A COMPARISON OF VEHICLE ALERT MODALITIES' TIME-TO-COLLISION WARNINGS TRIGGERED BY THE VEHICLE'S CONTROLLER AREA NETWORK SYSTEM

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ABSTRACT

Currently, the time-to-collision (TTC) is determined as the time when external instrumentation measures a data flag from the Controller Area Network (CAN) signal or at the time an alert modality can be used to evaluate the performance of a vehicle's Forward Collision Warning (FCW) system for the National Highway Traffic Safety Administration's (NHTSA's) New Car Assessment Program (NCAP). Many vehicle manufacturers assess FCW performance using the digital signal from the CAN to determine the onset of a warning which can then be used to determine compliance with TTC timing requirements listed in NHTSA's performance test procedure provided at www.regulations.gov in docket number NHTSA-2006-26555-0128. NHTSA has observed that the onset of an FCW alert can be substantially delayed when compared to the activation time of the CAN signal. The purpose of this paper is to compare the timing of the CAN signal to the actual visual and audial alerts obtained during the same trial, to determine the extent of these differences, and how they vary by vehicle manufactuer.

The CAN signal and two alert modalities (visual and sound) for seven vehicles were collected by Dynamic Research, Inc., and the subsequent TTCs were calculated using the test procedures and equations established by the agency. Data from the seven vehicles were analyzed for three separate test configurations. Initial analysis did not separate the vehicles by manufacturer; however, upon noticing a linear trend between the CAN signal and visual alerts, the data was grouped by manufacturer for further analysis.

A strong linear relationship (R^2>0.8) was discovered between visual and CAN signal warnings, which correlates to a constant amount of delay between the CAN and visual alerts for all seven (7) vehicles as well as the audial and CAN signal warnings for four (4) of the seven (7) test vehicles. For the remainder of the vehicles, an insonsistent delay was exhibited within models. The audial–CAN relationship was not discovered until vehicle data was separated by manufacturer.

Vehicles that exhibited a constant delay from when the CAN data flag was issued to when the visual or the audial alert was measured were more likely to pass the TTC requirements. Certain models had visual and audial alert modalities occur after the minimum safe TTC has passed. As a result, this paper will also attempt to conjecture potential reasons for the differences delay in the FCW alert modalities timing compared to that of the CAN data flag.

INTRODUCTION

The most frequent type of crash involving multiple vehicles is a rear-end collision. This type of crash accounts for approximately 30% of all light vehicles (less than 10,000 lbs. gross vehicle weight rating (GVWR)) crashes (National Highway Traffic Safety Adminstration, 2006). Of these, 60% are attributed to inattentive drivers. Inattentive driving, combined with tailgating, contributes to 90% of rear-end collisions (Mohebbi, Gray, & Tan, 2009). Recent findings illustrate that rear-end crash frequency have increased to 31.5% from 2006 to 2009. Of these crashes, 29.5% resulted in injuries and 5.4% resulted in fatalities. Of these fatalities, 12% of them were caused by inattentive or fatigued drivers (National Highway Traffic Safety Adminstration, 2009).

In an attempt to lower the frequency of rear-end collisions, technology has been developed and implemented into vehicles for early detection and warning of potential collisions. These systems are typically called Forward Collision Warning (FCW) systems. The “lead vehicle” ,also referred to as the principal other vehicle (POV), is detected by the subject vehicle (SV) using on-board systems based on radar, camera, or a combination of radar and camera system. These systems continually monitor the speed, distance, and closing rate between the vehicles, and if a collision risk is detected, the vehicle warns the driver through a visual, audial, or haptic warning. For the alert to be effective, the warning must be issued sufficiently early during the conflict event so that the driver can react by braking or maneuvering the vehicle to avoid or mitigate the crash.

To help ensure the capability and robustness of FCW systems, the National Highway Traffic Safety Administration’s (NHTSA’s) New Car Assessment Program (NCAP) developed performance tests and criteria to evaluate FCW systems. The system must meet the minimum performance specifications to obtain government recognition on the agency’s website, www.safercar.gov. The performance tests (www.regulations.gov, NHTSA-2006-26555-0128) are designed to objectively measure the system’s ability to warn a driver of an imminent crash with enough time to avoid or mitigate the severity of the crash. The FCW test procedure is designed to test the ability of an advanced technology to detect an imminent threat in different driving scenarios. The test procedure contains three tests that were designed to duplicate the three most common rear-end crash scenarios, (1) stopped lead vehicle, (2) suddenly decelerating lead vehicle, and (3) slower moving lead vehicle. To objectively test the FCW system, a metric called the time-to-collision or TTC was developed. The TTC is defined as the time it would take for a collision to occur at an instantaneous speed, distance, and acceleration associated with the driver’s vehicle and the nearest lead vehicle. In practice, the FCW system continually updates the estimate TTC values as kinematic conditions between the SV and POV change. Each OEM then determines when to issue an alert to the driver based on the changing TTC estimates (as well as other proprietary factors). As noted, to be effective, the warnings must come sufficiently early (as measured by TTC) to be effective. These minimum values were determined by considering how the warning may interact with the driver, braking speed, and the ability of the vehicle to avoid a crash with a driving maneuver (www.regulations.gov, NHTSA-2006-26555-0120).

Due to an increasing number of vehicles with this advanced technology, NHTSA asks vehicle manufacturers to submit data validating each applicable vehicle’s FCW system by utilizing the test procedure developed by the agency. Vehicles are accredited with an FCW system upon submission and verification of the data. To highlight this accreditation, NHTSA places a checkmark next to this advanced technology on the agency’s website. In order to assure the quality of the submitted data, NHTSA randomly selects vehicles with an accredited FCW system and tests them using the agency’s developed performance tests and criteria. If a vehicle alerts the driver with a TTC greater than the minimum allowable TTC specified by the current NHTSA performance test and criteria, then the vehicle maintains its accreditation on the website. If the vehicle is unable to meet the minimum specifications, then the technology checkmark is removed from the website.

Currently, NHTSA allows manufacturers to self-validate the capability of a vehicle’s FCW system by calculating the TTC variable based on issuance (and subsequent detection) of a warning message (or signal) on the vehicle’s Controller Area Network (CAN). This signal is used to trigger the alert modality for the driver interface through the vehicle’s dashboard, speakers, seat, etc. Since the information of the signal (what the system interprets as an imminent threat to the vehicle, when to alert the driver, etc) is proprietary to the manufacturer, it is extremely difficult for non-OEM personnel to interpret that information. Therefore, many test contractors have begun to use the onset of a visual, audial, or haptic alert to determine compliance with NHTSA’s TTC threshold requirements. This method is preferable since its timing reflects the time at which a driver would see, hear, and/or feel the warning.

It was during the agency’s random testing that NHTSA observed the delay of the onset of an FCW alert through the driver-vehicle interface when compared to the activation of the CAN message signal. This paper will investigate the timing differences (as measured by TTC) between CAN message signals and their corresponding visual and audial alert TTCs, observed differences among various FCW systems evaluated, and whether such differences can be attributed to the type of driver-vehicle interface system employed.

METHODS

Data from seven (7) vehicles representing four (4) manufacturers were selected for this analysis (note that this paper uses the word "make" to refer to the subsidiary of a car manufacturer. For example, Lexus is a make of the manufacturer Toyota.). The capabilities and performance of each vehicle's FCW system were tested using the NHTSA's FCW performance test procedure described below. The first test consisted of the SV approaching a stopped POV. The second test consisted of the SV following the POV at a constant time gap. At a specified headway distance (gap between the front bumper of the SV and the back bumper of the POV), the POV suddenly decelerates. In the third test, the SV approaches a slower traveling POV. The three FCW tests are designed to evaluate the vehicle's ability to recognize common crash scenarios and inform the driver in a timely manner. In order to pass the NHTSA's FCW performance test, the vehicle must provide an FCW alert before the minimum allowable TTC established by NHTSA.

Prior to testing, the SV is delivered to the testing facility to be weighed and instrumented. Light and audial (microphones) sensors are placed in the vehicle to capture the alert modalities at the time of the alert. The CAN alert flag that states a warning has been issued is detected by accessing the diagnostic port on the vehicle or by tapping into the CAN system using manufacturers'. Currently, NHTSA's FCW test procedure allows for OEMs and contractors to validate the system using either the CAN message signal or by directly measuring an alert through the driver-vehicle interface. The earliest warning, as measured by TTC, is used to evaluate system performance.

Test 1: SV Approaches a Stopped POV

The SV is driven at a nominal speed of 45 mph (72.4 km/h) directly behind the stopped POV (Figure 1). The test begins when the SV is 492 feet (150 meters) from the POV (headway distance, s_{sv}) and ends when the FCW alert occurs or when the TTC falls below 90 percent of the TTC pass/fail criteria of 2.1 seconds.

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

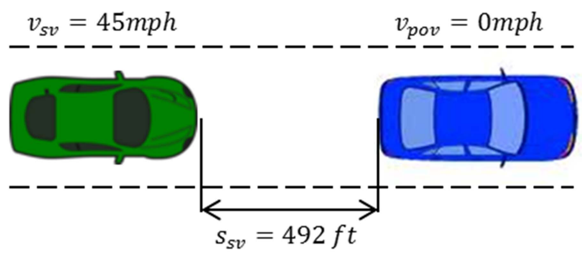

***Figure* 1. FCW Test 1 diagram.**

Test 2: SV Approaches a Decelerating POV

The test begins with the SV and POV traveling in a straight line at 45 mph (72.4 kph). The headway distance is maintained at 98.4 feet (30 meters) with the SV trailing directly behind the POV (Figure 2). Using a brake controller, the POV begins the braking maneuver. The POV is decelerated to 0.3 G within 1.5 seconds. The test ends when the FCW alert occurs or when the TTC falls below 90 percent of the TTC pass/fail criteria of 2.4 seconds.

$$TTC_{Test\ 2} = \frac{-\left(v_{pov,initial} - v_{sv,initial}\right)}{\left(a_{pov} - a_{sv}\right)} \ldots$$

$$\ldots \frac{-\sqrt{\left(v_{pov,initial} - v_{sv,initial}\right)^2 + 2(a_{pov} - a_{sv})s_{sv,initial}}}{(a_{pov} - a_{sv})} \qquad (2.)$$

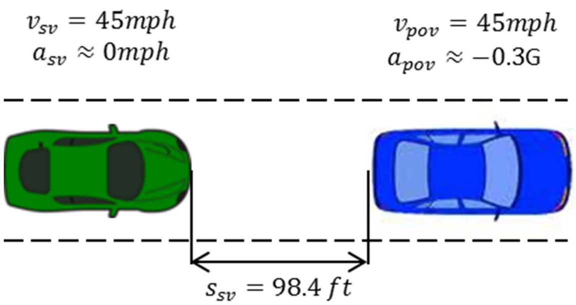

***Figure* 2. FCW Test 2 diagram.**

Test 3: SV Approaches a Slower Moving POV

The final FCW test consists of the SV approaching a slower moving POV vehicle (Figure 3). In this test, the SV is traveling at 45 mph (72.4 kph) while the POV is traveling at 20 mph (32.2 kph). The test begins when the headway distance is equal to 329 feet (100 meters) and ends when the FCW alert occurs or when the TTC falls below 90 percent of the TTC pass/fail criteria of 2.0 seconds.

$$TTC_{Test\ 3} = -\frac{(s_{sv,initial})}{(v_{sv,initial} - v_{pov,initial})} \qquad (3.)$$

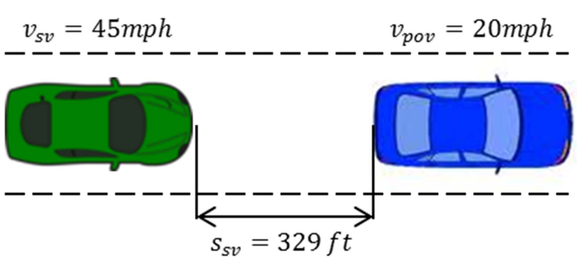

***Figure 3.* FCW Test 3 diagram.**

For an individual test to be valid, the following parameters must hold throughout the test validation period:

1. The speed of the SV cannot deviate from the test speed by more than 1.0 mph (1.6 kph);
2. The speed of the POV for test two (2) cannot deviate from the test speed by more than 1.0 mph (1.6 kph) for a period of three (3) seconds prior to breaking;
3. The speed of the POV for test three (3) cannot deviate from the test speed by more than 1.0 mph (1.6 kph);
4. The lateral distance between the centerline of the SV relative to the centerline of the POV cannot exceed 2.0 feet (0.6 meters);
5. The yaw rates for the SV and POV must stay between -1 and 1 degrees/second; and
6. No braking may be applied to the SV prior to the FCW alert or before the headway distance falls less than 90 percent of the minimum allowable distance.

Prior to analysis, all test data is filtered and synced to 100 Hz sampling frequency.

In order for a vehicle with an accredited FCW system to keep its checkmark on www.safercar, the FCW alert TTC must occur at a minimum of 2.1, 2.4, and 2.0 seconds for FCW test one (1), two (2), and three (3), respectively, and the system must pass a minimum of five out of seven trials.

LIMITATIONS

There are several limitations to this study. While there were several trial runs for each test and vehicle, only four (4) vehicle manufacturers were represented in this study. Furthermore, manufacturer C, only had one vehicle tested for model year 2012 while the other manufacturers had two vehicles each. Each trial recorded the TTC at the moment a CAN, visual, and audial alert was detected.

Table 1.
Population Distribution by Make and Model

	Model No.	
Make	1	2
1	n = 5,5,5	n = 5,5,6
2	n = 7,7,7	n = 7,7,7
3	n = 7,7,7	
4	n = 7,7,7	n = 7,7,7
	n = FCW test 1(LVM), test 2 (LVD), test 3 (LVS)	

Data was also limited by vehicle speed, thus limiting possible variations in results at different speeds.

RESULTS

A strong linear correlation (i.e., consistent amount of delay) was discovered between resulting visual warnings and the CAN activation signal for all test vehicles (Figure 4) and between the resulting audial warnings and CAN activation signal for four of seven test vehicles (R^2 value > 0.95) while the remaining vehicles had R^2 values of 0.67, 0.47, and 0.08 (Figure 5). The linearity of the audial warning resulting from the CAN activation signal (on select vehicles) was not discovered until the vehicle data was analyzed by make and model.

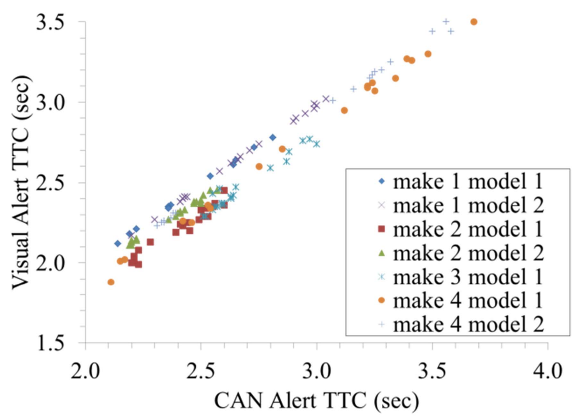

***Figure 4*. CAN vs. Visual Alert TTCs by Make and Model.**

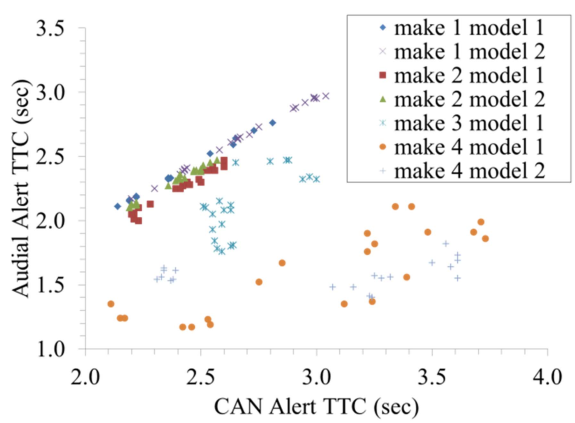

***Figure 5*. CAN vs. Audial Alert TTCs by Make and Model.**

Furthermore, data showed a high percentage of failures for each FCW alert modality despite exhibiting a linear relationship with the CAN signal. All but one trial of the CAN activation signal data met the allowable TTC requirements set forth in the NHTSA's performance test procedure. However, as indicated below (Figures 6 and 7), more of the visual and audial alerts were triggered below the minimum specified alert TTC when compared to the CAN alert TTC.

Horizontal dashed lines are placed in Figures 6 and 7 to mark the minimum acceptable TTC for a given FCW test. Bars below these lines had an average failed TTC. Note that even if the average TTC may have failed the minimum test specifications, the vehicle may still have passed the NHTSA FCW test by passing at least five (5) of seven (7) trials.

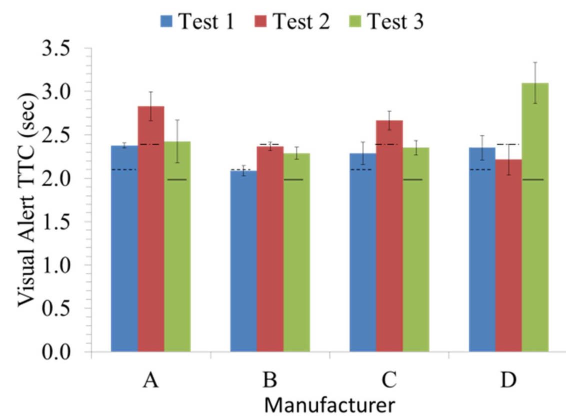

***Figure 6.* Average Visual Alert TTC by Manufacturer.**

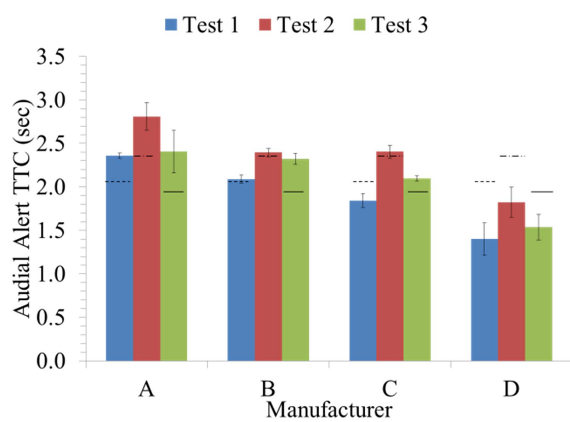

***Figure 7.* Average Audial Alert TTC by manufacturer.**

Tables 2 and 3 illustrate the differences between makes and models of various manufacturers and the differences between audial and visual alert timings. For each vehicle, the CAN triggers both the audial and visual FCW alert.

Table 2.
Average Visual Alert Differences Between Manufacturers

Manufacturer	Test 1 (sec)	Test 2 (sec)	Test 3 (sec)
Min. TTC	**2.1**	**2.4**	**2.0**
A	2.37±0.02	2.82±0.16	2.42±0.24
B	2.08±0.05	2.36±0.04	2.28±0.06
C	2.28±0.12	2.66±0.10	2.35±0.08
D	2.35±0.14	2.21±0.17	3.09±0.23

Table 3.
Average Audial Alert Differences Between Manufacturers

Manufacturer	Test 1 (sec)	Test2 (sec)	Test 3 (sec)
Min. TTC	**2.1**	**2.4**	**2.0**
A	2.35±0.03	2.80±0.16	2.40±0.24
B	2.09±0.04	2.39±0.04	2.32±0.06
C	1.84±0.07	2.40±0.07	2.09±0.03
D	1.40±0.18	1.82±0.17	1.53±0.14

For manufacturers C and D, there is a large difference between the visual and audial alert times for each of the three FCW tests. Furthermore, the average TTCs for these manufacturers as well as manufacturer B could have resulted in failed FCW tests if the vehicle was required to meet specifications for multiple alert modalities (Table 2 and 3).

Manufacturers A and B did not have a substantial delay in TTC from the CAN activation. Furthermore, the audial and visual alerts occurred almost simultaneously. Conversely, manufacturers C and D had substantial delays between the onset of the visual and audial alert times (Table 4).

Table 4.
Change in Average TTC for Visual and Audial Alerts Compared to CAN TTC

Manufacturer	Visual ΔTTC (sec)			Audial ΔTTC (sec)		
	T1	**T2**	**T3**	**T1**	**T2**	**T3**
A	0.01	0.01	0.01	0.03	0.03	0.02
B	0.12	0.14	0.15	0.12	0.12	0.12
C	0.22	0.21	0.20	0.73	0.47	0.43
D	0.13	0.11	0.10	0.94	1.68	1.66

An F-test was performed to determine if the mean CAN, visual, and audial alert TTC were significantly different from each other for a given make. Makes B, C, and D had significantly different means (p-value < 0.0001); while only Make A did not have statistically significant different mean TTCs.

DISCUSSION

The data suggests that there were differences not only between the different manufacturers, but also by the same manufacturer. Furthermore, the data suggests there could be substantial delays (Table 4) between the onset of the CAN alert message and the visual and audial FCW alerts.

Two potential theories for the delay will be explored below. The first theory proposes that the delay and differences could be a result of the temporal and spatial characteristics of the CAN bus system. The second theory suggests that the delay could be deliberate and part of the FCW detection algorithm.

Today's vehicles may have up to 70 electronic control units (ECUs) that control various subsystems such as the infotainment center, air bags, transmission, radars and cameras, etc. Many of these ECUs' functionalities require input from other ECUs within the vehicle. In order to receive this information, a signal must travel from one ECU to another through a physical connection. Due to the physical nature of the connection in the CAN bus systems, information travels along a single wire (Figure 8). Communications are constantly occupying space on the CAN bus system going from ECU to ECU.

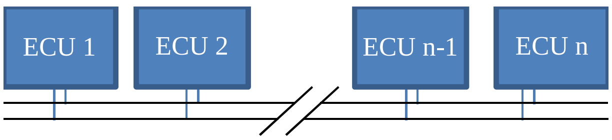

Figure 8. **Drawing of a CAN bus system in vehicle.**

Upon detection of an obstacle or a vehicle, the signal from the ECU that detects/processes the obstacle will need to send a signal to the ECU controlling the alert modality. This signal may have to interrupt other communication currently on the CAN bus communication line and make its way to the ECU that controls the alert modality. Without specific knowledge of the vehicle's CAN network, it is impossible to know the exact ECU and its location for the alert modality. It could possibly be on the same ECU that detects the object or an ECU located 5, 10, 15 feet or more (in cable length) from the origin of the signal. The physical distance between ECUs, the speed of the signal transmission, and other traffic on the CAN bus wires could cause some of the delays observed in the data and between different alert modalities.

The other potential reason for the observed delays and differences in the data is the possibility that manufacturers intentionally include a delay within their algorithms. This may be intended to keep the FCW system from aggravating the driver. If a driver becomes irritated with an FCW system because the alerts are occurring at high rates, then the driver may deactivate the system.

Evidence of the built in delay can be seen with the audial alert timings. All of the manufacturers displayed relatively low visual ΔTTCs for each FCW test; however, the corresponding audial alerts for each trial were substantially delayed for manufacturers C and D. The same CAN signal could theoretically be used to activate both alert modalities, or once the visual alert is signaled, another CAN signal from the ECU containing the visual alert is sent to the ECU containing the audial alert. One can speculate that the "intentional" delay could relate to the possible burden the audial alert has on a driver over the visual. The small, in-dash or HUD visible alerts that many models implement may be perceived as less abrasive than the high pitch beeps of an audial alert.

OBSERVATIONS

From the analysis of the data, it was observed that only four (4) of the seven (7) vehicles show a direct timing relationship to the CAN activation signal for both the visual and audial data (Figures 4 and 5). Furthermore, we observe that the differences between the activation timing of the visual and audial warnings from the CAN activation vary between manufacturer and test condition (Table 4). The majority of vehicles' visual alert modality timing occurred prior to the audial alert modality. This paper theorized two possible factors contributing to the delays between the CAN signal that activates the alert modalities and the actual measured timing of these alerts. The first suggested a physical delay due to the structure of the CAN bus system employed in vehicles. This is essentially a built-in delay resulting from the speed of the signal transmission and data processing. The second theory describes the possibility that some manufacturers may purposely delay one of the alert modalities (when multiple are present in the system). Test data showed significant delays between the timing of the visual and audial warnings from manufacturers C and D. These delays occurred during each test configuration. The delays may be purposely applied by manufacturers C and D, but it should be noted that due to the limited number of vehicles tested, and that this observation was discovered in post-test analysis, we cannot definitively state if these differences are a result of either theory or real-world testing scenarios. Observations such as these add to the importance of NHTSA's performance testing of FCW test systems.

In summary, both the visual and audial data, by make and model, illustrated a degree of linearity between the CAN and the alert modalities. This linearity suggests that vehicle manufacturers have a degree of control as to when FCW alerts should occur once the CAN message signal is received. This could theoretically be achieved through the physical design of the CAN bus system or the FCW alert processing algorithms that vehicle manufacturers apply. In order to account for all possible reasons for driver distraction (i.e. changing the radio, looking to side view mirrors, changing lanes, etc.), manufacturers should consider minimizing any delay onset between the CAN signal and the FCW alerts, as well as between multiple FCW alerts.

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