

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 as 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 COLLISION 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](#)

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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 these 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 directly 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 as 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.

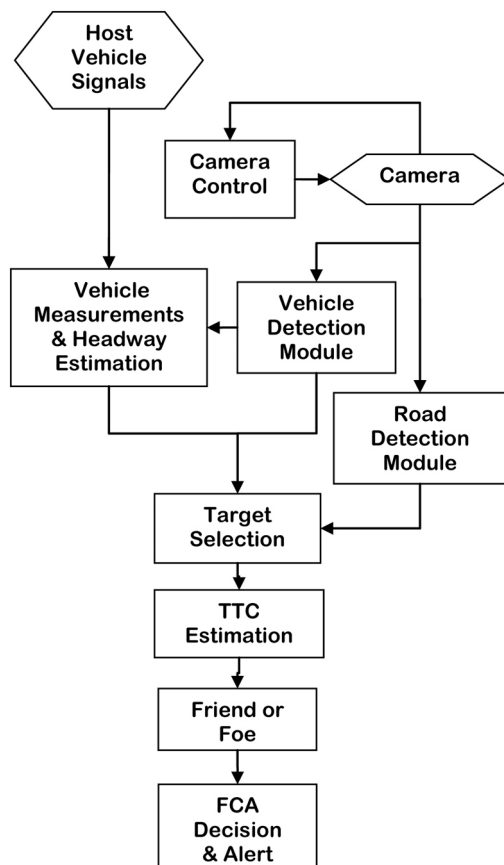


Figure 1. Block Diagram of the Camera-Based FCA sensing approach

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.

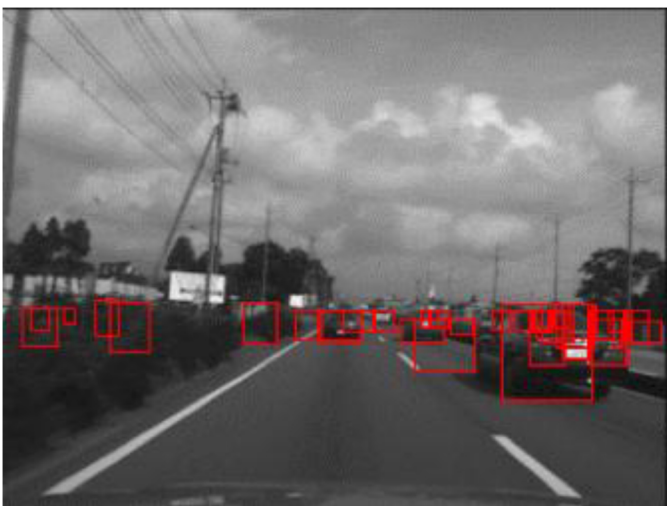


Figure 3. Candidate Targets for Processing

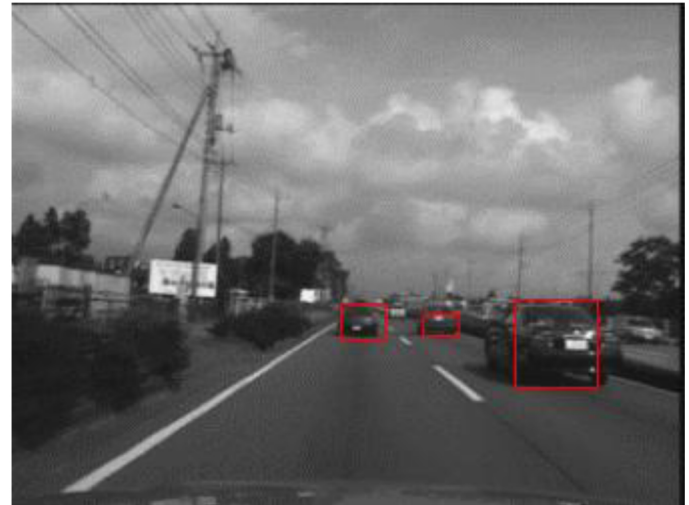


Figure 4. Approved Targets for Processing

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