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Development of a Camera-Based Forward Collision Alert System

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ABSTRACT

Forward Collision Alert (or Forward Collision Warning) systems provide alerts intended to assist drivers in avoiding or mitigating the harm caused by rear-end crashes. These systems currently use front-grille mounted, forward-looking radar devices as the primary sensor. In contrast, Lane Departure Warning (LDW) systems employ forward-looking cameras mounted behind the windshield to monitor lane markings ahead and warn drivers of unintended lane violations. The increasing imaging sensor resolution and processing capability of forward-looking cameras, as well recent important advances in machine vision algorithms, have pushed the state-of-the-art for camera-based features. Consequently, camera-based systems are emerging as a key crash avoidance system component in both a primary and supporting sensing role. There are currently no production vehicles with cameras used as the sole FCA sensing device. This paper discusses the development of a camera-based FCA system that uses a camera in place of a radar device for sensing rear-end crash situations. This paper provides an overview of the system, including how the system detects vehicles, tracks vehicles, projects collision course trajectories, and estimates time-to-collision (TTC) using image scale change. Results from test track and public road testing support the deployment of a camera-based FCA system, and indicate this system would meet the United States Department of Transportation New Car Assessment Program (NCAP) Forward Collision Warning confirmation test requirements. Furthermore, the conditions under which most rear-end crashes occur suggests that this system provides a promising approach to reduce the harm caused by rear-end crashes.

INTRODUCTION

FORWARD COLLLISON ALERT (WARNING) SYSTEM OVERVIEW

Forward Collision Alert, also known as Forward Collision Warning, is a feature that provides alerts intended to assist drivers in avoiding or mitigating the harm caused by rear-end crashes. The Forward Collision Alert (FCA) system may alert the driver to an approach (or closing) conflict a few seconds before the driver would have detected such a conflict (e.g., if the driver's eyes were off-the-road) so they can take any necessary corrective action (e.g., hard braking). In addition, these systems can reduce the amount of tailgating behavior, that is, the amount of time drivers spend following a vehicle ahead at short time headways under “steady-state” driving conditions. A lengthening of headway times can provide the driver with additional time to respond should an unexpected rear-end crash scenario unfold. These tailgating conflicts, as well as closing conflicts involving approaching a vehicle too rapidly, can ultimately lead to a rear-end crash. It should be noted that although FCA systems may be integrated with automatic braking control-related systems, such as Crash Imminent Braking (CIB) systems, FCA systems do not take active control of the vehicle.

Key to driver acceptance of the FCA feature is appropriate crash alert timing, which refers to the necessary underlying vehicle-to-vehicle kinematic conditions for triggering crash alerts. The goal of the alert timing approach is to allow the driver enough time to avoid the crash, and yet avoid annoying the driver with alerts perceived as occurring too early or unnecessary (Kiefer et al., 1999; Kiefer, LeBlanc, and

Flannagan, 2005; LeBlanc et al., 2001). The FCA timing approach (as well as the alert suppression approach noted below), coupled with the FCA alerting approach, play important roles in ensuring system effectiveness and driver acceptance. Addressing this acceptance issue is important for ensuring that the driver does not turn the system OFF or avoid purchasing a vehicle equipped with the FCA feature.

CRASH PROBLEM OPPORTUNITY

FCA systems have the potential to address a significant part of the overall crash problem. This problem can be characterized by using the recent "37-crashes" pre-crash scenario typology developed by Najm, Smith, and Yanagisawa (2007), which updated the "44-crashes" pre-crash scenario typology previously developed by General Motors (44 crashes, 1997). This typology, based on data from the United States 2004 General Estimates System (GES) crash database, includes 37 pre-crash scenarios accounting for approximately 5,942,000 police-reported light-vehicle crashes, an estimated economic cost of 120 billion dollars, and an estimated 2,767,000 functional years lost. Four of these 37 pre-crash scenarios appear to be directly applicable to FCA systems. These scenarios include Lead Vehicle Stopped, Lead Vehicle Decelerating, Lead Vehicle Moving at a Lower Constant Speed, and Lead Vehicle Accelerating. Altogether, these four scenarios accounted for approximately 1,631,254 police-reported light-vehicle crashes, an estimated economic cost of approximately 26 billion dollars, and an estimated 422,000 functional years lost. (This latter measure sums the years of life lost to fatal injury and the years of functional capacity lost to nonfatal injury.) Put in another way, the (light vehicle) "crash problem opportunity" for FCA systems include 28% of police-reported crashes, 22 % of the economic cost, and 15% of the functional years lost. Note that the ultimate harm reduction attributable to the FCA system will depend on how effective the FCA system proves to be within the crashes defined by the crash problem opportunity.

Furthermore, with an eye toward addressing a significant portion of these crashes, it should be noted that 85% of these FCA-applicable crashes were reported to have occurred under clear weather conditions, and that 74% of these crashes were reported to occur where posted speed limits were 45 MPH or less. Consequently, these crash data suggest that it is important to continue to develop alternative FCA systems (e.g., a camera-based system) that are not only effective and well-accepted, but also systems that are affordable and promising for increasing deployment across the entire vehicle fleet.

FORWARD COLLISION ALERT SENSING

There are currently no production vehicles with cameras used as the sole FCA sensing device. The primary FCA ranging device used on current production vehicles are either radar- or lidar-based sensors. These sensors are used for both ACC and FCA purposes. These sensors transmit beams of electromagnetic radiation (radar and laser beams, respectively) and measure properties of the beam's reflection to detect, classify, and to assess rear-end crash threats. The ACC feature is currently offered in conjunction with the FCA feature, since these features require primarily the same sensing capabilities. The current OEM cost for the radar/lidar sensors used to perform the ACC-FCA functionality is approximately $300 to $600. While increased volumes and continued developments are driving down the cost of theses sensors, more affordable solutions should be explored to facilitate a broader implementation of the FCA feature across the entire vehicle fleet.

This provided the impetus to investigate using the camera-based Lane Departure Warning (LDW) sensor for FCA sensing purposes. (Note that although radar and lidar sensors can provide ACC functionality, such sensors cannot direct detect lane markings.) It should be noted that beyond this dual-feature camera-based FCA-LDW possibility, additional camera-based features are also emerging and under development (e.g., Automatic High Beam Headlighting Control, Traffic Sign Recognition, etc.) that are enabling multi-feature, forward-looking camera system functionality.

Regardless of the FCA sensing approach employed, the FCA-equipped vehicle (referred to as the "Host Vehicle") must be capable of detecting, classifying, tracking and monitoring "Objects of Interest" (typically considered to be licensable vehicles such cars, trucks, motorcycles, etc.). In addition, the FCA sensor must be able to discriminate these objects from all other objects (e.g., signs, road markings, roadside clutter/ litter, snow, etc.) in the forward scene. The ability to correctly classify and discriminate objects of interest from all other objects, as well as alert suppression methods, is critical to minimize issuing unwanted false alerts to the driver. Alert suppression methods may include using the brake signal and accelerator pedal position to infer that the driver is attentive.

The FCA system uses a variety of Host Vehicle signals to improve and monitor system performance (e.g., vehicle velocity, headlamp status, windshield wiper status, steering angle, vehicle yaw rate, brake switch status). For example, the FCA system uses information from the Host Vehicle to estimate its trajectory. When lead vehicles (referred to as "Target Vehicles") are identified, the trajectories of these Target Vehicles are also estimated. When these estimated trajectories predict a collision course between the Host Vehicle and Target Vehicle, a measure of crash threat (e.g.,

Time-to-Collision or TTC) can be determined and then compared to the criterion used to trigger the FCA warning. In addition, the FCA system must also be able to determine when conditions (e.g., due to sensor blockage or adverse weather) are beyond the capabilities of the sensor and be able to notify the driver of these conditions.

The remainder of this paper discusses the development and initial testing results from a FCA sensing approach that uses a forward-looking camera as the sole FCA sensing mechanism.

DEVELOPING A CAMERA-BASED FORWARD COLLISION ALERT SYSTEM

In sharp contrast to FCA systems that use either radar or lidar as the primary sensing mechanism, the camera-based FCA system uses machine vision algorithms to analyze the image of the roadway scene ahead and determine crash threats. The following section describes the camera-based FCA sensing approach using the block diagram shown in Figure 1, with a particular focus on describing the more unique aspects of this camera-based approach.

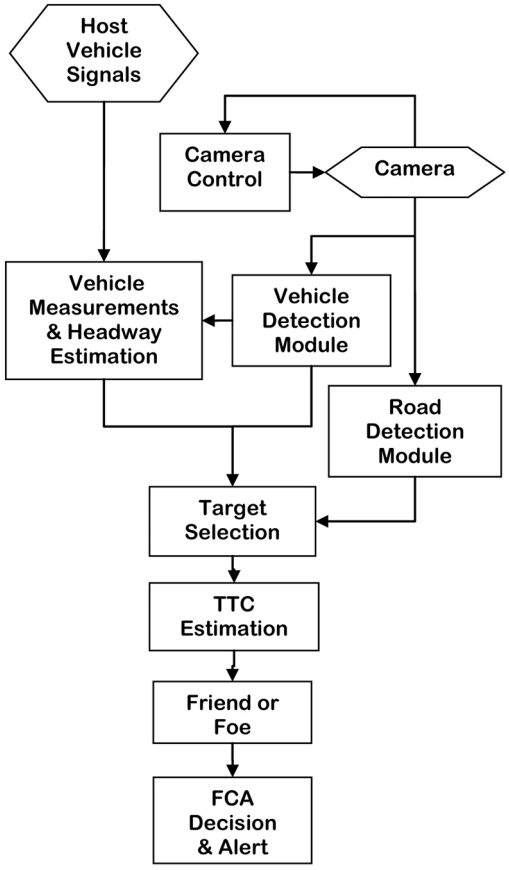

Figure 1. Block Diagram of the Camera-Based FCA sensing approach

CAMERA

Image sensing and algorithm processing can all be performed in one box. The camera proposed to provide FCA functionality is an automotive CMOS imaging sensor with a customized lens. As illustrated in Figure 2, this camera module can be mounted to the windshield or to the structure above the windshield. An example of a camera/processor module is shown below.



Figure 2. Forward Collision Alert Camera Sensor

CAMERA CONTROL

Camera-based FCA systems impose very specific requirements on the camera and the images generated by the camera. Providing satisfactory images across the wide range of lighting and weather conditions that are desirable for FCA systems to operate are a formidable challenge. For example, good textural separation on all vehicle targets in the forward scene is desirable to allow proper detection, extraction of vehicle features, and to enable tracking objects across consecutive image frames. In addition, lane marker detection (which is used to establish the lane assignment of the Target Vehicle) requires that sufficient lane marker contrast is maintained on the road in front of the vehicle out to a distance (e.g., 100 m) in front of the Host Vehicle. Even though many daytime driving scenes could be potentially addressed by a single exposure setting, scenes with more complex lighting conditions, (e.g., strong shadows, tunnel exits, or low sun angles) drive the need for the camera-based system to have multiple exposure settings even during daytime driving conditions. (See Stein, Gat, and Hayon (2008) for further a discussion of this issue.)

Extracting FCA-relevant camera-based information from nighttime driving scenes is particularly challenging since the task of the texture- based analysis has very conflicting exposure demands relative to the task of light source detection and tracking. The texture-based analysis, which involves extracting information from objects ahead and from the surface of the road (e.g., vehicle classification, lane mark detection, etc.) implies a need for longer camera exposure. In contrast, the task of obtaining good separation of neighboring

light sources (e.g., distant taillight and street lights) implies a need for shorter camera exposure.

To address the need for multiple camera exposure settings in order to obtain satisfactory forward scene images across a broad illumination range, a scheme was developed by which the camera switches among four different exposure settings. This set of four exposures are interleaved, giving a combined frame rate of about 14 frames per second for a set of four images of different exposures. In addition, these exposure settings are dynamically controlled to best utilize the effective dynamic range in the current scene.

VEHICLE DETECTION

For each frame (consisting of four exposure images) a process, referred to as the **Attention Mechanism** is executed to look for candidate Target Vehicles. This process involves searching images of relevant exposure and finding rectangles in the image that qualify as having vehicle-like characteristics. This process can produce a large amount of candidate rectangles, some of which may be redundant and others that may contain objects of non-interest (see Figure 3). At night-time, an additional process is used that involves searching the relevant exposure images for pairs of light sources that are deemed to have a high probability of being taillights of a Lead Vehicle. This vehicle classification algorithm has very strong generalization capabilities since it has been developed based on a very large data set of known examples that cover a wide range of appearance possibilities. The Target Vehicle candidates are tracked over time along with metrics (e.g., classification scores, consistency across time, etc.) that measure the likelihood that the tracked candidate is indeed a real vehicle.

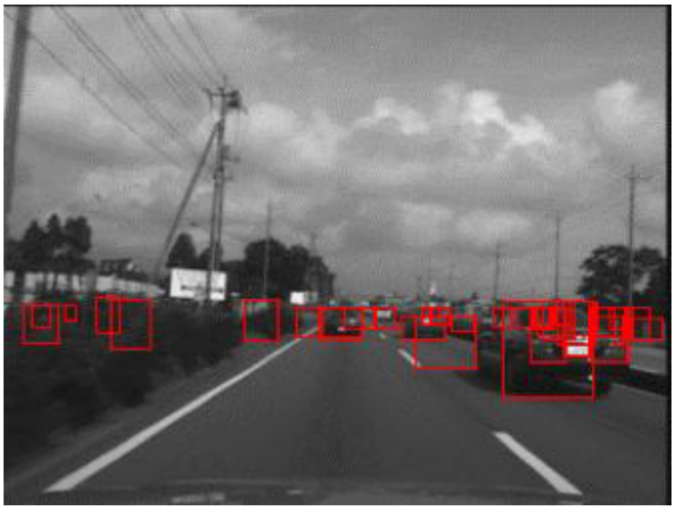

Figure 3. Candidate Targets for Processing

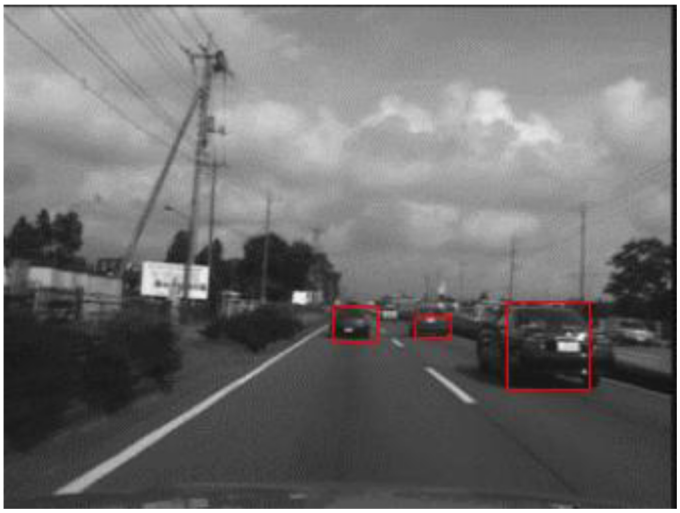

Figure 4. Approved Targets for Processing

HOST VEHICLE SIGNALS / VEHICLE MEASUREMENTS & HEADWAY ESTIMATION

The camera-based FCA system requires information from other systems on the Host Vehicle such as the vehicle velocity, headlamp status and windshield wiper status. Additional Host Vehicle information such as steering angle, vehicle yaw rate and brake switch status can enhance the performance of the camera-based FCA system.

Each Target Vehicle candidate is tracked over time providing the system with sub-pixel accuracy of object motion within the image, covering both translation and scale change (rate of expansion of the object in the image). These measurements, as well as the object position in the image and the estimated vehicle class (e.g., car versus truck) are provided as input to a Dynamics Model filter. Inputs on Host Vehicle dynamics (longitudinal and lateral), estimated camera pitch changes, and an estimated model of the vertical road surface geometry are also provided as input to this filter.

A Hidden Markov Model (HMM) filter generates and updates the estimated real-world position and dynamics of each Target Vehicle. This is done during the vehicle candidate stage, prior to when the vehicle has been approved as real vehicle. The HMM employs different visual cues as inputs, such as the Target Vehicle size and position in the image, as well as the rate at which the Target Vehicle size is changing. These inputs are combined with prior knowledge of camera height, vehicle type (using appearance classification), and Host Vehicle speed and steering data to update the hypothesis of Target Vehicle dynamics.

Given the results of the Dynamics Model filter, the motion of each Target Vehicle candidate is also analyzed to define its

motion status (e.g., stationary, moving, or oncoming). This signal is used in the target selection process and can also be used in the FCA decision stage to implement different alert trigger criterion based on this assumed motion status. A time headway measure is derived directly from the estimated distance to the Target Vehicle (taken from the Dynamics Model) divided by the Host Vehicle velocity.

TARGET SELECTION / ROAD DETECTION

As Target Vehicles transition from being a candidate to an approved Target Vehicle (which have corresponding estimated positions and speeds), the next step is to determine which Target Vehicles (if any) are within the predicted path (or trajectory) of the Host Vehicle (see Figure 4). Target Vehicles that are not within this path are not relevant for an FCA warning. The predicted path of the Host Vehicle relies on two sources of (possibly conflicting) information; the road lanes as defined by the lane markings ahead (and a road geometry model) and the predicted Host Vehicle path (based on Host Vehicle steering angle, yaw and speed). The target selection process combines these two sources of information to assign for each vehicle a probability that a vehicle is a relevant Target Vehicle for potential warning. When the FCA-equipped vehicle is above the minimum operating speed (e.g., above 25 MPH), a green "Vehicle Ahead" symbol is typically used to indicate to the driver that such a Target Vehicle has been detected, and hence, that a FCA warning can occur. In cases where lane markings are not available, Host Vehicle steering and speed information is used to predict the path of the Host Vehicle.

TTC ESTIMATION

TTC estimation is used for assessing whether an imminent, closing conflict FCA warning is merited. The FCA camera sensor estimates TTC based on object scale change without the need to estimate the position, speed and acceleration of either the Host Vehicle or the Target Vehicle (or relative velocity or relative acceleration). TTC is calculated using a constant acceleration assumption approach, as well as a constant speed assumption approach. The former approach assumes that the current relative acceleration will be maintained until the estimated collision time, whereas the latter approach (sometimes referred to as "simple TTC" or "momentary TTC") assumes the current relative speed difference (without regard to acceleration of the vehicles) will be maintained until the estimated collision time. Both TTC estimation approaches assume that if the Target Vehicle comes to a stop prior to this collision time, the Target Vehicle is assumed to remain stopped and the remainder of the event continues by assuming a constant relative velocity between the vehicles.

This TTC estimate is accomplished by using state-of-the-art tracking methods to measure the rate at which the relevant object expands (or looms) in size in the image. By tracking the pattern of a object (e.g., a Target Vehicle) and the features on that object from frame-to-frame (e.g., taillights, license plate, and other texture on the vehicle), and measuring the rate at which they change in size relative to one another, one can estimate the change in the object size within the image relative to its actual size to derive TTC estimates. In order to incorporate relative acceleration into the TTC estimate, a geometric model (which assumes a constant acceleration) is also applied to the observed growth rate information. The rate of object growth is used to estimate when the object will reach infinite size in the image (and hence, the time until the object reaches the camera). In order to correct for the distance between the camera image and the front bumper, a minor extension of this approach is needed. Further details on this TTC estimation process are provided in the Appendix and in Dagan, Mano, Stein, and Shashua (2004).

A constant acceleration approach is reactive to changes in dynamics between the Host Vehicle and Target Vehicle (e.g., during lead vehicle braking conditions), but is sensitive to noise associated scale change signal, as it depends on estimated changes in the signal (i.e., the signal derivative). In contrast, the constant velocity approach provides a more conservative (i.e., higher) TTC estimate, since it does not take into account Target Vehicle deceleration and reacts slower to changes in relative velocities. On the other hand, this approach is less sensitive to noise associated with the scale change signal. Together, the constant acceleration and constant velocity approaches to estimating TTC, along with certainty measures associated with each approach, are used to estimate TTC. This value is then compared to a pre-defined TTC-based threshold for triggering the alert associated with the FCA system. These TTC thresholds can be adjusted based on the current vehicle dynamic conditions. These thresholds define the alert timing (or sensitivity) level of the FCA feature.

As indicated earlier, the calibration of the TTC thresholds is of primary importance for achieving an effective and well-accepted FCA system. For this reason, the FCA system may also employ a FCA timing (or sensitivity) control, which may also incorporate the ability to turn the FCA system OFF. Based on naturalistic driving data (Automotive Collision Avoidance System Field Operational Test Report: Methodology and Results, 2005), drivers strongly prefer the capability of adjusting FCA system alert timing and use such a capability when it is made available. Multiple factors can cause drivers to adjust FCA sensitivity, including traffic conditions, weather conditions, whether they are in a rush, and their perceived state of alertness (e.g., tired versus alert). Providing the driver with FCA timing adjustment capability can also serve to mitigate potential annoyance associated with FCA warnings by allowing the driver some control over the

number/rate of alerts perceived as unnecessary (e.g., "too early" alerts or alerts due to out of path vehicles or objects) and may also help ensure that the driver does not turn the FCA system OFF (e.g., if only one FCA setting is provided).

FRIEND OR FOE

Given that TTC threshold has been met for triggering an alert to a Target Vehicle within the Host Vehicle's lane, one still needs to establish whether at the time of longitudinal convergence, the lateral position of the Host Vehicle and Target Vehicle will be such that a collision would occur. For example, the vehicles may quickly veer off a collision course path either due to Host Vehicle lateral motion (e.g., when initiating a passing maneuver) or a Target Vehicle steering maneuver (e.g., turning out of the Host Vehicle's path). To establish a lateral convergence decision, a mechanism called **Friend or Foe** uses Host Vehicle and Target Vehicle motion dynamics (e.g., yaw and yaw rate change) to estimate the lateral relative position of the Host Vehicle and Target Vehicle at the time of longitudinal convergence (as determined by the TTC value), and will suppress an FCA warning if lateral convergence is not predicted.

FCA DECISION AND ALERT

The imminent, FCA closing conflict alert is issued if the pre-defined TTC threshold for a closest in-path Target Vehicle is met and there is a "Friend or Foe" process confirmation that the Host Vehicle and Target Vehicle will laterally converge at the time of longitudinal convergence. This alert should consist of both a flashing visual alert and non-visual alert (e.g., auditory beeps and/or haptic cues). The requirement for both visual and non-visual FCA imminent closing alerts is based on the following rationale. First, drivers may not hear crash alert sounds either due to hearing impairments (e.g., older, hearing-impaired drivers or deaf drivers) and/or competing noises coming from either inside the vehicle (e.g., children making noise, loud music) or outside the vehicle (e.g., noisy trucks). Similarly, drivers may not perceive accompanying haptic crash alerts under certain conditions. Second, the visual alert can serve to help explain non-visual crash alerts to the driver, which may rarely occur with FCA systems for some drivers. Third, when properly designed, a FCA visual alert can facilitate the driver to look toward and attend to the direction of the forward crash threat so that they can quickly determine what action (if any) to take. With respect to the positioning of the FCA imminent closing alert, recent driver performance studies (Lind, 2007; Perez, Kiefer, Haskins, and Hankey, 2009) support the SAE J2400 (Society of Automotive Engineers, 2003) recommendation advising against the use of the instrument panel location for this FCA visual closing alert, and support the use of either a HUD or a "high" top of dashboard location for the positioning of this visual alert (as shown in Figure 5).



Figure 5. FCA Imminent Closing Alert Display

PERFORMANCE ASSESSMENT OF THE CAMERA-BASED FORWARD COLLISION ALERT SYSTEM

The initial vehicle-level performance assessment of the camera-based FCA system included both highly controlled, test track tests and less controlled, in-traffic, public road testing. The test track tests examined if and when an alert was issued under valid crash threat conditions, whereas in-traffic, naturalistic driving testing was conducted primarily to assess the false alarm-related performance of the FCA system under a much richer set of (vehicle-to-vehicle) kinematic, surrounding traffic, roadway geometry, and weather conditions than could be readily accomplished under test track conditions. An overview of the results from this initial performance assessment will now be provided.

NCAP FORWARD COLLISION WARNING CONFIRMATION TEST REQUIREMENTS

More recently, the United States Department of Transportation's (US DOT) National Highway Transportation Safety Administration (NHTSA) has enacted a consumer metric for Collision Avoidance technologies. Starting with the 2011 model year, NHTSA will inform the public of the availability of Lane Departure Warning, Forward Collision Alert and Electronic Stability Control on light vehicles at the www.safercar.gov website. While voluntary, the creation of this consumer metric is intended to encourage automakers to offer FCA available on more vehicles and increase the penetration of the FCA feature across the vehicle fleet. NHTSA has defined test procedures and performance metrics for FCA systems, which are described in the New Car Assessment Program (NCAP) Forward Collision Warning (FCW) confirmation test requirements (Forward Collision Warning System Confirmation Test, 2008).

An overview of these NCAP FCW requirements is provided in Table 1. The FCW system must meet each of three crash alert test requirements in order for the vehicle to be listed at

the website as having this feature. These three tests correspond to three of the four FCA applicable pre-crash scenarios (Lead Vehicle Stopped, Lead Vehicle Decelerating, and Lead Vehicle Moving at a Lower Constant Speed) discussed above and described in Najm, Smith, and Yanagisawa (2007). Each of the tests is to be conducted under clear, daytime weather conditions and involve the FCA-equipped vehicle approaching a Lead Vehicle on a straight road at 45 MPH (72.4 kph). Furthermore, an alert must be issued prior to the time-to-collision (TTC) criterion associated with each test (shown in Table 1) in at least five of seven test trials, and must not fail to meet the criterion on two consecutive trials.

Table 1. Overview of United States Department of Transportation New Car Assessment Program (NCAP) Forward Collision Warning (FCW) confirmation test requirements

NCAP FCW Test	Following Vehicle / Lead Vehicle Speeds	Time-to-Collision Requirement
Lead Vehicle Stopped (LVS)	45 MPH (72.4 kph) / 0 MPH (0 kph)	2.10 sec
Lead Vehicle Decelerating (LVD); (vehicles coupled at 30 m distance when lead brakes at 0.3 g's)	45 MPH (72.4 kph) / 45 MPH (72.4 kph)	2.40 sec
Lead Vehicle Moving (LVM) at a Lower Constant Speed	45 MPH (72.4 kph) / 20 MPH (32.2 kph)	2.00 sec

In order to initially assess the crash alert test performance of the FCA camera system, this system was subjected to each of the three NCAP FCW confirmation tests shown in Table 1. It should be noted that the focus of this preliminary assessment was to determine if the FCA camera sensor was capable of providing alerts that met the requirements of these tests, rather than to necessarily optimize alert timing. Based on the Lead Vehicle Stationary test described in Table 1, the FCA camera system must be capable of issuing an alert at a theoretical minimum of 42 meters. However, prior to issuing this alert, the FCA sensor must detect, classify, and estimate the range (TTC) to the Target Vehicle and accommodate various system latencies (i.e., network communication, interface delays, etc.) Consequently, in order to ensure robust operation, the FCA camera system needs to detect, classify and estimate the range (TTC) to the target lead vehicle at a range of approximately 60 meters (which corresponds to 3.0 seconds TTC under the NCAP FCW Test 1 conditions shown in Table 1).

The NCAP FCW tests were conducted at the General Motors Milford Proving Grounds (in Milford, Michigan) using a high accuracy, differential GPS-based approach for ground-truthing purposes. The results provided in Figure 6 are based on the ground-truth measurement. After this testing was completed, further work was conducted to assess the latency between the alert request and when the auditory alert was actually issued. Results indicated an average auditory alert latency of 0.12 sec, with a corresponding standard deviation of 0.04 seconds. Consequently, this average latency value was subtracted from the observed TTC at alert request to calculate the observed TTC at alert onset.

Figure 6 provides the mean TTC at alert onset for each of the three FCW NCAP tests, as well as the individual test trial results. Even if one assumes a 200 ms speaker latency (84 ms longer than what was assumed), these results indicate the FCA camera system tested would meet the NCAP FCW confirmation test requirements for each of the three required tests. In addition, as shown in Figure 6, the FCA camera alert timing across tests, as well as the associated variability of this alert timing across these tests, compare favorably relative to results recently reported for three production radar-based FCW systems on these exact same NCAP FCW tests (Forkenbrock and O'Harra, 2009).

NATURALISTIC DRIVING ASSESSMENT

In order to initially assess the public road, in-traffic performance of the FCA camera system, this system was subjected to 2317 miles of naturalistic driving, which consisted of 83% daytime driving and 17% nighttime driving. From a roadway type perspective, 50%, 33%, 16%, and 2% of the driving was conducted under interstate, urban, city, and rural roads, respectively. In addition, rain was present during 12% of this driving. The radar on the test vehicle was used for ground-truthing purposes.

Results from this testing were encouraging and indicated the following. First, no false alarm FCA closing alerts were observed. Second, false "vehicle detect" indications (e.g., due to vehicles in adjacent lanes or oncoming vehicles) were observed at a rate of once every 129 miles. Third, 96% of vehicle detections observed by the FCA radar within 60 meters of the vehicle were also observed by the FCA camera system, and 90% of vehicle detections observed by the radar within 90 meters of the vehicle were also observed by the FCA camera system. Fourth, time headway (error) was overall 9% and 11% for vehicles detected within 0-60 meter and 60-90 meter ranges, respectively.

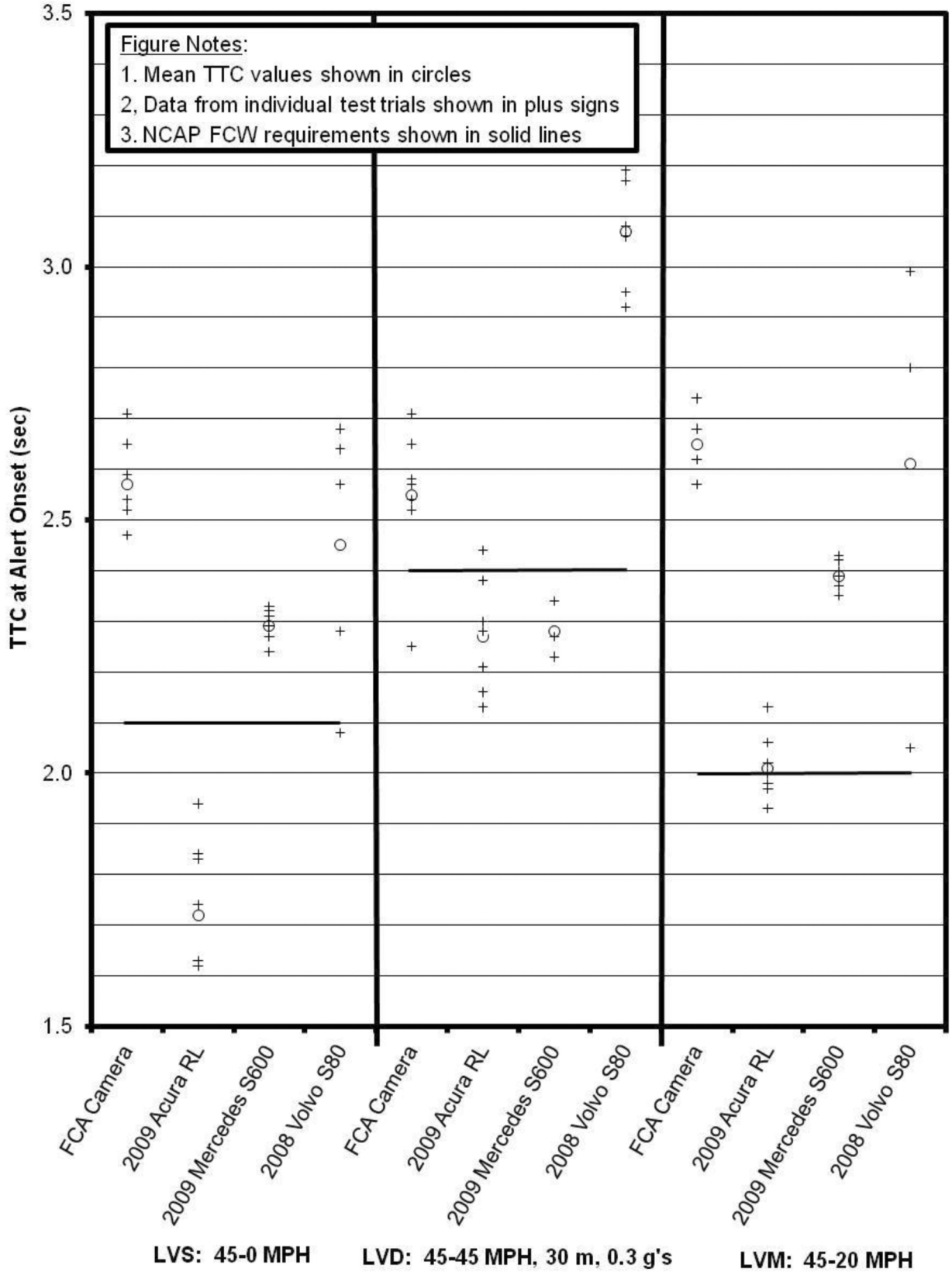

Figure 6. New Car Assessment Program (NCAP) Forward Collision Warning (FCW) confirmation test requirements results for the Forward Collision Alert camera-based system under development, as well as corresponding results for production FCW system reported by Forkenbrock and O'Harra (2009)***.***

SUMMARY/CONCLUSIONS

This paper discussed the development and initial testing results from an alternative FCA sensing approach that uses a forward-looking camera rather than a radar/lidar device as the sole Forward Collision Alert (FCA) sensing mechanism. The FCA system provides alerts intended to assist drivers in avoiding or mitigating the harm caused by rear-end crashes. With respect to the harm caused by light vehicle crashes in the United States, the rear-end crash problem can be characterized as accounting for 28% of police-reported crashes, 22 % of the economic cost, and 15% of the functional years lost (based on crash data reported by Najm, Smith, and Yanagisawa (2007)). Consequently, these crash data suggest that it is important to continue to develop alternative FCA systems (e.g., a camera-based system) that are not only effective and well-accepted, but also systems that are affordable and promising for increasing deployment across the entire vehicle fleet.

This paper also provided a discussion of the camera requirements and desired input signals needed for the camera-based FCA feature. In addition, a description was provided on how the system detects and approves lead vehicle candidates, projects collision course trajectories between vehicles, and estimates TTC (using image scale change principles) for the purposes of identifying potential rear-end crash situations.

Results from test track and public road testing support deployment of a camera-based FCA system, and indicate this system would meet the United States Department of Transportation New Car Assessment Program (NCAP) Forward Collision Warning confirmation test requirements. It should be stressed that beyond this initial testing, additional testing is needed to address a number of additional scenarios. For example, testing should be conducted under a broader range of vehicle-to-vehicle kinematic conditions, night-time driving, curved roads, and inclement weather conditions.

As discussed above, the conditions under which most rear-end crashes occur (e.g., clear weather, at posted speeds of less than 45 MPH) suggests that the camera-based FCA system provides a promising approach to reduce the harm caused by rear-end crashes. In addition, a camera-based FCA feature approach may facilitate increasing deployment across the fleet owing to the affordability of camera systems and the coupling of this feature with the Lane Departure Warning feature and other emerging camera-based features (e.g., Automatic High Beam Headlighting Control, Traffic Sign Recognition, etc). Finally, as imaging sensors continue to improve (wider dynamic range, larger pixel array size, etc) and machine vision algorithms are further developed, it is reasonable to expect efforts will be made to develop collision mitigation braking, ACC, and other features based solely on camera-based technology.

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APPENDIX

TIME-TO-COLLISION (TTC) ESTIMATION USING SCALE CHANGE

Time-to-Collision (TTC) can be estimated directly from image domain measurements without the need to estimate the position, speed, and acceleration of either host (i.e., FCA-equipped) vehicle or the target (i.e., lead) vehicle. This is accomplished by accurately measuring the rate at which the relevant "object of interest" (e.g., the target vehicle) grows in size in the image. By tracking the pattern of a rigid object and the features of the object (e.g., taillights) and measuring the rate at which they change in size (e.g., expand) relative to one another, one can achieve with sub-pixel accuracy an estimator of the term ***ds***, which is defined to be the change in the object scale relative to its actual scale (defined as ***w***, in pixel units).

$$ds = \frac{(w_2 - w_1)}{w_1} = \frac{w_2}{w_1} - 1$$

Equation (1)

Using pinhole geometry equations, as shown in Equation 2, ***w*** can be expressed as the product of the focal length (**focal** in pixel units) and the actual width that the pattern tracked occupies in the world (**W** in meters) divided by the distance from the camera to the target (**Z** in meters). As shown in Equation 3, if one substitutes ***w*** from Equation 2 into Equation 1, ***ds*** also equals (ignoring the change in sign) the change in distance to the target between the tracked frames relative to the distance obtained at the latter frame.

$$\frac{W}{Z} = \frac{w}{focal} \Rightarrow w = \frac{W \cdot focal}{Z}$$

Equation (2)

$$ds = \frac{(w_2 - w_1)}{w_1} = \frac{\left[\frac{1}{Z_2} - \frac{1}{Z_1}\right] \cdot W \cdot focal}{\frac{1}{Z_1} \cdot W \cdot focal} = \frac{(Z_1 - Z_2)}{Z_2}$$

Equation (3)

Now if one divides ***ds*** in Equation 3 by the time interval between the two tracked frames (defined as ***dt*** in seconds), this gives an expression shown in Equation 4 that under the assumption of constant acceleration (***a*** in m/sec^2) dynamics is equivalent to relative velocity at the mid-point between the frames tracked

$$\frac{ds}{dt} = \frac{\frac{-(Z_2 - Z_1)}{dt}}{Z_2} = \frac{\frac{-\left(\left[Z_1 + v_1 \cdot dt + \frac{a}{2} dt^2\right] - Z_1\right)}{dt}}{Z_2}$$

$$= \frac{-(v_1 + a\frac{dt}{2})}{Z_2} = \frac{-V(t = now - \frac{1}{2} dt)}{Z_2}$$

Equation (4)

If one then uses two ***ds/dt*** measurements tracked from two different frames into the current frame, which have corresponding two different mid-points ***t1*** and ***t2***, one can estimated acceleration ***a*** as shown in Equation 5:

$$a = \frac{v_2 - v_1}{t_2 - t_1} = Z_{current} \cdot \left(\frac{\left(\frac{-ds_2}{dt_2}\right) - \left(\frac{-ds_1}{dt_1}\right)}{t_2 - t_1} \right)$$

Equation (5)

As shown in the series of equations below, if one assumes a constant acceleration, it is then straightforward to express the current relative velocity ($V_{current}$) as a function of ***a***, the current distance ($Z_{current}$) and one of the scale change measurements (***ds/dt***).

$$V_{current} = V_2 + a \cdot (t_{current} - t_2)$$

Equation (6)

$$V_{current} = \frac{-ds_2}{dt_2} \cdot Z_{current} + a \cdot (t_{current} - t_2)$$

Equation (7)

As shown in the series of equation provided below, it is then possible to express the constant acceleration equation used for estimating **TTC** with expressions that contain only Z and ***ds/dt*** measurements. Since Z is non-zero, the equation can be divided by Z to derive a quadratic equation that contains only scale change measurements.

$$Z(ttc) = 0 = Z + v_{current} \cdot ttc + \frac{a}{2} \cdot ttc^2$$

Equation (7a)

$$0 = Z + \left[Z \cdot \frac{-ds_2}{dt_2} + a \cdot \left(t_{current} - t_2\right) \right] \cdot ttc + 0.5 \cdot \left[Z \cdot \left(\frac{\frac{-ds_2}{dt_2} - \frac{-ds_1}{dt_1}}{t_2 - t_1} \right) \right] \cdot ttc^2$$

Equation (7b)

$$0 = Z + \left[Z \cdot \frac{-ds_2}{dt_2} + Z \cdot \left(\frac{\frac{-ds_2}{dt_2} - \frac{-ds_1}{dt_1}}{t_2 - t_1} \right) \cdot \left(t_{current} - t_2\right) \right] \cdot ttc + 0.5 \cdot Z \cdot \left[\frac{\frac{-ds_2}{dt_2} - \frac{-ds_1}{dt_1}}{t_2 - t_1} \right] \cdot ttc^2$$

Equation (7c)

$$0 = 1 + \left[\frac{-ds_2}{dt_2} + \left(\frac{\frac{-ds_2}{dt_2} - \frac{-ds_1}{dt_1}}{t_2 - t_1} \right) \cdot \left(t_{current} - t_2\right) \right] \cdot ttc + 0.5 \cdot \left[\frac{\frac{-ds_2}{dt_2} - \frac{-ds_1}{dt_1}}{t_2 - t_1} \right] \cdot ttc^2$$

Equation (7d)

Consequently, all the information needed to calculate TTC with a camera is encoded in the scale change signal and its change (or derivative) over time. Hence, this approach is robust to (and immune to) the image-to-real world conversions that would be needed to estimate distance, velocity, and acceleration, and the noise factors surrounding such conversions.

One extension to this approach is needed to estimate the TTC to the front bumper (rather than the camera), which is located a defined distance (*X*) in front of the camera position. (Note this distance is a calibration parameter of the system.) In this extension shown in the series of equations below, TTC is defined as the time it will take until ***Z(ttc) = X***.

$$Z(ttc) = X = Z + v_{current} \cdot ttc + \frac{a}{2} \cdot ttc^2$$

Equation (8a)

$$X = Z + \left[Z \cdot \frac{-ds_2}{dt_2} + a \cdot \left(t_{current} - t_2\right) \right] \cdot ttc + 0.5 \cdot \left[Z \cdot \left(\frac{\frac{-ds_2}{dt_2} - \frac{-ds_1}{dt_1}}{t_2 - t_1} \right) \right] \cdot ttc^2$$

Equation (8b)

$$0 = Z - X + \left[Z \cdot \frac{-ds_2}{dt_2} + Z \cdot \left(\frac{\frac{-ds_2}{dt_2} - \frac{-ds_1}{dt_1}}{t_2 - t_1} \right) \cdot \left(t_{current} - t_2\right) \right] \cdot ttc + 0.5 \cdot Z \cdot \left[\frac{\frac{-ds_2}{dt_2} - \frac{-ds_1}{dt_1}}{t_2 - t_1} \right] \cdot ttc^2$$

Equation (8c)

$$0 = 1 - \frac{X}{Z} + \left[\frac{-ds_2}{dt_2} + \left(\frac{\frac{-ds_2}{dt_2} - \frac{-ds_1}{dt_1}}{t_2 - t_1} \right) \cdot \left(t_{current} - t_2\right) \right] \cdot ttc + 0.5 \cdot \left[\frac{\frac{-ds_2}{dt_2} - \frac{-ds_1}{dt_1}}{t_2 - t_1} \right] \cdot ttc^2$$

Equation (8d)

Note that this extension approach depends on the estimation of distance (***Z***). Nonetheless, since some arbitrary length measurement unit exists for which the current estimation is correct, the impact of the distance inaccuracy can be quantified in term of how this measurement unit relates to 1 meter (***X*** is measured in meters). In effect, this means that the TTC will be correct as the estimation of TTC to a point that is ***X*** such measurement units from the camera. Since ***X*** is approximately 2 meters, even a distance error of 10% will have a relatively minor impact on TTC estimation; since such an error will only result in a TTC that is calculated to a point that is around 0.2 m away from the actual bumper.

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

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