), and the target is towed by a vehicle using about 15 m of low-stretch rope (0.25%). The sled consists of two strips of very tough mining conveyor belt material. The target/sled interface and the sled/rope interface are both attached using tie wraps so that a sizable impact results in the target breaking free from the sled and springing away from the striking vehicle. Should the striking vehicle drive on top of the sled, the sled/rope interface breaks away for safety. (See Figure 5.)

Note that the friction of the sled material is quite high, so that the sled's motion mirrors that of the towing vehicle. Therefore decelerating lead vehicle scenarios can be performed, as the rope remains taut during decelerations of at least 0.5g. The sled supports travel up to at least 30 mph (higher speeds can introduce excessive aerodynamic lift or pitching.)

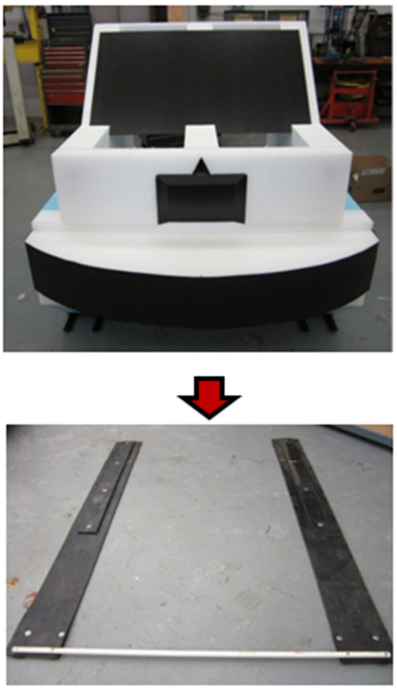

Figure 4. Sled for moving target tests.

Impacts in moving scenarios have been performed at target speeds of 30 mph, as well as strikes at relative speeds of 25 mph without negative consequences.

Figure 5. Vehicle approaching towed sled.

The towing vehicle is outfitted with GPS and acceleration sensors. The lateral position of the target at impact is known through means of a subject vehicle-mounted camera. The longitudinal position of the target is known from the towing vehicle's data.

CONCLUSIONS

Evaluating pre-collision systems requires testing equipment that allows safe, efficient, and accurate execution and data measurement. The crash record and prior literature was examined to define the rear-end crash problem for the purposes of developing objective test procedures to evaluate PCS. This paper summarized the analyses of crash data and the derivation of a set of test scenarios.

Also presented were requirements and the ultimate design for a surrogate target that can be used in test track evaluations of PCS. The surrogate target is a towed, low-weight and low-cost design that includes

several specific radar scattering elements so the target appears to a radar as a normal car would. The design is done using a set of requirements including impactability, cost and ease of use, radar and visual characteristics, ability to use with given speed and deceleration bounds, and the ability to safely hit off-center on the vehicle. Better targets will lead to more accurate evaluation and designs which will enable better designs on the highway.

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