A FORWARD COLLISION WARNING (FCW) PERFORMANCE EVALUATION

Garrick J. Forkenbrock
National Highway Traffic Safety Administration
United States of America

Bryan C. O'Harra
Transportation Research Center, Inc.
United States of America

Paper No. 09-0561

ABSTRACT

This paper describes tests performed by the National Highway Traffic Safety Administration (NHTSA) to evaluate the forward collision warning (FCW) systems installed on three late model passenger cars. NHTSA defines an FCW system as one intended to passively assist the driver in avoiding or mitigating a rear-end collision via presentation of audible, visual, and/or haptic alerts, or any combination thereof. The test maneuvers described were designed to emulate the top three most common rear-end pre-crash scenarios reported in the 2004 GES database.

FCW system performance was quantified by specifying the average time-to-collision (TTC) between the subject vehicle (SV) and principle other vehicle (POV) at the time of the SV's FCW alert.

BACKGROUND

During the summer of 2008, the National Highway Traffic Safety Administration (NHTSA) performed an evaluation of the forward collision warning (FCW) systems installed on three late model passenger cars. All tests were performed by researchers at the agency's Vehicle Research and Test Center (VRTC), located on the Transportation Research Center, Inc. (TRC) proving grounds in East Liberty, OH.

NHTSA defines an FCW system as one intended to passively assist the driver in avoiding or mitigating a rear-end collision. FCW systems have forward-looking vehicle detection capability, provided by technologies such as RADAR, LIDAR (laser), cameras, etc. Using the information provided by these sensors, an FCW system alerts the driver that a collision with another vehicle in the anticipated forward pathway of their vehicle may be imminent unless corrective action is taken. FCW system alerts consist of audible, visual, and/or haptic warnings, or any combination thereof.

At the time the work discussed in this paper was performed, the number of US-production light vehicles available with FCW was very low, with only three vehicle manufacturers offering such systems on limited variants of certain vehicle makes and models. So as to best evaluate the current state of FCW technology implementation, sample offerings from each of these vehicle manufacturers were procured: a 2009 Acura RL, 2009 Mercedes S600, and a 2008 Volvo S80. Although each of these vehicles present the driver with auditory and visual alerts, the manner in which these cues were presented differed, as shown in Table 1.

Table 1.
FCW Alert Modality

Vehicle	FCW Alert	
	Visual	Auditory
Acura RL	Message on instrument panel	Repeated beeps
Mercedes S600	Icon on instrument panel	Repeated beeps
Volvo S80	HUD using up to two sequences of red LEDs	Repeated tones

THE REAR-END COLLISION CRASH PROBLEM

When determining what kinds of tests would be appropriate for use in FCW evaluation, work performed by the agency's Automotive Rear-End Collision Avoidance System (ACAS) project [1], the Integrated Vehicle-Based Safety Systems (IVBSS) and Crash Avoidance Metrics Partnership (CAMP) programs [2,3], and research by the Volpe Center (part of DOT's Research and Innovative Technology Administration) [4] was reviewed. Based on 2004 General Estimates System (GES) statistics, a summary performed by Volpe shows that overall, approximately 6,170,000 police-reported crashes of all vehicle types, involving 10,945,000 vehicles, occurred in the United States. These statistics also indicate that overall, all police-reported light-vehicle crashes resulted in an estimated cost of $120 billion, and functional years lost (a measure of harm) totaled approximately 2,767,000 [5]. These societal harm measures were based on the GES crash sample and did not incorporate data from non-police-reported crashes.

Using the 37 crash typology described in [5], Volpe identified that many of these crashes involved rear-end collision scenarios. Of the 37 groupings used to describe the overall distribution of pre-crash scenario types, the Lead Vehicle Stopped, Lead Vehicle Decelerating, and Lead Vehicle Moving at Lower Constant Speed crashes represented in the 2004 GES database were found to be the 2nd, 4th, and 12th most common crash scenarios overall, respectively, and were the top three rear-end pre-crash scenarios. Note that in 50% of Lead Vehicle Stopped crashes, the lead vehicle first decelerates to a stop and is then struck by the following vehicle, which typically happens in the presence of a traffic control device or the lead vehicle is slowing down to make a turn. Tables 2 through 4 presents summaries of these rear-end pre-crash scenarios, ranked by frequency, cost, and harm (expressed as functional years lost), respectively.

Based on the crash frequency, cost, and harm data presented in Tables 2 through 4, NHTSA decided use of test maneuvers designed to emulate these real-world crash scenarios would provide an appropriate way to evaluate FCW performance. Building on the efforts put forth by the ACAS and IVBSS programs, NHTSA researchers subsequently developed three objective test procedures to perform the work described in this paper. The objectives of this work were twofold: (1) identify the time-to-collision (TTC) values from the time an FCW alert was first presented to the driver, and (2) refine the test procedures, as necessary, to enhance the accuracy, repeatability, and/or reproducibility by which the FCW system evaluations could be performed.

Table 2.
Crash Rankings By Frequency (2004 GES data)

Scenario	Frequency	Percent
Lead Vehicle Stopped	975,000	16.4
Lead Vehicle Decelerating	428,000	7.2
Lead Vehicle Moving at Lower Constant Speed	210,000	3.5

Table 3.
Crash Rankings By Cost (2004 GES data)

Scenario	Cost ($)	Percent
Lead Vehicle Stopped	15,388,000,000	12.8
Lead Vehicle Decelerating	6,390,000,000	5.3
Lead Vehicle Moving at Lower Constant Speed	3,910,000,000	3.3

Table 4.
Crash Rankings By Functional Years Lost (2004 GES data)

Scenario	Years Lost	Percent
Lead Vehicle Stopped	240,000	8.7
Lead Vehicle Decelerating	100,000	3.6
Lead Vehicle Moving at Lower Constant Speed	78000	2.8

TEST METHODOLOGY

Overview

The tests described in this paper were designed to evaluate the ability of an FCW system to detect and alert drivers of potential hazards in the path of their vehicles. Three driving scenarios were used to assess this technology. In the first test, a subject vehicle (SV) approached a stopped principle other vehicle (POV) in the same lane of travel. The second test began with the SV initially following the POV at the same constant speed. After a short while, the POV stopped suddenly. The third test consisted of the SV, traveling at a constant speed, approaching a slower moving POV, which was also being driven at a constant speed. For the sake of brevity, these three tests will be referred to as the “Lead Vehicle Stopped,” “Decelerating Lead Vehicle,” and “Slower Moving Lead Vehicle” tests, respectively, for the remainder of this paper.

The tests were each performed on the TRC skid pad, a 3600 ft (1097 m) long flat (0.5 percent upwards longitudinal slope, with a negligible cross slope) concrete roadway comprised of seven paved lanes. The pavement of the skid pad lanes used for the FCW evaluations was in good condition, free from potholes, bumps, and cracks that could cause the subject vehicle to pitch excessively. Each lane was approximately 12 ft (3.7 m) wide, and was delineated with solid white pavement lines. All tests were performed during daylight hours with good visibility (no fog, rain, or snow) and very windy conditions were avoided (wind speeds ranged from 0 to 17 mph during the testing timeline). The ambient temperatures present during test conduct ranged from 63 to 83 ºF (17 to 28 ºC).

A 2008 Buick Lucerne was used as the POV for all FCW tests discussed in this paper. The vehicle, as shown in Figure 1, was selected to represent a "typical" mid-sized passenger car. Use of an artificial representation was considered (e.g., an inflatable or foam car), but ultimately not deemed necessary for three reasons: safety considerations, test consistency, and test complexity.

Figure 1. Buick Lucerne (POV) and Mercedes S600 (SV) during an FCW test performed on the TRC skidpad.

The evaluations discussed in this paper were intended to evaluate when FCW alerts occurred. As such, SV-to-POV collisions were not expected. For an FCW to be effective in the real-world, it was believed there would be sufficient time from (1) when an FCW alert was presented to the driver to (2) when the driver would be able to comprehend the alert and take some corrective action to avoid a crash. A professional test driver was used to pilot the SV, and was aware of what actions would be taken by the POV during each trial. This, and the fact there was sufficient room to maneuver around the POV in the case of an aborted trial on the test pad, gave reason for NHTSA researchers to believe the tests could be safely performed with a "real" POV.

NHTSA researchers also believed it would be best to perform each of the three tests series with a common POV. Each test scenario contained a unique interaction between the SV and POV. By not using the same POV for all tests, researchers were concerned that scenario-based performance comparisons could be confounded by differences in how the FCW systems may have perceived the different POVs. Evaluating artificial test targets, with a radar return signature comparable to that of the "real" POV, was outside of the scope of the project.

Use of an artificial POV would have introduced significant test complexity for some tests. Although NHTSA presently owns a full-size inflatable balloon car intended for used in collision avoidance/ mitigation testing, two of the three test scenarios described in this paper required the POV accurately and consistently travel in a straight line at speeds up to 45 mph. Additionally, the "SV approaches a decelerating POV" tests required the POV achieve and maintain a set deceleration magnitude. Development of a new artificial test apparatus able to accommodate these demands was outside of the scope of the project.

Instrumentation

Table 5 provides a summary of the instrumentation used during NHTSA's FCW evaluations. The POV and each SV and were equipped with instrumentation and data acquisition systems. All analog data was sampled at 200 Hz. For the SV, vehicle speed, lateral and longitudinal position (via GPS), range to POV (via radar), yaw rate, and FCW alert status data were recorded. In the case of the Mercedes S600, FCW alert output from the high speed controller area network (CAN) also was collected using equipment discussed in the next section. For the POV, vehicle speed, position, brake pedal travel, and longitudinal acceleration data were collected. Signal conditioning of these data consisted of amplification, anti-alias filtering, and digitizing. Amplifier gains were selected to maximize the signal-to-noise ratio of the digitized data.

For both vehicles, vehicle speed was directly recorded as an analog output from a stand-alone GPS based speed sensor and calculated from the output of a second GPS system; that which provided the position data later used to determine TTC. The GPS data produced by the second system were sampled at 10 Hz, and were differentially corrected during post-processing. All data (analog and GPS-based data from the SV and POV) were then merged into a single data file per trial for the ease of subsequent data analysis.

Redundant vehicle speed sensors provided two functions. First, the stand-alone GPS-based speed sensor provided the drivers of the SV and POV with accurate real-time vehicle speed information. The GPS system used to provide position data did not have this capability. Second, during merging of the analog and differentially corrected GPS data files for an individual trial, use of common speed information from two independent sources improved the synchronization accuracy.

Table 5.
Instrumentation Used During FCW Evaluation

Type	Output	Range	Resolution	Accuracy
Differentially-Corrected GPS Data	Vehicle speed	0.5 – 125 kph* (0.3 - 77 mph)	0.01 kph* (0.001 mph)	0.1 kph* (0.06 mph)
	Longitudinal position of SV and POV	N/A	5 cm (2 in)	< 10 cm (4 in) absolute; 1 cm static
	Lateral position of SV and POV	N/A	5 cm (2 in)	< 10 cm (4 in) absolute; 1 cm static
Radar-Based Headway	Distance between SV and POV	1 – 100 m (3-300 ft)	0.5 m (1.6 ft)	+/- 5% of full scale
Rate Sensor	Yaw rate	+/- 100 deg/s	0.004 deg/s	+/- 0.05% of full scale
Accelerometer	Longitudinal acceleration	+/- 2 g's	+/- 10μg	+/- 0.05% of full scale
Brake Pedal Travel	Linear brake pedal travel	0 – 5 in	+/- 0.001 in	+/- 1% of full scale
Data Flag (FCW Alert)	Signal from FCW system that indicates if the FCW warning was issued	0 – 10V (optional: could be a binary flag from CAN Bus)	N/A	Output response better than 10 ms
Vehicle Dimensional Measurements	Location of GPS antenna, vehicle centerlines, and two bumper measurements	N/A	1 mm (0.05 in)	1 mm (0.05 inch)

*Values for the stand alone vehicle speed sensor used to provide output to the dashboard display and for data synchronization. The GPS-based vehicle speed ultimately used for TTC calculation, was derived using vehicle position and time data.

Table 5 provides a summary of the instrumentation used during NHTSA's FCW evaluations. Note that in addition to this equipment, the driver of the SV was also presented with real-time range-to-POV data produced with a laser-based distance measuring system to facilitate accurate conduct of the Decelerating Lead Vehicle tests. The output of the laser-based system was not recorded.

FCW Alert Monitoring

When activated, the FCW systems discussed in this paper provided the SV driver with auditory and/or visual alerts. Recording when these alerts first occurred was of great importance since this information would later be used to calculate the TTCs for each test scenario, the objective measure by which FCW performance was quantified. The methods used to record the FCW alerts differed from vehicle to vehicle, as shown in Table 6.

Table 6.
FCW Alert Monitoring Methods

Vehicle	Monitor
Acura RL	Auditory cue only (monitoring the visual display deemed too invasive)
Mercedes S600	High-speed CAN bus output (monitoring the visual and/or aural cues deemed too invasive)
Volvo S80	1. Low severity HUD 2. High severity HUD 3. Auditory alert (direct tap) 4. Auditory alert (via microphone)

<u>Volvo S80</u>

The Volvo S80 was the first vehicle evaluated, and its FCW alerts were monitored the most comprehensively (i.e., to provide an indication of how best to evaluate the subsequent vehicles). The auditory alert originated from a piezoelectric speaker installed behind the instrument cluster. Visual alerts were presented via a heads-up display (HUD) comprised of multiple LED clusters. These clusters provided two levels of illumination, where the system's perceived risk of a collision would dictate whether some or all of the HUD LEDs would be illuminated.

To monitor the status of the auditory alert, the leads of the piezoelectric speaker were directly tapped, and their output (i.e., the signal sent to the speaker) was recorded. Additionally, an external microphone was positioned near the speaker, and its output recorded. This was to allow researchers to examine the feasibility of using a less invasive method of capturing the FCW speaker output, a practical consideration for future NHTSA test programs.

To monitor the status of the FCW HUD, the dash-mounted LED circuit was removed and tapped. Additionally, five photocells were placed over the HUD to record when and how many LEDs were illuminated during each FCW alert. Conceptually similar to the use of the microphone being used to monitor the piezoelectric speaker output, use of the photocells allowed researchers to examine the feasibility of using a less invasive method of capturing the FCW HUD illumination. Figure 2 provides an output comparison of the FCW HUD taps, photocells, audible alarm tap, and microphone during a Lead Vehicle Stopped test performed with the Volvo S80.

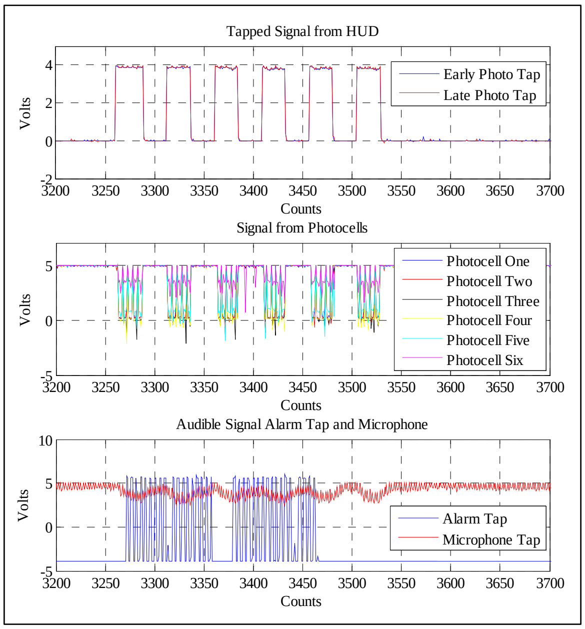

Figure 2. Outputs of the FCW warning light taps, photocells, audible alarm tap, and microphone during a test performed with the Volvo S80.

Of particular interest was the response time and signal-to-noise ratio of the microphone and photocells. For the tests described in this paper, each FCW alert presented both levels of HUD illumination, accompanied by the audible alert. Illumination of both LED clusters occurred at the same instant; the auditory alert was found to occur 20 to 65 ms later. Indication of an HUD-based alert provided by photocell output typically lagged that provided by the direct tap by 5 to 15 ms. The signal-to-noise ratio of the microphone output used to monitor the piezoelectric speaker was poor, and was affected by signal noise bleed through. As such, results from the microphone-based outputs were not considered during data analysis.

Based on comparison of each technique used for monitoring the Volvo S80 FCW alerts, the authors concluded use of the outputs provided by the direct tap of the HUD were the most appropriate. Subsequent TTC calculations for this vehicle were therefore based on the instant HUD illumination was first detected.

Acura RL

The Acura RL auditory alerts originated from a piezoelectric speaker installed behind the instrument cluster. The visual alert was presented via a multi-function display located in the center of the instrument cluster, where the message “BRAKE” was shown at the time of the alert. Subjective impressions from the SV test driver indicated the visual and aural cues were presented simultaneously.

Based on a combination of test feasibility and consideration of observations made during the Volvo S80 evaluation, the FCW alert detection methods used for the Acura RL was simplified. To monitor the status of the auditory alert, the leads of the piezoelectric speaker were directly tapped, and their output was recorded. For previously-stated reasons, an external microphone was not used to provide a redundant measure of this speaker’s output. The visual FCW alert status was not recorded during evaluation of the Acura RL. Since the vehicle’s message center was used to present the driver with information beyond just FCW alerts, use of photocell-based monitoring was not appropriate. In other words, absolutely discerning an FCW alert from some other display was not possible with this method. Researchers did not have a way to decode CAN-based FCW data for the Acura RL.

Since it was the only FCW alert information recorded, data from the piezoelectric speaker tap was used to calculate the TTC values for the Acura RL; considered at the instant speaker output was detected. Figure 3 provides an example of these data.

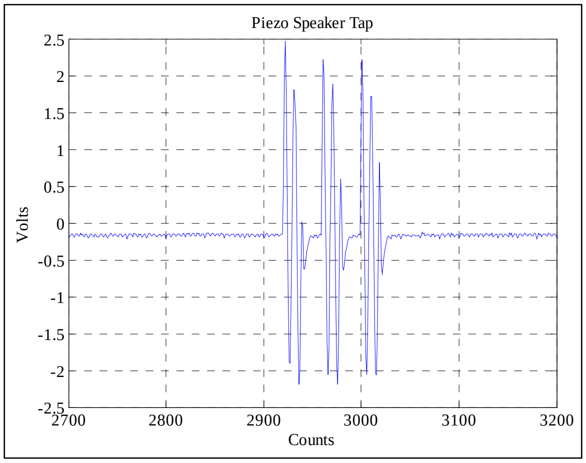

Figure 3. Alert outputs recorded during an FCW test performed with the Acura RL.

Mercedes S600

The Mercedes S600 auditory alert originated from a piezoelectric speaker installed behind the instrument cluster. Visual alerts were presented via a small icon on the instrument cluster. Although a direct tap of either alert would have provided information necessary to calculate TTCs, accessing the respective circuits would have requiring much of the dash be disassembled. Given the high cost of the vehicle, and since it was acquired via a short term lease, researchers sought to identify a less invasive means to monitor the FCW alert status.

NHTSA researchers were able to identify the FCW indicator status data via the S600 CAN bus (see Figure 4). After interfacing with the appropriate connector, the CAN data was fed into a NHTSA-developed programmable board designed to isolate and monitor the FCW status, and to output it as an analog signal to the vehicle's data acquisition system. Accessing the vehicle's CAN was necessary since the FCW alert status was not accessible via the OBD II connector.

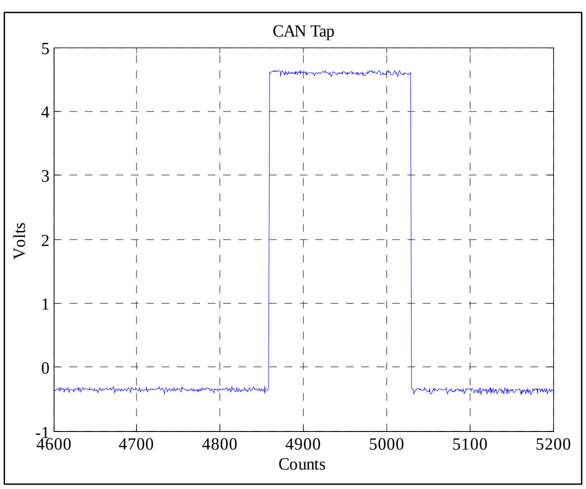

Figure 4. FCW alert status accessed via the CAN during a test performed with the Mercedes S600.

Since it was the only practical way by which the FCW alert recorded, data from the CAN was used to calculate the TTC values for the Mercedes S600 (i.e., the instant a message commanding the FCW alert was detected). Figure 4 provides an example of these data.

SV-to-POV Proximity

Accurate measurement of SV and POV position over time was of great importance for the tests described in this paper. In each scenario, the distance between the vehicles (i.e., the headway) at the time of the FCW alert was used in the calculation of the respective TTC values. Additionally, the ability of the SV to maintain and/or establish the appropriate headway to the POV and the vehicles' lateral lane positions were considered during the pre-brake validity assessments performed for the Decelerating Lead Vehicle and Slower Moving Lead Vehicle tests.

Although the most accurate SV and POV positions were ultimately derived from differentially corrected GPS data, two supplemental methods were also used: (1) via a forward-looking radar, and (2) via a laser-based range measurement sensor. Both supplemental units were attached to the front bumper of the SV, as shown in Figure 5.

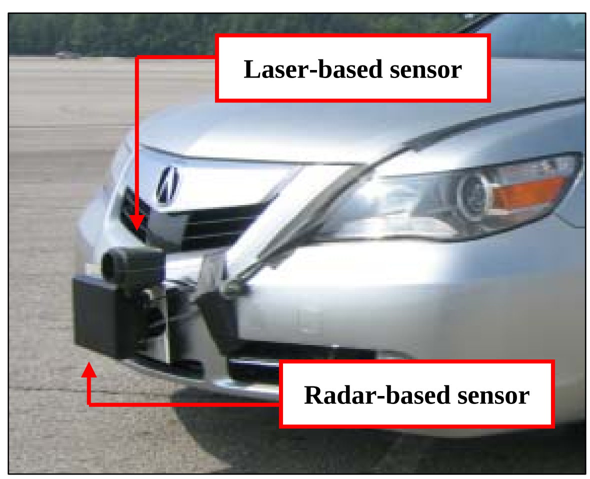

Figure 5. Instrumented test vehicle (Acura RL shown). Note bumper-mounted distance measuring equipment.

The reasons for using the supplemental distance measuring equipment were two-fold. First, to benchmark radar-based range performance against that of the GPS. This was to assess whether the radar-based system could provide an acceptable alternative to, or substitute for, differentially corrected GPS for future NHTSA tests requiring such data. Second, the laser-based range measurement provided real-time headway information to the SV driver. Such information was essential for conduct of the Decelerating Lead Vehicle tests, and not available from the GPS or radar-based measurement systems.

Programmable Brake Controller

The Decelerating Lead Vehicle tests required the POV establish and maintain moderate deceleration with minimal overshoot and variability. Since repeatably accomplishing this with even a skilled test driver is difficult, a programmable brake controller was used for these tests, as shown in Figure 6. Although this controller was expected to offer researchers the ability to command a desired deceleration, such functionality could not be realized during the tests described in this paper. Alternatively, a feedback loop that applied and maintained a constant brake pedal displacement was used. The combination of this feedback loop, and maintaining a consistent amount of time between trials[1], ultimately produced POV deceleration within the tolerances specified by the Decelerating Lead Vehicle validity criteria described later in this paper.

Figure 6. Programmable brake controller used during the Decelerating Lead Vehicle tests.

[1]Maintaining a consistent amount of time between trials was found to contribute to consistent within-series POV brake temperatures. This resulted in more consistent POV deceleration.

Test Maneuvers

Although there were three unique test scenarios discussed in this paper, a number of common validity requirements were imposed on the individual trials so as to perform the tests as objectively as possible.

1. The SV vehicle speed could not deviate from the nominal speed by more than 1.0 mph (1.6 kph) for a period of three seconds prior to the required FCW alert.

2. SV driver was not allowed to apply any force to the brake pedal before the required FCW alert occurred

3. The lateral distance between the centerline of the SV, relative to the centerline of the POV, in road coordinates, could not exceed 2.0 ft (0.6 m).

4. The yaw rate of the SV could not exceed ±1 deg/sec during the test.

5. Since each SV was equipped with an automatic transmission, all tests were performed in "Drive"

Subject Vehicle (SV) Encounters a Stopped Principle Other Vehicle (POV)

These tests are also known as "Lead Vehicle Stopped" trials. To perform this maneuver, the POV was parked in the center of a travel lane facing away from the approaching SV, oriented such that its longitudinal axis was parallel to the roadway edge, as shown in Figure 7.

The SV was then driven at a nominal speed of 45 mph (72.4 kph), in the center of the lane of travel, toward the parked POV. The test was taken to begin when the SV was 492 ft (150 m) from the POV, and concluded when the subject vehicle's FCW alert was presented. To assess FCW alert variability, performing seven valid tests was desired.

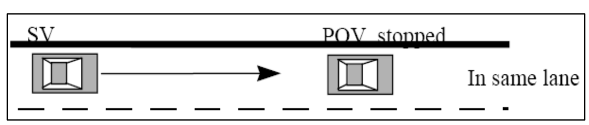

Figure 7. Lead Vehicle Stopped crash scenario.

Subject Vehicle (SV) Encounters a Decelerating Principle Other Vehicle (POV)

These tests are also known as "Decelerating Lead Vehicle" trials. To begin this maneuver, the SV and

POV were driven in the center of same travel lane at a speed of 45 mph (72.4 kph). After driving with a constant headway distance of 98.4 ft (30 m), the driver of the POV suddenly applied the brakes in a manner intended to establish constant deceleration of 0.3 g within 1.5 seconds. For this test series, the individual trials were taken to begin 3 seconds prior to the initiation of the POV braking, and concluded when the subject vehicle's FCW alert was presented. To assess FCW alert variability, performing seven valid tests was desired. Figure 8 presents the decelerating lead vehicle crash scenario.

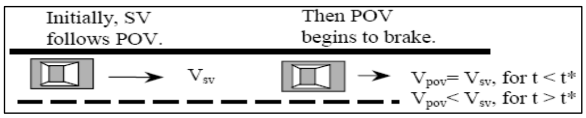

Figure 8. Decelerating Lead Vehicle crash scenario.

In addition to the previously mentioned validity requirements, the Decelerating Lead Vehicle test scenario includes the following parameters:

1. The initial POV vehicle speed could not deviate from the nominal speed by more than 1.0 mph (1.6 kph) for a period of three seconds prior to the initiation of POV braking.

2. The POV deceleration level was required to nominally be 0.3 g within 1.5 seconds after initiation of POV braking. The acceptable error magnitude of the POV deceleration was ± 0.03g, measured at the time the FCW alert first occurred. An initial overshoot beyond the deceleration target was acceptable, however the first local deceleration peak observed during an individual trial was not to exceed 0.375 g for more than 50 ms. Additionally, the POV deceleration was not permitted to exceed 0.33 g over a period defined from (1) 500 ms after the first local deceleration peak occurs, to (2) the time when the FCW alert first occurs.

3. The tolerance for the headway from the SV to the POV was required to be ± 8.2 ft (± 2.5 m), measured at two instants in time: (1) three seconds prior to the time the POV brake application was initiated, and (2) at the time the POV brake application was initiated.

Subject Vehicle (SV) Encounters a Slower Principle Other Vehicle (POV)

These tests are also known as "Slower Moving Lead Vehicle" trials. To begin this maneuver, the POV was driven in the center of a travel lane at a speed of 20 mph (32.2 kph). Shortly after the POV had established the desired test speed, the SV was driven in the center of same travel lane at a speed of 45 mph (72.4 kph), approaching the slower-moving POV from the rear. For this test series, the individual trials were taken to begin when the headway from the SV to the POV was 492 ft (150 m), and concluded when the subject vehicle's FCW alert was presented. To assess FCW alert variability, performing seven valid tests was desired. Figure 9 presents the decelerating lead vehicle crash scenario.

Figure 9. Slower Moving Lead Vehicle scenario.

As was the case for the Decelerating Lead Vehicle test scenario, the Slower Moving Lead Vehicle trials also required the POV vehicle speed not deviate from the nominal speed by more than 1.0 mph (1.6 kph) for a period during the test.

TEST RESULTS

General Observations

Performing the three tests scenarios proved to be quite straight-forward, however there were some important observations made during their conduct.

First, these tests do not lend themselves to some of the variability-reducing steps presently used by other track-based tests presently performed by NHTSA (i.e., dynamic rollover or electronic stability control testing). For example, cruise control could not be used to maintain the SV test speed. Many of the sensors used by the FCW systems discussed in this paper were shared with the vehicles' respective adaptive cruise control (ACC) systems. For at least two of the maneuvers, the decelerating and slower-moving POV tests, ACC interventions would not be expected to allow the combination of pre-FCW alert headway distances and tight SV and POV vehicle speed tolerances be realized and/or maintained.

Maintaining SV speed also required the driver to use careful throttle modulation using small, smooth inputs. Prior to actually performing the FCW tests, discussions with vehicle manufacturers indicated some systems monitor the driver's throttle inputs, and that use of abrupt throttle inputs could cause an FCW system to suppress the alert NHTSA was interested in evaluating. The rationale for such suppression involves a desire to achieve the high consumer acceptance, with the logic being that if the driver is deliberately commanding a sudden throttle input, they are providing an indication of being alert, capable of making good driving decisions, and that providing an FCW alert (an alert intended to primarily benefit inattentive drivers) may not be appropriate.

For the previously-stated reasons, the driver of the SV was also required to make small, smooth steering corrections to maintain lane position. NHTSA researchers were cautioned that use of abrupt or coarse changes in steering position, even with small magnitudes, could also result in FCW alert suppression. Evaluating whether these concerns were relevant to the test vehicles described in this paper, or attempting to determine the minimum throttle and/or steering input magnitudes necessary to evoke FCW alert suppression was not performed in this study, but may provide an interesting area for future research.

Maneuver Results

Subject Vehicle (SV) Encounters a Stopped Principle Other Vehicle (POV)

Since the POV was stationary for the entire test, the Lead Vehicle Stopped trials were the simplest to perform. The TTC for this test, a prediction of the time it would take for the SV to collide with the POV from the time of the FCW alert, was calculated by considering two factors at the time of the FCW alert: (1) distance between SV and POV at the time of the FCW alert ($s_{sv,initial}$) and (2) the speed of the SV ($v_{sv,initial}$). The corresponding TTC values were simply computed using Equation 1:

$$TTC_{Test1} = \frac{s_{sv,initial}}{v_{sv,initial}} \qquad (1)$$

Table 7 provides a summary of the TTCs calculated with data collected from tests that satisfied all validity criteria. In the case of the Volvo S80, the full suite of seven valid tests was not realized after data post processing (SV speed at the time of the FCW alert was too high for some tests). For this vehicle, the mean and standard deviations were based on five trials.

Generally speaking, and despite the prohibition of cruise control and tight allowable tolerances, the experimenters were able to successfully execute the tests without issue. That said, the Lead Vehicle Stopped tests did call to attention to two important details regarding test conduct. First, it appears the absence of a POV rear license plate was capable of influencing the FCW effectiveness for at least one vehicle used in this study. Second, although conduct of the maneuver was free of incident, some safety concerns were raised.

Table 7.
Lead Vehicle Stopped TTC Summary

Trial	Acura RL	Mercedes S600	Volvo S80
1	1.63	2.24	2.08
2	1.84	2.32	2.64
3	1.62	2.29	2.28
4	1.94	2.30	2.68
5	1.74	2.31	2.57
6	1.83	2.27	n/a
7	1.46	2.33	n/a
Ave	**1.72**	**2.29**	**2.45**
Stdev	**0.16**	**0.03**	**0.26**

During a brief pilot study comprised of Lead Vehicle Stopped tests, no license plate was installed on the rear of the POV. This was not intentional; it simply happened that since the vehicle was only being driven within the controlled confines of a proving ground, it was not so-equipped. When the Volvo S80 was evaluated in this condition, an FCW alert was not presented during three of the ten pilot tests. Seeking to understand whether the manner in which the tests were performed may have influenced the test outcome, NHTSA researchers considered a variety of experimental refinements. One such consideration was installing a license plate on the rear of the POV, since it was more representative of how the POV would be seen in the real world, and would provide a vertical metallic surface capable of being more easily detected with forward-looking radar (used to provide range and range rate data to the respective FCW systems). With the rear license plate installed on the POV, each of the valid Lead Vehicle Stopped tests performed with the Volvo S80 produced an FCW alert.

Due the low sample size of the tests performed during pilot testing, it is unclear whether the presence of the POV license plate can be absolutely attributable to the Volvo S80's apparently improved FCW performance. However, the fact remains there was at least some evidence suggesting this was the case, and that inclusion of the rear plate on the POV does indeed enhance the face validity of the test scenario. Therefore, all subsequent tests were performed with the rear license plate installed on the POV, including those of the two other test scenarios.

Subject Vehicle (SV) Encounters a Decelerating Principle Other Vehicle (POV)

Given the tight tolerances and careful choreography required by these tests, the Decelerating Lead Vehicle tests were generally the most challenging to perform. Use of the dashboard mounted headway display in the SV, and maintaining a consistent amount of time between trials, improved the efficiency these tests could be performed with. However, since the actual range between the vehicles (calculated with GPS data), and the actual deceleration produced by the POV throughout the maneuver (corrected for pitch angle) could not be calculated until these data had been output after post-processing, obtaining an acceptable number of valid trials required repeated test series for some vehicles.

The TTC for this test, a prediction of the time it would take for the SV to collide with the POV from the time it initiates braking, was calculated by considering three factors at the time of the FCW alert: (1) the speed of the SV ($v_{sv,initial}$), (2) the speed of the POV ($v_{pov,initial}$), and (3) the deceleration of the POV (a_{pov}), as shown in Equation 2. Note: To simplify calculation of the TTC for Test 2, the deceleration of the POV was taken to remain constant from the time of the FCW alert until the POV comes to a stop (i.e., a "constant" deceleration rate assumed).

$$TTC_{Test2} = \frac{-(v_{pov,initial} - v_{sv,initial}) - \sqrt{(v_{pov,initial} - v_{sv,initial})^2 - 2 * a_{pov} * s_{sv,initial}}}{a_{pov}} \quad (2)$$

Table 8 provides a summary of the TTCs calculated with data collected from tests that satisfied all validity criteria. In the case of the Mercedes S600, the full suite of seven valid tests was not realized after data post processing (the headway between the SV and POV at the onset of POV braking was found to be too short). For this vehicle, the mean and standard deviates are based on three trials.

Table 8.
Decelerating Lead Vehicle TTC Summary.

Trial	Acura RL	Mercedes S600	Volvo S80
1	2.30	2.23	3.17
2	2.16	2.34	3.06
3	2.44	2.27	2.95
4	2.21	n/a	3.08
5	2.38	n/a	3.08
6	2.28	n/a	2.92
7	2.13	n/a	3.19
Ave	**2.27**	**2.28**	**3.07**
Stdev	**0.11**	**0.05**	**0.10**

Subject Vehicle (SV) Encounters a Slower Principle Other Vehicle (POV)

Although they were more involved than the Lead Vehicle Stopped tests, the Slower Moving Lead Vehicle tests were generally quite simple to perform. That said, these tests can use considerable real estate if the POV is given an excessive head start before the SV driver begins their approach toward the POV. To maintain a constant POV speed, researchers used the vehicle's cruise control.

The TTC for this test, a prediction of the time it would take for the SV to collide with the POV from the time it initiates braking, was calculated by considering two factors at the time of the FCW alert: (1) the speed of the SV ($v_{sv,initial}$) and (2) the speed of the POV ($v_{pov,initial}$). Equation 3 was used to calculate the TTC for the Slower Moving Lead Vehicle tests.

$$TTC_{Test3} = \frac{s_{sv,initial}}{v_{sv,initial} - v_{pov,initial}} \quad (3)$$

Table 9 provides a summary of the TTCs calculated with data collected from tests that satisfied all validity criteria. In the case of the Volvo S80 the full suite of seven valid tests was not realized after data post processing. For this vehicle, the mean and standard deviates were based on three trials.

Table 9.
Slower Moving Lead Vehicle TTC Summary.

Trial	Acura RL	Mercedes S600	Volvo S80
1	1.97	2.42	2.05
2	2.13	2.43	2.80
3	2.00	2.39	2.99
4	2.02	2.37	n/a
5	1.93	2.37	n/a
6	1.98	2.35	n/a
7	2.06	2.40	n/a
Ave	**2.01**	**2.39**	**2.61**
Stdev	**0.07**	**0.03**	**0.50**

The slower moving lead vehicle test procedure required the SV and POV speeds remain constant for at least 3 seconds prior to the LDW alert. For the Volvo S80 these criteria resulted in most tests being deemed non-valid (the desired speeds were achieved too late). Increasing the pre-brake speed tolerances and/or the amount of time the vehicles were required to remain constant before the alert occurred would have increased the number of valid trials for this test condition. Had they not been deemed non-valid for minor speed infractions, each of the five Volvo S80 trials would have produce TTCs ranging from 2.40 to 3.03 seconds.

Headway Calculation Comparison

TTC values calculated with distance measurements from the radar-based range measurement equipment and differentially corrected GPS are provided in Table 10. All TTC values presented in this table used the same vehicle speed and, in the case of the Decelerating Lead Vehicle tests, deceleration data; only the distance measurements used in the calculations differed.

Whether use of the radar-based equipment would provide an acceptable alternative to, or substitute for, differentially corrected GPS for future NHTSA tests requiring such data ultimately depends on what precision is required. Use of the less accurate radar-based distance measurements resulted in TTC values 5.0 to 12.5 percent longer than those more accurately derived with differentially corrected GPS data. This error was close to the radar manufacturer's sensor accuracy specification of 5 percent, as previously shown in Table 5.

CONCLUSION

Forward collision warning (FCW) system functionality is of great interest to NHTSA. Given the prevalence of rear-end collisions in the crash data, and the high societal costs they impose, better understanding how advanced technologies may be able to mitigate these crashes is an agency priority. This paper has provided details of how NHTSA evaluated the FCW performance of three contemporary passenger cars using three test scenarios designed emulate the most commonly occurring rear-end crash scenarios. Specifically, the time-to-collision (TTC) values, predictions of the time it would take for the SV to collide with the POV from the time of the FCW alert, associated with each vehicle/scenario combination was calculated.

Although performing the tests described in this paper was generally straight-forward, some details pertaining to FCW monitoring and test conduct were challenging. The processes used to accurately monitor the FCW alert status was somewhat intrusive for the Acura RL and Volvo S80, and required cooperation with the vehicle manufacturer for evaluation of the Mercedes S600. Adhering to the tight SV-to-POV headway and POV deceleration requirements of the Decelerating Lead Vehicle tests

Table 10.
Comparison of GPS and Radar-Based TTC Values.

Vehicle	Lead Vehicle Stopped				Decelerating Lead Vehicle				Slower Moving Lead Vehicle			
	GPS	Radar	Difference		GPS	Radar	Difference		GPS	Radar	Difference	
			(sec)	(%)			(sec)	(%)			(sec)	(%)
Acura RL	1.72	1.90	**0.17**	**10.0**	2.27	2.43	**0.16**	**7.0**	2.01	2.18	**0.16**	**8.1**
Mercedes S600	2.29	2.44	**0.14**	**6.3**	2.28	2.56	**0.28**	**12.5**	2.39	2.59	**0.20**	**8.4**
Volvo S80	2.45	2.59	**0.14**	**5.5**	3.07	3.23	**0.16**	**5.0**	2.61	2.82	**0.21**	**7.8**

was demanding. To maximize efficiency when performing these tests, the authors found that providing the SV driver with accurate real-time headway information (e.g., via a dashboard-mounted display, etc.) and use of a programmable brake controller in the POV was helpful. To obtain accurate vehicle-to-vehicle range information, use of highly accurate GPS-based position data of the SV and POV was found to be very effective.

REFERENCES

[1] Zador, P.L., Krawchuk, S.A., Voas, R.B., "Final Report—Automotive Collision Avoidance System (ACAS) Program," DOT HS 809 080, August 2000.

[2] Ference, J.J., Szabo, S., and Najm, W.G., "Objective Test Scenarios for Integrated Vehicle-Based Safety Systems," Paper Number 07-0183, Proceeding from the 20th Enhanced Safety of Vehicle Conference, Innovations for Safety: Opportunities and Challenges, 2007.

[3] Kiefer, R., LeBlanc, D., Palmer, M., Salinger, J., Deering, R., and Shulman, M., "Development and Validation of Functional Definitions and Evaluation Procedures for Collision Warning/Avoidance Systems," DOT HS 808 964, August 1999.

[4] Najm, W.G., Stearns, M.D., Howarth, H., Koopmann, J., and Hitz, J., "Evaluation of an Automotive Rear-End Collision Avoidance System," DOT HS 810 569, April 2006.

[5] Najm, W.G., Stearns, M.D., and Yanagisawa, M., "Pre-Crash Scenario Typology for Crash Avoidance Research," DOT HS 810 767, April 2007.