IVHS COUNTERMEASURES FOR
REAR-END COLLISIONS

LIGHT VEHICLE FORWARD-LOOKING, REAR-END COLLISION WARNING SYSTEM PERFORMANCE GUIDELINES

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ABSTRACT

This document presents performance guidelines for the design and development of forward looking, rear-end, collision warning systems to improve vehicular safety by eliminating or mitigating vehicular rear-end collisions through driver notification or warning. All aspects of performance are addressed including general system requirements, driver / vehicle interface methodology, collision dynamics, standardized testing and estimation of associated benefits.

These guidelines are intended to be used by manufacturers and developers of vehicular based forward-looking, rear-end collision warning systems as a tool to: 1) standardize system requirements, 2) standardize driver interface and control among systems developed by different manufacturers and, 3) standardize testing to be used in verifying proper system operation.

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KEY WORDS

Intelligent Vehicle Highway Systems (IVHS), Intelligent Transportation System (ITS), forward-looking collision avoidance, forward-looking collision warning, driver warning, rear-end collisions, forward-looking rear-end collision warning.

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PREFACE

This document presents performance guidelines for the development of forward-looking, rear-end collision warning systems to improve vehicular safety by elimination or mitigation of vehicular rear-end collisions through driver notification or warning. Numerous variations exist within this category such as adaptive cruise control, automatic collision avoidance, and driver warning system types. This document is specific to those systems designed to detect potential rear-end collisions and provide a warning to the driver to avoid the collision. In addition, guidelines are presented for adaptive cruise control systems as they relate to forward-looking, rear-end collision warning systems.

These guidelines are intended to be used by manufacturers and developers of vehicular based forward-looking, rear-end collision warning systems as a tool to: 1) standardize system requirements, 2) standardize driver interface and control among systems developed by different manufacturers, and 3) standardize testing to be used in verifying proper system operation.

The parameters specified within this document should be considered guidelines for minimum acceptable performance. System performance that significantly deviates from these guidelines will degrade driver acceptance and overall system effectiveness. These guidelines are also intended to be as technology-independent as possible and allow for development of both autonomous and cooperative systems.

This document represents the second generation of performance specifications associated with this forward-looking, rear-end collision avoidance research. It represents a significant change in philosophy from the previous version that provided parametric specifications for a forward-looking, rear-end collision warning system. This change in philosophy is a result of a peer review workshop held in December 1995 to receive feedback from industry participants. The workshop consensus was to provide guidelines associated with system performance rather than specifications. The performance guidelines will focus on "what" the forward-looking, rear-end collision warning system is supposed to do, but not "how" to do it.

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1 INTRODUCTION

This document presents performance guidelines for forward-looking, rear-end collision warning systems (abbreviated FCW) for improving vehicular safety by preventing or mitigating vehicular rear-end collisions through driver notification or warning.

The intent of these guidelines is to aid the developer in the design and deployment of a minimum acceptable system. Systems that significantly deviate from these guidelines, especially in the nuisance and false alarm performance should be considered unacceptable and are not expected to have sufficient user acceptance for deployment in mass marketed passenger vehicles.

1.1 SCOPE

This document is specific to those systems that detect potential rear-end collision situations with both stopped and moving vehicles and provide a warning to the driver as an aid in avoiding the collision. In addition, guidelines are presented for adaptive cruise control systems (ACC) as they relate to FCW systems. Other types of systems such as Automatic Control Systems (ACS) are excluded from the scope of this document, but are addressed in separate reports.

1.2 OBJECTIVE

The objective of a forward-looking, rear-end collision warning system following these guidelines is to increase driver awareness and subsequently reduce deaths, injuries and economic losses resulting from vehicular rear-end collisions. Additionally, forward-looking, rear-end collision warning systems are intended to be compatible with ACC systems as an aid to deployment.

1.3 BACKGROUND

According to data from the General Estimates System (GES) and Fatality Analysis Reporting System (FARS) databases, rear-end collisions are the second largest single category of vehicular collisions. They represent 23% of all collisions, 1.45 million per year out of 6.26 million police reported crashes per year. In greater than ninety percent of rear-end collisions, driver inattention/distraction and/or following-too-closely were contributing factors. This leads to the conclusion that a system which detects and warns the driver of potential rear-end collisions could significantly reduce the number and severity of rear-end collisions.

2 DEFINITIONS

The following definitions form a basis for further discussions of forward-looking, rear-end collision warning systems.

2.1 SYSTEM DEFINITIONS

Rear-end collision -- A rear-end collision is defined as an on-road, two vehicle collision in which both vehicles are moving forward in the same direction prior to the collision or a collision in which the vehicle in the forward path has come to a stop.

Forward-looking, rear-end collision warning system -- A "forward-looking, rear-end collision warning system" (FCW) is a system designed to aid the driver (driver-in-the-loop) in avoiding or mitigating collisions with the rear-end of vehicles in the forward path of travel through driver notification or warning of the impending collision. The FCW system does not attempt to control the host vehicle in order to avoid an impending collision. However, some vehicular control is allowed as a potential method of providing warnings to the driver. The extended title "forward-looking, rear-end collision warning system" was chosen as an aid in developing an accurate mental model of the system. Additionally, this type of system is specific to avoiding collisions with vehicles and is not specifically intended to warn the driver on other types of roadway objects or longitudinal collision scenarios (head-on, etc.).

Host vehicle, Subject vehicle (SV) - Refers to the vehicle on which the forward-looking, rear-end collision warning system is installed and operating.

Lead vehicle (LV), Vehicle in forward path, Principal other vehicle (POV) - Refers to the on-roadway, closest in-path, licensed vehicle that the forward-looking, rear-end collision warning system must detect. The closest in-path vehicle is assumed to be the highest threat vehicle in the forward path.

Relative speed – Relative speed is the speed differential between the lead and host vehicles. A negative relative speed indicates the vehicles are closing and a positive relative speed indicates the vehicles are receding. The term velocity implies a vector quantity (speed and direction) and should not be used in this context.

Closing speed – A variation of the relative speed between the lead and host vehicles, for which a positive value indicates that the distance between the two vehicles is decreasing.

Autonomous system – An autonomous system requires no modifications or additions to the infrastructure or to vehicles in the forward path in order to perform the intended function. An autonomous system only detects objects within its sensor coverage zone. The system only responds to objects visible by sensor line-of-sight from the subject vehicle.

Cooperative system – A cooperative system relies on infrastructure, either other vehicle or roadway based, to perform the intended function.

Automatic Control System -- An "automatic control system" (ACS) is a system that provides temporary control such as braking and/or steering to avoid a collision. These systems are excluded from the scope of this document.

Adaptive Cruise Control -- An "Adaptive Cruise Control" (ACC) system is an extension of conventional cruise control (speed control only) systems found in passenger vehicles today. ACC systems provide a headway maintenance function to control the headway to a vehicle in the forward path by longitudinal control of the host vehicle. ACC systems utilize similar technology to FCW systems and FCW systems may be a superset of ACC systems. These guidelines have been developed in close cooperation with ACC guidelines in order to avoid requirements that would render each system incompatible with the other. ACC systems are also known as Intelligent Cruise Control (ICC) and Autonomous Intelligent Cruise Control (AICC) systems.

Roadway objects **–** Roadway objects are defined as all non-vehicular objects that can be found on-roadway and in-path. Included in this definition are bicycles, skateboards, pedestrians, debris, etc.

Roadside objects **–** Roadside objects are defined as all stationary objects that are out-of-path. Roadside objects include: curbs, guardrails, trees, shrubs, signs, poles, vehicles parked off-road, overhead objects, etc.

On-road **–** Defines all manner of driving on public and private roadways, and includes driving environments such as driveways, alleys, and parking lots, etc. that are common for vehicular travel. On-road defines all objects and vehicles that are physically on the road surface. This includes embedded roadway objects such as manhole covers and objects normally found on the road surface such as pedestrians, vehicles, motorcycles, bicycles, debris, etc. Excluded from this definition are roadside objects.

In-path, Forward-path **–** In-path is defined as the predictable path forward of the host vehicle that remains on-road out to the sight distance of the driver. The forward-path includes the road surface and the volume above the road surface up to the height of the vehicle.

Range **–** Range is defined as the distance from the front of the host vehicle to the rear of the vehicle in the forward path.

Acquisition Range **–** The acquisition range is defined as the maximum sensor range at which the vehicle in the forward path can be reliably detected within the system delay time required for system performance.

Coupled Headway **–** Coupled headway driving occurs when the host vehicle is following the lead vehicle at or near zero relative speed.

2.2 DRIVER DEFINITIONS

Mental model – The mental model refers to the system performance that would reasonably be anticipated by a naïve (untrained) driver of the FCW system. Drivers would reasonably expect a forward-looking, rear-end collision warning system to behave like an "ever-vigilant" observer who monitors the road ahead of the vehicle and only provides warnings when necessary to assist in avoiding rear-end collisions. The observer is defined as someone with the same driving habits and abilities as the driver. The mental model of the system includes warning the driver in following-too-closely (tailgating) scenarios.

Attentive driver – The driver of the subject vehicle is alert and is in full control of the subject vehicle. The driver is able to perceive the forward scene and is capable of making corrections to the vehicle to avoid collisions with other vehicles without the assistance of notifications or warnings.

Inattentive / distracted driver – The driver of the subject vehicle is not focused on the longitudinal control portion of the driving task. Inattentive or distracted drivers are assumed to have longer reaction times than attentive drivers. Inattention may be detectable by certain physiological sensors (if available), distraction may be detected by other means.

Imminent warning - An imminent collision avoidance situation is one in which the potential for a collision is such that it requires an immediate vehicle control response or modification of a planned response in order to avoid a collision.[1]

Cautionary warning - A cautionary collision avoidance situation is one in which the potential for a collision requires immediate attention from the driver, and may require a vehicle maneuver but does not meet the definition of an imminent crash avoidance situation. The cautionary warning also may include the following-too-closely (tailgating) warning.

Following-too-closely – A following-too-closely (tailgating) situation is one in which the driver of the host vehicle is following a lead vehicle at a constant (near zero) relative speed and at a range (time) that may not provide for adequate avoidance maneuvers if needed.

[1] "Preliminary Human Factors Guidelines for Crash Avoidance Warning Devices" COMSIS, 1993

Efficacy rate – Efficacy rate is defined as the number of times the system provides a correct warning compared to the number of times that a warning is required according to the following table. Efficacy rate is also known as the "hit" rate and the complement is known as the "miss" rate.

System Response	**Situations requiring a warning**	**Situations in which a warning is not required**
Warning	Correct Warning (hit or true positive)	Incorrect Warning (false alarm or false positive)
No Warning	Incorrect Non-Warning (miss or false negative)	Correct Non-Warning (true negative)

False Alarm - False alarms are incorrect warnings that occur when the system does not function as expected such as misinterpreting roadside objects as threats.

Nuisance Alarm - Nuisance alarms are warning indications that occur when the system functions as expected but when the situation does not constitute a true crash threat for the driver in question, i.e. driver disagrees with the need for the warning or the timing of the warning. The nuisance alarm potential is directly proportional to the intrusiveness of the warning display methodology. From the driver's perspective, nuisance alarms and false alarms may appear to be the same but the causes and remedies are different.

Misses - Misses occur when the situation requires a warning but the system does not provide a warning to the driver.

2.3 APPLICABLE DOCUMENTS

The following list of documents that contain closely related information associated with the development of these guidelines.

"Assessment of IVHS Countermeasures for Collision Avoidance: REAR-END CRASHES", NHTSA May 1993

"Rear-End Crashes: Problem Size Assessment and Statistical Description" USDOT, NHTSA, OCAR, May 1993.

Task 1 Interim Report for IVHS Countermeasures for Rear-End Collisions, Frontier Engineering Inc., "Thorough analysis of the crash problem", NHTSA Project No. DTNH22-93-C-07326, Volumes I-VI, February 1994.

Task 2 Interim Report for IVHS Countermeasures for Rear-End Collisions, Frontier Engineering Inc., "Establish Functional Goals", NHTSA Project No. DTNH22-93-C-07326, April 1994.

National ITS Program Plan, First Edition March 1995

Task 4 Interim Report for IVHS Countermeasures for Rear-End Collisions, Frontier Engineering Inc., NHTSA Project No. DTNH22-93-C-07326, June 1995.

Task 5 Interim Report for IVHS Countermeasures for Rear-End Collisions, Frontier

Engineering Inc., “State-of-the-Art Technology Reviews”, NHTSA Project No. DTNH22-93-C-07326, July 1996.

Task 6 Interim Report for IVHS Countermeasures for Rear-End Collisions, Frontier Engineering Inc., “Design Testbed System”, NHTSA Project No. DTNH22-93-C-07326, September 1996.

Task 8 Interim Report for IVHS Countermeasures for Rear-End Collisions, Frontier Engineering Inc., “Test Results to Support Development of Performance Specifications”, NHTSA Project No. DTNH22-93-C-07326, November 1997.

“Preliminary Analysis of Driver Warning Time for a Forward-Looking Collision Warning System” IVHS Countermeasures for Rear-End Collisions, Sensor Technologies & Systems Inc., NHTSA Project No. DTNH22-93-C-07326, September 1997.

Wortman, R.H., Matthias, J.S. “Evaluation of Driver Behavior at Signalized Intersections” Transportation Research Record.

Wortman, R.H., Fox, T.C. “An Evaluation of Vehicle Deceleration Profiles” Journal of Advanced Transportation, Vol 28, No. 3, pp. 203-215.

Preliminary Human Factors Guidelines for Crash Avoidance Warning Devices, NHTSA DOT HS 808 342 January 1996.

New Rules to Increase the Amount of Spectrum Available for Commercial Use, Federal Communications Commission, ET DOCKET 94-124, Adopted: October 1994.

SAE J1879 *General Qualification and Production Acceptance Criteria for Integrated Circuits in Automotive Applications*, October 1988.

SAE J1113 *Electromagnetic Susceptibility Measurement Procedures for Vehicle Components*, August 1987.

SAE J1211 *Recommended Environmental Practices for Electronic Equipment Design*, November 1978.

“Motor Vehicle Crash Involvement: a multi-dimensional problem size assessment”, draft report, DOT NHTSA NRD-53 1995

A. Burgett “DOT’s Approach to ITS Safety Evaluations”, Presented at the ITS America Workshop on ITS Safety Evaluations, May 1, 1995.

J. Lee, D. McGehee, T. Dingus, T. Wilson *“Collision Avoidance Behavior of Unalerted Drivers Using a Front-to-Rear-End Collision Warning Display on the Iowa Driving Simulator”* Sensor Technologies & Systems, IVHS Countermeasures for Rear-End Collisions, NHTSA Project No. DTNH22-93-C-07326, 1996.

McGehee, T. Brown *“Examination of Driver’s Collision Avoidance Behavior in a Lead Vehicle Stopped Scenario Using a Front-to-Rear-End Collision Warning System”* Sensor Technologies & Systems, IVHS Countermeasures for Rear-End Collisions, NHTSA Project No. DTNH22-93-C-07326, September 1997.

3 PERFORMANCE GUIDELINES

This section presents the guidelines for a forward-looking, rear-end collision warning system. These guidelines are operating performance parameters that should be considered as part of the system.

A block diagram of a representative forward-looking, rear-end collision warning system is shown in Figure 1. The forward-looking, rear-end collision warning system uses a sensor to detect vehicles or objects in the forward path. A collision warning algorithm processes the sensor input and determines if a collision threat or unsafe following distance exists and if so, provides a warning to the driver.

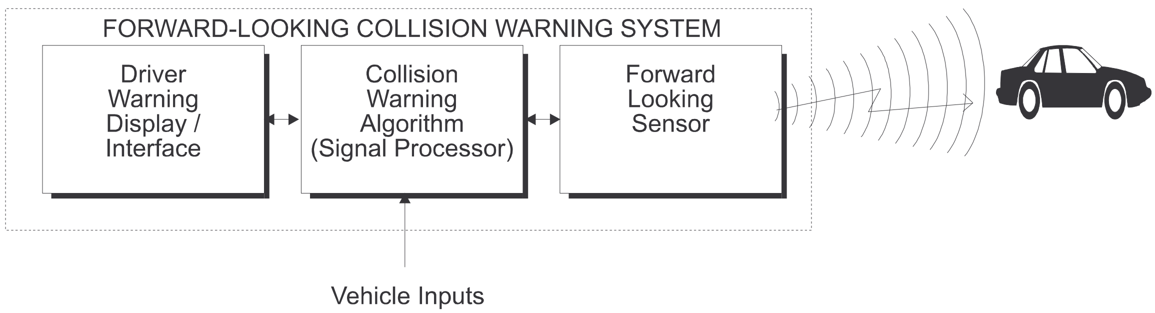

Figure 1 Forward-looking Collision Warning System Block Diagram

3.1 WARNING ALGORITHM METHODOLOGY

The task of a forward looking collision warning system is to mitigate rear-end collision damage and to prevent the greatest possible number of collisions. The system accomplishes this by constantly sensing and evaluating the inter-vehicular dynamics, , and if the situation warrants, warning the driver to take defensive action. The warning algorithm is the mechanism employed to evaluate and warn. The algorithm is a group of equations combined with conditional switches at decision points to transition between driving states.

This section discusses issues associated with the core set of equations and identifies some of the key decision points. The intent is to provide basic guidance on system performance as a function of the warning algorithm. Detailed implementation of a warning algorithm methodology is left to the system developer or OEM.

3.1.1 Multiple Mode Alerting

The guidelines presented here support a multiple mode approach to driver alerting that is able to warn the driver of potential collision situations. It can provide continuous situational awareness to the driver and may also provide cautionary information or a following-too-closely warning when required.

3.1.2 The Extended System

The extended system is comprised of the FCW, the driver and the vehicle. The designer cannot expect to provide an adequate system by designing hardware and software without regard for the rest of the extended system. The human element is of course the most difficult to provide for but it must be remembered that without the FCW, drivers are typically good for 1.2 million miles[2,3] of same-direction collision free driving. It is the designers' job to enhance this capability and to do so, the system must accommodate the driver.

3.1.3 Lost Time

The FCW system must account for lost time. Lost time is driver reaction time, brake actuation time, warning actuation time, and processing delays. Processing delays are small, usually on the order of 0.1 seconds. Driver reaction time is the main contributor to lost-time and varies from person to person. Individual means may range from about 0.9 to 2.4 seconds[4] and discrete reactions vary about the mean. It appears that reaction time also varies as a function of the driving environment, traffic density, speeds etc. The effects of this widely varying parameter are discussed in subsequent sections in depth.

Warning means prediction. It does little good to warn of past events. Lost-time defines the minimum time projection that the system may entertain. If the lost-time value is 1.5 seconds then the system must always warn based on what is predicted to occur at least 1.5 seconds in the future. It is this time projection that is the root of most nuisance alarms. Therefore, a reduction in lost time equals a reduction in nuisance alarms.

3.1.4 Nuisance Alarms

The key to driver acceptance of a FCW system is not in knowing when to warn the driver, but rather in knowing when not to warn the driver. In order for the system to reduce collisions it must be deployed, and in order to be bought and used it will have to maximize warnings of potentially dangerous conditions while truly minimizing the occurrence of nuisance alarms (this includes both false alarms and nuisance alarms from the drivers' perspective). In light of the necessarily predictive nature of the controlling algorithm and the system it supports, these two conflicting requirements present a colossal challenge.

Testing performed in conjunction with this program has shown significant variation in benefit based on when the driver is warned prior to collision[5,6]. The more conservative

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[2] T.D.Gillespie, "Fundamentals of Vehicle Dynamics, Society of Automotive Engineers", 1992

[3] R.Knipling, M.Mironer, et al, "Assessment of IVHS Countermeasures for Collision Avoidance: Rear-End Crashes", NHTSA, 1993

[4] G.Davis, "Measurement of the Minimum Reaction Time for Braking of Vehicles", Not Published, 1990

[5] J. Lee, D. McGehee, T. Dingus, T. Wilson "Collision Avoidance Behavior of Unalerted Drivers Using a Front-to-Rear-End Collision Warning Display on the Iowa Driving Simulator" Sensor Technologies & Systems, IVHS Countermeasures for Rear-End Collisions, NHTSA Project No. DTNH22-93-C-07326, 1996.

(earlier) the warning, the more drivers may find the warning to be a nuisance and thus lower overall driver acceptance and system effectiveness. It also appears, that if the collision threat is beyond the perception (view) of the driver, then issuance of the warning may actually contribute to a collision by distracting or otherwise affecting the driver's vigilance. Also, drivers appear to react differently to different types of dynamic situations which may require different warning times for lead vehicle decelerating, lead vehicle stopped, etc.

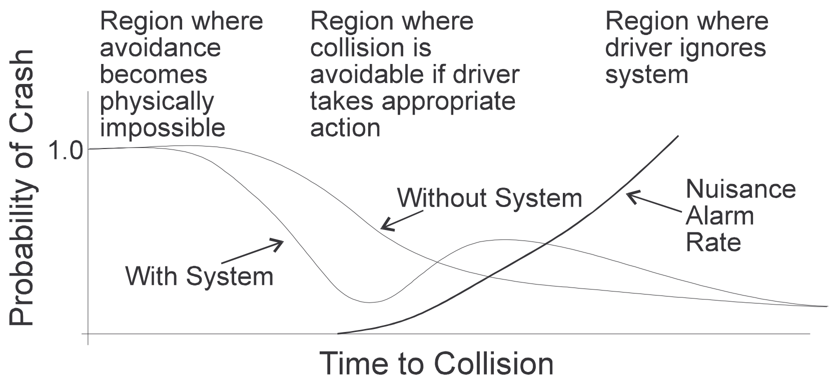

Figure 2 Diminishing Likelihood Curve

The diminishing likelihood curve shown in Figure 2 represents the probability of a crash in comparison with the time to collision. In any circumstance there is a region where the prevention of a collision is physically impossible. In this region, the probability of a crash approaches unity. It is not possible to quantitatively define the diminishing likelihood curve as it is individualistic, and changes as a function of dynamic situation, and driving environment.

Backing away (in time) from the collision there exists a region where the crash is avoidable if the driver takes appropriate action. The concept of the forward-looking, rear-end collision warning system is to reduce the probability of a collision through driver notification. However, if the warning to the driver occurs too soon before the potential collision, the driver will consider the warning a nuisance and the driver's overall reliance on the system may diminish, thus, the probability of a crash may increase with the use of the FCW system.

Receiving a warning in a situation in which the driver does not agree with the need for the warning is the definition of a nuisance alarm. It is likely for a minimum acceptable system that when situations develop where a FCW system is unsure of when to warn then warnings should be inhibited. This may occur in scenarios such as lane change / merging / cut-in, etc.

6 McGehee, T. Brown "Examination of Driver's Collision Avoidance Behavior in a Lead Vehicle Stopped Scenario Using a Front-to-Rear-End Collision Warning System" Sensor Technologies & Systems, IVHS Countermeasures for Rear-End Collisions, NHTSA Project No. DTNH22-93-C-07326, September 1997.

Even in the presence of valid collision threats, the FCW system has no accurate means of assessing the driver's intentions. This means that the driver may respond to the threat before the FCW system warns, may act in the midst of the lost-time interval, may recognize the threat, and plan to act well after the FCW system would sound the alarm. Furthermore, due to some circumstance beyond the simple sensory capabilities of the FCW system, the driver may see no need to act at all. The driver's assessment of the situation and responses, planned and executed, modify the perceived danger level in ways that the forward-looking, rear-end collision warning system cannot predict.

Ideally the system will warn only when the driver is truly in danger. But there are a number of influences that must be addressed to approach this ideal. Target recognition and discrimination must be achieved by the object detection algorithm. Some sense of the vehicle's likely and intended course might be provided by a scene processing algorithm. The strengths and limitations of the employed forward looking sensor must be understood. Lost time effects must be minimized. Tailoring for specific traffic encounters may be required. And finally there is the definition of nuisance to contend with.

3.1.5 Working Definition

Nuisance alarms are any alarms issued to the driver that the driver deems unnecessary. The driver's viewpoint is always valid and may, as discussed above be based on a myriad of reasons, but included in the driver's perception must be some evaluation of the immediate urgency or danger inherent in the situation. Therefore two simplifying divisions are used here. They are that nuisance alarms are alarms issued in non-urgent situations or alarms issued after the action has been taken. This working definition of nuisance alarms is consistent with the general definition given above.

3.1.5.1 Non-urgent alarms

Ignoring nuisance alarms that result from false alarms (i.e. crossing vehicles, left turn across the subject vehicles, etc.), non-urgent alarm generators may include, lane change, cut-ins, sliders (cut-ins that continue across and out of the subject vehicle's lane), various merge scenarios and of course the simple act of pulling up behind a vehicle at a stop light.

All of these examples are discussed in the 3.1.17 Tuning and Traffic Scenarios section, but the last condition is a problem for all algorithms investigated, and is dealt with in the structure section. It is mentioned here as the seed for a definition of urgency built on the most common situation, simple overtaking and braking.

The chosen measure of urgency is the level of deceleration required by the subject to avoid the collision, so a deceleration level warning threshold is needed. Other questions raised are of timing and response. In the presence of a potential threat how soon or late should the system warn, and what form does the response curve take?

It is known that drivers have preferential levels of braking. A large body of research shows that the population at large finds the comfortable braking level to be less than 4 m/s² (0.4g). Olson and Rothery[7] give a 15th to 85th percentile spread of 2.4-3.7 m/s^2 (8-12 ft/sec^2) at stop lights while Gillespie[8], showing similar results, says that only 1% of brake applications are made at greater than 3.5 m/s² (0.35g) and that less than one in a thousand brake applications exceeds 5 m/s² (0.5g).

Olson and Rothery, discussing driver response to amber lights at intersections state, "…drivers were virtually certain to stop if their required deceleration was less than 8 ft/sec^2 and virtually certain to continue if the decelerations required were in excess of 12 ft/sec^2". They conclude, "This implies that drivers are reluctant to expose themselves to the forces corresponding to decelerations in excess of about 3.7 m/s² (12 ft/sec^2) in stopping for a traffic light."[9] In other words something more serious than a mere run through a yellow or red control signal is necessary to suffer a more severe stop.

It is our goal to maintain a level of braking in excess of the driver's comfort level with warnings issued by the FCW. It is assumed that warnings that require braking in excess of the driver's preferred value will not be considered a nuisance while warnings issued within the driver's habitual comfort zone will be. The state diagrams in the physical analog structure section are built on these perceptions and they are used as the foundation for the algorithm.

These assumptions are supported by anecdotal evidence from drivers using these algorithms. It is anticipated that the further the algorithm warnings are beyond the comfort level the lower will be the nuisance alarm rate. Benefit of course is a combined measure of nuisance and crash mitigation/prevention, so the extension of warning beyond the comfort threshold, has the capabilities of the driver and machine as an ultimate upper bound.

3.1.5.2 Driver Responding Alarms

Generally caused by the combination of attentive drivers and the time projection due to lost-time, these nuisance alarms are characterized by drivers reacting to a threat before a warning is given or during the warning actuation time. Inhibiting the warning to the driver would eliminate nuisance alarms to drivers who are already responding to the threat.

3.1.6 Inputs

A minimal autonomous forward-looking, rear-end collision warning system would have limited sensor capability and would have as inputs only host vehicle speed, relative speed and inter-vehicular range.

Compared to this minimum, the drivers have stereoscopic sight and hearing, vision capability approaching 360°, an active memory, great scene processing power, color

[7] Olson and Rothery "Deceleration Levels and Clearance Times Associated with the American Phase of Traffic Signals", Traffic Engineering, 1972
[8] T.D.Gillespie, "Fundamentals of Vehicle Dynamics, Society of Automotive Engineers", 1992
[9] Olson and Rothery

vision with very fine resolution, some knowledge of their own reaction times and following preferences, and years of experience.

The driver uses clues and information unavailable to the FCW system such as tail lights, traffic lights, lateral awareness, traffic ahead, traffic behind and knowledge of the roadway geometry, including the locations of roadway entrances and exits, to assess the developing situation and to act and react. Generally drivers react rather well.

3.1.7 Driver Efficiency

The average driver is expected to experience only 15 panic stops per year while executing 15,000 non panic stops in the same period (based on an average of 1.5 brake applications per mile, 10,000 vehicle miles traveled per year[10]) and will go approximately 60 years, on average, without being the striker in a rear-end collision[11].

It is when the driver is inattentive or distracted that the FCW system is to warn, hopefully in time to avoid a collision. The installed warning system and the driver must work together to prevent collisions.

3.1.8 Driver Inattention

Knipling et. al. provide us with this: "The rear-end crash is largely a dry/straight road phenomenon associated with driver inattention"[12]. Ideally the FCW system would be able to measure the drivers attentiveness level and respond accordingly. Because of the limited success in that direction, this study has concentrated on the task of frontal collision warning without the benefit of such clairvoyance. The baseline established here is however, flexible, and future advances in driver attentiveness detection will be extremely welcome and easily adapted.

3.1.9 Countermeasures

The countermeasures available to the FCW system are limited in comparison with those available to the driver. The driver and the installed forward-looking, rear-end collision warning system are both attempting to predict when the risk of collision is high enough to act, but the driver may respond or plan to respond by combinations of steering, throttle adjustment and braking. In the absence of side and rear directed sensors the forward-looking system must assume that braking is the only recourse.

3.1.10 Basis for the Algorithm

R.G.Mortimer[13] referencing Solomon, cites a strong relationship between rear-end crash probability and the relative speed of a vehicle pair, stating that "…following vehicles

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[10] T.D.Gillespie, "Fundamentals of Vehicle Dynamics, Society of Automotive Engineers", 1992

[11] R.Knipling, M.Mironer, et al, "Assessment of IVHS Countermeasures for Collision Avoidance: Rear-End Crashes", NHTSA, 1993.

[12] R.Knipling, M.Mironer, et al, "Assessment of IVHS Countermeasures for Collision Avoidance: Rear-End Crashes", NHTSA, 1993.

[13] R.G.Mortimer, "Studies of Automobile and Truck Rear Lighting and Signaling Systems", HSRI,1974

traveling at a 30-35 mph differential are 30 times as likely to be involved in a rear-end collision than a vehicle pair traveling at a 15 mph differential…". Knipling et. al. report that about 70% of all rear-end crashes are classified as lead vehicle stopped which defines the upper bound for relative speed differential of rear-end collision avoidance. It also emphasizes the need for sensitivity to high speed differential and vehicle stopped scenarios.

The FCW system should therefore work well (as a minimum) on dry and straight roads, and be sensitive to relative speed and lead vehicle stopped situations, and since the driver's perception can produce a million miles of accident free driving, the system must not falsely warn the driver.

The warning algorithm:

- is responsible for in-path collision warning prediction
- is not responsible for threat discrimination i.e. out-of-path, crossing vehicles, etc.(this is the task of the target discrimination or scene processing algorithm)
- should minimize nuisance alarms
- must handle lead vehicle stopped scenarios
- must handle following-too-closely scenarios
- must handle lead vehicle slowing, constant speed and accelerating scenarios
- should transition smoothly and transparently over all driving scenarios
- should support changes to adapt to an individuals preferences and habits
- should support changes to adapt to changing driver, vehicle and driving environments
- should be applicable to the most basic and the most advanced systems
- may provide situational awareness as well as imminent collision warnings
- assumes that braking is the only recourse

3.1.11 Approach

An algorithm methodology may be evolved from the assumptions above and a systematic design approach. Beginning with the question: "What is the algorithm attempting to do?", we find that the algorithm is not preventing collisions. Rather the algorithm is trying to guide the relative speed of the subject and lead vehicles to, or near to, zero without having them collide while leaving the subject vehicle at some distance behind the lead vehicle consistent with both the lead vehicle speed and the urgency of the situation. This must be done in a manner that is consistent with the capabilities of the car and driver.

3.1.12 Physical Analog

The warning algorithm may be predicated on a physical model, be an empirical construct designed to optimize some value set or it may be a combination. The algorithm presented here follows a specific physical model, but is tuned (and requires additional evolution) to optimize performance across a variety of scenarios.

This section discusses the kinematics, driver braking habits and lost time effects that are the physical basis for an algorithm. A series of state diagrams are presented to describe the underlying relationships between the kinematics of the involved vehicle pair and the prediction of threat and the timing of the warning. The diagrams will be used in the Algorithm Structure section to define the kinematic and central warning equations of the algorithms.

3.1.12.1 Approaching a Lead Vehicle

The state diagram Figure 3, depicts the subject vehicle (SV) moving at speed v_S and approaching (overtaking) a lead vehicle (LV). The vehicle pair moves together to create a constant relative speed of Δv. The diagram shows two constant deceleration curves, one depicting a higher deceleration rate and the other lower. The curves terminate at the origin indicating zero relative speed and zero separation distance. Their shape is strictly a function of relative speed and deceleration level. The sooner braking is initiated the lower the necessary level.

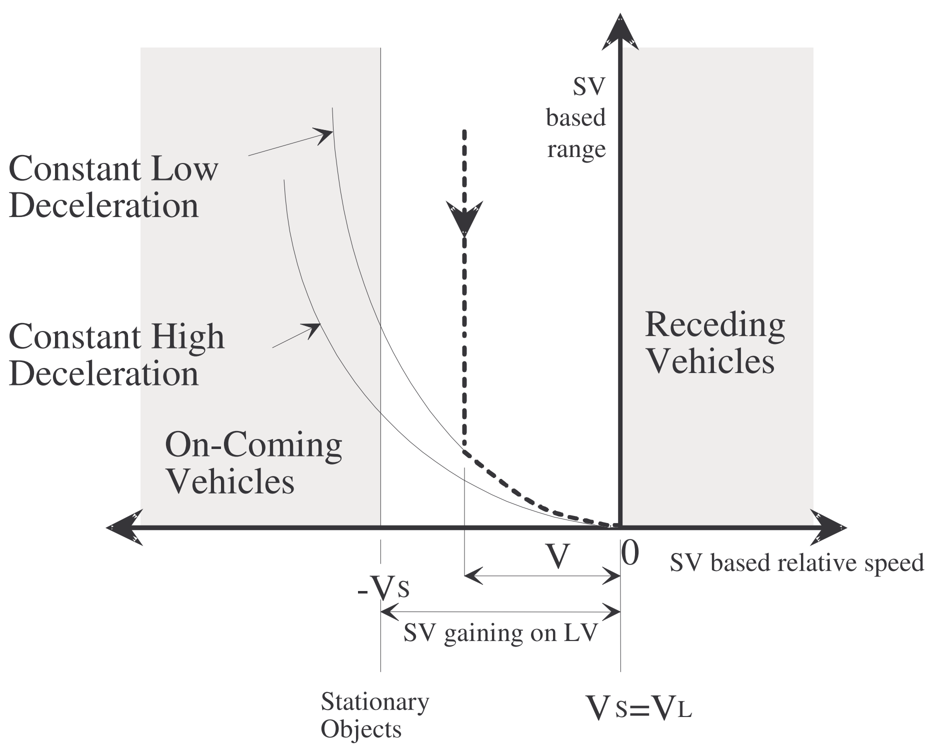

Figure 3 Approaching a Lead Vehicle

The heavy dashed line depicts the relative speed and range relationship as the subject vehicle approaches the lead vehicle. The vertical segment represents a constant relative speed (Δv) and the vehicle-to-vehicle range is shown (by the arrows) to be decreasing. By applying the brakes at the intercept with the upper deceleration curve and effecting a constant deceleration, the subject vehicle will, as range and relative speed decrease, follow the curve to its terminus until it is bumper-to-bumper with the lead vehicle and moving at the same forward speed.

This final position relates to lead vehicle stopped and urgent braking scenarios where the separation distance between the lead and subject vehicles may reasonably be near zero.

The constant deceleration curves may be viewed as driver preferences or vehicle deceleration limits, or a better interpretation might be a braking level within the driver-vehicle capability that is beyond the driver's usual braking preference, either way, the sooner the braking commences, the lower the necessary level required to stop.

3.1.12.2 Approaching a Moving Lead Vehicle: Coupled Headway

It is generally considered desirable to not tailgate and so for routine (non-urgent) braking, the recommended final position would not be as represented in Figure 3, but would ideally be as diagrammed in Figure 4. Here the following vehicle again follows the path to zero relative speed, but because the plot is specific to a lead vehicle absolute speed greater than zero, the inter-vehicular range at zero relative speed is not zero but some minimum headway value providing a buffer between the lead and subject vehicles.

The term *coupled headway* is used here to represent the range between the vehicles when the subject vehicle is traveling coupled, behind the lead at a relative speed that is close to (and probably varying around) zero.

This final position is compatible with normal, in traffic braking scenarios where the resulting separation distance between the lead and subject vehicles must reasonably be greater than zero.

Again the constant deceleration curves may be viewed as driver preferences or vehicle deceleration limits, or a better interpretation would be a braking level within the driver-vehicle capability that is beyond the driver's usual braking preference.

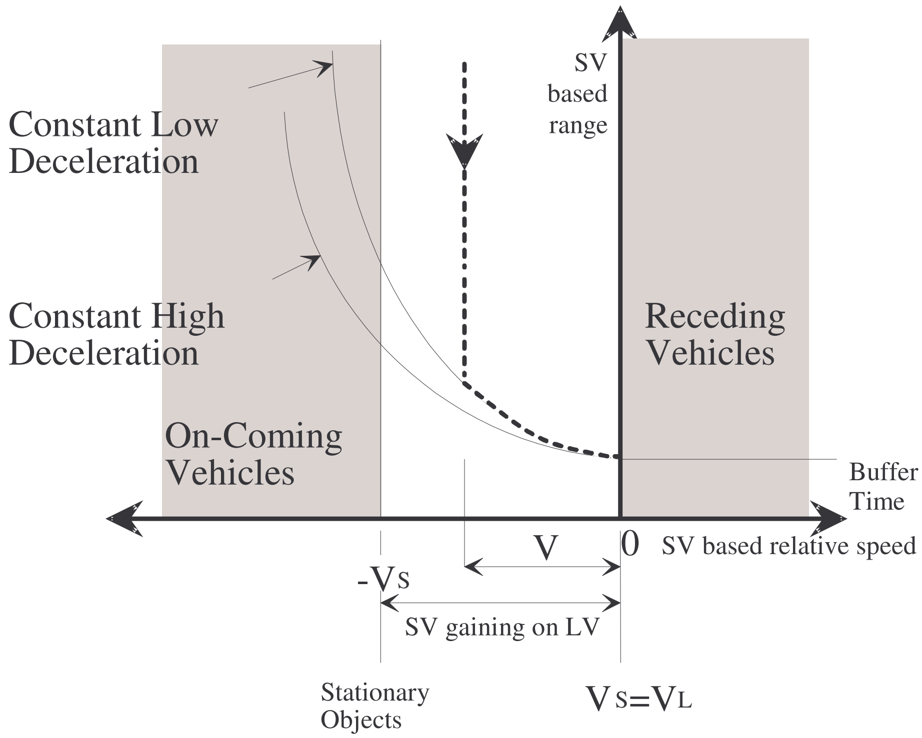

Figure 4 Coupled Headway State Diagram

3.1.12.3 Approaching a Lead Vehicle: Lost-Time

As previously discussed, lost time is driver reaction time, brake actuation time and processing delays. A lost time value is associated with each and every individual driver, and will vary based on the driver, driver condition, driving environment, etc. Drivers do not, or cannot respond to a warning instantaneously. The overall system must take lost time into account, but errors in determining lost time lead directly to nuisance alarms. Working backwards from a constant deceleration curve, lost time is the time required for the driver to respond as shown in Figure 5. The driver warning must take an estimate of lost time into account in determining when to warn. A shaded zone that is a representation of distance traveled due to lost-time (driver response/ reaction time) has been added to the diagram in Figure 5. It is applied as a function of the relative speed. If in the figure the upper deceleration curve is the intended braking profile, then the upper boundary of the lost-time zone may be seen as the warning range.

Because of lost-time and assuming that the driver does not recognize the threat, an alarm must be issued at the point labeled “Warning Distance” in order for the driver to respond and brake in time to put the vehicle onto the desired deceleration curve.

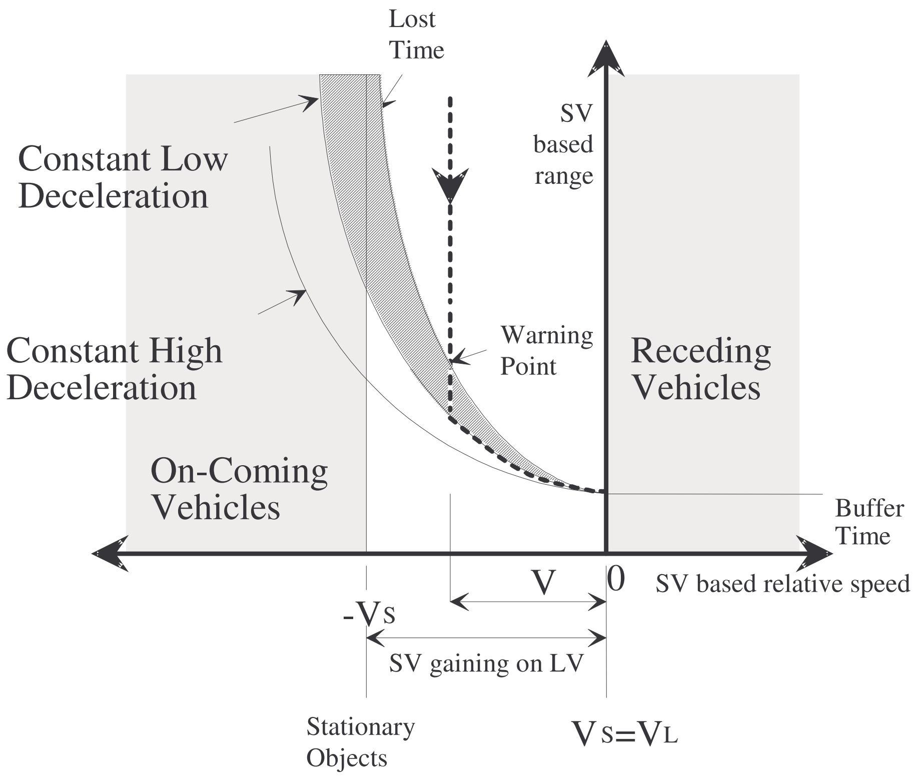

Figure 5 Lost Time State Diagram

Figure 5 also illustrates that the path of the subject vehicle along the prescribed deceleration curve is entirely within the warning zone. It may be overly optimistic to alarm only at the entrance to the warning zone and it is certainly unacceptable to alarm continuously when the driver is in no danger and following the prescribed profile. This problem is addressed in the 3.1.17.2 Managing Nuisance Alarms section.

3.1.12.4 Idealized Equation

By adding a third axis to Figure 5, the range/relative speed state diagram is expanded to depict a range of lead vehicle speeds from 0 to 30 m/s. Figure 6 includes a coupled headway buffer that is a function of the lead vehicle absolute speed, resulting in the triangular wall on the lower right. The figure is valid for a single deceleration value. The surface in Figure 6 represents an idealized vehicle performance that is assumed consistent with both the perception of typical drivers and the notion that a constant deceleration can represent the desired performance of the driver under varying speed and range conditions. (See section 3.1.4 Nuisance Alarms) Though there is some debate whether a single deceleration level, or profile, suffices for all speeds and conditions and it has been shown that driver's deceleration profiles vary based on absolute speed[14], this notion provides good results in current simulations and is amenable to tuning and conditioning.

[14] Wortman, R.H., Fox, T.C. "An Evaluation of Vehicle Deceleration Profiles" Journal of Advanced Transportation, Vol 28, No. 3, pp. 203-215

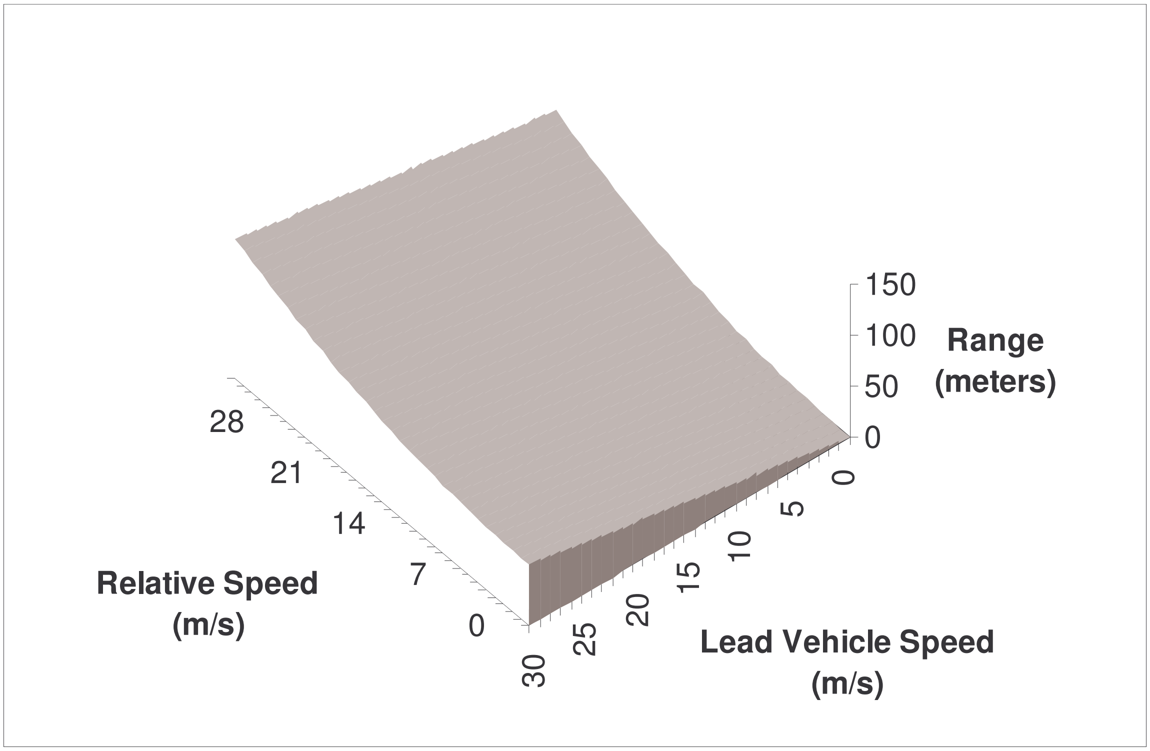

Figure 6 “3-D” Diagram of Idealized Equation

3.1.13 Warning Equation Structure

3.1.13.1 Output

3.1.13.1.1 Warning Distance

The standard output of collision warning equations is a warning distance (WD), calculated from the current speeds of the vehicles and one or more assumed deceleration rates. The calculated distance is then compared to the measured range (r) and a warning is issued when $r \leq WD$. This approach is used here for consistency.

3.1.13.1.2 Deceleration Level

An alternate approach that has the benefit of providing an indication of the urgency of the situation across different absolute and relative speeds is to use the speeds and range as inputs while solving for the required deceleration. Warnings are then issued at selected deceleration (g) levels.

This method allows warning level compensation for changes in road conditions, driver preferences and vehicle performance variation, by merely changing an offset. For the researcher, deceleration or g-level values also reveal the predicted mean braking level (relative to the assumed braking thresholds represented in the state diagrams) for the condition being explored.

3.1.14 Kinematic Core Equation

The kinematic core equation for the deceleration curves plotted on the state diagrams is:

$$r = \frac{(v - v_f)^2}{2g\alpha}$$

r	=	*inter-vehicular range (change in range between v and* v_f *)*
v	=	*initial (current) speed (meters / second)*
v_f	=	*final speed(meters / second)*
g	=	*9.8 (meters / second)*
α	=	*acceleration (g's) (assumed constant either positive or negative)*

This is a general kinematic equation for constant acceleration/deceleration and all algorithms use a version of it. There are however, major differences in how it is applied which intentionally or not relate to some physical model.

3.1.14.1 Interpretation of v_f

v_f represents the final speed of the vehicle pair. Ideally, it would be beneficial if the final speed were known, but the driving environment is unpredictable, and as discussed earlier, the FCW system can not always predict the final speed of the vehicle pair. As a result, an assumption must be made regarding the final speed.

Two extremes are possible, either v_f will be zero, or v_f will be a constant equivalent to the speed of the lead vehicle, neglecting for a moment, any acceleration components. Between these extremes there are an infinite number of intermediate values or potential approaches.

3.1.14.2 Interpretation of α

α represents the relative acceleration that is applied between the current speed (v) and the final speed (v_f) of the vehicle pair. Ideally, it would be beneficial if the final speed were known, but the driving environment is unpredictable, and as discussed earlier, the FCW system can not always predict the final speed of the vehicle pair. As a result, an assumption must be made regarding the final speed.

The stopping distance, warning equation (Knipling, others) is found more often in the literature than any other warning equation. The stopping distance equation assumes that v_f is zero. In the stopping distance equation, two terms use the kinematic core equation for r as difference terms to predict the stopping distance required. The stopping distance equation "assumes" that the lead vehicle and as a result, the subject vehicle will be coming to a stop ($v_f = 0$ *in the kinematic core equation).*

The problem with the stopping distance equation is that the assumption that the lead vehicle is stopping causes the equation to be overly conservative, this in turn leads to the possibility of nuisance alarms in benign conditions such as pulling up behind a lead vehicle at a stop light as has been found by implementing this equation on the testbed vehicle developed under this program.

3.1.14.3 Lead Vehicle Constant Speed Equation

The Lead Vehicle Constant Speed Equation (LVCS) assumes the opposite extreme, that the lead vehicle is at a constant speed. The initial benefit of the LVCS equation is that by providing the terms for v_f in the equation, the issues of acceleration, deceleration, or changes in the speed of the vehicle pair can be included. In the examples of the state diagrams, v_f equals the final speed of the vehicle pair. If for example, in Figure 3 Approaching a Lead Vehicle, the condition depicted is assumed to be lead-vehicle-stopped, then $v_f = 0$, if however the figure is representing an urgent braking scenario and the lead is moving at some forward speed, say 22 m/s, then $v_f = 22\ m/s$.

The notion that the value of v_f is equal to the lead vehicle speed and that the equation predicts and warns based on that number has led this approach to be labeled the lead-vehicle-constant-speed (LVCS).

3.1.15 Lost Time Effects

The algorithm lost-time elements are necessary to adjust kinematic predictions to accommodate driver and system delays. Using the LVCS model, the lost-time elements are converted to distance by multiplying by the difference of the speeds. The resulting lost-distance effectively shortens the inter-vehicular range and heightens the predictions of stopping urgency as illustrated in Figure 7.

Figure 7 represents the output of the algorithm plotted as a function of deceleration (g) level (k), a continuous representation of the deceleration required to slow the host vehicle to the lead vehicle speed. The figure shows a driver input response (removing foot from accelerator and braking) and three output curves that are functions of different values of lost-time.

The system response curve is the predicted deceleration required, calculated with a realistic lost-time. The vehicle response curve at the top of Figure 7 results when lost-time requirements are removed. The vehicle response curve is reflecting the kinematic reality of the scenario. This curve defines what the vehicle must do without regard to the assumed driver and system induced delays. A comparison of the two curves yields, at the peak of the curve where the brakes were applied, predicted values of – 9.8 m/s² (1.0g) (algorithm with lost-time) and –1.8 m/s² (0.18 g's) (kinematic core equation only), the difference results solely from the distance compression caused by lost time effects. The result is clear, eliminate excessive lost-time.

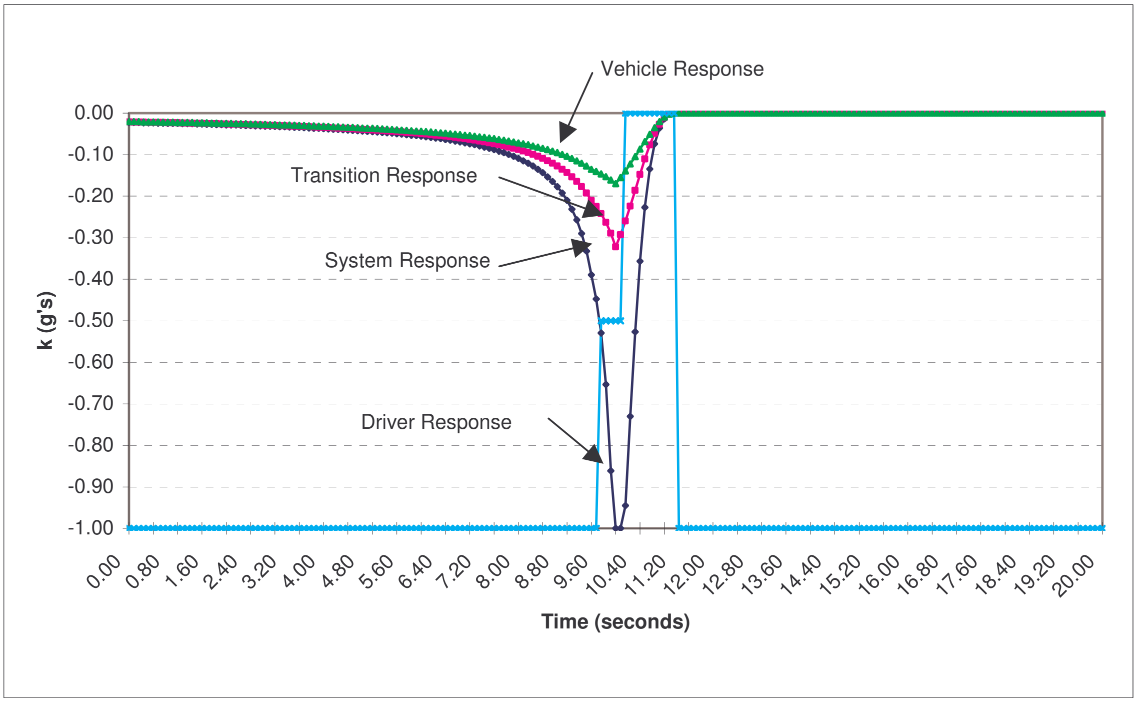

Figure 7 Output of the Algorithm

3.1.15.1 Driver Delays

There are two driver braking reaction times to consider when dealing with the algorithm. They are the driver's immediate situational reaction time (accurately reflecting the mood, sobriety and attentiveness level of the individual driver) and the reaction time value of the FCW system (A_{RT}).

3.1.15.1.1 Algorithm Reaction Time (A_{RT})

The ideal algorithm reaction time is the specific reaction time of the driver. If the FCW system had this reaction time, the predictions of the FCW would be extremely accurate and nuisance alarms would be eliminated (see Section 3.1.17 Tuning and Traffic Scenarios). The present reality requires that the system designer, as well as the analyst, must make do with the information available and employ a value or values from a distribution representing the driver reaction population at large and suffer the time uncertainty that results.

3.1.15.1.2 Reaction Time Distributions

A number of studies have been done that report braking reaction time data on unalerted drivers. A skewed distribution (or lack of symmetry) of the data is prevalent in the studies. Taoka[15] shows that a log-normal probability density function can be fit to the data, providing a practical numerical description of the observed distribution.

G.T. Taoka, "Brake Reaction Times of Unalerted Drivers", ITE Journal, March 1989.

An estimate of the reaction time of the driving population is shown in Figure 8. The driver reaction time distribution (Drt) for the driving population is modeled as a random variable having a log normal probability distribution. The probability density function of Drt is:

$$p(Drt) = \{1/[(2\pi)^{1/2} \bullet \zeta \bullet Drt]\}e^{\{-[Ln(Drt)-Ln(\lambda)]^2/(2\bullet\zeta^2)\}}$$

where

Drt = Driver reaction time (Seconds)
Drtm = The mean of Drt = 1.14 Seconds
Drts = Standard deviation of Drt = 0.3 Seconds

$\zeta = \{Ln[(Drts/Drtm)^2 + 1]\}^{1/2}$ = Dispersion of Drt

$\lambda = Drtm \bullet e^{(-\zeta^2/2)}$ = Median of Drt (Seconds)

It should be noted that this data was compiled on unalerted but probably attentive drivers and therefore may under represent the driver reaction times of inattentive or distracted drivers.

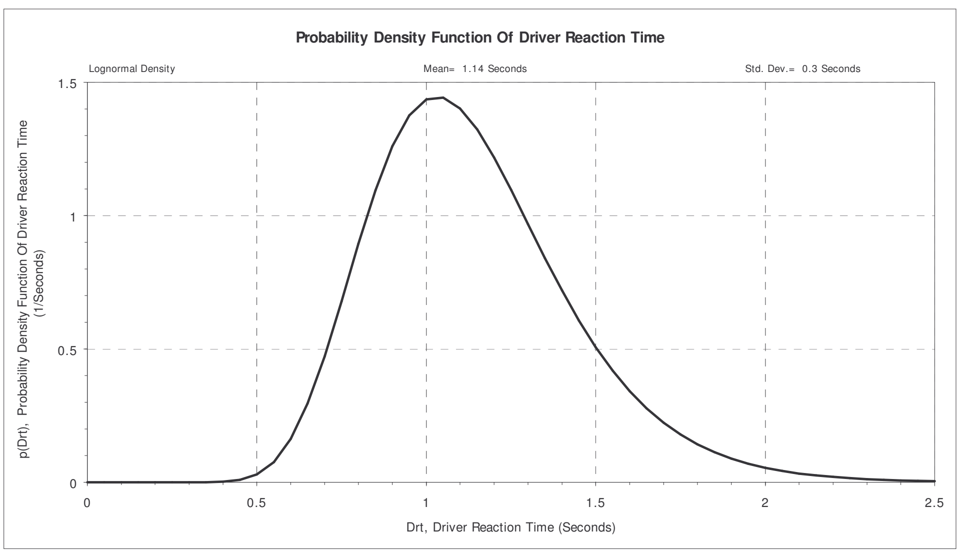

Figure 8 Log-Normal Population Reaction Time Model

This model of driver reaction time approximates the population, however, it is likely that individual drivers have less driver to driver variance but still may exhibit means that are significantly based on the mood of the driver or the driving environment. No quantitative research was performed on this program to determine individual driver reaction time. If a FCW system could measure or otherwise estimate the individual's reaction time, then significant advances could be made toward elimination of nuisance alarms to the driver.

3.1.15.2 System Delays

3.1.15.2.1 System Processing Delay

The processing delay (t_p) represents the sampling and update rate of the system. The processing delay assumes that the object under consideration has already been acquired and is being tracked by the FCW system. The system processing delay includes sensor sampling, filtering, object classification, scene processing, and warning algorithms as well as updating the object track files. The system processing delay is anticipated to be less than one tenth of a second. Algorithmically, the system processing delay t_p should be replaced with the actual delay of the FCW system.

3.1.15.2.2 Braking Actuation time

The braking actuation time is the time delay from brake initialization to braking effect and is made up of the brake response time and the pressure build up times. Values for t_B can vary with individual systems, their condition, frequency of use (hot brakes, cold brakes) etc. A standard value is 0.36 seconds. If platform specific information is available it should be used in place of the default. The brake actuation time is different from a warning actuation time that uses braking initiation.

3.1.15.2.3 Warning Actuation Time

The time required for the processor output to become an identifiable stimulus presented to the driver is the warning actuation time (t_W). Incredulously delays approaching 0.8 seconds have been reported[16] for some display modalities. As with all lost-time effects this must be minimized. The cost for excessive delay is decreased benefit and increased nuisance alarms. An upper limit of 0.1 seconds is assumed but should be replaced by the system specific value.

3.1.15.2.4 Acquisition Delay

It is expected that forward-looking, rear-end collision warning systems will employ filters to improve the accuracy of the sensor data and reduce false alarms due to momentary reflections or system noise. The initial categorization of a vehicle in the forward path will require multiple samples to verify range, speed, size and location information. The number of samples to perform this function is the acquisition delay of the system. This acquisition delay should not be confused with processing delay. Acquisition delay will reduce the warning capability in scenarios where the lead vehicle is acquired near or inside the optimum warning time.

If, for example, the FCW system initially requires five samples to provide accurate estimates of range and speed and the system samples at 20 Hz then at least 0.25 seconds will be consumed waiting for the first recognition of a new object. The 0.25 seconds lost to initial multiple sensor samples is the acquisition delay and cannot be compensated.

[16] D.V.McGehee, J.Lee, "Examination of Drivers' Collision Avoidance Behavior using a Front-to-Rear-End Collision Warning Display", The University of Iowa, IVHS Countermeasures for Rear-End Collisions, Contract Number DTNH22-93-C-07326, September 1996.

3.1.16 Collision Warning Equation

Combining the kinematic core equation with the lost-time elements that are collectively converted to lost-distance, yields the collision warning equation. This warning core equation has been shown to be acceptable when used in a lead vehicle constant speed (LVCS) mode in a representative algorithm over the majority of driving conditions.

The derivation tags this equation as LVCS though its application may be more general. Note that v_f is meant to represent the final speed of the subject vehicle, and not necessarily the current speed of the lead. The equation is provided here in two forms, with both warning distance and g-level outputs.

WD	=	Warning distance
v	=	subject vehicle current speed (meters / second)
v_f	=	subject vehicle final speed (meters / second)
g	=	9.8 (meters / second^2)
α	=	assumed (assigned) deceleration (g's)
A_{RT}	=	Algorithm assumed driver reaction time (seconds)
t_P	=	platform specific processor delay
t_B	=	platform specific brake actuation delay
t_W	=	platform specific warning actuation delay
k	=	g-level
r	=	range (meters)

3.1.16.1 Warning Distance Form

The output WD (meters), is compared with the measured range to determine the warning:

$$WD = \frac{(v - v_f)^2}{2g\alpha} + (A_{RT} + t_P + t_B + t_W)(v - v_f) \qquad \text{(meters)}$$

3.1.16.2 Deceleration Level Form

The output k (g's), is compared to a predefined braking level to determine the warning:

$$k = \frac{(v - v_f)^2}{2g\alpha((A_{RT} + t_P + t_B + t_W)(v - v_f) - r)} \qquad \text{(g's)}$$

3.1.17 Tuning and Traffic Scenarios

The current LVCS Collision Warning Equation has been shown to provide a manageable compromise between crash prevention, crash mitigation and nuisance alarms. It is not considered optimized. Numerous issues remain regarding the non-linear driving effects of normal naïve drivers that must be delineated prior to fielding of an acceptable algorithm. Additionally, the LVCS equation does not consider driving environment or dynamic situations, assumes perfect scene processing and object classification. Additional normative driving data is necessary along with rear-end collision specific driver data in order to complete the algorithm development.

3.1.17.1 Tuning Devices

3.1.17.1.1 Dependent v_f

Defining the algorithm expected final velocity (v_f) as a function of absolute speed, relative speed or some other parameter (lead vehicle deceleration, a threshold) is a useful means of shaping the response of the collision warning equation to tune the algorithm.

3.1.17.1.2 Offsets

A variety of offsets, positive or negative, constant, increasing, decreasing, linear or exponential may be added to the collision warning equation. Generally they are manifested as distance terms and either compress or expand the apparent range, thereby increasing or decreasing the predicted urgency of the situation.

3.1.17.1.3 Response Shaping

A simple but flexible approach is to shape the response by direct modification of the collision warning equation output. Any function of speed, relative speed, following distance, etc., can be applied as a factor, enabling a number of minor tweaks with or without logical branches to be easily and cleanly incorporated. This method has the advantage of maintaining a discernible separation between the core and the various modifications.

3.1.17.1.4 Lock Outs and Logic Switches

The output of the algorithm may be turned off, or parameters switched in or out responding to auxiliary sensors, speeds or, if known, the condition of the driver. Any switched outputs that result in sudden display changes should have a situational justification for that change, i.e. sudden speed changes etc.

3.1.17.2 Managing Nuisance Alarms

3.1.17.2.1 Driver Responding

Three obvious driver responses to a developing situation are steering, braking and releasing the accelerator (coasting). In order to compensate for these driver activities the extended system must provide adequate sensor information. Brake light signals exist, and accelerator presence and steering level sensors are reasonably inexpensive devices. In order to manage nuisance alarms and prevent the occurrence of warnings after the driver has responded these additional sensors may be necessary.

3.1.17.2.2 Accelerator/Brake

Figure 9 shows the continuous output of three implementations of the collision warning equation for a simple lead vehicle stopped scenario. The driver in this case responds to the scenario and removes his foot from the accelerator, then brakes and slows to a stop just behind the lead vehicle, a scenario depicted in Figure 3 Approaching a Lead Vehicle.

The vertical lines in Figure 9 represent the driver's response. The leftmost vertical line (extending from k = -1 to –0.5) indicates the removal of the driver's foot from the accelerator (transition indicator), while the line to the right (extending from k = –0.5 to 0) indicates the application of the brake. Simulator studies[17] at the University of Iowa have shown that approximately 0.5 seconds is required for the driver's foot to move from the accelerator to the brake and this is seen to be relatively constant, even in panic situations. This value is used in the figure as a typical response time and is used to compensate for driver activities.

Note the rapid increase in the predicted required deceleration, between the transition indicator and the application of the brakes. This is the result of the lost-time values becoming dominant as the inter-vehicular range decreases.

The lowest curve (System Response) in Figure 9 is the deceleration required to avoid the lead vehicle assuming the driver is driving normally with his foot on the accelerator. It is calculated with all lost-time factors. The middle curve (Transition Response) represents the same conditions, but the lost-time has been calculated with an A_{RT} of 0.5 seconds, a value consistent with the driver responding by letting off the accelerator pedal (transition). This assumes that the driver is responding to the scenario which may not be accurate under all circumstances. The top curve (Vehicle Response) is the deceleration calculated without lost-time, representing the physics of the situation without regard to driver lost time.

It should be noted, that the algorithms studied all provide the driver a warning under certain benign slow approach scenarios similar to pulling up behind a vehicle at a stoplight. This is a significant source of nuisance alarms. A number of approaches are possible to reduce driver-responding induced nuisance alarms. A simple lock out of the warning when the driver is off the accelerator or on the brake is a first order approach. Unfortunately, this approach eliminates monitoring capability, and slow and go traffic situations find drivers spending a lot of time coasting, 5 or 10 mph not being a challenge for many automatic transmission vehicles. It is therefore desirable to implement a scheme to provide a reduction in nuisance alarms while still maintaining contact with the developing traffic situation in order to provide the driver more comprehensive protection.

Continuous monitoring with the adjusted lost-time values will provide protection while reducing nuisance alarms. The algorithm output would then follow the lowest curve to the accelerator transition line, then up the vertical line to the transition curve and so on in a stair step manner.

[17] D.V.McGehee, J.Lee, "Examination of Drivers' Collision Avoidance Behavior using a Front-to-Rear-End Collision Warning Display", The University of Iowa, IVHS Countermeasures for Rear-End Collisions, Contract Number DTNH22-93-C-07326, September 1996.

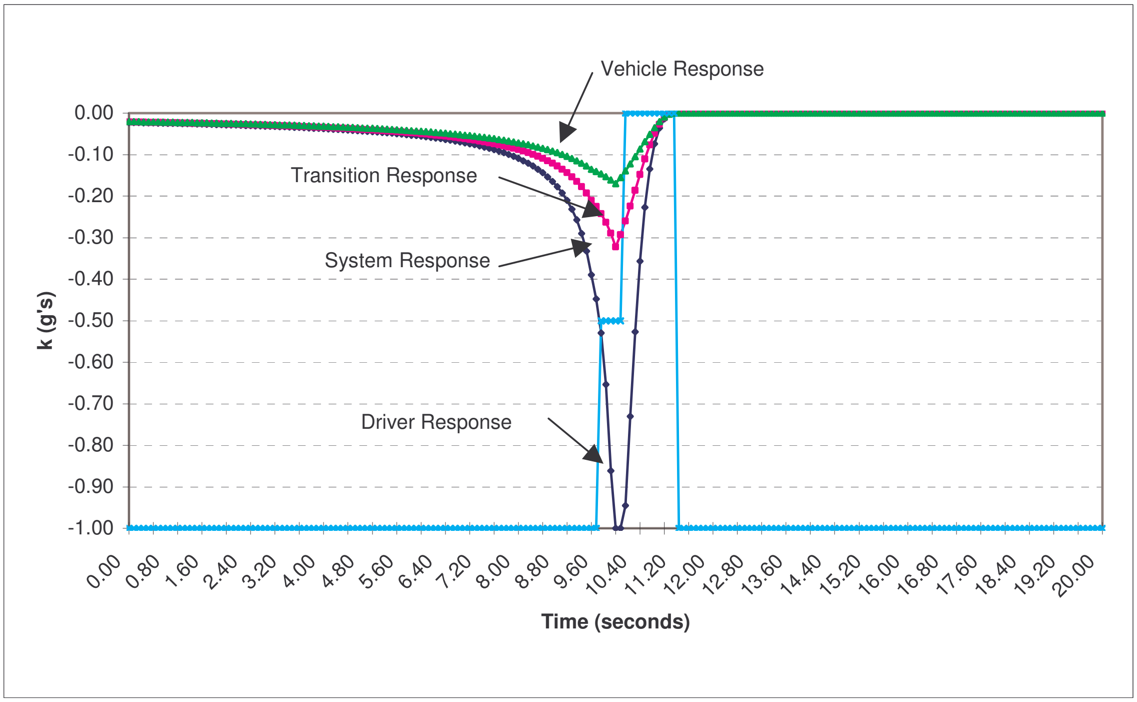

Figure 9 Output of the Algorithm

3.1.17.2.3 Steering

Feedback, either directly from the steering mechanism or as an input from an accelerometer can be used to detect an avoidance-by-steering maneuver. This measurement of lateral acceleration may be useful in lane change / merging and cut-in scenarios by is not completely reliable under all conditions.

The sudden lateral shift of the field of regard relative to the target group, may also be a viable indicator of a sudden steering adjustment. (The complete disappearance of the threat from the field may result.) Target and scene processors are reluctant to make pronouncements based on single readings and a number of passes through the sampling loop (with the resultant loss of time), but will probably be required before the adjustment can be made. A value study on this persistence of information could determine an optimum filtering approach.

Since indication of a timely steering maneuver does not necessarily imply recognition of the threat, or an avoidance maneuver, continuous monitoring with an adjustment of lost-time is suggested.

3.1.17.2.4 Warning Delays

Excessively long warning delays are doubly damaging because they artificially increase the lost-time, thereby increasing the predicted urgency, and because they are systemic they must be maintained throughout steering or accelerator action compensations, continuing to dictate an unnecessary urgency.

3.1.17.3 Slow Speed Overtaking

This is the seemingly benign case of a motorist pulling up behind a stopped lead vehicle. Very slow speed, close in situations may trigger a warning response under non-collision conditions. Three approaches are suggested to reduce the nuisance alarm potential to the driver, others are possible dependent upon algorithm topology.

A constant negative offset can be added to the collision warning equation. This has the effect of desensitizing the equation at slow speed and close quarters, but has little effect in other higher speed scenarios. In a Monte Carlo simulation the addition of a –3 meter offset resulted in an improvement of 60 fold in the nuisance alarm rate, but with the penalty of a minimal decrease in mitigation effectiveness and a 3% increase in low speed collisions below 5 mph.

A relative and/or absolute speed dependent factor can be used to increase the value of v_f, again reducing the sensitivity at slow speeds.

Response shaping can also be accomplished by a separate, speed dependent function that is applied to the output (warning distance (WD) or deceleration rate (k)) of the collision warning equation, as shown by example in Figure 10.

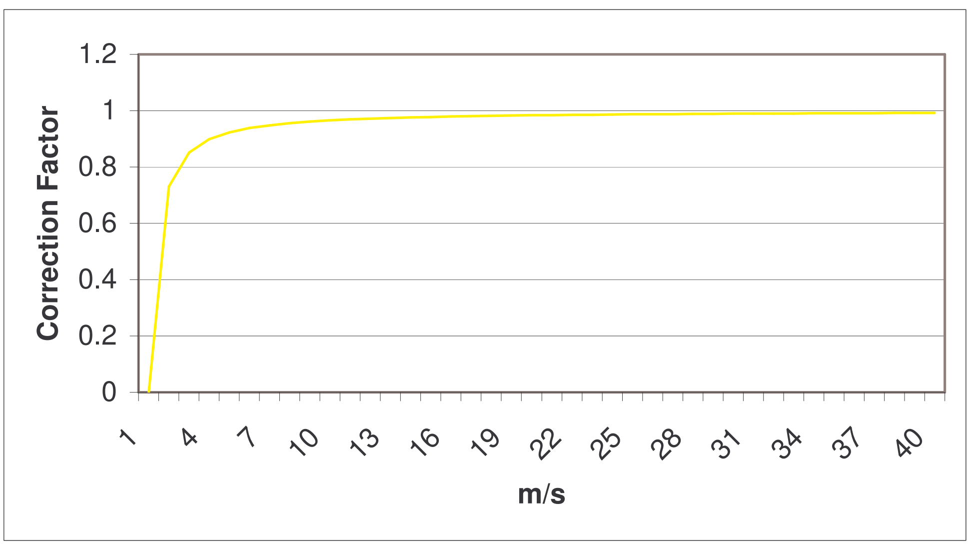

Figure 10 Slow Speed Response Correction Function

3.1.17.4 Coasting

See section 3.1.17.2.2 Accelerator/Brake.

3.1.17.5 Cut-ins / Sliders / Mergers / etc.

Cut-ins are sudden, close range merging vehicles which may or may not slow in front of the subject vehicle forcing a following-too-closely condition. Sliders are cut-ins that continue across and out of the subject vehicle's lane. These, along with more mannered merging vehicles share some common characteristics. They all suddenly appear in the immediate frontal path. Generally they present no real danger and indeed the GES database shows only 1% of the rear-end collisions resulting from these scenarios.

If they appear and disappear within the acquisition time, they are never passed to the warning algorithm and are not a concern. If they are recognized as targets and are pulling away, the collision warning equation will not force an alarm. Leaving us with the case where they are too close and the subject vehicle is closing on them.

As illustrated in Figure 2 Diminishing Likelihood Curve, there is a region where the prevention of a collision is physically impossible and as noted, the probability of a crash approaches unity in that region. An intrusive warning within that region may actually distract an attentive driver and cause a response delay[18] that actually delays an alert driver's chance to avoid the crash. A warning under these circumstances will not aid the inattentive driver.

An adjusted collision warning equation with a low (5^{th} percentile, 0.3 - 0.5 second) reaction time could be used to set a minimum warning range and any warning falling below that threshold could be suppressed. In these cases, the driver may be aware that warnings have been artificially eliminated. Times above the minimum will cause a system warning.

One of the disturbing scenarios is the suddenly exposed lead vehicle. A slow moving or stopped vehicle that is masked to the driver and FCW system by the lead vehicle, that is itself moving at a relatively high rate of speed. The obscuring lead anticipates the threat represented by the vehicle in-path and force merges or turns off, out of the lane, avoiding the collision but leaving the subject vehicle in close proximity, near or inside the optimum warning time. This scenario is affected by long acquisition delay times. The percentage of same direction accidents attributed to suddenly exposed lead vehicles is unknown. By observation, the occurrence is, in urban driving, relatively common and near collisions are common. The system response to the suddenly exposed lead is the same as the cut-in family of scenarios.

3.1.17.6 Lead Vehicle Decreasing Speed

The LVCS derived algorithm, though demonstrating good performance[19] across the range of driving scenarios is not as efficient as the stopping distance equations when the lead vehicle is decelerating. Not a surprising circumstance since the stopping distance equation is based on that activity and the physical basis for the collision warning equation

[18] D.V.McGehee, J.Lee, "Examination of Drivers' Collision Avoidance Behavior using a Front-to-Rear-End Collision Warning Display", The University of Iowa, IVHS Countermeasures for Rear-End Collisions, Contract Number DTNH22-93-C-07326, September 1996.

[19] T. Wilson "Algorithm Comparison for a Forward-Looking Collision Warning System", IVHS Countermeasures for Rear-End Collision, Contract Number DTNH22-93-C-07326, Sensor Technologies & Systems, Inc., December 1997.

used here is lead vehicle constant speed. Though it is reported[20] that a large fraction of same direction collisions are lead vehicle slowing, the severity of the braking is not defined and Knipling discussing lead vehicle stopped investigation, report, "…raising the question of whether some of the lead vehicle stopped crashed may be "disguised" lead vehicle moving crashes in which a lead vehicle braked to a stop immediately prior to being struck by a following vehicle…. However, clinical analysis identified no cases meeting this scenario description."

There are at least three ways to approach the lead vehicle decreasing speed situation. All three approaches must be considered in light of nuisance alarms and efficiency.

3.1.17.6.1 Optimized Values

This approach uses the lead vehicle constant speed equation with values optimized for a statistical mix of collision scenarios and is the method used here. In an effort to further optimize the algorithm or if the frequency or import of lead vehicle decelerating cases warrants, two alternative approaches are offered.

3.1.17.6.2 Measured Lead Vehicle Deceleration

If the sensor subsystem allows, measurement of the lead vehicle deceleration can augment these scenarios. Unfortunately, sensors don't measure acceleration directly, they must measure relative speed between the vehicles and then estimate deceleration by differentiation of the absolute speed of the lead vehicle. Errors are induced in the measurement of relative speed, and absolute speed of the host vehicle. Delays are induced in filtering the measurements in order to provide accurate estimates of lead vehicle deceleration. These errors and delays make the use of measured lead vehicle deceleration difficult. Even if a perfect estimate of lead vehicle deceleration is known, it does not provide information about the duration of the lead vehicle deceleration or the resultant final speed. A cooperative system using information handed-off from the lead vehicle would obviously benefit these scenarios, but cooperative systems require all vehicles to be equipped in order to be effective and this would delay deployment of systems that could truly benefit the driving public. In either case if the deceleration of the lead vehicle is unknown, or cannot be accurately measured by the sensor subsystem then the algorithm reverts to the lead vehicle constant speed case.

3.1.17.6.3 Deceleration Rate Equation

For the lead vehicle decelerating case it is known that the lead vehicle is decelerating, but there is no knowledge of what will be the final speed of the lead vehicle. One approach is to assume that the lead vehicle will come to a complete stop, but this may force the algorithm to be overly conservative and as a result have an unacceptably high number of nuisance alarms in benign scenarios. Another approach would be to assume that the lead vehicle will slow to a percentage of the absolute speed.

The deceleration rate equation can augment the LVCS equation for this circumstance and

[20] See footnote 3

is developed to bring the vehicles together at the speed v_f after both vehicles decelerate to that value. In this equation, α_l is the assumed deceleration of the lead vehicle and v_l is the lead vehicle current speed. The equation can be rewritten to facilitate the transition from lead vehicle slowing to LVCS.

$$WD = \frac{(v_f - v_l)^2}{2g\alpha_l} - \frac{(v - v_f)^2}{2g\alpha} + (A_{RT} + t_P + t_B + t_W)(v - v_f) \qquad \text{(meters)}$$

3.1.17.6.4 Threshold Detection

The third approach is to use the lead vehicle constant speed equation combined with a deceleration threshold detection scheme to trigger reductions in v_f when in the presence of a lead vehicle deceleration that exceeds the threshold. This approach may have the benefit of requiring only a gross approximation of deceleration, simplifying sensor and processing accuracy.

3.1.17.7 Lead Vehicle Accelerating

It is possible that a warning may be issued when the lead vehicle accelerates from in front of the host vehicle. This is the result of the squared term in the core equation. A simple logical trap to suppress warnings on negative relative speeds will prevent this from happening.

3.1.18 Situational Awareness Algorithm Structure

The discussion so far has concentrated on collision warnings and the considerations required to develop a real-world algorithm. This section deals with situational awareness information and following-too-closely warnings.

It is reasonable to assume that the naïve driver would expect a warning or advisory in situations where they are following-too-closely. This type of warning is intended to be less intrusive and may be disabled by the driver due to the increased nuisance potential. This type of warning is specific to following-too-closely (tailgating). The warning system output to the following-too-closely display is simply the continuous output of the warning algorithm, scaled and filtered to produce a stable output. The following-too-closely display is used to warn the driver that an unsafe or cautionary, tailgating condition exits.

The following-too-closely display needs to not only be intuitive to the driver, but may need to operate harmoniously with the collision warning display such as giving the driver situational awareness in high closure rate scenarios as well as tailgating scenarios.

3.1.18.1 Coupled Headway

Coupled headway is the condition experienced when the subject vehicle's absolute speed is dependent upon vehicles in the forward path. In this case, the driver of the subject vehicle is following the lead vehicle at near zero relative speed and is controlling the speed of the subject vehicle in response to the actions of the lead. Zero relative speed between the subject vehicle and lead vehicle may occur at any absolute speed as suggested in Figure 4 Coupled Headway State Diagram. Coupled headway distance is the range between coupled vehicle pairs and is used to define a safety zone or buffer between the coupled vehicles. This is not what driver's do, but perhaps what they should do dependent upon the absolute speed. This safety zone is defined as a minimum coupled distance, which creates an interval for warning and reaction time.

Since reaction time (within the collision warning equation) is implemented as a product of relative speed, the separation distance dictated by such a product requires zero separation at zero relative speed and provides no buffering at low relative speeds. The coupled headway buffer is therefore made proportional to lead vehicle speed, an approach that is consistent with the scheme of Figure 4. The buffer or coupled headway distance and the lost time are separate and distinct.

Assuming that a buffer zone is desirable how big might it be? Germany uses 0.9 seconds as a legal minimum following distance[21]. The state of Arizona recommends a 2 second minimum. About twenty-five percent of the 40,000 vehicle pairs surveyed on New Mexico's highways were coupled at less than 1 second[22]. Therefore, it is necessary to develop the capability in the algorithm to handle closely coupled scenarios.

Constant coupled headway times (at any practical values) are not consistent with observed driver behavior, since vehicles are often coupled at less than 0.5 seconds at 20 m/s (45 mph), a habit that appears unsafe, however, yielding to driver preferences may be necessary. Not only for driver acceptance but also because drivers at these following-too-closely headways seldom have collisions. To provide practical time margins for coupled pairs at various speeds, a headway time value that is proportional to speed is desirable. It should be noted that this headway time value is separate and distinct from headway time values discussed in conjunction with ACC systems.

Headway values are used to maintain a buffer between vehicles under routine driving conditions (Figure 4) and should be reduced to zero during severe-braking-required episodes to allow imminent warnings to reflect crash conditions, with the expectation that a satisfactory end to an urgent braking is the bumper to bumper condition of Figure 3.

Coupled headway distance is a function of the anticipated final speed of the subject vehicle and the coupled headway time (t_{CH}) which is itself a function of the assumed final speed. Coupled headway time (t_{CH}) is nominally defined as varying from a standoff time t_{so} at $v_f = 0$ at a slope of t_{SL}. This allows for a minimum standoff time and a lead vehicle speed dependent coupled headway time. Values are unavailable due to a lack of normative driver data and as a result, are left to the system developer.

$$d_{CH} = t_{CH} \cdot v_f \text{ (meters)} \quad t_{CH} = t_{SL} \cdot v_f + t_{SO} \text{ (seconds)}$$

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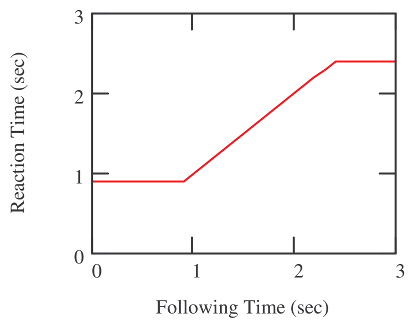
[21] D.V.McGehee, A.D.Horowitz, "effect of a "Headway" Display on Driver Following Behavior; Experimental Field Test Design and Initial Results", Proceedings "Intelligent Vehicles '93 Symposium," Tokyo, Japan 1993

[22] E.Farber, "Using the REMACS Model to Compare the Effectiveness of Alternative Rear-End Collision Warning Algorithms", Ford Motor Co., IVHS America 1994

To provide the most optimum possible collision warning thresholds it is necessary to reduce and then remove d_{CH} from consideration or treat it as a separate warning system independent of collision warning. Without this, the algorithms and the resultant driver warning displays will be erratic.

3.1.18.2 Following Time/Response Time

This definition of A_{RT} is an interpretation of work from the University of Iowa[23]. The assertion is, that drivers in known coupled headway environments exhibit faster response time to changes in the lead vehicle due to the knowledge that the lead vehicle exists in the forward path. This has been somewhat quantified to show that there is a 1:1 correspondence in the interval 0.9 – 2.4 seconds between following time (t_{F}) and the reaction time (D_{RT}) and zero slope plateaus beyond those points.
D_{RT} definition:



A further restriction is that this relationship applies to somewhat attentive drivers who are aware that they are in a closely coupled situation and are therefore focused. A driver merely progressing closer and closer to the lead vehicle (which may be the result of either the subject vehicle speed or the lead vehicle deceleration) and therefore constantly reducing following time may be asleep, distracted, etc. In order to prevent the algorithm-assumed reaction time from being a strict and instantaneous function of the actions of the lead vehicle, the subject vehicle following time input to the A_{RT} function, may need to be an averaged value of the following time t_{F} or discrimination must be made between coupled and non-coupled cases.

3.1.19 Situational Awareness/Following-Too-Closely Equation

The situational awareness/equation is the collision warning equation combined with the d_{CH} term.

WD	=	Warning Distance
v	=	subject vehicle current speed (meters / second)
v_f	=	subject vehicle final speed (meters / second)
g	=	9.8 (meters / second²)

[23] G.Davis, "Measurement of the Minimum Reaction Time for Braking of Vehicles", Not Published, 1990

α	=	assigned deceleration (g's)
A_{RT}	=	Algorithm assumed driver reaction time (seconds)
t_P	=	platform specific processor delay
t_B	=	platform specific brake actuation delay
t_W	=	platform specific warning actuation delay
t_{ch}	=	headway time (seconds)
k	=	g-level
r	=	range (meters)

3.1.19.1 Warning Distance Form

The output WD (meters), is compared with the measured range to determine the warning:

$$WD = \frac{(v - v_f)^2}{2g\alpha} + (A_{RT} + t_P + t_B + t_W)(v - v_f) + t_{ch} v_f \qquad \text{(meters)}$$

3.1.19.2 Deceleration Level Form

The output k (g's), is compared to a predefined braking level to determine the warning:

$$k = \frac{(v - v_f)^2}{2g((A_{RT} + t_P + t_B + t_W)(v - v_f) - r) + t_{ch} v_f} \qquad \text{(g's)}$$

3.1.20 Braking Profile

Individual drivers have preferred stopping profiles[24], and approach a developing situation with their own habits about closing and deceleration rates. Individual stopping routines in slowly developing scenarios may be to brake at a low relatively constant rate over a long distance or to brake at higher rates for shorter distances. Drivers with less accurate judgment may find themselves braking rapidly initially while adjusting their braking rate as they better gage the stopping force required. Others with equally poor judgment may brake gradually and adjust their stopping force as the situation ahead worsens.

In more rapidly developing situations the same three performance patterns can be expected. The last situation with increasing deceleration rate is common in lead-vehicle slowing situations. The driver recognizes that the vehicle ahead is slowing, but if the purpose of the slowing is not readily apparent, can't predict the depth of the stop. The driver begins to slow while constantly updating the status of the vehicle ahead. If the lead continues to slow at a constant or increasing rate, the following driver is required to stop harder and harder. This case may be the result more of circumstance than preference, but seldom are drivers observed to brake suddenly without provocation.

Conversely, algorithms typically assume a constant deceleration for the driver.

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[24] R.H.Wortman, T.C.Fox, "An Evaluation of Vehicle Deceleration Profiles" Journal of Advanced Transportation, Vol 28, No 3, pp 203-215

Wortman and Fox[25] have investigated driver's stopping profiles and have quantified the relative constancy (or lack thereof) of deceleration for vehicles approaching stop lights. Not surprisingly they determined that constant deceleration is not the norm.

Plotting speed against time they offer three generalized curves to describe typical stopping behavior. Their regression equation relates a dimensionless index, Q to initial speed, v expressed in miles per hour, thus:

$$Q = 0.3 + 0.04(\tfrac{v}{15})^{2.5}$$

Q is the ratio of calculated uniform accelerations α_{vx}/α_{xt} with α calculated from $(\Delta v, \Delta x)$ or $(\Delta x, \Delta t)$ respectively. Figure 11 shows the condition when Q equals one and the driver is stopping with truly uniform deceleration. This case is consistent with the commonly used constant deceleration equations.

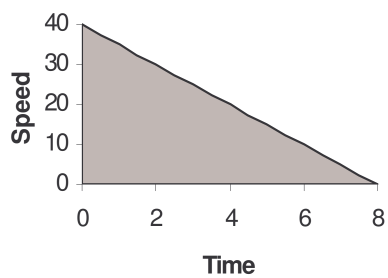

Figure 11 Uniform Deceleration Profile

As initial speed decreases, the curve shape of Figure 12 dominates and Q<1. Drivers use lower initial braking rates followed by more severe braking, with the effect of requiring more distance to stop than would be predicted by a constant deceleration equation.

[25] R.H.Wortman, T.C.Fox, "An Evaluation of Vehicle Deceleration Profiles" Journal of Advanced Transportation, Vol 28, No 3, pp 203-215

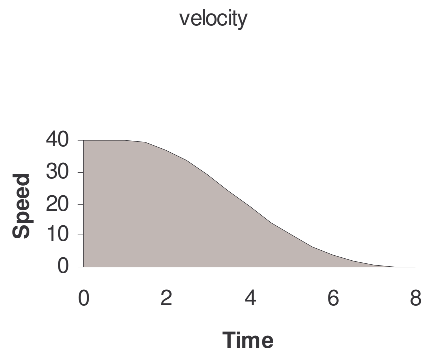

Figure 12 Low Speed Deceleration Profile

As initial speed increases, the curve shape of Figure 13 dominates and $Q > 1$. Drivers use harder initial braking followed by a relatively benign runout. More speed is scrubbed off early and the effect is a shorter than predicted stopping distance.

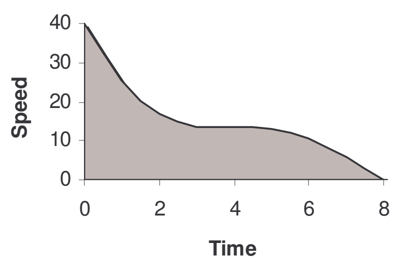

Figure 13 High Speed Deceleration Profile

According to their study, braking is uniform and $Q = 1$ at initial speeds of approximately 47 mph, but braking is strongly non-uniform at the extremes of their data, with Q values of 0.4 at 20 mph and 1.5 near 60 mph.

Commonly used warning algorithms predict results based on constant, linear deceleration profiles. This does not accurately reflect driver's actions and may result in nuisance alarms under certain conditions. The result of such non-uniform braking is that commonly used acceleration equations will not yield accurate results and uncompensated predictions of stopping distance or time-to-stop may be in error. These errors would result in a decrease in benefit (an increase in the nuisance alarm rate, and/or a decrease in the crash avoidance/mitigation rate) in uncompensated systems.

3.1.21 Population versus Single User Installation

In attempting to make a system that routinely predicts the actions of the extended system, the largest single hurdle is the fitting of the broad population based curves to the behavior of the driver behind the wheel.

The lead vehicle and driver are drawn from a large pool and are well represented by a Monte Carlo approach. The driver behind the wheel is unique and though his or her reaction times, daydreaming habits etc. introduce variation into the mix. It should be expected that their variation should be less than the population at large but unknown on the drive by drive basis. Most non-urgent nuisance alarms and a large percentage of the deficiency in crash avoidance or mitigation will be the result of a mismatch between these two.

Taoka[26], analyzing the data of Chang, Sivak and others, suggests that a log-normal distribution can be used to emulate the dispersion in the analyzed driver reaction time data. He also suggests that in a car following situation "… a value of 1.8 seconds may be … representative for the reaction time of the 85th percentile driver". Both Wortman and Sivak show 85th percentile values of approximately 1.8 seconds (Wortman is reported as 1.80 and Sivak 1.78 with means of 1.12 and 1.07 respectively). So based on good statistical evidence let's use 1.8 seconds for driver reaction time and review its effectiveness.

Comparing the suggested 1.8 second value to the drivers' capability, at 27 km/h (60 mph) the system warns the median driver 18 meters (0.68 sec) too soon and the 95th percentile driver 15 meters too late. Neither case is desirable. A three car length conservatism for the average driver becomes a chorus of annoying nuisance alarms, while the slower reacting driver has apparently come to a stop by colliding with the lead vehicle. Neither result is the desired effect of a forward-looking, rear-end collision warning system.

"The American Association of State Highway and Transportation Officials (AASHTO) design standard is 2.5 seconds for the perception and reaction time used in computing stopping distances", a 95th percentile value, according to Taoka's synopsis. Choosing a driver reaction time of 2.5 seconds will certainly improve the slower drivers survivability but will warn the median driver (again @ 27 km/h) 37 meters too soon and the 5th percentile driver 2 seconds (54 meters, 8+ car lengths) too soon.

These conservative errors overwhelm the following distances found acceptable by modern drivers. The Federal Highway Administration records[27] for Interstate 40 near Albuquerque in New Mexico describe 36,919 vehicle pairs for 25 September 1991 and 31,612 pairs from 11 July 1993. Approximately 25% of the vehicles were spaced at time gaps of 1 second or less and about 6% at time gaps of 0.5 seconds or less. This at median speeds of 54 and 61 mph respectively. The respective median following times were 1.67 and 1.97 seconds. Well under the suggested 2.5 second warning design time.

[26] G.T.Taoka, Brake Reaction Times of Unalerted Drivers, ITE Journal March 1989
[27] As reported by Farber

This conservatism is of course merely the result of trying to cover all cases with a single value system. It is obvious that a system that is capable of adjusting the various assigned values in the driver warning algorithm to match the performance of the individual driver and vehicle will reduce the number of nuisance alarms and provide a more efficient and acceptable system.

Driver adaptation of the forward-looking, rear-end collision warning system does not remove the need to develop a single value system. The single value system is still necessary as a minimum starting point from which the system can begin to adapt to the driver. This minimum must be based on reasonably aggressive driving tendencies to reduce the possibility of nuisance alarms. Additionally, the minimum should be compatible with other systems such as Adaptive Cruise Control.

3.1.21.1 Effectiveness

Due largely to the dearth of valid, driver response information, reports on the efficiency of algorithms and the systems they might power tend to ignore the human element and concentrate on the ability of the warning system to sense the presence of a threat in the path of the host vehicle. While these provide a measure of the efficiency of the subset warning system, the real system in question is usually not even mentioned. Studies are run with ground rules such as: "the system always works perfectly up to its range limitation, i.e., it never fails to detect the lead vehicle, never detects the 'wrong' vehicle and provides accurate speed and distance information… and …the following driver always responds after some response time",[28] and the projected efficiencies approaching 100% reported are creating unrealizable expectations about the number of collisions that implementing these systems may prevent. The reports usually contain a statement of concern about driver acceptance or the large number of false alarms produced, but the glow from the high efficiency numbers tend to obscure these caveats. It must be understood that it is the interaction of the warning system with the driver that will define the effectiveness of the system.

3.1.22 Beyond The Minimum System

3.1.22.1 Information Sources

There are a number of obvious information sources (beyond the primary forward-looking, rear-end collision warning sensor) that can be used to adapt the system to the driver, the vehicle and environmental conditions. Multiple sensors either newly installed as part of a forward-looking, rear-end collision warning system, or with functionality borrowed from existing auto applications should not represent a major impact in costs whether measured in processing capability, installation or integration difficulty or of course - cost. Some are already in place - all are possibilities.

Host vehicle sources include: IR probes (active or passive), driver alertness indicators,

[28] E.Farber, Using the REMACS Model to Compare the Effectiveness of Alternative Rear End Collision warning ALGORITHMS, Ford Motor Co., IVHS America, 1994

driver diversion indicators, lidar, radar, visibility sensors, brake light switches, accelerometers, humidity sensors, wheel slip/traction indicators, clock, driver haptic controls, photo-optical sensors, vehicle load sensors, side looking and rear looking sensors, pedal activation, hydraulic system sensors, tilt indicators, CCD's, acoustic and ultrasonic sensors, windshield wipers, internal and external temperature sensors.

Extravehicular information sources include: coded and transmitted weather data, traffic density information, overtaking vehicle warning, leader-follower information exchange (i.e. lead vehicle tells following vehicle that react mode is active; or that lane is clear), cooperative speed and acceleration exchange, lane markers and side of road markers.

3.1.22.2 Approach

There are various parameters that define the habitual driving environment for each specific driver. The two most obvious are deceleration and following distance. Deceleration is the driver's habitual rate of change of speed (stopping or slowing expressed in g's or m/s^2). It is suggested that habitual deceleration is a function of absolute vehicle speed and is related to the driving environment and perception distance of the driver. Following distance is the distance, usually expressed in time, that drivers habitually follow other vehicles in coupled headway environments. There are other obvious parameters that define the habitual driving environment such as vehicle type and condition, driver state: fatigued, alert, bored, preoccupied, impaired, etc., roadway environment: hills, curves, etc., atmospheric and roadway conditions, etc. These inputs affect the driving habits in various ways dependent on the mental state of the driver.

If some or all of these parameters could be measured they would benefit the performance of the forward-looking, rear-end collision warning system in adapting to the driver and thereby reduce nuisance alarms associated with driver behavior.

3.1.22.3 Driver Warnings

Getting the driver's foot off the gas is necessary for all primary avoidance maneuvers other than steering. It is suggested that a driver's conditioned response to any extraordinary driving circumstance is to release the accelerator. This may not include complete removal of pressure (input) to the vehicle's accelerator. Of the various visual, auditory and tactile/haptic warnings that have been discussed and debated a thump or upward pressure on the accelerator foot is suggested as a possible initial (cautionary) warning mechanism. Unlike beeps, buzzers and dashboard lights the pedal actively pushing back would be unique to a headway hazard. The ability for the driver to override can be maintained, and the warning can be accomplished in a very non-intrusive way thereby limiting the driver's interpreting the warning as a nuisance. This is critical for the cautionary warning that is expected, and designed, to occur frequently in comparison to the imminent warning (approximately 100 times more often).

Unfortunately, getting the driver's foot off the accelerator does not solve the entire problem because there exists a reasonable possibility that the driver is coasting with his/her foot off the accelerator when the warning is initiated and as a result, the driver never perceives the warning. This suggests that the next display modality for the imminent warning should be associated with brake initiation or pulse braking. Braking is unique to the longitudinal direction and can be perceived by anyone in the vehicle regardless of position. This braking could be a single transient to the braking system (brake initiation), or could be a scripted series of transients to the braking system (pulse braking). Braking is not without it's own problems.

If we describe a nuisance alarm as occurring when the driver is warned at a distance that requires less stopping force than the driver habitually uses, then a correct alarm can be described as a warning that occurs when the driver must apply more stopping force than the driver habitually uses. For imminent collisions, a "brake to avoid" is anticipated to occur approximately 15 times per year[29]. One problem with the cautionary and imminent warnings is that they are not closely related, one gets the driver's foot off the gas pedal and the other thumps the brakes. Both are unique to the longitudinal direction of the vehicle, which is good, but the cautionary warning may not allow the driver to develop a proper mental model of the system operation. As a result, the driver may be responsive to the cautionary warning, but on the chance that the cautionary warning is missed as described previously the driver may be startled by the braking initiation, not respond properly or not respond in a timely manner due to the infrequency of the imminent warning. Additionally, braking initiation that slows the vehicle can cause collisions in close merging or lane changing scenarios. Scripted braking transients (a thump, thump, thump on the brakes) may be considered an embarrassment to the driver if other passengers sense the occurrence and are familiar with the cause.

The driver is assumed to be reasonably efficient and taking the defensive driving tools out of the driver's hands on the basis of a straight-line-stopping-only strategy gives a conservative estimate of system effectiveness. The effectiveness of a real system would likely be higher because real drivers posess these additional options.. Evasive steering and accelerating out of danger are valid reactions to a threat and a real driver would be expected exercise them some portion of the time.

Automatic braking is only justified when a collision is imminent and the time to impact is below the warning (driver reaction) time. It should be limited to low speed, close in situations such as stop and go traffic with the threat directly in front of the host vehicle.

There must be a concentrated effort to define, track and report a "coefficient of human interaction". It is ultimately more useful to designers, planners and decision makers to report this factor as an estimate than to not mention it at all. Without a realistic baseline, changes in the technology cannot be honestly or meritoriously assessed. This baseline is offered. No one who understands the current warning system wants to drive with one. Therefore the current driver acceptance probability is zero and the actual effectiveness of the system is zero.

[29] See Footnote 8

3.1.23 Summary

The warning algorithm is defined as a set of equations based on vehicle dynamics and various decision points used to transition between driving states. This section discussed issues associated with the core set of equations and identified some of the key decision points. The intent is to provide some basic guidance on system performance as a function of the warning algorithm. Detailed implementation of a warning algorithm methodology is currently left to the system developer or OEM.

A minimum autonomous forward-looking, rear-end collision warning system as envisioned would have limited sensor and processing capability. A minimum system will have only host vehicle speed, relative speed and range between vehicles as inputs.

Driver warning algorithms by nature make certain inherent assumptions. Driver warning algorithms operate on only two vehicles, the subject vehicle and the lead vehicle. Driver warning algorithms do not include any geometry curve, hill, lane change, merges, etc. that are present in normal driving. Driver warning algorithms assume perfect input from the sensor, no guard rails, signs, debris, etc. Additionally, driver warning algorithms do not include how the warning is presented to the driver.

The concept that a forward looking collision avoidance system is not a stand alone device, but is just one element of an extended system consisting of the FCW, the driver and the vehicle is presented.

A warning algorithm was developed in terms of a physical model and the assumption is made and supported that drivers will adversely respond to nuisance alarms, and that those alarms can be classified according to the severity of the braking maneuver required to avoid a particular threat. Drivers preferential braking threshold is defined as less than or equal to 4 m/s^2 (0.4g).

Lost time, comprised of driver and system delays was identified as the largest contributor to nuisance alarms and system inefficiency. The notion that an adaptable platform may ultimately provide maximum efficiency is explored.

The algorithm is divided into three functional groups, imminent collision avoidance, tailgating and situational awareness. The sample algorithms are built on a kinematic equation with terms added to adjust for lost time. The resulting algorithms are described as collections of elements, each answering some observed, or simulation predicted problem or area of concern such as traffic scenarios or optimization. A number of devices and mechanisms are suggested for the implementation of the tuning and compensation mentioned above.

The reliance of such systems on mean acceleration for prediction of times, distances and warnings is contrasted with the apparent non-uniform nature of braking in the population at large. An increase in nuisance and lack of efficiency is predicted for non-compensated systems[30].

3.2 DRIVER WARNING METHODOLOGY

This section discusses the issues relevant to the presentation of warnings to the driver.

Warning presentation is critical for system effectiveness and driver acceptance. In order for the forward-looking, rear-end collision warning system to function, the presentation of the warning must be perceived by the driver, orient the driver's attention and elicit an appropriate response to avoid the collision or unsafe situation. All of the potential benefits of a forward-looking, rear-end collision warning system can be lost due to a poorly designed driver interface.

The presentation of the warning is highly dependent upon the sensing and processing functions of the system as a whole. If the FCW system is poorly designed and cannot eliminate false alarms to the driver, then it is expected that non-intrusive display modalities would be utilized to minimize nuisance to the driver. As FCW systems become more capable, then more intrusive display modalities can be selected and overall system effectiveness should increase. Non-intrusive display modalities such as visual, except in the case of following-too-closely warning, and auditory may be a good indication of a poorly designed FCW system.

Three possible display modalities exist: visual (must be seen), auditory (must be heard) and haptic (must be felt; either tactile (touch) or proprioceptive (pressure, resistance)).

It is not known if an optimal warning modality solution exists. Drivers approach changing situations differently and respond to stimuli differently. As a result, this document only discusses characteristics of display modalities. Detailed display design has been left to the OEM or system developer. Consideration of space limitations and aesthetic requirements for vehicular instrument panels is beyond the scope of this research. Additionally, due to the sheer number of combinations between driver, driving scenario, system and display it is impractical to test all possibilities and provide a comprehensive assessment of which display modality is superior. There exists a need to develop the normative driving data as well as rear-end collision specific driver data necessary to finalize the display modality recommendations for FCW systems. This document can only provide guidance for future research necessary to develop warning display modalities.

3.2.1 Background

The primary rear-end collision causal factor is driver inattention to the driving task (approximately 66% to 77%)[31]. Driver inattention in this context includes both inattention

[30] "Analysis of Driver Warning for a Forward-Looking Collision Warning System", IVHS Countermeasures for Rear-End Collision, Contract Number DTNH22-93-C-07326, Sensor Technologies & Systems, Inc., December 1997

[31] Sensor Technologies & Systems, "IVHS Countermeasures for Rear-End Collisions", Contract Number DTNH22-93-C-07326, Task 1 Interim Report, Volume I, Summary, Table 8.8-1, pp 41, February 1994, DOT HS 808 561.

and distraction. Drivers are constantly scanning the roadway environment (i.e., looking down the road, left side, right side, scanning the mirrors and attending to internal and external stimuli). Drivers can only focus well on one thing at a time because the eyes focus together. So, for example, when drivers are attending to other stimuli they may not be able to adequately perceive the roadway in front of the vehicle. It is often necessary for drivers to take their eyes off the roadway and "attend" to other stimuli when operating in-vehicle controls and possibly carrying on conversations. Often drivers use multiple glances to attend to other stimuli thus taking their eyes off the roadway. These glances distract the driver and lead to inattention to the driving task. The glances may be momentary or extended duration. Driver distraction accounts for approximately 11% to 24%[32] of the driver inattention. Drivers can also exhibit a behavior where they are focused on the roadway ahead but don't perceive the changes that are occurring. This "looked by didn't see" phenomenon is also indicative of driver inattention.

There is evidence that suggests that rear-end collisions may occur because the driver of the striking vehicle does not see the vehicle ahead because of complex perceptual factors (Mortimer, 1988). Several perceptual factors are present in determining distances and rate of closure information for following vehicles. When making judgments regarding depth, pictorial cues such as relative size can be one of the strongest (Levine & Shefner, 1991). When a vehicle is far ahead, it looks smaller than it does when it is close (Mortimer, 1990). This can also be described in terms of visual angle, for instance, when a vehicle is far away the visual angle is small and when the vehicle is close the visual angle is larger. In a study conducted by Braunstein and Laughery (1964), it was found that using vehicles and deceleration of 0.8-1.48 ft/s^2 obtained changes in visual angle of 0.09-0.12 degrees for headway change detection. Another study (Mortimer, 1971) measured the sensitivity of the driver's changes in headway from initial headways at 70 mph of 120 feet and 320 feet and at 35 mph of 40 feet and 120 feet. The visual angle change was 0.12 degrees for headway detection which is similar to that found by Braunstein and Laughery.

For the inattentive driver, the FCW system is operating in a collision warning mode where the FCW system detects the imminent collision and provides a warning to the driver who perceives the warning and responds to avoid the collision[33]. In this case, the detection, warning, perception and reaction occurs sequentially. The collision warning mode requires a high level of perceived reliability by the driver. In this mode, the system is detecting a collision threat that requires immediate intervention by the driver to avoid the collision. In this mode, the FCW system must elicit the proper response from the driver in an extremely timely manner. Collision warning display modalities require a certain amount of intrusiveness in order to capture the drivers attention and elicit a response.

The secondary rear-end collision causal factor is following-too-closely (approximately 12% to 27%)[34]. According to Evans (1991)[35] there are two likely reasons why drivers

[32] See Footnote 31
[33] L.Tijerina, R.Garrott "A reliability Theory Approach to Estimate the Potential Effectiveness of a Crash Avoidance System to Support Lane Change Decisions" SAE Paper 970454.
[34] See Footnote 31

tend to become comfortable following at headways that increase the risk of involvement in rear-end collisions. First, dominant cue when following is the relative speed between coupled pairs of vehicles. In normal vehicle following, relative speed is very close to zero and there is no risk of a rear-end collision if no transient event occurs with the lead vehicle. Evans believes that the largely static visual impression in vehicle following tends to lower the awareness and concern regarding speed. The second reason Evans believes drivers become comfortable when following-too-closely is that they have learned from repeated experience that it is safe to do so in the sense that they have been doing it for years without adverse consequences. Evans also indicates that experience teaches drivers that the vehicle in front usually does not suddenly slow down. Driver's can also perceive the forward path in front of the lead vehicle and use this information to drive at close following distances. The FCW system is operating in a situational awareness mode. No collision potential exists as long as no transient events occur. In this case, the FCW system provides the driver situational awareness or advisory information regarding vehicles in the forward path. The situational awareness mode does not require as high a level of perceived reliability by the driver since it operates in a supervisory mode assisting the driver in modification of behavior. Situational awareness display modalities suggest that they are less intrusive than collision warning display modalities for this reason.

Based on the available literature, drivers are able to judge accurately whether a gap between them and another vehicle is opening or closing (Hoffman, 1966, Mortimer, 1971, Olson et al., 1976). However, it also appears that drivers base their closure rates heavily on changes in visual angle. Mortimer (1988) has found that drivers are able to derive little information from the absolute and relative speed of the vehicle ahead. However, drivers are able to make relatively accurate estimates on the distance to the car ahead of them (within twenty percent) and are reasonably sensitive in determining a change in the headway between their vehicle and one ahead of them within approximately twelve percent. A study by Hoffman (1966) found that in many situations drivers do not have the opportunity to estimate relative speed because the threshold for human perception of relative speed is often not exceeded. Hoffman (1974) also determined that the threshold for angular speed is on the order of 0.0035 radians per second. The same study showed, in a car-following simulator, that the driver made little use of relative speed information, but was able to scale the absolute speed of the car being followed in a more effective way. It was concluded, that unless the relative speed between the two vehicles becomes quite high drivers will respond to changes in their headway or the change in angular size of the vehicle ahead, and use that information to determine the speed they adopt when following another vehicle. Hoffman (1974) also found that the relative speed has to be quite high to make use of this cue. Even then, drivers cannot scale relative speed into more than three or four categories. Hoffman suggested that this implies rear-end collisions could be reduced if drivers were aided by a display which indicated the speed of the car being followed. The display could then relate relative speed to drivers who know their own speed.

[35] Evans

Based on the rear-end collision causal factors, if the forward-looking collision warning system does not provide a following-too-closely warning then the corresponding system effectiveness is reduced by 12% to 27% which is the number of rear-end collisions that are caused by drivers following-too-closely[36]. The intent of a following-too-closely warning is to modify driver behavior by exposure, over a period of time and create safer following distances since following-too-closely can very quickly advance to an imminent collision situation. The following-too-closely display can provide continuity between following-too-closely and collision situations and may aid the drivers understanding of system operation. Drivers would reasonably expect some type of notification for unsafe following distances in closely coupled headway scenarios.

Other rear-end collisions (approximately 4%)[37] are due to vehicle failure, driver incapacitation (seizure), etc., and countermeasures are not considered here.

3.2.2 Warning Display Characteristics

The following list describes the potential elements of a forward-looking, rear-end collision warning display. Some elements are unique to the collision warning mode, others are unique to following-too-closely warning mode, still others apply to both modes.

The warning display should:

- be usable by naïve drivers in mass marketed passenger vehicles
- meet or match the driver’s mental model
- be intuitive
- not confuse the driver
- not startle the driver
- not annoy the driver
- contain both collision warning[38] and a following-too-closely (tailgating) warning
- aid the driver’s understanding of system operation
- focus the driver’s attention on the hazard ahead
- elicit an automatic or conditioned response
- be unique to the longitudinal motion of the vehicle
- suggest a course of action for the driver
- not cause other collisions to occur
- be perceived (salient) by the driver over all background noise, at all levels of ambient lighting, at all levels of vehicular shock (hitting potholes, etc.), at all levels of vehicular vibration (rough roads) and over all host vehicle speeds
- be distinguishable from other collision types of display modalities (run-off-road, side looking, crossing path, etc.)

[36] See Footnote 31
[37] See Footnote 31
[38] See footnote 1

- not embarrass
- not promote risk taking by the driver
- not compromise the driver's ability to override the system and perform other avoidance actions such as braking, steering or accelerating
- provide situational awareness (trend) information for presence, changes in relative speed, and distance to vehicles in the forward path

As a general approach to collision warning methodology, multiple levels of warning are anticipated. Each level becomes more intrusive at the collision becomes more imminent. In addition to collision warning, following-too-closely is an additional, less intrusive, warning mode.

3.2.3 Following-too-Closely Warning Methodology

Following-too-closely (tailgating) occurs when the host vehicle is following the vehicle in the forward path (coupled headway) at or near zero relative speed and close distance. Following-too-closely is a common occurrence under normal driving conditions (Wasaileki, 1979). Drivers routinely follow vehicles at a distance (time) that is inside what would be considered safe driver reaction times. Drivers learn over time that generally nothing bad will happen but this does not make following-too-closely a safe or proper practice. Driver's following-too-closely would reasonably expect a warning under these conditions. The following-too-closely warning methodology must inform the driver of the unsafe following practices. Following-too-closely displays may be haptic or auditory but will predominantly be visual. The average driver may consider intrusive haptic and auditory warning methodologies objectionable.

The following-too-closely warning methodology must be able to present situational awareness information, but not prevent the driver from overriding. Following-too-closely displays should:

- be usable by attentive drivers
- convey safe, cautionary and unsafe following practices to the driver (not provide the driver with an optimum following distance, but rather to make the driver aware of unsafe following practices)
- present the driver with situational awareness and trend information (rate of change)
- be compatible with collision warning display modalities (i.e., not present the driver with conflicting warnings)
- be intuitive, not confuse or startle the driver
- convey changes (relative speed) to lead vehicle scenarios
- accentuate the natural looming (distance) cues experienced in normal driving, i.e. close vehicle big, far vehicle smaller
- not promote risk taking by the driver
- not require a great deal of driver concentration to perceive or understand
- relate to the longitudinal motion of the vehicle
- be compatible with the adaptive cruise control system

The following-too-closely warning should provide feedback to the driver of safe following, following close and unsafe following practices. Because drivers routinely drive at apparent unsafe following distances, the following-too-closely display may be considered more of a nuisance to the driver than collision warning displays. This may provide justification for allowing the driver to turn off the display. However, there is a corresponding reduction in system effectiveness if this is allowed. This includes the ability to “dim” the display (assuming a visual display) along with the vehicle dash lights. The cautionary and imminent collision warnings are separate and still required. These guidelines do not restrict the following-too-closely display from being adjustable by the driver. This adjustability may lower overall system effectiveness and some minimum value must be maintained. No empirical data is available to assess the subtleties associated with the following-too-closely display.

3.2.3.1 Visual Warnings

As previously discussed, visual displays are not considered viable for collision warning displays due to the inattentive or distracted nature of the driver. However, visual displays should provide a good indication to the driver for following-too-closely warning scenarios. A visual display should:

- be usable by attentive drivers
- convey safe, cautionary and unsafe following practices to the driver (not provide the driver with an optimum following distance, but rather to make the driver aware of unsafe following practices)
- present the driver with situational awareness and trend information
- be compatible with collision warning display modalities
- convey changes (relative speed) to lead vehicle scenarios
- accentuate the natural looming (distance) cues experienced in normal driving, i.e. close vehicle big, far vehicle smaller
- be mounted such that it is centered in the dashboard as high as possible and be positioned within 15° of the driver’s line of sight, both vertical and horizontal – a heads-up-display (HUD) would also be possible
- be separate from all other dashboard displays and be large enough with sufficient contrast and intensity for the driver to perceive the display in his or her peripheral vision
- must be perceivable under all ambient lighting conditions
- be able to be turned off by the driver (possibly, including dimming with the dashboard lights).
- be usable by persons who are color blind or color deficient
- be compatible with the adaptive cruise control system

A visual display can also convey system operation (system on and functioning) and assist in development of the mental model of system operation to the driver. An example visual display is shown in Figure 14. It should be noted that this is an example display and not a recommendation.

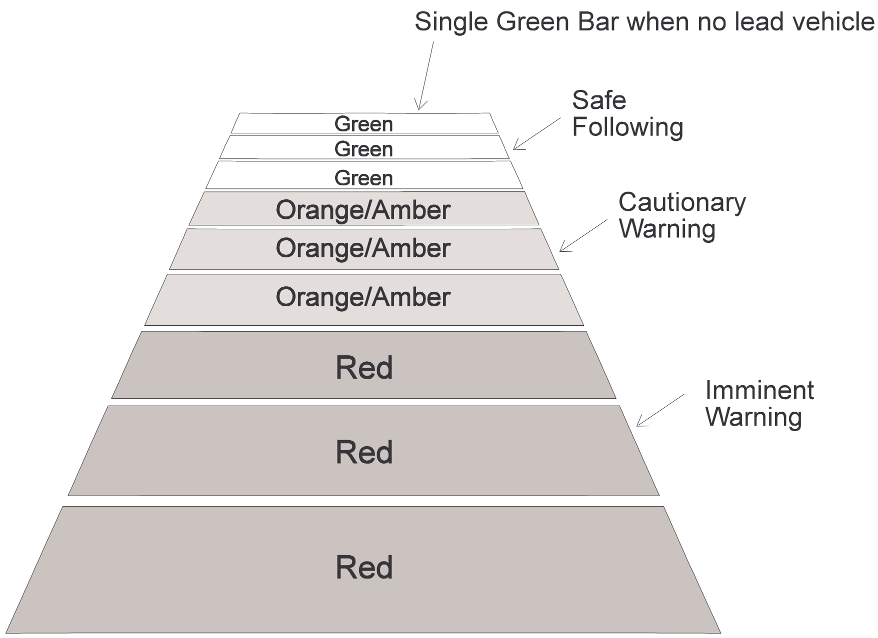

Figure 14 Example Following-to-Closely Graded Visual Display

Visual display methodologies lend themselves to following-too-closely warnings. Visual displays are perceivable by the attentive driver, but can be ignored if the information is unusable by the individual driver.

3.2.4 Collision Warning Methodology

A forward-looking, rear-end collision warning system is intended to provide a suitable warning for the inattentive driver. An inattentive driver, by definition, is not focused on the driving task and may not be focused on the roadway ahead. Drivers would reasonably expect a warning in these instances.

The inattentive nature of the driver eliminates visual displays from consideration because the driver must be oriented toward the visual display in order for it to be perceived. Visual display modalities may be viable as secondary displays for situational awareness, system operation, status information, or for following-too-closely warning scenarios. The inattentive driver warning display must then be auditory or haptic. The issue is which method, auditory or haptic, has the best potential for capturing the driver's attention and eliciting the proper response.

As a general approach to collision warning methodology, multiple levels of warning are anticipated. Each level becomes more intrusive as the collision becomes more imminent. Two levels of collision warning are discussed: imminent and cautionary. An imminent collision avoidance situation is one in which the potential for a collision is such that it requires an immediate vehicle control response or modification of a planned response in order to avoid a collision. A cautionary collision avoidance situation is one in which the potential for a collision requires immediate attention from the driver, and may require a vehicle maneuver but does not meet the definition of an imminent crash avoidance situation. The cautionary warning also may include the following-too-closely (tailgating) warning or the following-too-closely warning may be a separate and unique type of warning. It should be noted, that these two levels of warning may not work under all situations.

3.2.4.1 Imminent Collision Warning Methodology

An imminent collision warning must be perceived by the driver in a timely manner in order to eliminate or mitigate a collision. Imminent collision scenarios are anticipated to be extremely rare. The definition of an imminent collision scenario is dependent upon the individual driving habits and perceptions of the driver, but are arbitrarily defined as occurring when a driver must decelerate at or above 5 m/s^2 (0.5 g's) in order to avoid a potential collision. Imminent collision scenarios are estimated to occur on the order of 15 per year based on 1.5 brake applications per mile and an average of 10,000 vehicle miles traveled per year[39]. The rare occurrence of imminent collision scenarios and associated warnings does not keep the driver aware of the FCW system, or aid the driver in understanding FCW system operation. Rather, when the imminent collision condition occurs, the driver may be startled by the warning and may not respond or may respond inappropriately. Additionally, drivers may feel the need to operationally experience the warning to prove to themselves that the system is on and functioning. For the imminent warning methodologies little or no empirical evidence exists. It may be difficult, if not impossible, to gather empirical data for imminent collision warning scenarios. Currently this type of testing can only be performed using simulators such as the Iowa Driving Simulator and certain display modalities and scenarios cannot be properly simulated as well as possible due to the simulated environment.

Because imminent collision scenarios are rare, a cautionary warning may be beneficial to the driver. The purpose of the cautionary warning is to remind the driver that the FCW system is on, operating and vigilantly aiding the driver to avoid imminent collision scenarios. Cautionary warnings are issued for the same circumstances as imminent warnings but are more conservative. Cautionary warnings occur more frequently and may require a less intrusive display modality in order to reduce nuisance to the driver. Imminent warnings may not be appropriate under all situations, likewise the combination of imminent and cautionary may not be appropriate under all situations.

3.2.4.2 Cautionary Warning Methodology

Imminent collisions are anticipated to be extremely rare events So rare that they will not assist the driver in developing a mental model of the forward-looking, rear-end collision warning system. As a result, a cautionary warning is recommended. The cautionary warning is more conservative in comparison to the imminent collision warning and therefore will be active more often. Additionally, the cautionary warning may reduce the

[39] T.D.Gillespie, "Fundamentals of Vehicle Dynamics, Society of Automotive Engineers", 1992.

startling potential of the imminent warning and also may serve to modify driver behavior by exposure over time.

The purpose of the cautionary warning is threefold: First, the cautionary warning aids the driver in understanding the operation of the FCW system. Second, the driver can purposefully activate the cautionary warning in order to verify system operation. Third, the cautionary warning may modify driver behavior by exposure over time by creation of safer following distances and more attentive driving.

Cautionary warnings are intended to be perceived by the driver on a routine basis and serve to increase the driver's understanding and awareness of the FCW system. This premise must be proven by naïve driver testing. The cautionary warning should be as salient but not as intrusive as the imminent warning.

The cautionary warning should be a less intrusive display since it occurs more frequently and has a greater potential of being a nuisance to the driver. There is no empirical data available as part of this research to justify selection of the display modality. Drivers typically respond to lead vehicle events by first releasing the accelerator pedal. Drivers may "coast" a great deal of the time during changes in lead vehicle events, either hovering over the accelerator or brake. Studies as part of this research have found that during imminent collision situations, drivers aided with a warning responded faster in release of the accelerator pedal[40]. In fact, just the release of the accelerator pedal causes significant reduction in impact speeds and a significant reduction in damage or injury potential for rear-end collisions. Thus, it is beneficial to provide a warning that promotes accelerator release.

Cautionary warnings should occur at a level that maintains the mental model of the FCW system performance. Issuance of too many cautionary warnings may be considered a nuisance by the driver. As with imminent warnings, cautionary warnings are dependent upon the individual driver. It should be noted that an accelerator cautionary warning modality must not prevent the driver from overriding the system to perform other avoidance maneuvers such as steering or accelerating. The cautionary collision warning methodology may also be utilized for following-too-closely warnings.

Collision warnings can be either auditory or haptic. Additional normative driver research as well as rear-end collision specific research is necessary to determine the optimum selection of the warning methodology. However, discussion of auditory and haptic warnings is of interest.

3.2.4.3 Auditory Warnings

Auditory warnings include all modalities that are perceived by the human sense of hearing. Examples of auditory warnings include auditory icons such as chimes, horns,

[40] D.V.McGehee, J.Lee, "Examination of Drivers' Collision Avoidance Behavior using a Front-to-Rear-End Collision Warning Display", The University of Iowa, IVHS Countermeasures for Rear-End Collisions, Contract Number DTNH22-93-C-07326, September 1996.

tones, buzzers, and voices both digitized and synthesized. Some issues concerning auditory displays are:

- Auditory warnings can be used by naïve drivers and are therefore acceptable to passenger vehicle deployment. Studies in conjunction with this research used an auditory "car horn" warning in experiments performed on the Iowa Driving Simulator. Results showed that the driver was able to perceive the warning and respond appropriately in a controlled environment.
- Auditory displays can represent both imminent and cautionary warnings. An early auditory display that was used in simulator tests included an imminent "Brake" digitized voice and a cautionary "Look Ahead" digitized voice. The auditory display does not lend itself to following-too-closely warnings as well as other display modalities.
- Auditory warnings are not unique to the longitudinal motion of the vehicle and may not be intuitive, may be confusing or may not assist the driver in developing an accurate mental model of the FCW system.
- The auditory warning may generally be salient, but it may not be detectable over background noise under all driving environments. Auditory warnings that significantly override background noise may startle the driver
- Auditory warnings can be scripted to draw the driver's attention toward the hazard
- Auditory warnings should not promote other collisions to occur as long as the driver is not startled by the warning
- An auditory display that can be heard by every occupant of the vehicle may be an embarrassment to the driver.

Auditory displays are acceptable, and will probably be the initial display of choice by system developers and OEMs. It is anticipated that auditory displays will not have as high a user acceptance as other display modalities. Additionally, the effectiveness of auditory displays for collision warning is anticipated to be lower than modalities that are unique to the longitudinal motion of the vehicle. Additional naïve driver testing is necessary to determine the limits of user acceptance and system effectiveness in relation to auditory warning methodologies.

3.2.4.4 Haptic Warnings

Haptic displays include all display modalities that are perceived by the human sense of touch or feeling. Haptic displays include tactile (sense of touch) and proprioceptive (sense of pressure or resistance). Haptic displays are intrusive and may only be acceptable for FCW systems that eliminate false alarms and mitigate nuisance alarms to the driver. Haptic displays are anticipated to provide better system effectiveness by compelling driver response. Examples of possible haptic displays for FCW systems include braking initiation, pulse braking, accelerator counterforce, steering wheel shaking, seat belt tensioning and others.

Some issues concerning haptic warnings are:

- Haptic warnings should be usable by naïve drivers and are therefore acceptable to passenger vehicle deployment.
- Haptic displays can represent both imminent and cautionary warnings.
- Haptic displays are unique to the longitudinal motion of the host vehicle.
- Haptic displays can be used in following-too-closely scenarios but may be considered to intrusive in comparison to other display modalities
- By proper selection of the parameters, the haptic displays should not startle the driver.
- Even though other occupants in the vehicle may sense the haptic displays (pulse braking, braking initiation), they may not know if the driver performed the maneuver and as such the warning should not necessarily be an embarrassment to the driver.
- These displays will operate under all lighting levels, and should be able to operate under all levels of vehicular shock, and vibration by proper control and selection of parameters.
- Haptic displays may not work under all host vehicle speeds dependent upon the display modality chosen.
- Haptic displays may cause loss of control in certain applications (i.e. brake initiation on slippery road surface)
- Haptic displays may cause other collisions (aggressive merging coupled with braking initiation)
- Haptic displays may limit the drivers ability to override or delay the drivers ability to override (brake initiation with accelerating and steering override)

Haptic displays appear to hold great promise for high system effectiveness by compelling driver response. Haptic displays are also intrusive and can have a high nuisance level. Implementation of haptic displays requires an FCW system capable of eliminating false alarms and reducing nuisance alarms to the driver. Additional naïve driver testing with haptic displays is required, with a capable FCW system, in order to assess user acceptance and system effectiveness. Of the possible haptic display modalities, pulse braking, braking initiation and accelerator counterforce are unique to the longitudinal motion of the vehicle and are potential displays for FCW systems.

Brake initiation consists of application of the brakes to a predefined deceleration level or at a predefined jerk-rate-limit that is not intended to startle the driver (i.e. not full braking). Once the braking level is achieved, it is held constant by the system. By definition, the forward-looking, rear-end collision warning system does not control the vehicle except to allow for warnings to the driver. Based on this definition, full braking is excluded since full braking falls under the category of an automatic control system. When an imminent collision warning condition is reached, the forward-looking, rear-end collision warning system would apply the brakes. The rate of change of braking (jerk-rate) must be specified for systems of this type. Too little jerk-rate-limiting and the driver will not perceive the warning quickly. Too great a jerk-rate and the driver may be startled. The maximum level of brake initiation must be determined for driver acceptance. The benefit of brake initiation is that it allows the system to begin the braking process automatically, the host vehicle slows quicker and the collision, if unavoided, will be of lower severity[41]. However, brake initiation is not without problems. The advent of braking unexpectedly can lead to collisions in aggressive lane change or merge scenarios. Brake initiation could also cause loss of control on low friction surfaces such as snow or ice. Brake initiation is already occurring as a standard control methodology for some ACC systems with deceleration limits up to approximately 3 m/s^2 and jerk-rate-limits up to approximately 75 m/s^3. This warning display modality is then advantageous because the electronically actuated braking system may already be available as part of the ACC system. Levels of braking or jerk-rate-limit can be adjusted based on the platform, driver acceptance, etc., and need to be determined through further naïve driver testing.

The brake initiation warning must not prohibit the driver from applying additional braking or from accelerating. The brake initiation must not adversely affect the dynamics of the host vehicle for other possible avoidance maneuvers. Braking initiation is a continuous display and continues to be active until the driver responds to the warning by accelerator release, brake press, steering input, etc., and the collision threat diminishes.

Note: if the forward-looking, rear-end collision warning system employs brake initiation as a haptic warning to the driver, then the system should illuminate the brake lamps when the deceleration system is active above a predetermined level which is left to the system developer.

Pulse braking consists of application of the brakes to a predefined level or at a predefined jerk-rate-limit. Once the level is achieved, the system disengages. This pulse braking allows for the warning to be given to the driver without a significant deceleration component to the vehicle. For pulse braking, the warning could be a single pulse or a scripted series of pulses to make the warning more salient. The use of pulse braking may eliminate the aggressive lane change / merging problem associated with braking initiation while still providing a salient display to the driver. Pulse braking must not prohibit the driver from applying additional braking, or from accelerating. Pulse braking is a discrete warning and could be performed periodically while the driver was within the warning zone. As with brake initiation, it may be beneficial to illuminate the tail lights when the warning is activated.

Accelerator counterforce is used to describe a number of methods that provide a warning to the driver by communicating haptically through the driver's contact with the accelerator pedal. The accelerator counterforce can be applied as a constant force that presses back on the driver's foot or through various pulses or vibrations of the accelerator pedal. Accelerator counterforce is acceptable for collision warning as well as following-too-closely warning. Accelerator counterforce is unique in that only the driver can perceive the warning so the potential for embarrassment is diminished. Unfortunately, the driver may not always be in contact with the accelerator pedal so the warning may not be

[41] T.A. Dingus "IVHS Countermeasures for Rear-End Collisions", Contract DTNH22-93-C-07326, Phase II presentation, April 1996

perceived. It also may be an error to assume that if the driver is not in contact with the accelerator pedal that the driver is responding to the scenario. Drivers may not be in contact with the accelerator pedal and still exhibit inattentive or distracted tendencies. Research performed on this program observed that drivers tend to hover over the accelerator and brake a great deal of the time during encounters with other vehicles.

Good human factors design recommends that haptic display modalities should be enhanced by visual or auditory secondary displays. These secondary displays can provide feedback to the driver that the haptic warning is a function of proper operation of the vehicle and the FCW system. The additional displays can also present status information to the driver. However, complex secondary displays that require the driver's attention may slow the driver's response to the collision hazard while the driver perceives and processes the warning.

3.2.5 Risk Compensation

Risk compensation is the drivers' tendency to drive at unsafe levels with the aid of a forward-looking, rear-end collision warning system. Risk compensation is possible, but not considered likely with the collision warnings display methodologies discussed. Visual following-too-closely displays are considered more likely to promote risk compensation. Risk compensation may be a natural result of this type of information being provided to the driver and generally may be unavoidable. Naive driver testing is required to evaluate this condition.

3.2.6 Standard Interface

It is beneficial to the driving public if the various forward-looking, rear-end collision warning systems utilize a standard interface. It is unknown if this will be possible considering the competition between vehicle OEM's. A well designed forward-looking, rear-end collision warning system will have many features that will become common throughout the industry. Poorly designed driver interfaces and systems will have low driver acceptance and will be eliminated because of the lack of popularity. It is desirable for systems developed by different manufacturers to have a consistent driver interface. This includes driver interface issues associated with ACC systems. A standard driver interface will mitigate confusion by the driver when using different systems and increase overall system effectiveness once systems are widespread. Significant deviation among displays can lead to collisions under benign conditions if the design and function of the displays present conflicting results.

One possible standard visual indicator (if a visual display is utilized) for a forward-looking, rear-end collision warning display is shown in Figure 15. This display consists of a pyramid of color bars labeled with standard symbology and informative key words.

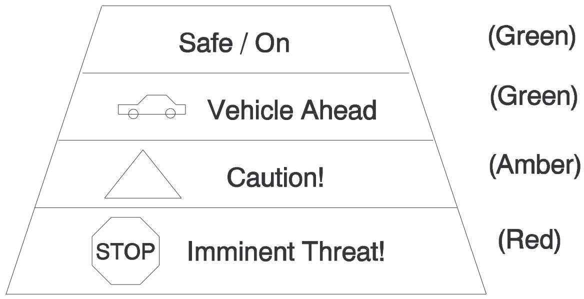

Figure 15 Example Standard Visual Indicator Example

The pyramid shape of this display is intended to simulate the driver's perspective view of the road ahead. The top bar of the display indicates that the system is on and functioning correctly. Vehicles in the forward path at a safe following distance are in the safe zone. Vehicles in the forward path at a close following distance are in the amber zone. Vehicles in the forward path that are too close are in the red zone. The color scheme ranging from green to red is meant to reinforce the close (unsafe) proximity of the lead vehicle. The pyramid shape presents a larger color bar indication as the threat level increases. The icons included with this display provide feedback for those drivers unfamiliar with the color codes, who are color deficient or colorblind. If the system becomes non-functional a status message should be presented to the driver.

3.2.7 Icon

To aid in reinforcing of the driver’s mental model and to identify vehicles equipped with forward-looking, rear-end collision warning systems, some type of standardized symbolic icon is recommended. The icon should be intuitive to the FCW system. The icon should be uniquely different (superset or subset) from ACC or other collision warning icons that may be present in the vehicle. It is recommended that the industry developing these systems form a consensus on a particular icon to be included with vehicles equipped with forward-looking, rear-end collision warning systems. Two example icons are shown in Figure 16.

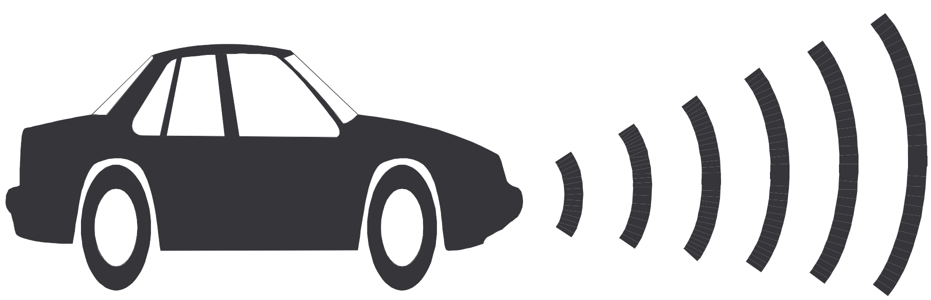

Figure 16 Example Icon

3.2.8 Additional Displays

The forward-looking, rear-end collision warning system may contain additional displays such as a fault indication when the system fails or is unable to perform the intended function.

A visual status display is recommended to provide the driver feedback that the system is functioning properly. Additional displays may contain fault and/or status information as long as this information is separated from any visual warning display. Other conditions exist that may necessitate warning the driver.

The status display must inform the driver when the forward-looking, rear-end collision warning system is inoperable or cannot reliably detect vehicles in the forward path.

Note: if the forward-looking, rear-end collision warning system employs brake initiation or pulse braking to warn the driver, then the system should illuminate the brake lamps when the system is active.

3.2.9 Summary

Collision warning presentation is critical for system effectiveness and driver acceptance. Due to the dynamics of the situations under which rear-end collisions occur, and the conflict between providing drivers correct warnings while minimizing nuisance alarms, it is necessary to develop a driver interface that elicits an automatic or conditioned response from the driver to avoid the collision. For this reason, it is desirable for the warnings to be unique to the longitudinal motion of the vehicle and that other collision warning systems not use longitudinal motion cues. Any potential benefit that forward-looking, rear-end collision warning systems provide can be lost due to an improperly designed driver interface.

To increase system effectiveness, the collision warning methodology should be as intrusive as possible in order to elicit a driver response. This requires a high level of FCW performance in order to suppress false and nuisance alarms to the driver.

This section outlines the need to gather normative driver data as well as rear-end collision specific driver data to formulate recommendations regarding display modality.

3.3 DRIVER CONTROLS

This section discusses what controls the driver should have over the FCW system.

3.3.1 Standard Driver Controls

Standardized driver controls should be used to avoid confusing the driver when using systems from different manufacturers.

3.3.2 Warning Time Adjustment

Based on the range of driving abilities across the driving population, there might be some gain in having the system automatically adjust to the individual driver. This would allow for reduction of nuisance alarms, which are driver specific, and should improve system effectiveness and driver acceptance. The question becomes, "are normal naïve drivers capable of selecting a warning time?" The answer is, probably not. By allowing the driver to choose the warning time, it places the driver in the role of expert.

It is also difficult to determine what parameters in the warning algorithm the driver would have the ability to adjust. Additionally, the driver response is different for each type of dynamic situation and would complicate the adjustment process. Therefore, further testing with naïve driver is necessary before concluding whether a warning time adjustment is appropriate.

3.3.3 Power-On Activation

The forward-looking, rear-end collision warning system should power-on with application of ignition power. All other settings should be automatic.

Drivers cannot be relied on to turn on their collision warning devices each time they turn on the vehicle ignition. Therefore, the system should turn on automatically each time the vehicle is started. To prevent rear-end collisions, the forward-looking, rear-end collision warning system must always be active. The turn-on self test time required for the FCW system to warm up and start functioning must be as short as possible for the provided technology because the naïve driver would reasonably expect the FCW system to provide vigilant protection from the start of vehicle operation.

3.3.4 Driver Disable

It is possible that if the ability to disable the forward-looking, rear-end collision warning system is provided then it will be off when a collision situation is encountered. Only by following the guidelines presented within this document regarding system performance and driver display modality can result in a system acceptable and usable by naive drivers. A poorly designed FCW system would provide a good basis for providing a driver disable. The recommendation is that under no circumstances should the driver have the ability to turn-off or disengage the forward-looking, rear-end collision warning system. As a result, the FCW system must be developed with this in mind. The FCW system must perform to the driver's expectations in order to eliminate the need for the driver disable.

In all cases the driver should have the capability to override all actions taken by the warning system. The warning system must not affect the driver's ability to control the vehicle.

Without a Federal mandate the system developer or vehicle OEM may allow the driver to disable the FCW system. The following-too-closely warning, because of the possible nuisance potential, may need a driver disable capability, but additional naïve driver testing is necessary to determine the display modality requirements to eliminate this need.

3.4 SYSTEM FUNCTIONS

The system requirements are driven by the notion that false alarms must be eliminated and nuisance alarms must be reduced to the greatest extent possible. This is an obvious result from the need to increase driver acceptance in order to maximize system effectiveness. The system requirements place a great deal of emphasis on development of sophisticated signal processing for inclusion / exclusion of vehicles and objects, curve detection, etc. over that currently known to be available in today’s prototype systems. These requirements are considered to be necessary for a minimum acceptable system. A minimum acceptable system must approach the ideal in order to be acceptable in mass marketed passenger vehicles.

3.4.1 In-Path Detection Requirements

The naïve driver would reasonably expect the forward-looking, rear-end collision warning system detect all licensable vehicles ranging from motorcycles to large trucks. The naïve driver would reasonably expect that warnings only be issued on in-path vehicles that the driver would consider a collision threat. The naïve driver may expect to be warned on bicycles and pedestrians, etc. but this may be overly burdensome on a minimum system. It must be expressed to the naïve driver that the forward-looking, rear-end collision warning system only warns on the rear-end of vehicles that are on-road and in the forward path. Therefore, the FCW system must detect and generate a warning to the driver in the presence of all licensable vehicles in the subject vehicle’s forward path which are considered a collision threat. Although not required, it is acceptable that the FCW system warn on smaller in-path objects which are a collision threat to the vehicle. The problem is to define which of these smaller objects constitute a collision threat to the vehicle.

Collision threats are defined in this document as any in-path object of sufficient size to cause significant physical damage to the body or chassis of the subject vehicle should a collision occur. While a glass bottle may cause tire damage, it does not constitute a collision threat because of its inability to do significant damage to the vehicle’s chassis, body or occupants. Examples of collision threats include: all licensable vehicles, bicycles, pedestrians, trees, tires, rocks, animals, etc. Examples of non-collision threats include: cans, bottles, trash, water on the roadway, pot holes, manhole covers, reflective lane markers, etc.

The forward-looking, rear-end collision warning system has these "in-path" detection goals:

- Detection of the rear-end of the closest "in-path" vehicle from motorcycles to the largest trucks
- Detection of other "on-roadway" and "in-path" objects is acceptable if the objects would reasonably cause damage to the vehicle.
- Rejection of "in-path" debris (cans, bottles, etc.) and roadway surface features (potholes, manholes, rough pavement, etc.) that do not represent a collision threat to the vehicle

The detection of in-path objects requires that the FCW system know the "forward path" of the vehicle. The goal is to eliminate false alarms. If a situation is encountered where the FCW system cannot determine if an object in the forward path represents a threat, then the FCW system should err on the side of avoiding false alarms and provide no warning to the driver. It is likely that the FCW system will encounter situations that it cannot determine if a true collision threat exists. These situations are anticipated to be more common than true collision threats and as a result, the FCW system should provide no warning to the driver.

3.4.2 False Alarms and False Alarm Rate

False alarms are false positive indications that occur when the system does not function as intended such as warning the driver on non-threatening objects. Warning on roadside objects, adjacent lane objects, overhead objects, road surface objects, etc. that do not constitute a true crash threat are considered false alarms. False alarms represent a significant technical challenge for deployment of a naïve driver acceptable FCW system. A naïve driver would reasonably consider a forward-looking, rear-end collision warning system whose false alarm rate does not approach zero a nuisance.

The roadway (both on road and roadside) environment is extremely complex. The FCW system must be robust enough to perform to the naïve driver's mental model in all types of roadway and roadside environments. This means that the FCW system must exclude all non-vehicular objects and some vehicular objects as threats. This is difficult when considering the necessity of warning the driver on stopped vehicle scenarios that may appear like roadside objects.

To perform this task, the FCW system should process information regarding the driving environment to include the forward path and exclude everything outside the forward path. To perform this task, the FCW system may use the primary sensor or supplemental sensor technology.

To eliminate false alarms, the FCW system:

- Should measure the position and speed of objects in the forward field-of-regard to the highest accuracy and resolution possible
- Should be able to classify objects based on size, amplitude, speed, position,

etc.

- Should interpret the driving environment in a fashion similar to the driver.

The FCW system should have sufficient field of view, maximum range capability, range measurement accuracy and resolution, range rate accuracy and resolution, and forward path prediction capability to produce a system false alarm rate which approaches zero in all driving environments.

False alarms are a function of the driving conditions and environment. The goal of the FCW system is a false alarm rate of 1 / 286 operating hours. Which is based on 10,000 miles per year at an average of 35 mph. The driver's ability to deal with false alarms is directly proportional to the intrusiveness of the cautionary and imminent warnings. The warning methodologies discussed are considered intrusive and therefore, the false alarm rate must approach zero. This can be traded off against not protecting the driver under all driving scenarios as long as the driver does not notice this limitation.

3.4.3 Out-of-Path Detection Requirements

The naïve driver would reasonably expect the forward-looking, rear-end collision warning system to not provide warnings on objects that are not in the vehicle's forward path. This is readily achievable on straight and level roadways, but becomes more difficult in situations where the subject vehicle may be momentarily pointing directly toward roadside objects which do not constitute collision threats because they are not in the true vehicle path. All out-of-path objects and vehicles must be classified at non-threatening by the FCW system and warnings to the driver must be suppressed.

The FCW system must employ a variety of processing techniques in order to separate in-path and out-of-path objects and eliminate false alarms to the driver. The FCW system may use other vehicle inputs such as longitudinal and lateral acceleration, steering angle, brake sensors, turn indicator, and absolute speed to determine current driving conditions. Scene processing techniques that look at size, shape and position of objects within the forward field-of-regard should be used to predict the road edge and the boundaries of adjacent lanes. All of this information processed together would allow the exclusion of off-road, out-of-path objects. This information can also be used to predict the host vehicle's forward path and allow the FCW system to more closely predict the true path. Examples of non-collision threats include: bushes, trees, bridges, overpasses and tunnels light poles, mailboxes, fire hydrants, other vehicles, buildings, road signs, etc.

The forward-looking, rear-end collision warning system has these "out-of-path" detection goals:

- Rejection of all "out-of-path" roadway objects such as signs, curbs, poles, fire hydrants, guardrails, etc. These are the primary cause of false alarms to the driver
- Rejection of overhead objects such as signs, bridges, traffic lights, etc.
- Rejection of all cross-traffic or near cross-traffic. This includes left turn across path

- Rejection of roadway objects that are in front of the host vehicle but are not "in-path" due to roadway curvature or "T" intersections, etc.
- Rejection of vehicles in adjacent lanes
- Rejection of all on-coming out-of-path vehicles

The exclusion of out-of-path objects requires that the FCW system know the "forward path" of the vehicle. The goal is to eliminate false alarms. If a situation is encountered where the FCW system cannot determine if an object represents a threat, then the FCW system should err and provide no warning to the driver. It is likely that the FCW system will encounter situations that it cannot determine if a true collision threat exists. These situations are anticipated to be more common than true collision threats and as a result, the FCW system should provide no warning to the driver. The occurrence of situations where the FCW system cannot determine the collision threat must be rare.

The key to determination of in-path and out-of-path is the ability to process the scene with high horizontal angular resolution. This will aid in the determination of in-path and out-of-path objects as well as collision threat based on the angle rate to the object.

3.4.3.1 Curve Detection

The FCW system must be able to detect the path of the vehicle when approaching curves in order to eliminate false alarms at the curve entrance and exit points. These false alarms occur because the system is momentarily pointing toward roadside objects or adjacent lane vehicles that are not in the true forward path of the host vehicle.

A mass marketed system must reject false warnings due to roadway curvature, especially curve entrance and exit points. Curve performance is more a requirement for elimination of false alarms to the driver than providing the driver collision protection on curves. Curve performance should be specified as a function of lateral acceleration, which includes both radius of curvature and subject vehicle speed.

The forward-looking, rear-end collision warning system has these curve detection goals:

- Detection of roadway curvature for path prediction
- Detection of opposite direction traffic for path prediction
- Detection of same direction traffic for path prediction
- Rejection of all roadway features on curves, either by curve / path prediction or object identification / classification

If the forward-looking, rear-end collision warning system is to eliminate false alarms due to out of path vehicles and objects, then it must be equipped to sense, or otherwise be told, the forward path of the host vehicle. If the predicted forward path of the host vehicle is not known to the system then the false alarm performance will likely be poor and thus unacceptable to the driver.

Forward path prediction may be accomplished by processing the information from the primary sensor, or by using secondary sensors to predict the forward path. Detection of the forward path allows the system to distinguish between in-path and out-of-path objects and allows the exclusion of objects that would present false alarms to the driver.

3.4.3.2 Lane Change / Merge Detection / Cut-In

In lane change and merging conditions, the system's sensor may be momentarily pointing toward roadside objects which are not in the vehicle's true forward path. The FCW system must not generate false alarms on these objects. A second problem arises when lane change and merge maneuvers cause vehicles to suddenly appear in the forward path at short distances. However, few rear-end collisions (approximately 1%) occur in these situations.

The FCW system should eliminate false alarms due to lane change / merge / cut-ins. In lane change and merge conditions, the FCW system may use the same object exclusion techniques discussed in the Out-of-Path Detection Requirements section to exclude out of path objects as threats. This exclusion may also involve temporary suspension of driver warnings until the system transitions to a steady state condition. Suspension of driver warnings may not be necessary if the FCW system has sufficient longitudinal horizontal resolution to detect these conditions.

The FCW system should be able to react quickly to in-path vehicles that suddenly appear due to cut-ins. The FCW system delay determines how quickly the system can respond to these collision threats. Shorter system delays allow faster warnings and the driver more time to react. For this reason, the FCW system acquisition delay must be minimized.

The forward-looking, rear-end collision warning system has these lane change / merging / cut-in detection goals:

- Detection of new in-path vehicles when changing lanes / merging behind
- Exclusion of out-of-path objects as threats during lane change and merging
- Detection of vehicles during cut-ins
- Temporary suspension of path prediction
- Temporary suspension of warnings (lane change / merge only)

3.4.4 Misses

Misses occur when the situation requires a warning but the system does not provide a warning to the driver. Misses may occur due to limitations in the employed sensing technology, or when warnings are suppressed due to system delay or to eliminate false alarms for other scenarios. Misses must not be caused because the employed sensing technology cannot reliably detect the objects. Misses may be caused because the processing is unable to distinguish the object in the forward path as a threatening vehicle or a non-threatening roadside object. Misses should not be perceptible by the driver due to limitations in the sensor field of view, maximum range capability, range measurement accuracy and resolution, range rate accuracy and resolution, or forward path prediction capability of the FCW system. Misses must be infrequent enough that the typical driver would not notice their occurrence. Obstruction due to road profile, roadway objects, are other potential cause of misses. Weather (atmospheric conditions) degrades sensor performance and may possibly cause misses.

3.4.5 Nuisance Alarms and Nuisance Alarm Rate

Nuisance alarms are cautionary or imminent warnings that the driver either disagrees with the need for the warning or the timing of the warning. Following-too-closely warnings may also present nuisance alarms to the driver but this may be done purposefully in order to modify driver behavior.

The interpretation of warnings as nuisance alarms is dependent upon the individual driver. For collision warning, the measure of nuisance is determined by the deceleration necessary to avoid the collision as compared to the driver's habitual deceleration. As previously discussed, drivers who habitually decelerate at higher levels may consider a warning that only requires a medium deceleration level a nuisance. Also, the type of display modality will influence the driver's interpretation of a nuisance. Additional normative driver data is necessary to determine the nuisance requirements for systems of this type. The nuisance potential of a particular system can be adjusted by changing the timing of the warning, reducing the intrusiveness of the display, adapting the FCW system to the individual driver, or for following-too-closely displays, allowing the driver to disable the warning.

Imminent warnings are expected to occur during 0.1% of all braking applications. Cautionary warnings are arbitrarily specified to occur during at least 10% of all braking applications. It is likely that the nuisance alarm rate is a function of the cautionary warning and how intrusive the display modality is perceived to be. It is also likely that nuisance alarms are more tolerable, compared to false alarms, because they occur on valid threats. It is doubtful that a nuisance alarm rate can be adequately quantified because they are measured in relation to individual driving habits.

3.4.6 System and Processor Delay Time

To be effective, the FCW system must warn the driver of an impending crash situation in time for the driver to take corrective action. A system that has a slow response to collision threats may allow the collision to occur while the system is still in the process of generating the warning.

System delay is defined as the time required for the system to determine a vehicle is present in the forward path (acquisition) and to warn the driver by changing the status of the warning indicator. The system delay time contains the processing delay time (sensor sampling, acquisition and track initiation, state estimation, warning algorithm) and the time required to change the status of the warning indicator. Too long a system delay can cause warnings to the driver to be issued late thereby reducing overall effectiveness. Compensating for long system delays by beginning the warning earlier contributes to lost time as discussed previously. For vehicles that are being tracked, the system delay is reduced to the processor delay time because acquisition and track initiation have already been established. Processor delay should be on the order of 1/5th of the system delay. The processor delay is equivalent to the sample rate of the system, see the section on Sample Rate. As a rule of thumb, several samples are necessary to build good estimation of range and speed to vehicles and objects in the forward path.

For scenarios where the lead vehicle is acquired at long range (either straight line or curves) longer system delay times can be compensated by longer acquisition ranges or wider horizontal fields of regard (for curves). The area where the system delay impacts overall effectiveness is in lane change, merging, cut-in and high closure rate situations where lead vehicles are in relative close proximity and warning the driver of collision threats must occur quickly.

Even with an infinitely small system delay, the FCW system can encounter scenarios where the physics of the situation prevent the driver from avoiding a collision. Additionally, the requirements regarding system delay are somewhat dependent on the type of display modality. For a minimum system, it may be acceptable to inhibit warnings for lane-change, merge and cut-in scenarios. However, if the driver warning methodology contains situational awareness information, then the driver may notice the inhibiting of warnings that may tend to reduce the driver's reliance on the system.

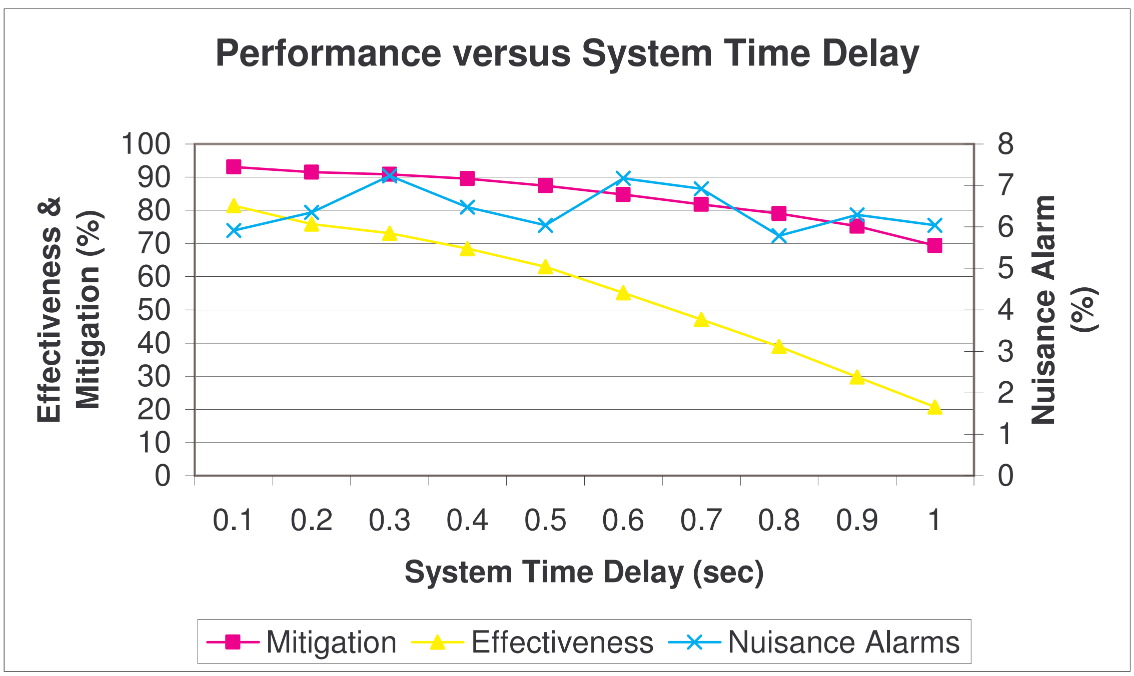

Figure 17 Effectiveness and Mitigation to System Delay Time

Effectiveness and mitigation to system delay time have been developed using mathematical modeling and simulation techniques to vary the system delay over a collection of representative rear-end collisions and note the overall system effect[42].

[42] Mathematical Modeling and Simulation for Forward-Looking Collision Avoidance, IVHS

3.4.6.1 Sample Rate

Based on modeling and simulation results an optimized FCW system bandwidth is approximately 2 Hz. The sample rate is defined as the periodic rate. The sample rate of the system should be 5-10 times the system bandwidth of 2 Hz. Sample rates that approach 10 Hz, may be a nuisance to the driver due to a driver perceptible processing delay (a function of display modality and warning algorithm).

3.4.6.2 Warm Up Time

There is most likely a warm up time associated with the forward-looking, rear-end collision warning system that is finite. However, a naïve driver would reasonably expect the FCW system to be available from initial vehicle start. As a result, and as a matter of completeness, the FCW system should be developed to have a minimum warm up time requirement. This warm up time should be less than thirty seconds under most conditions, but is dependent upon the sensing technology and the current environmental conditions (storage / operating).

3.4.7 System Self Test and Status Reporting

The FCW system is composed of electrical and mechanical components and is subject to periodic failure. A failure of the FCW system must not impose a safety hazard to the driver over and above the normal hazards associated with driving a vehicle that is not equipped with a FCW system.

This is considered a secondary reporting function and therefore should be left to the system developer or vehicle OEM. It is mentioned here within this document for completeness.

The forward-looking, rear-end collision warning system should be capable of providing status information to the driver under some or all of the following conditions:

- The system fails its power-on self test (inoperable at startup)
- The system detects conditions have rendered it ineffective
- The system is not working due to component failure, or other causes (during operation)
- The system is being used outside the limitations of the system (such as "driving at a speed which is beyond the sensor limit")

The system should continuously provide the driver with a clear visual indicator that the collision warning system is on and functioning correctly. Or conversely, as drivers learn to rely on the FCW system, they would want to be informed when the system was unavailable.

Countermeasures for Rear-End Collisions, Contract Number DTNH22-93-C-07326, Sensor Technologies & Systems, February 1998

If a system failure occurs, all warning displays should remain inactive.

It should be noted that systems that are overly susceptible to weather (atmospheric) or other conditions that render them ineffective, may be considered a nuisance to the driver and may reduce driver reliance, acceptance and system effectiveness.

3.4.8 Scene Processing / Path Prediction

An important function of the FCW system is the elimination of false alarms. The FCW system should provide correct alarms under most driving scenarios. In order to perform this function, a FCW system should process the scene forward of the host vehicle and predict the forward path as well as in and out of path vehicles and objects. This is called scene processing. Scene processing can be accomplished with the primary forward-looking sensor or through supplemental sensing technologies. In order to perform this function it is desirable that the forward field-of-regard be “sensed” with the highest degree of accuracy and resolution attainable.

Scene processing is likely a necessary function in order for a system to operate to the expectations of the driver. It is unlikely that without this function that the FCW system will be acceptable for mass marketed passenger vehicle applications.

3.5 SENSOR FUNCTIONS

This section discusses issues associated with the sensing of vehicles in the forward path. Autonomous systems tend to be the primary focus for system developers.

3.5.1 Acquisition Range, Accuracy, Resolution

In order for a forward-looking, rear-end collision warning system to perform the intended function, it is necessary for the system to measure the range between the host vehicle and vehicles in the forward path. Acquisition range is defined as the maximum distance, from the front of the host vehicle to the back of the vehicle in the forward path, at which the lead vehicle can be detected and tracked within the system delay requirements, range accuracy and range resolution required for system operation.

The minimum and maximum range requirements are a function of providing the driver adequate warnings under all conditions. The acquisition range is a function of the approach speed of the host vehicle to a stationary lead vehicle (largest relative speed). A limited acquisition range or excessive speed will allow drivers to “drive beyond the sensor limit” of the forward-looking, rear-end collision warning system. The ability to drive beyond the sensor limit may necessitate a warning to the driver in those cases where the sensor limit has been exceeded. At a minimum, the ability to drive beyond the sensor limit will degrade system effectiveness in those situations.

Because of the statistical nature of forward-looking sensors used in forward-looking, rear-end collision warning systems, it is unrealistic to require the detection of all licensable vehicles at the maximum sensor range. This is due to the potentially small “effective” cross-sectional area of some vehicles such as motorcycles. However, the forward-looking, rear-end collision warning system must detect and react to small lead vehicles to the greatest extent possible. The acquisition range for a minimum system is based upon the line-of-sight from the driver.

The maximum acquisition range to a stopped lead vehicle of 130 meters is necessary, based on 33.5 m/s (75 mph), 6 m/s² (0.6 g's) deceleration and a system time delay of 0.3 seconds and a driver reaction time of 0.8 seconds. The equation is: range = $V*(0.3+0.8)+V^2/(2*6)$. It should be noted, that a driver reaction time of 0.8 seconds is well below the average driver reaction time and does not represent an inattentive or distracted driver. The system time delay of 0.3 seconds may be below the capability of some systems assuming five or six sample periods for the system delay. Some degradation in the maximum range is expected as the atmospheric conditions degrade. Figure 18 shows the effectiveness and mitigation to acquisition range.

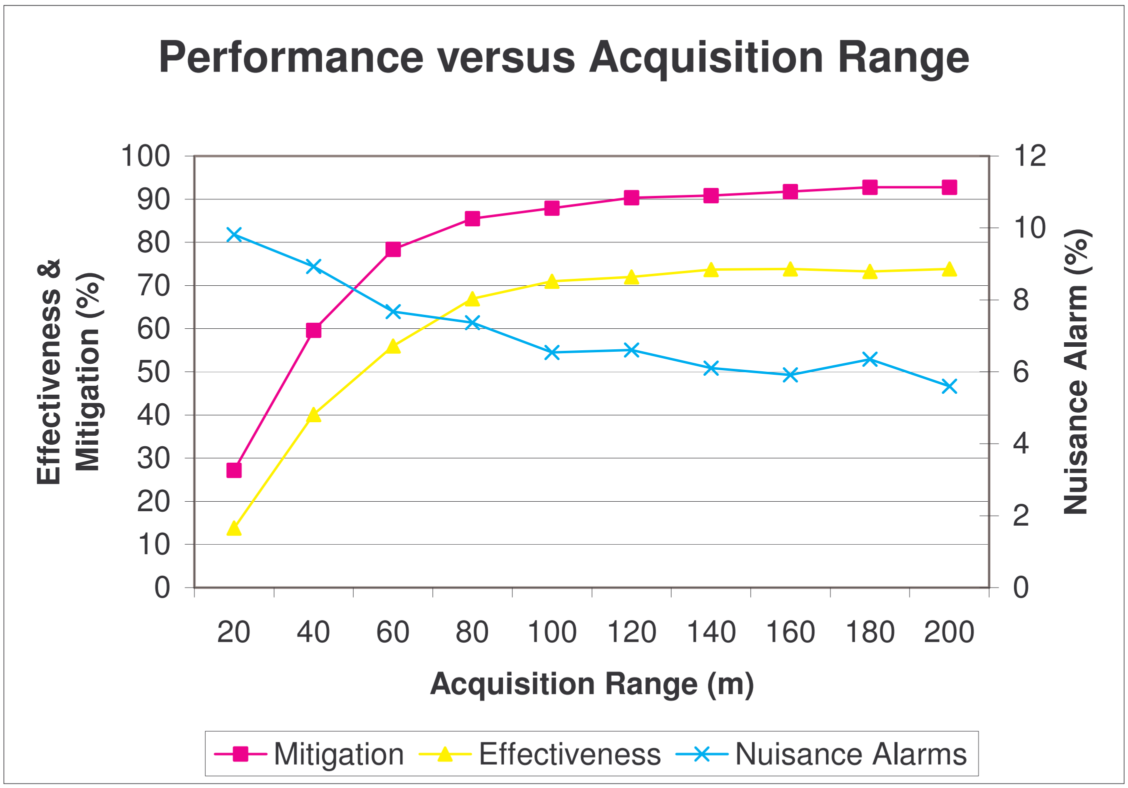

Figure 18 Effectiveness and Mitigation to Acquisition Range

The minimum range is important in providing warnings to drivers in low speed / stopped too closely and stop-and-go driving environments. No statistical data exists for minimum ranges, although a large number of rear-end collisions occur at low speeds and short ranges[43]. The resultant collisions do not meet the classification for inclusion into the Federal crash databases. A naïve driver would reasonably expect a warning in very low speed situations. A minimum range is difficult to quantify since very little data exists for

[43] Knipling, et. al., 1993

the low speed close range collisions. The naïve driver would reasonably expect a warning in slow speed, stop-and-go driving environments where the range to the lead vehicle is less than 2 meters.

The forward-looking, rear-end collision warning system must have sufficient range resolution and range accuracy performance to allow vehicles and objects to be identified and tracked. The most troublesome scenario occurs with a small vehicle (motorcycle) positioned closely behind a much larger vehicle (semi-truck). In this case, it is not necessary to separate the two objects, but rather range on the closest object. Some sensing and processing technologies may have problems due to the proximity of the small and the large objects.

The noise variance in the measured range doesn't change system effectiveness, it primarily causes early or late nuisance alarms. The maximum rms noise (with a 2 Hz reference bandwidth) in the measured range is limited to 0.04 * Range or 0.4 meters which ever is larger.

The bias error in the measured range is a function of the desired effectiveness as well as the value of the range measured. The host vehicle travel speed also plays a part. For host vehicle travel speeds of 16 km/h (10 mph) to 120+ km/h (75 mph), the allowable rms range error is limited to 0.07 * Range or 0.7 meters which ever is larger. The recommended range resolution is $\leq$ 0.7 meters for effective warning and scene processing capability.

3.5.2 Relative and Absolute Speeds

In order for a forward-looking, rear-end collision warning system to perform the intended function, it is necessary for the system to know the relative speed between the host vehicle and vehicles in the forward path and the absolute speed of the host vehicle. By definition, the forward-looking, rear-end collision warning system must detect and warn the driver for all kinematic and dynamic situations involving the host and lead vehicles, especially stopped and stopping vehicles in the forward path.

Most rear-end collisions (approximately 70%) occur with the vehicle in the forward path stopped while the remainder occur with the vehicle in the forward path moving (decelerating, constant slower speed, etc.). The ability to detect and warn the driver for stopped lead vehicle scenarios is an important characteristic of forward-looking, rear-end collision warning systems.

Associated with this requirement is the ability for the forward-looking, rear-end collision warning system to measure the relative speed and absolute speed to a resolution and accuracy that allows the system to perform the intended function. The most troublesome scenario is a lead vehicle stopped and a host vehicle approaching at a maximum speed.

The speed difference between the host vehicle and the lead vehicle is the relative speed. Relative speed varies from small positive values (lead vehicle pulling away), to large negative values (high closure rates). The minimum absolute host vehicle speed approaches zero for low speed and stopped-too-closely warnings. The FCW system should detect and track vehicles that are stationary to a maximum speed that is equal to the maximum absolute host vehicle speed plus design margin. This allows the forward-looking, rear-end collision warning system to detect stationary vehicles while allowing it to exclude on-coming vehicles which have a relative velocity greater than the host vehicles absolute speed. Excluding oncoming vehicles helps to eliminate some false alarms. . A minimum FCW system does not need to provide warnings for head-on scenarios.

The maximum absolute host speed is a function of posted speed limits and/or driver habits (posted speed limits with some additional margins). An unlimited absolute speed will allow the driver to “drive beyond the sensor limit”, which may necessitate a warning or alert to the driver indicating system effectiveness has degraded.

The goal of the FCW system is to operate effectively up to the US maximum speed limit. Operation beyond the maximum speed limit should gradually degrade system effectiveness.

3.5.3 Horizontal Field-of-Regard

The FCW sensor has a limited coverage zone in comparison with the driver. The coverage zone is a three dimensional volumetric space enclosed by the minimum and maximum sensor range, minimum and maximum horizontal (azimuth) field-of-regard and the minimum and maximum vertical (elevation) field-of-regard. For purposes of discussion, the origin of the coverage zone is relative to the center of the front bumper of the host vehicle.

The horizontal field-of-regard in front of the host vehicle identifies a region in which the warning system should detect vehicles. The horizontal field-of-regard should encompass, in general, the forward path and accommodate road curvature, driver lane keeping maneuvers (lateral changes required to remain “in-lane”), lane change, merging, cut-in, adjacent lane vehicles, etc.

The FCW system should detect the path of the travel lane as an aid in forward path prediction and elimination of false alarms from vehicles in adjacent traffic lanes, parked vehicles, roadside objects, etc. Associated with the horizontal field-of-regard is the need to resolve multiple vehicles and/or objects and accurately measure their position and speed with respect to the host vehicle.

The horizontal field-of-regard for the minimum system will be of finite size. Under certain circumstances, this horizontal field-of-regard limitation will exhibit a reduction in acquisition range, warning range and as a result, overall system effectiveness. An example is curve scenarios where the vehicle in the forward path may be outside the horizontal field-of-regard due to road curvature. This is considered acceptable for a minimum acceptable system as long as the naïve driver is unaware of the limitation.

For the FCW system to function effectively, it should be capable of detecting vehicles in the forward path on curves. By providing this capability, the number of nuisance alarms received by the driver should be reduced in relation to curved roadways. Also, a number of rear-end collisions (approximately 9%) occur on curves and a system that ignores road curvature will have a resulting decrease in overall system effectiveness. Due to the statistical nature of forward-looking, rear-end collision warning systems, it will not be possible to respond properly to all curved road scenarios. The tail of the distribution of curve radii represents extremely sharp curves which would require restrictively large fields of view. Scenarios on curves greater than the horizontal field-of-regard will manifest themselves as a reduction in acquisition range and late warnings to the driver will result. This still provides an opportunity for collision mitigation, but will lower overall system effectiveness. As the horizontal field-of-regard becomes smaller, the system effectiveness does not go to zero, rather a reduction in system effectiveness will result that the driver may not notice depending on the display modality implemented.

Horizontal field-of-regard may be classified as a function of warning distance and lateral acceleration experienced by the host vehicle when negotiating curves. Lateral acceleration is proportional to curve radius and absolute speed.

The half horizontal field-of-regard is related to speed, warning distance and lateral acceleration as follows:

$$\theta = \frac{90 \bullet \alpha_{lat}}{\pi \bullet V_f^2} \bullet WD$$

where

- θ = half horizontal field-of-regard (degrees)
- α_{lat} = lateral acceleration (m/s²)
- V_f = Host vehicle speed (m/s)
- WD = Warning Distance (meters)
- α = Host Vehicle Longitudinal Deceleration (6 m/s²)
- V_r = Relative Speed (m/s)
- V_l = Lead Vehicle Speed (m/s)
- t_{rt} = Driver reaction time delay (1.1 seconds)
- t_{ch} = Coupled headway time (seconds)
- Radius = Radius of Curvature (V_f^2 / α_{lat})

This is plotted in Figure 19

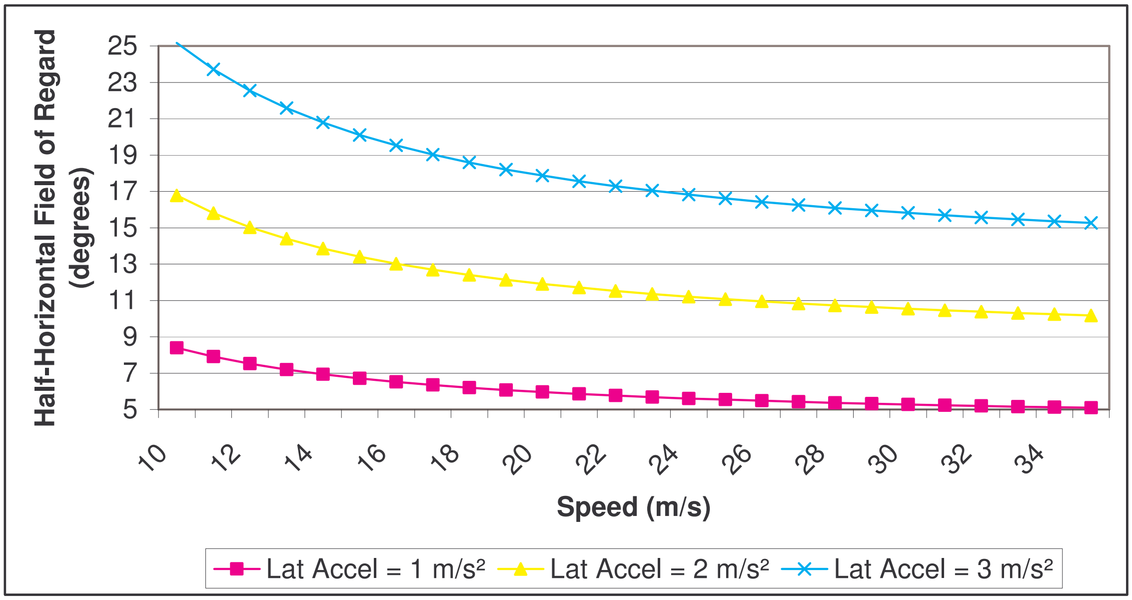

Figure 19 Half-Horizontal Field-of-regard versus Lateral Acceleration

The key to an effective FCW system is horizontal resolution. High horizontal resolution would simplify the basic FCW system by allowing objects that do not pose threats to be excluded with less processing and thereby reduce the potential for false alarms. A high horizontal resolution also aids in scene processing, curve prediction and threat prediction. High horizontal resolution can be achieved using the primary FCW sensor, or secondary sensors. The minimum horizontal field-of-regard allows resolution of vehicles in the forward path and adjacent lanes from roadside objects. Based on data from rear-end collisions from the 1985 NASS, the effectiveness as a function of Half Horizontal Field-of-Regard is shown in Figure 20.

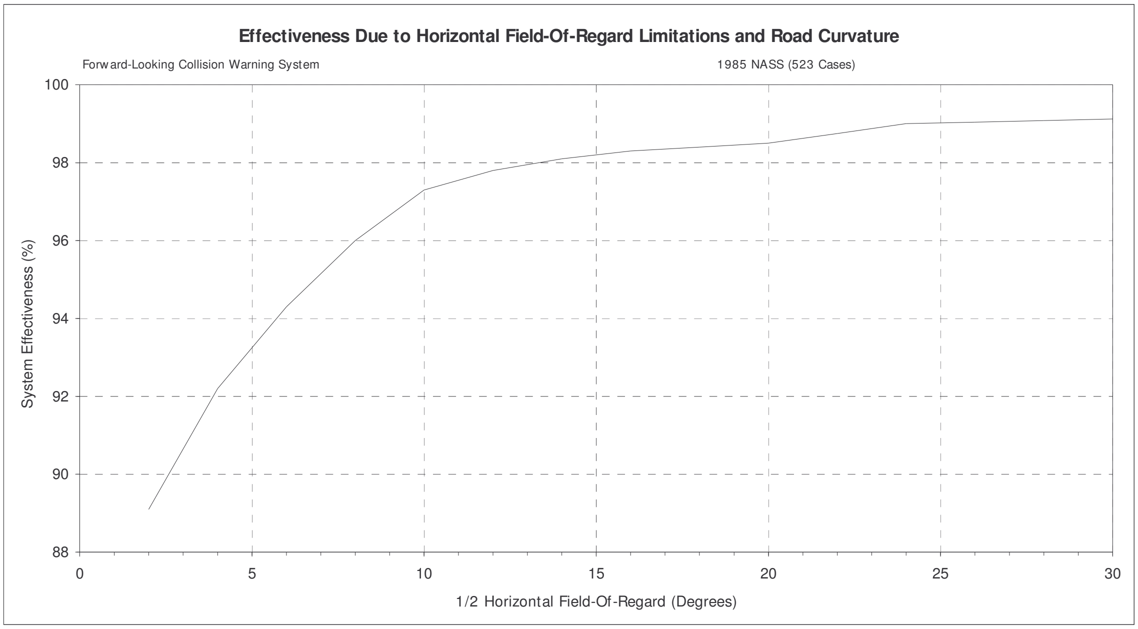

Figure 20 Effectiveness versus Half-Horizontal Field-of-Regard

3.5.4 Vertical Field-of-Regard

The FCW system must be able to detect and track in-path vehicles whose elevation may be varying with respect to the subject vehicle. The vertical field-of-regard should encompass the forward path and accommodate vehicle pitch and roadway changes in grade, etc. This is an aid to preventing misses and late alarms.

For the FCW system to function effectively, it should be capable of detecting vehicles in the forward path on changes in grade and during variations in vehicle pitch. A more stringent requirement is the need to exclude overhead objects from causing warnings to the driver. Therefore, the vertical field-of-regard must be large enough to include lead vehicles that may be at different vertical levels caused by vehicle pitch or changes in grade and the vertical field-of-regard must be narrow enough to exclude overhead objects. This issue may be eliminated by vertical resolution, but this may not be practical with certain sensor technologies.

If the trade off exists between handling more change in grade and vehicle pitch scenarios or the detection of overhead objects as threats, then the vertical field-of-regard should be reduced to eliminate false alarms on overhead objects. A minimum FCW system can operate effectively with vertical resolution equal to the vertical field of regard. Finer vertical resolution is desirable to eliminate false alarms due to overhead objects. F shows the effectiveness versus vertical field-of-regard.

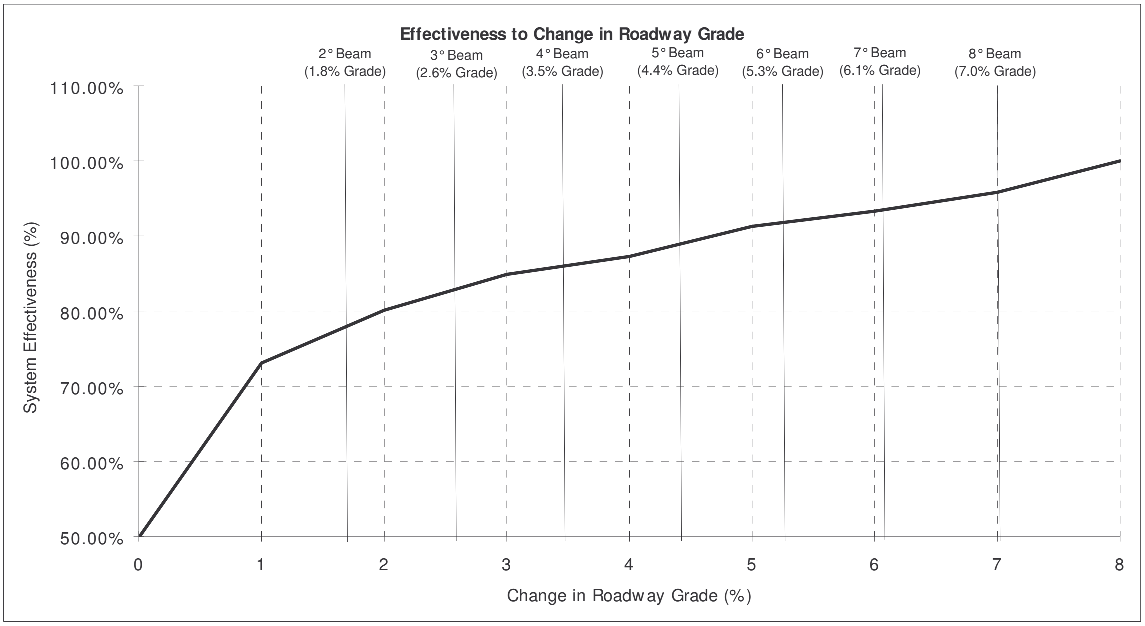

Figure 21 Effectiveness versus Vertical Field-of-Regard

3.5.5 Atmospheric Conditions

Atmospheric conditions relate to those conditions that the FCW system must “see” through. Examples of atmospheric conditions include rain, road spray, snow, fog, etc. Atmospheric conditions, in this context, are independent of roadway surface conditions. Regardless of the sensing technologies employed, it is anticipated that atmospheric conditions will cause FCW system performance degradation. Degraded system performance due to atmospheric conditions should not result in false alarms to the driver. The FCW system is not intended to function as a “fair weather” device only. As drivers become reliant upon the FCW system then it must perform to their expectations even under degraded atmospheric conditions.

The ability of the FCW system to directly detect degraded system sensor performance is dependent on the sensing technology implemented. The notification of system shutdown should indicate to the driver the weather related nature of the shutdown. This will aid the mental model of the driver as to when the system might not be available. It should also heighten the awareness of the driver to the degraded weather conditions and hopefully cause the driver to exercise more caution. It should be noted that an FCW system that is routinely shut down due to inclement but not necessarily poor atmospheric conditions may be considered a nuisance to the driver and could reduce the drivers reliance on the system. The system should automatically re-enable operation when the atmospheric conditions improve, so that the system can once again perform the collision warning task.

To the greatest extent possible, the FCW system should perform its function under conditions degraded due to weather. It is beneficial if the FCW system can directly detect degraded performance, inhibit warnings to the driver and possibly notify the driver of system shutdown. Atmospheric Conditions are highly correlated to roadway conditions.

Unless the FCW system has the ability to detect and compensate for the roadway condition, it is anticipated that as conditions degrade the overall system effectiveness will degrade (independent of the FCW system performance degradation) due to the associated longer stopping distances required. This degradation though not desirable, is acceptable for a minimum system. Figure 22 shows the reduction in effectiveness as a function of atmospheric condition. This is based on an analysis of the GES database and does not include effects due to road spray. Additionally, it includes collisions caused by poor visibility as well as longer stopping distances.

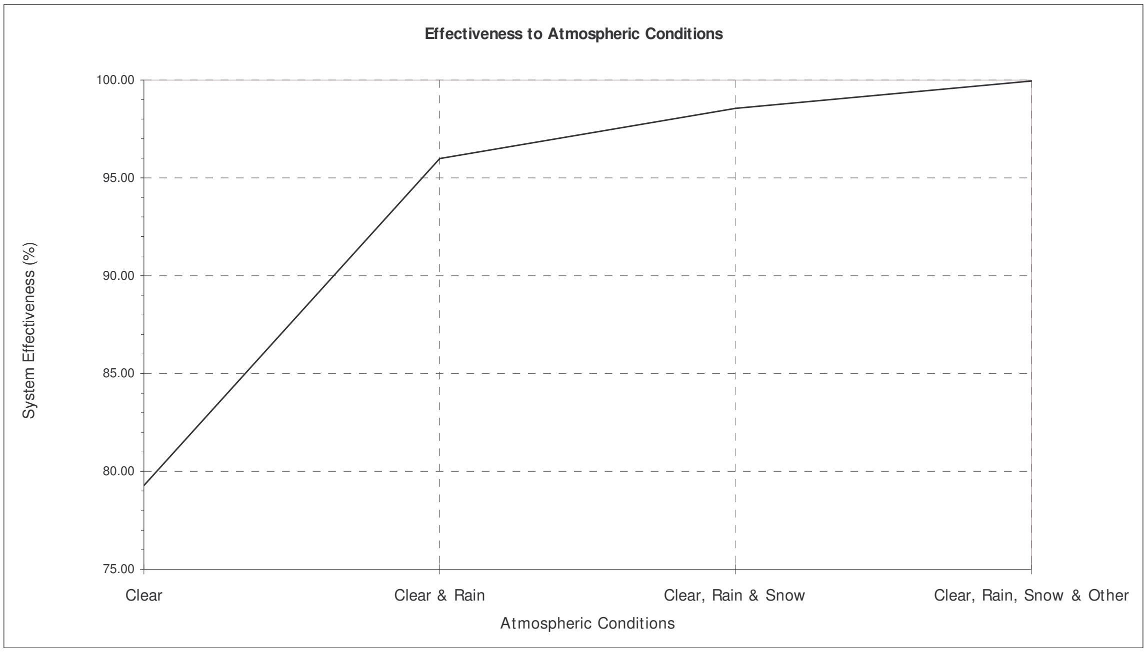

Figure 22 Effectiveness versus Atmospheric Conditions

3.5.6 Electromagnetic Compatibility / Electromagnetic Interference

Based on the safety nature of FCW systems, it is necessary to require that other devices not be allowed to produce harmful interference that would cause FCW system degradation. The nature of this compatibility is beyond the scope of this document. The IEEE is producing a document to address this compatibility issue.

3.5.7 Safety

Certain types of sensors that utilize directed energy transmission pose a safety exposure threat to humans and other life forms. The forward-looking, rear-end collision warning system must pose no significant threat to human safety and must meet or exceed all regulations for the provided technology.

3.5.8 Foreign Matter Buildup

The FCW system must not suffer serious degradation due to the buildup of foreign matter on the sensor aperture. This includes insects, dirt, mud, etc. Some system degradation is allowable as long as the system doesn't provide false alarms to the driver and the driver can rely on the system to provide proper warnings under most conditions. It is reasonable to expect that driver's will not take care in keeping the sensor aperture free of foreign matter. The FCW system design must be capable of self cleaning, detecting and alerting on foreign matter buildup, or be tolerant of foreign matter buildup.

4 DRIVING ENVIRONMENT

The driving environment is defined as the interaction between the FCW system and the environment in which it operates. Categories include traffic, atmospheric conditions, vehicles and roadway conditions.

4.1 ROADWAY ENVIRONMENT

The roadway environment includes all types of roadway geometry, such as on-road and all off-road features. The condition of the roadway: dry, wet, ice, etc., is discussed under roadway conditions.

4.1.1 Straight Roadways

A minimum FCW system must be able to detect, track and warn appropriately on straight and level roadways. The system must generate zero false alarms in this scenario independent of the complexity of the roadside environment. A straight and level roadway is statistically the most likely scenario in which rear-end collisions may occur[41]. The system must exclude as threats all roadway objects that are not in-path in order to eliminate false alarms.

4.1.2 Curves

A minimum FCW system must not generate false alarms to the driver from objects within the field of regard due to road curvature. This includes roadside objects, on-coming traffic and adjacent lane traffic. Curves are divided into three categories, constant radius, non-constant radius and curve entry / exit points.

Constant radius curves are those curves that allow a constant turning radius for the driver to negotiate, neglecting curve entry / exit points, lane keeping or lane changing maneuvers. A vehicle negotiating a constant radius curve can utilize supplemental yaw rate type sensors to detect the radius of curvature and predict the in-path and out-of-path vehicles but only after the host vehicle has entered the curve. Non-Constant radius curves are those curves that require a non-constant turning radius in order for the driver to negotiate, neglecting curve entry / exit points, course correction, lane keeping maneuvers or lane changing maneuvers. Non-Constant radius curves are typical of left and right turns at intersections normally found in urban driving environments.

The FCW system should provide appropriate warnings on curved roadways. However, some reduction in acquisition and warning range may be acceptable due to roadway curvature. If a tradeoff exists between false alarm reduction on curves and a reduction in acquisition range or warning distance due to roadway curvature then the forward-looking, rear-end collision warning system should not provide false alarms on curves.

A naïve driver may reasonably expect the FCW system to warn the driver on non line-of-sight collision threats, but these are considered rare and overly burdensome for a minimum system. Therefore, the forward-looking, rear-end collision warning system is not expected to detect objects in the forward path for which there is no line of sight path for the driver. An example of this is vehicles in the forward path but out of the line of sight due to roadside objects, parked vehicles, etc.

4.1.3 Change-in-Grade (Road Profiles)

A minimum FCW system must not generate false alarms to the driver from objects within the field of regard due to roadway changes in grade, vehicle pitch, etc. Under certain road conditions where there may be changes in roadway grade, the FCW system may be unable to detect and/or track vehicles in the forward path. This is due to the lead vehicle moving vertically out of the sensor field-of-regard even though the lead vehicle remains in the forward path. Positive changes in grade, negative changes in grade, crest and sag are all features of road changes in grade.

To combat the problem of false alarms on overhead objects the FCW system needs to have enough vertical resolution to determine the vertical direction of the roadway as well as the vertical location of the detected object. While this situation rarely occurs, it is a source of false alarms. The small improvement in system effectiveness by adding vertical resolution may not be worth the added complexity required to provide this capability. If a tradeoff exists between false alarm reduction on change in grade scenarios and a reduction in system effectiveness then the forward-looking, rear-end collision warning system should not provide false alarms on change in grade scenarios.

The forward-looking, rear-end collision warning system has these roadway profile detection goals.

- Detection of in-path vehicles due to changes in roadway grade
- Rejection of overhead objects
- Rejection of road surface objects due to changes in roadway grade

Abrupt changes in grade are reasonably rare under most driving environments and the collision potential at these abrupt changes in grade is considered low. The potential for false alarms is high and must be dealt with by the FCW system.

4.1.4 Surface Type

Certain road surfaces can produce false alarms dependent on the road profile and the sensor technology implemented. Examples of this type of road surface include steel bridges with rough metal surfaces, cattle guards, speed bumps, drainage troughs etc.

These types of road surfaces are anticipated to be rare. According to the national crash database, all reported rear-end collisions occurred on either concrete or asphalt (bituminous) surfaces.[44] However, this doesn't represent the special road surfaces that may be encountered by a forward-looking, rear-end collision warning system that can potentially cause false alarms to the driver. It may be possible to eliminate reflective road surface false alarms simply by aligning the sensor coverage area so that the intersection

[44] Task 1 Interim Report, IVHS Countermeasures for Rear-End Collisions, Contract DTNH22-93-C-07326, February, 1994

of the coverage area with the ground is outside the typical warning range (for lower travel speeds). Aligning the sensor coverage area to eliminate false alarms on road surfaces may cause problems in certain road profile situations as discussed previously. False alarms due to reflective road surfaces may be eliminated by object classification, adjustment of the sensor beam alignment, or other measures. It is also possible that some types of road surfaces can be detected and eliminated by noting the size of the road surface object in comparison to vehicle sizes. The type of road surface may create a situation where the system may be temporarily unable to detect in-path threats. In this case, it is better to suspend warnings to the driver without any notification so that it does not pose a nuisance to the driver.

The naïve driver would expect the FCW system to function properly on other road surfaces such as dirt, gravel, etc. and not provide false warnings due to those types of road surfaces. In addition to the road surface, a number of objects can be part of the roadway. These include speed bumps, potholes, manhole covers, etc.

4.1.5 Road Surface Condition

This section discusses issues with the road surface conditions under which the driver is operating the host vehicle. Road surface conditions include dry, wet, snow, ice, dirt, gravel, sand, etc. These road surface conditions may affect the host vehicle's braking and deceleration capabilities, rendering the FCW system less effective. No false alarms should be given to the driver due to the road surface conditions. A minimum performance system assumes dry, clear conditions and the effectiveness degrades based on the road conditions occurring at the time.

Road surface conditions can enhance or degrade FCW sensor performance. Road surface conditions can change how the sensor perceives the forward field-of-regard and can significantly affect system performance. Varying road surface conditions must not cause false alarms to be issued to the driver. If roadway surface conditions are detectable then that information can be used to modify the issuance of the warning.

Vibration generated on rough roads may cause increased measurement noise and cause problems detecting and tracking vehicles in the forward path. All of these influences degrade FCW system performance. FCW system developers must be aware of the possible problems presented by non-standard road surfaces.

4.1.6 Intersections

Intersections present a range of complex driving situations that may confuse the FCW system causing false alarms. These conditions include situations in which the subject vehicle is slowly approaching an intersection and there is cross or adjacent lane traffic present that could be mistaken as threats. Left and Right turns at intersections are transient events in which roadside objects may be in the forward path and on a collision course for brief periods of time. Intersections present the FCW system with a wide range of overhead objects that must be rejected as collision threats.

Cross traffic can become a source of false alarms if not specifically excluded by the FCW system. If due to varying reflectivity, the system believes the crossing vehicle has a component of speed in its direction. Therefore, it is recommended that false alarms be eliminated by simply preventing warnings when the host vehicle is stationary or braking.

False alarms during turns at intersections can be eliminated using a combination of scene processing, path prediction, lateral acceleration, object classification and elimination. Overhead objects may be eliminated as threats by adjusting the sensor coverage area as previously discussed. The FCW system must not provide false warnings due to out-of-path objects at intersections. Particular to this requirement are the objects that are directly within the forward sensor's view when the driver negotiates a right or left turn. Turning traffic from other lanes must not cause false alarms.

The FCW system should not warn the driver when the vehicle is stationary at intersections where there is stationary or moving traffic directly in front of the vehicle. This includes four way intersections and "T" intersections. The system should not warn on cross traffic moving laterally in front of the vehicle including left turn across path. Intersections include all roadway junctures and all typical and atypical roadway intersections.

4.1.7 Special Roadways/Environments

Special roadways include parking lots, driveways, alleys, off-road, etc. The FCW system should not generate false alarms in these special environments.

Unlike an Automatic Cruise Control system, an FCW system is always active. It is important that the FCW system not provide false warnings to the driver in these special environments. This may be a natural result of the low speeds at which the subject vehicle usually encounters these environments.

If the forward-looking, rear-end collision warning system experiences a special roadway that it is unable to operate in then it should do the best possible job to detect the degradation and inhibit false warnings to the driver. The FCW system can accomplish this through scene processing, object identification, accurate measurement of threats, etc.

4.1.8 Travel Lane

It is desirable, but not required, for the FCW system to determine the lane of travel. FCW systems which are dependent on lane markings or special lane designators (embedded magnetic strips for example) become ineffective if these markings are obstructed or damaged or are not visible to the system due to various conditions.

FCW systems that do not sense lane position tend to make assumptions about lane width. These assumptions, while usually correct, can lead to problems in special roadway environments. For example, when the host vehicle is going around a curve with many traffic lanes, a stopped vehicle in an adjacent lane can give a false alarm.

A FCW system that has the ability to distinguish between multiple lanes on the roadway will perform its warning function more efficiently, i.e. fewer false alarms. The ability to determine if vehicles are in lane or in adjacent lanes is important in determining if a lead vehicle is an in-path collision threat. This lane discrimination is particularly useful on curving multiple lane highways where vehicles may be in the sensor coverage area but not in the forward path.

A minimum FCW system need not determine the lane of travel, but should predict the forward path. In order to minimize system degradation in roadway environments where the lane markers are not usable, the FCW design should minimize the system's reliance on special lane designators. The FCW system must provide appropriate warnings independent of the lane width, lane markings, etc. The FCW system should function correctly on multi-lane roadways. The FCW system should provide appropriate warnings independent of the number and direction of roadway lanes.

4.2 TRAFFIC ENVIRONMENT

The traffic environment section discusses the interaction between the forward-looking, rear-end collision warning system on the host vehicle and other vehicles on and off the roadway. The traffic environment includes all types of traffic, from rural to urban. The FCW system must perform to these guidelines in the following traffic environments.

4.2.1 Level of Traffic

The forward-looking, rear-end collision warning system should perform, to the greatest extent possible, in all levels of on-road traffic from downtown urban to stop-and-go and open-road. The downtown driving environment is considered the most difficult, not because of the traffic encountered, but because of the density and proximity of roadway objects such as: signs, poles, parked vehicles, etc. that may be encountered. Stop-and-go traffic is common in high density commuter environments where vehicles are moving in small increments and rear-end collisions are likely. Open-road traffic is common for interstate, freeway and rural driving and can be characterized by a lower occurrence of roadside objects in general.

4.2.2 Dynamic Situations

A finite set of dynamic situations describe the kinematics associated with the longitudinal encounters of vehicles. Table 1 shows a matrix of lead and following vehicle dynamic situations. The fifteen dynamic situations consist of all combinations of five lead vehicle and three following vehicle kinematic situations. The system must eliminate false alarms and provide appropriate warnings under all kinematics of the host and lead vehicle. The percentages shown are the actual occurrence of rear-end collisions as taken from an analysis of the 1992 National Accident Sampling System (NASS) Crashworthiness Data System (CDS) .[45]

[45] Task 1 Interim Report, IVHS Countermeasures for Rear-End Collisions, Contract Number DTNH22-93-C-07326, February 1994.

Table 1 Percent of Rear-End Collisions versus Dynamic Situations

Lead Vehicle	**Following Vehicle**			**Total**
	Accelerating	**Constant Speed**	**Decelerating**	
Stopped	1%	18%	1%	20%
Constant Speed	2%	7%	0%	9%
Decelerating	0%	14%	3%	17%
Accelerating	0%	2%	0%	2%
Decelerating & Stopped	1%	50%	1%	52%
Total	4%	91%	5%	100%

4.2.3 Suddenly Exposed Lead Vehicles

These traffic situations are specifically identified separately because they pose a particular problem for a forward-looking, rear-end collision warning system. It is possible that a lead vehicle may become suddenly exposed due to an evasive movement from the host vehicle, or from another vehicle in the forward path. This scenario is typical in situations where the view of the road ahead is blocked from the sensor and driver. The system delay time must be minimized in order for the FCW system to effectively respond to suddenly exposed lead vehicles.

This scenario may not allow sufficient time for an attentive driver to react and stop, or to allow the system to warn the driver to avoid the collision. Certain kinematic situations exist with this scenario that may make the collision unavoidable. From a human factors standpoint, it may be desirable if this scenario can be detected that the warnings be inhibited as generating warnings during such an imminent scenario may delay the driver's response to avoid the collision. Recognition of situations where braking alone cannot prevent a collision can be accomplished based upon the measured range and range rate.

The forward-looking, rear-end collision warning system must respond rapidly to suddenly exposed vehicles in the forward path during merge situations. Drivers would typically accept a small delay between the exposing of the vehicle and the warning. This creates a requirement for as small a system delay as possible. System delays that are too great will be perceived by the driver and the driver's reliance on the system will be diminished. Certain situations exist where, with or without the forward-looking, rear-end collision warning system, the driver would be unable to avoid a collision. A lack of warning in this case is not expected to be perceived as a nuisance or limitation to the driver.

It is possible that other vehicles in the forward path might constitute a higher collision threat than the closest in-path vehicle. It is expected that a driver presented with a warning on a vehicle that is not the closest in-path vehicle will not understand the warning and will consider the warning a nuisance alarm (at least the first time). It is probably better for the FCW system to only warn on the closest in-path vehicle. Further studies on human subjects might give a more complete understanding of driver expectations. The population of drivers is not homogeneous so it will be impossible for every driver's mental of the FCW system to be entirely correct. Human factors studies would help to determine whether it would be statistically beneficial to a large number of drivers to warn on collision threats other than the closest-in-path vehicle.

4.2.4 On-Coming Traffic (Head-On)

The FCW system may exclude as threats any vehicle with a closing speed greater than the host vehicle's absolute speed. In other words, the system may ignore oncoming traffic. By definition, the forward-looking, rear-end collision warning system is not required to warn the driver of head-on collision conditions. Head-on traffic may be detected and tracked to assist in scene processing, roadway prediction and curve entrance/exit prediction.

The FCW system may, at the discretion of the manufacturer, provide warnings to the driver in the presence of vehicles that are known to be in-path and on-coming (head-on). A system that warns on head-on threats might see increased false alarms due to warnings on adjacent lane vehicles. If a tradeoff exists between warning of head-on conditions and not warning on adjacent lane on-coming conditions then the FCW system should omit head-on warnings and thus minimize attendant false alarms.

4.2.5 Lane Change / Merging / Cut-in

The FCW system must not provide false warnings to the driver, therefore, it is considered acceptable to suppress warnings in situations involving lane changes, merging, and cut-ins. However, dependent upon display modality, the driver may notice the suppression of warnings in these instances.

The FCW system must not provide false warnings to the driver; therefore, it is acceptable to suppress warnings during lane changes (in and out of path) by the lead vehicle. Figure 23 and Figure 24 show graphically a lead vehicle cut-in and lane change / merge respectively. A forward-looking, rear-end collision warning system that relies solely on the direction of travel of the lead vehicle to predict curves may become confused in these situations.

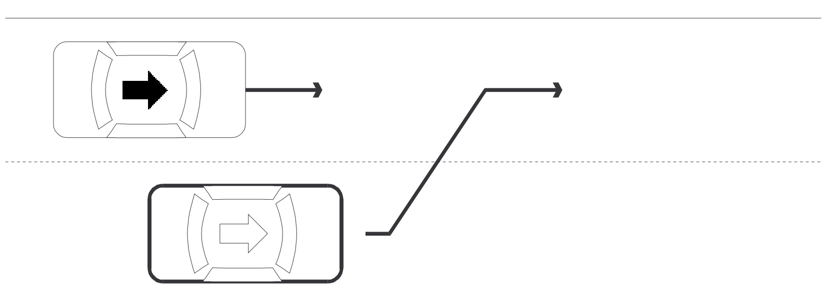

Figure 23 Lead Vehicle Cut-In

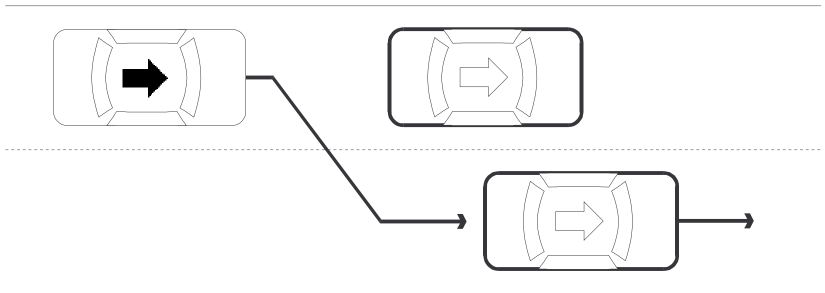

Figure 24 Lane Change / Merge

Lane changes by the host vehicle are defined as those occurrences when the predicted path changes from that currently defined as in-lane. Lane changes by the host vehicle can be aggressive or casual. Path estimation may be temporarily suspended until the host vehicle again reaches a steady state travel condition following the lane change. False warnings due to roadside objects must not be generated during host vehicle lane changes.

The forward-looking, rear-end collision warning system must be robust enough to prevent nuisance alarms associated with aggressive or casual lane changes or merges caused by roadway objects being momentarily in the forward field.

4.3 ATMOSPHERIC ENVIRONMENT

The atmospheric conditions are those weather conditions under which the driver is operating the host vehicle and the driver would reasonably expect the forward-looking, rear-end collision warning system to be functioning.

It is of primary importance that the forward-looking, rear-end collision warning system not report atmospheric conditions as false alarms to the driver. Of secondary importance is that the forward-looking, rear-end collision warning system operate under all adverse atmospheric conditions to the greatest extent possible. Atmospheric conditions include rain, road spray, snow, ice, fog, dust, dirt, smog, smoke and ambient light conditions. A system that can detect atmospheric conditions and adjust operating parameters is considered optimum. This type of system can also inform the driver when atmospheric conditions have rendered the system non-functional; however, an excessive number of atmospheric related system shutdowns may be considered a nuisance to the driver and lower driver reliance on the system.

The possible degradation to system performance is likely to come from two mechanisms: increased sensor error and loss of braking capability. When calculating system performance as described in the Benefits Estimates section, it is important to include both of these effects. The increased sensor error can cause early alarms (i.e. increasing the false alarm rate). The loss of braking capability causes a reduction in system effectiveness if the driver warning system does not take into account the resulting increase in stopping distance required. A system that includes environmental sensors can take into account the reduced braking capability and can subsequently increase warning distance to compensate. A more basic, and therefore less expensive, system which lacks environmental sensor can still have a net benefit. However, the benefit will be less effective overall due to atmospheric related degradation.

4.3.1 Rain, Road Spray, Fog, Snow

The FCW system should be operational under rain, road spray, fog, snow conditions. System degradation is allowable at higher levels as long as the system doesn't provide false alarms to the driver and the driver can rely on the system to provide proper warnings under most conditions.

Rain, road spray, fog and snow have the undesirable effect of increasing the reflections (back scatter) back to the FCW sensor and can cause threats and roadside objects to not be reliably detected. This can have the effect of causing the system to issue false alarms that must be prevented. These types of atmospheric conditions can also result in decreases in acquisition range and FCW sensor accuracy.

Wet pavement associated with rain and road spray can also decrease braking capability and necessitate longer warning times to compensate. For a minimum acceptable system detection of stopping distance required is not necessary but will lower system effectiveness under certain circumstances. Snow and fog can be associated with degraded FCW sensor performance an longer stopping distances. According to the accident statistics, only 15% percent of rear-end collisions occur on wet roadways or during rainy conditions.

The ability of the forward-looking, rear-end collision warning system to "see" through environments that the driver cannot has the potential to cause problems in risk compensation dependent upon the display modality utilized. In heavy fog, rain, dust or snow a driver may use the FCW system to navigate through the visual obscurant while maintaining a driving speed for normal conditions. The system is not intended nor is it to be designed for navigating in adverse atmospheric conditions. If a trade off exists between risk compensation and system operation in adverse atmospheric conditions, then system operation in adverse atmospheric conditions is considered more crucial.

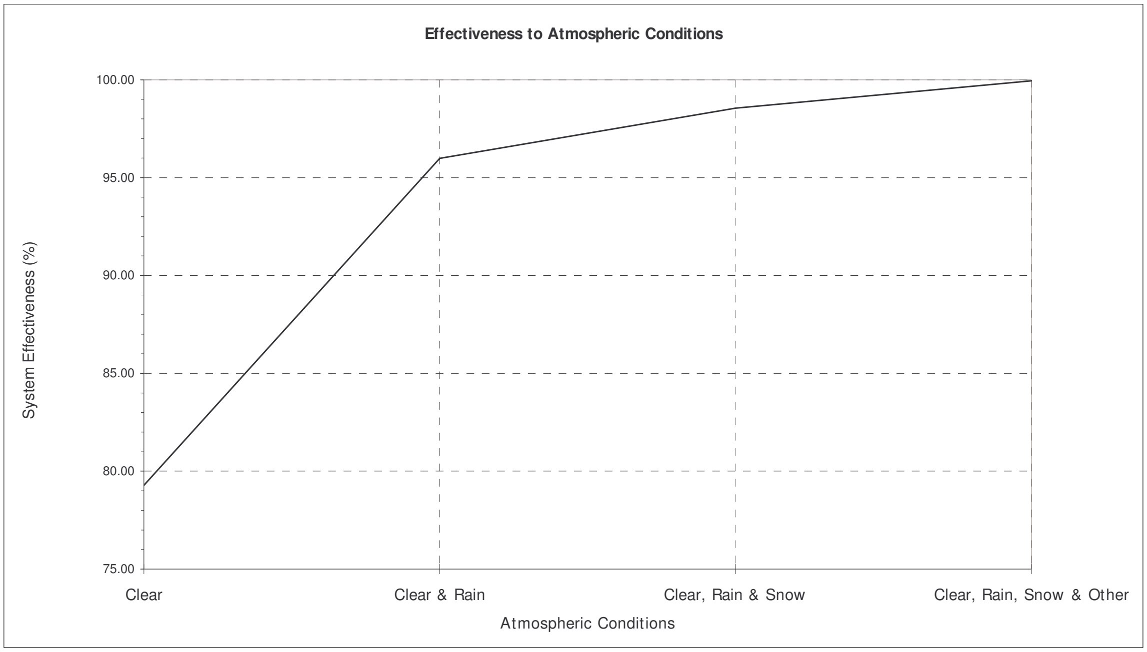

Figure 25 Effectiveness versus Atmospheric Conditions

4.3.2 Dust, Dirt, Smog, Smoke

The FCW system should be operational in dusty, dirty, smoggy, and smoky atmospheric conditions. Some system degradation is allowable as long as the system doesn't provide false alarms to the driver and the driver can rely on the system to provide proper warnings under most conditions.

System performance is similar to rain conditions except the road surface and stopping distance are not anticipated to be degraded due to these conditions. Sensor performance and errors are similar.

4.3.3 Ambient Light

The FCW system must operate in all levels of ambient light and must minimize false alarms due to light (i.e. the sun, etc.). Some system degradation is allowable as long as the system doesn't provide false alarms to the driver and the driver can rely on the system to provide proper warnings under most conditions. See Figure 25.

5 BENEFITS ESTIMATES

Prior to widespread deployment of forward-looking, rear-end collision warning systems, an estimate of potential system benefit is desirable. The benefits estimates are an aid to Federal regulators in justification of these types of systems for the driving public and as a result will be an aid to deployment of forward-looking, rear-end collision warning systems. As previously stated, Rear-End Crashes represent 23% of all collisions or about 1.5 million per year out of 6.26 million police reported crashes.

Crash costs may take a number of forms, including financial (e.g., property damage, insurance), personal (e.g., injuries, death), or time (e.g., waiting in a traffic jam). Assume 1.5 million accidents per year at $33,600 total damage per accident[46] and 157 million hours of crash caused delay and human time being worth about $10/hour, on average. Then there is $1.6 billion of delay. Therefore, the possible benefits add up to a total of about $50 billion, and each 1% reduction in cost would amount to a saving of $500 million. Crash prevention and mitigation through the use of rear-end collision avoidance devices would thus be an effective means of providing societal benefits.

To develop benefits estimates, a mathematical model of the forward-looking, rear-end collision warning system has been devised. The mathematical model is based on a 6-Degree-of-Freedom model with various random variables and a Monte Carlo simulation. Data for the simulation is based on 159 real world rear-end collisions. All of the performance guidelines should be flexible and lead to some total overall benefit. Each possible guideline (e.g. range, noise, angular coverage etc.) should have some measurable impact on the stated desired benefit. This impact will be estimated by simulation. We can create a benefits budget that shows the degradation of the benefits (from some chosen baseline) for each portion of the guidelines. This approach would facilitate trading off one element for another; for example, sensor range versus resolution.

5.1 PERFORMANCE CURVES

System effectiveness (E) is defined as the number of crashes prevented, from the crash database, divided by the total number of potential collisions. The mitigation rate (M) is meant to give a broader measure of benefit than system effectiveness. The mitigation rate is an effort to take into account crash severity, while the effectiveness counts a 1 km/h crash the same as a 55 km/h crash. It is assumed that damage is proportional to kinetic energy which is proportional to the square of the impact speed. The total damage is then proportional to the sum of the squares of the velocities. Total damage is then normalized by dividing by the total maximum damage that could result if no action were taken. So the mitigation is defined as:

[46] J.Wang, R.Knipling, L.Blincoe, "Motor Vehicle Crash Involvements: A Multi-Dimensional Problem Size Assessment", ITS America, Sixth Annual Meeting, "Intelligent Transportation: Realizing the Benefits, Houston, TX, April, 1996.

$$Mitigation = 1 - \frac{\sum_{i=1}^{N} (\text{Final Lead vehicle velocity}(i) - \text{Final Following vehicle velocity}(i))^2}{\sum_{i=1}^{N} (\text{Initial Following vehicle velocity}(i))^2}$$

Where each speed in the denominator is the initial following vehicle speed and the speeds in the numerator are speeds measured at the time of impact. Both E and M will be used as measures of effectiveness for most of the system performance attributes described below.

5.1.1 Acquisition Range

Performance versus acquisition range is shown in Figure 26. The acquisition range plot includes both stationary and moving vehicles. For the purpose of these guidelines an acquisition range of $\geq$ 130 meters was selected. Because of the statistical nature of these systems a degradation of 6% is tolerable under most driving conditions. A minimum acquisition range of 2 meters is a guideline. It should be noted that even at an acquisition range of $\geq$ 130 meters the effectiveness drops off rapidly for high closure rate scenarios such as lead vehicle stopped. At 65 mph the effectiveness drops to 64% for a lead vehicle stopped scenario and to 15% at 75 mph. This drop in effectiveness at higher speeds is a problem with any acquisition range chosen.

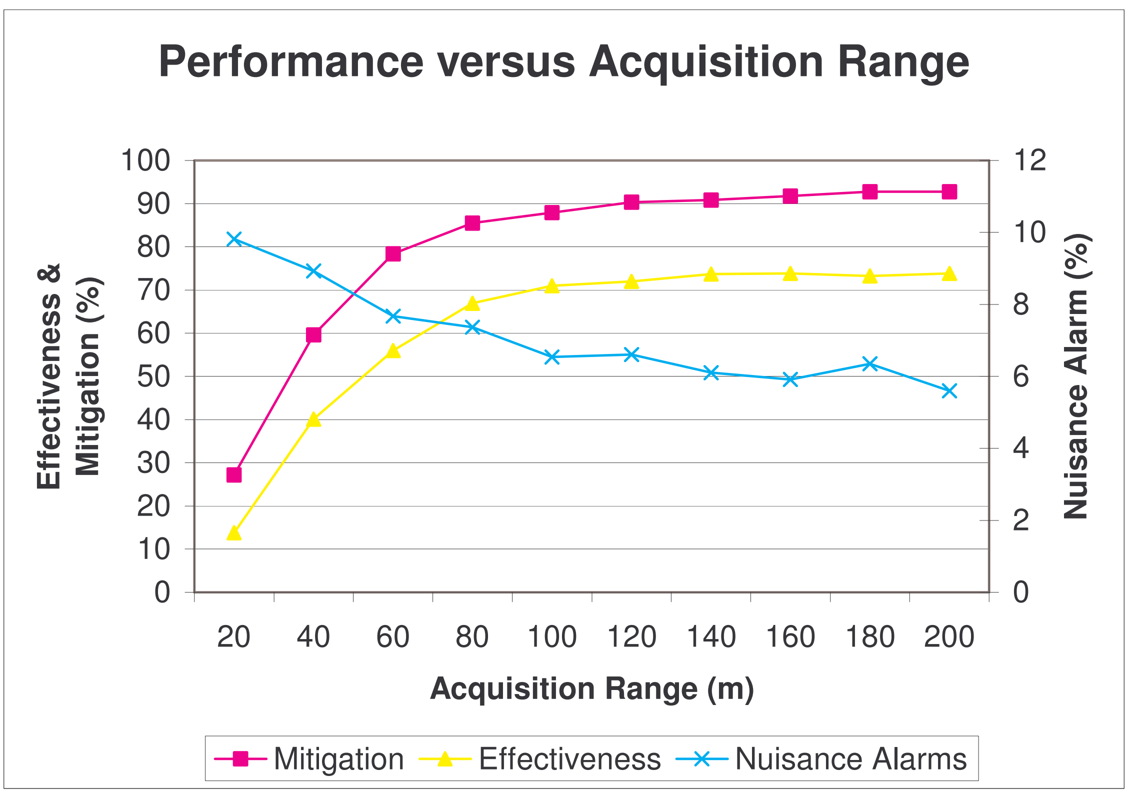

Figure 26 Effectiveness and Mitigation to Acquisition Range

5.1.2 Horizontal Field-of-Regard

Sensitivity of system effectiveness to horizontal field-of-regard is shown in Figure 27. The horizontal field-of-regard refers to the angle of view in the horizontal direction referenced to the longitudinal axis of the host vehicle. Because of the statistical nature of these systems a sensitivity to system effectiveness of 97% is sufficient to eliminate or mitigate most collisions. The sensitivity approaches 100% but never reaches 100% due to limitation of acquisition range.

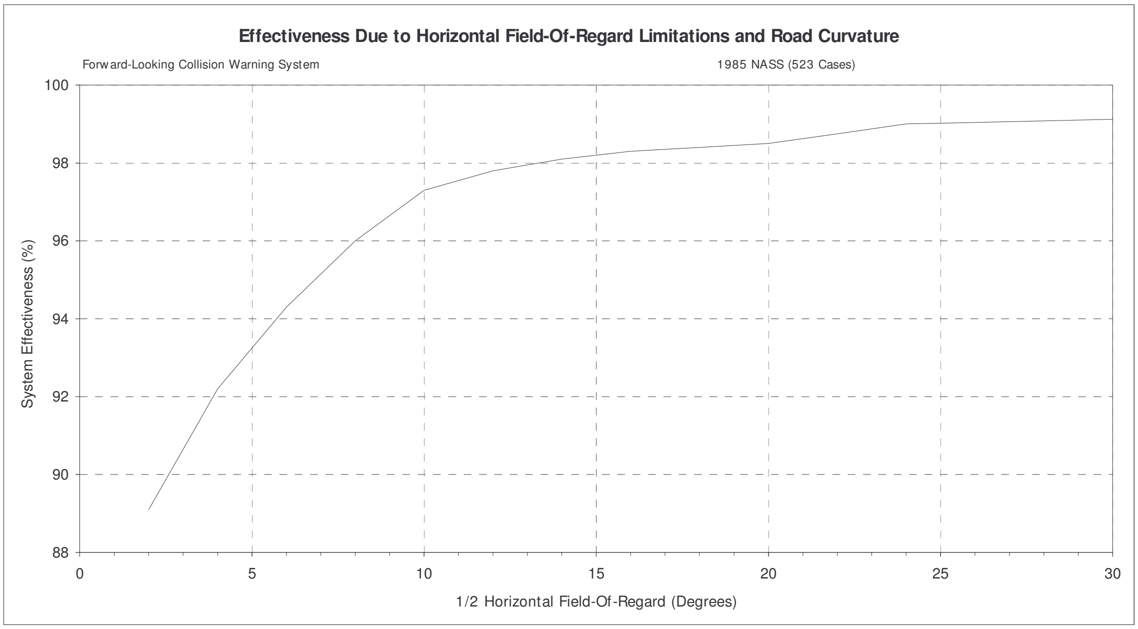

Figure 27 Effectiveness to Horizontal Field-of-Regard

To minimize nuisance alarms from vehicles in adjacent traffic lanes, parked vehicles, roadway signs, etc., the horizontal resolution must be fine enough to discriminate vehicles in adjacent lanes out to the acquisition range of the system.

5.1.3 Vertical Field-of-Regard

Effectiveness to vertical field-of-regard is shown in Figure 28. The vertical field-of-regard refers to the angle of view in the vertical direction referenced to the longitudinal axis of the host vehicle. Vertical field-of-regard relates system performance to roadway changes in grade and host vehicle pitch. The main issue for a forward looking system is the change in grade from the host to the vehicle in the forward path. This requirement affects the vertical field-of-regard required as well as the vertical angular resolution. The vertical field-of-regard should be large enough to overcome problems with the host and lead vehicle being on different roadway grades but not so large that overhead roadway objects present nuisance alarms.

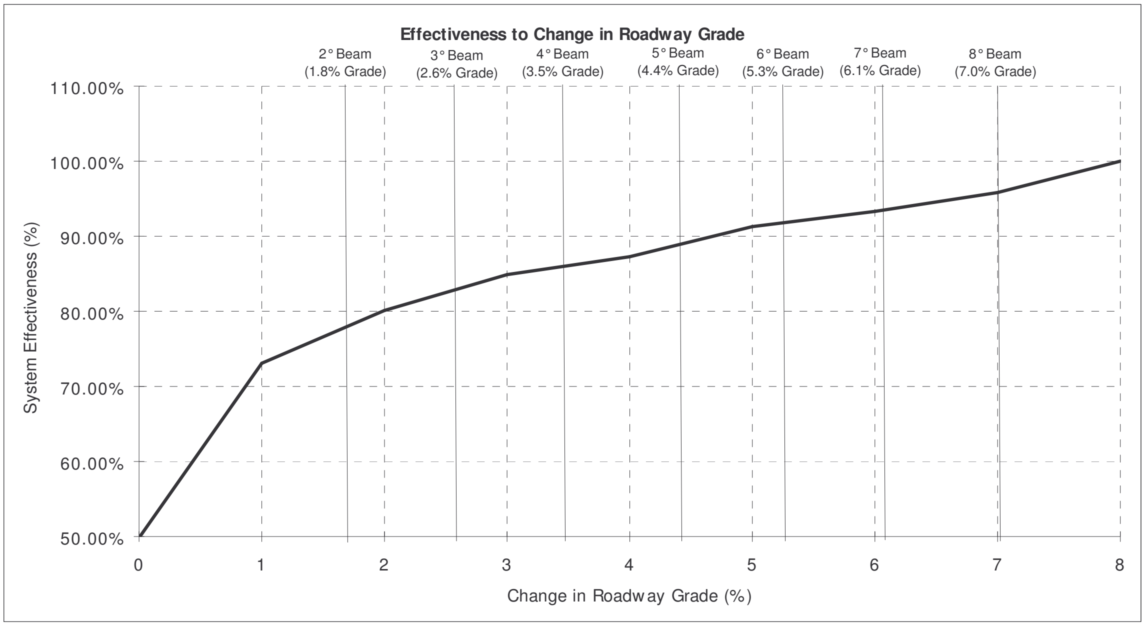

Figure 28 Effectiveness to Vertical Field-of-Regard

5.1.4 System Delay

Performance versus System Time Delay is shown in Figure 29. System time delay is defined as the time required for the system to determine an object is present in the forward path and warn the driver by changing the status of the display. The system delay time contains the acquisition delay time, the time to process through the warning algorithm and the time required to change the status of the display. The recommended value of 0.3 seconds delay gives about a 6% reduction in mitigation from the 0 delay case.

5.1.5 Atmospheric Conditions

Sensitivity of system effectiveness to atmospheric condition is shown in Figure 30. Atmospheric conditions relate to the system performance during various conditions: rain, snow, fog, dust, etc. If the system operates in clear and rainy conditions then the system effectiveness is approximately 96% instead of 79% for a system that only operates in clear atmospheric conditions. No quantitative measure of the amount or density of the atmospheric condition is available, but for a forward-looking collision warning system to be effective, it must operate correctly under degraded atmospheric conditions or notify the driver that it is non-functional.

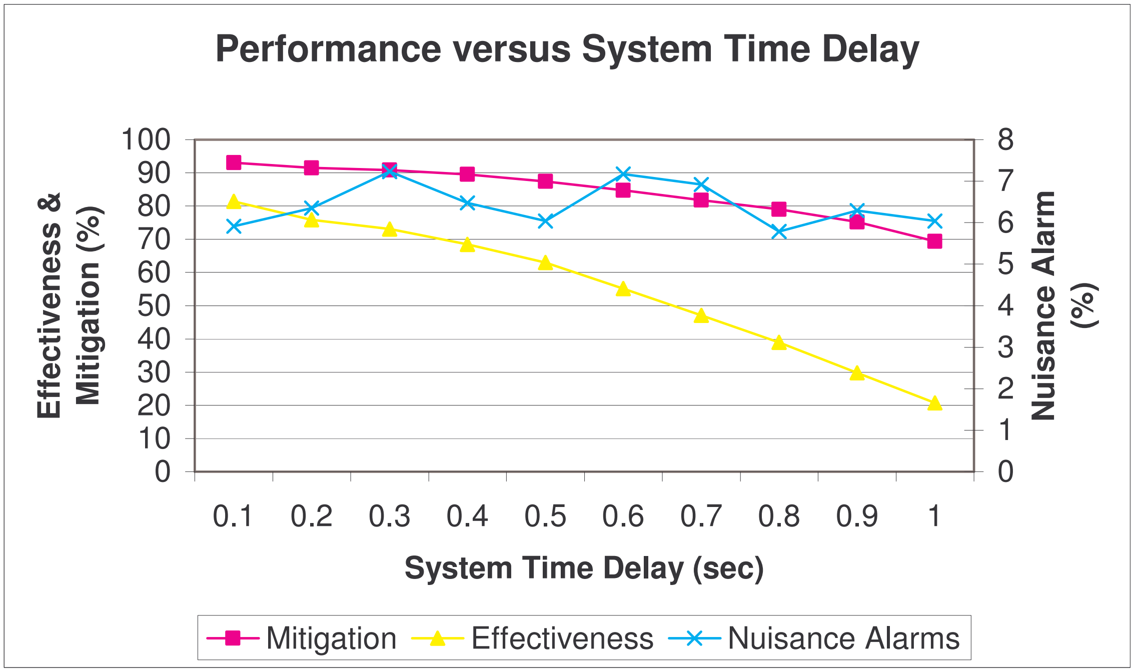

Figure 29 Effectiveness and Mitigation to System Time Delay

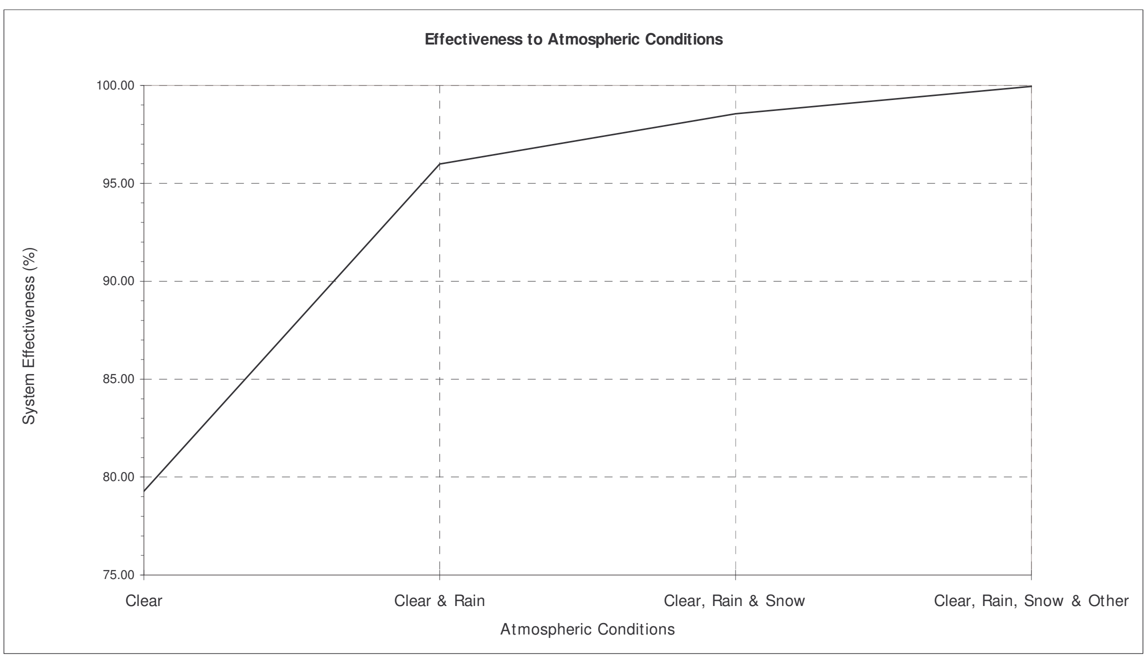

Figure 30 Atmospheric Condition vs. System Effectiveness

5.1.6 Sampling Period

Performance versus Sampling Period is shown in Figure 301. The sampling period is recommended to be about 15-20 Hz in order to provide adequate speed for the state estimation filters.

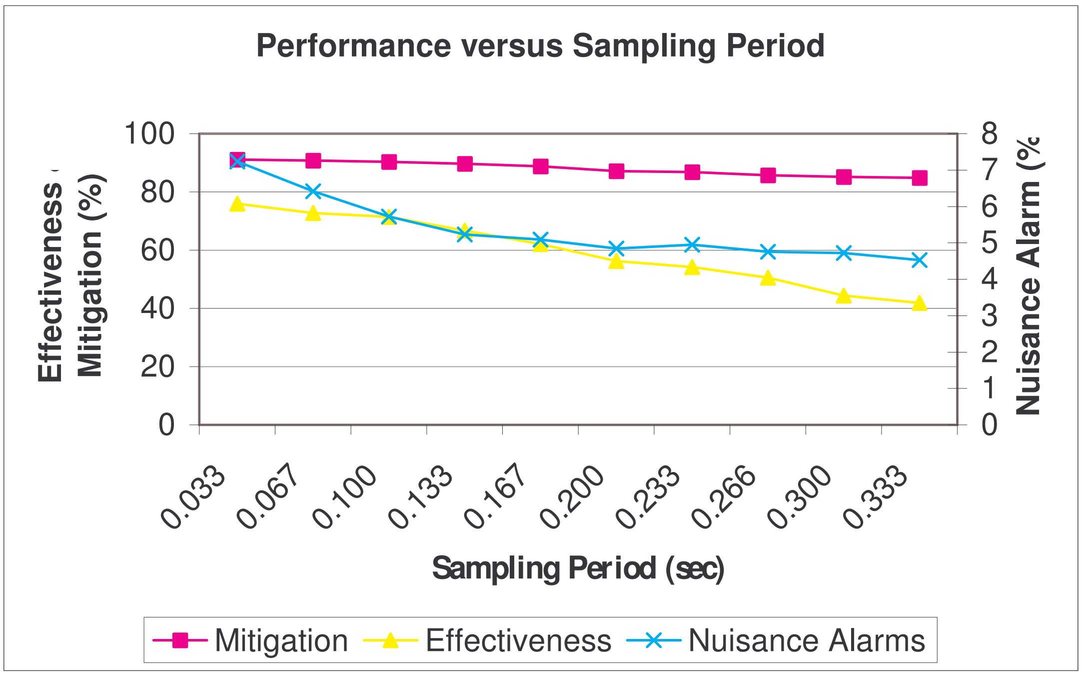

Figure 31 Performance versus Sampling Period

5.3.7 Sensor Noise

Performance versus RMS system noise per sample is shown in Figure 302. As expected, the nuisance alarm rate is shown to increase sharply with sensor noise, making it important to have fine resolution in measured range.

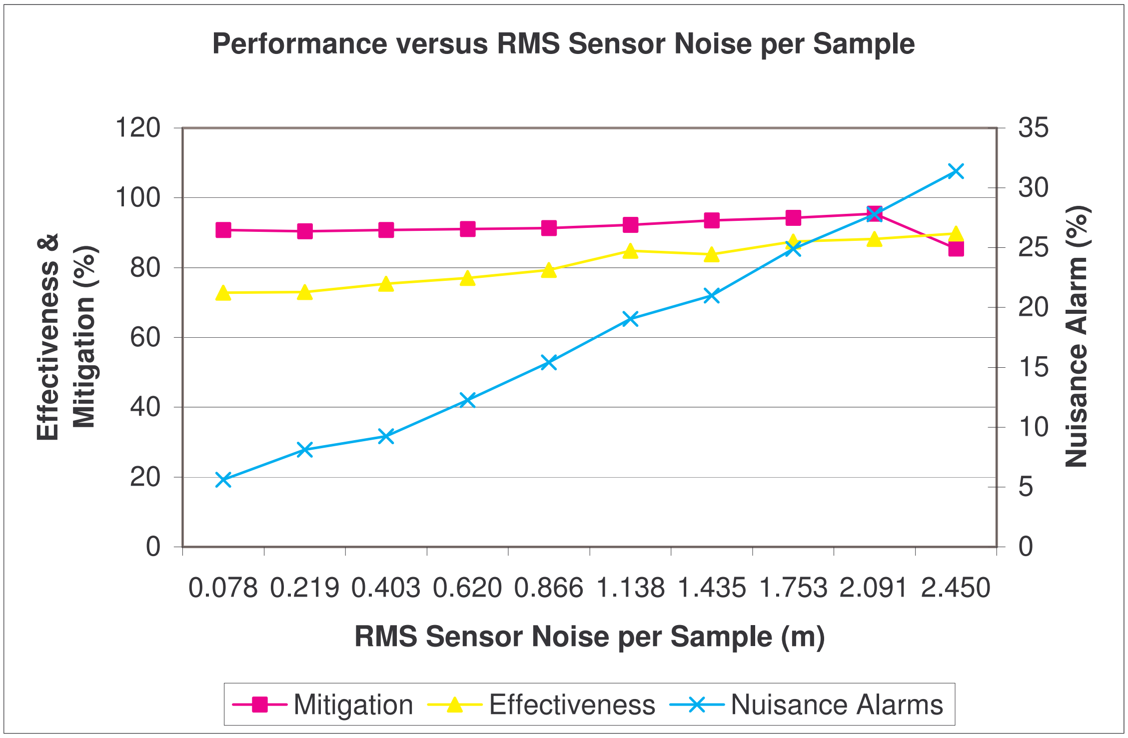

Figure 32 Performance versus System Noise

5.2 ESTIMATION OF BENEFITS

Table 2 shows recommendations and their associated system mitigation estimates. Note that the results in table 5-2 are the degradations from 100% due to each individual effect, while the plots show the net performance for the presence of several factors simultaneously. The sensor noise errors have almost no effect on the system effectiveness or crash mitigation, but they strongly effect the nuisance alarm rates, and therefore must be constrained as shown in the table.

Table 2 Forward-Looking Collision Warning System Recommendations

Mitigation	Description	Recommendation
96%	Driver Display Type	Collision Warning Display, Following-Too-Closely Display. Warning display only 77%.
96%	Moving and Stationary Threats	Both
no effect	Sensor Noise, scale factor and bias	0.07m, 7% 0.7 m.
93%	Acquisition Range	$\geq$130 meters
96%	Horizontal Field-of-regard	$\pm$ 8 degrees
92%	Roadway Profile, Vertical Field-of-regard	5.3% Grade, 6 degrees
98%	Atmospheric Condition	Clear, Rain, Snow
94%	System Delay Time	$\leq$ 300 milliseconds

Overall mitigation is calculated by the product of individual components (with assumed independence and equal weight). With these assumptions, the overall mitigation is 70%.

The total cost of rear end collisions per vehicle lifetime[47] is about $1500. If the overall benefit is 70% then this puts an upper bound of about $1000 on the total possible end-user cost of the forward looking rear-end collision system including unit cost, installation, maintenance, and the disvalue of nuisance alarms.

5.2.1 Cost

Current industry goals put a high volume production cost on ACC systems at $200-$300 to the OEM. This translates to a consumer cost of approximately $1000 - $1200 per vehicle. Additionally, it is apparent that if forward-looking, rear-end collision warning systems function adequately, they may replace (from a cost / benefit standpoint) other vehicle based safety features.

[47] Ibid.

6 LIMITATIONS

Limitations are defined as when the system performance deviates from the driver's anticipated expectations of the FCW system. Limitations may also consider those scenarios that cannot be overcome by the technology.

Inattentive / Distracted Drivers – The underlying premise for the development of forward-looking, rear-end collision warning systems is that rear-end collisions are caused primarily by driver inattention. An assumption can be made that inattentive or distracted drivers have longer response times compared to attentive drivers. A forward-looking, rear-end collision warning system designed specifically to aid the inattentive / distracted driver would be considered a constant nuisance to the attentive driver due to the longer assumed driver reaction times. It is therefore likely that an FCW system developed to balance the conflicting requirements of attentive and inattentive drivers may, for the inattentive, provide mitigation benefit rather than prevention. It is crucial that the FCW system be developed to be perceived as reliable by the driver so that as intrusive a display methodology can be utilized.

Operation beyond sensor limit – It is reasonable that the naïve driver would expect the forward-looking, rear-end collision warning system to provide rear-end collision protection under all vehicle speeds, but limitations in sensor acquisition range may allow the driver to "drive beyond the sensor limit" of the FCW system. This occurs when the warning range exceeds the sensor acquisition range. This problem is compounded on curved roadways. If the sensor range is limited, an advisory message to the driver may be advisable. If however, the sensor range is so limited that this routinely occurs below posted vehicle speeds then it is anticipated that the posting of an advisory "beyond sensor limit" message to the driver would be considered a nuisance and reduce driver reliance on the FCW system.

Operation outside the sensor field-of-regard – It is reasonable that the naïve driver would expect the forward-looking, rear-end collision warning system to provide rear-end collision protection under all driver line-of-sight roadway curve and change-in-grade conditions. Limitations in the sensor field-of-regard may cause some rear-end collision threats to be outside the sensor field-of-regard but inside the warning range. A reduction in warning range and an overall reduction in system effectiveness will result as a function of roadway curvature or change-in-grade and sensor field-of-regard. Obviously, this limitation in warning range should be transparent to the driver to the greatest extent possible.

Merge / Lane Change – It is reasonable that the naïve driver would expect the forward-looking, rear-end collision warning system to provide rear-end collision protection under all lane change and merging conditions. This is an area where the driver's perceived mental model may significantly deviate from the operation of an autonomous system where the driver may expect a warning in non-line-of-sight conditions. Dependent on the display methodology employed, the forward-looking, rear-end collision warning system may inhibit warnings in lane change and merging conditions though the naïve driver may not notice the limitation.

Non-Line-Of-Sight **–** Most (autonomous) systems utilize line-of-sight sensing techniques to perform the task. It may be reasonable that the naïve driver would expect warnings in non-line-of-sight scenarios such as suddenly exposed vehicles or vehicles obscured by roadway features on curves. This limitation may not be overcome by current technology.

Small Vehicles **–** It is reasonable that the naïve driver would expect the forward-looking, rear-end collision warning system to provide rear-end collision protection for all vehicle sizes including small vehicles such as motorcycles, bicycles, gopeds, etc. It is also reasonable that the current technology should detect these vehicles under moving conditions but may have difficulty distinguishing these vehicles from roadside objects in stationary scenarios. From a driver acceptance standpoint, if the tradeoff exists between warning the driver on motorcycles and bicycles while sacrificing false alarm suppression to roadside objects then false alarm suppression should be consider more essential.

Near Field-Of-Regard **–** Autonomous systems that rely on single point sensing technology do not adequately cover zones near the host vehicle where the naïve driver would reasonably expect a warning. For example, if the forward-looking, rear-end collision warning sensor were mounted centered in the grill area, it is not likely to be able to detect and warn the driver of vehicles and objects that are near the front corners of the host vehicle or those rear-end collisions that are near side-swipes where the host vehicle clips the corner of the lead vehicle.. However, naïve drivers would reasonably expect a warning in those conditions where objects or pedestrians are in those zones.

Pedestrians / Roadway Objects **–** It is reasonable that the naïve driver would expect the forward-looking, rear-end collision warning system to provide a warning on pedestrians and in-path roadway objects that are large enough to present a threat to the host vehicle. The forward-looking, rear-end collision warning system should detect in-path objects, but may have difficulty detecting the size of the objects so as to provide warnings consistent with the driver's mental model. Additionally, pedestrian collisions are not typically with or near the centerline of the vehicle and as a result a point type of autonomous sensor may be unable to detect the presence of the pedestrian and therefore be inconsistent with the driver's mental model. From a driver acceptance standpoint, if the tradeoff exists between warning the driver on in-path objects that are not considered threats (cans, bottles, etc.) and warning the driver of in-path objects that are considered threats then the FCW system should not warn on in-path objects. The mental model that is being developed is that the FCW system only warn on the rear-end of in-path vehicles.

On-Coming Traffic **–** It is reasonable that the naïve driver would expect the forward-looking, rear-end collision warning system to not provide warnings on out-of-path on-coming vehicles. If however, it is known that an in-path head-on collision threat exists then a warning may be acceptable. If a tradeoff exists between warning the driver due to in-path head-on conditions and not warning the driver on out-of-path on-coming conditions, then the FCW system should not warn the driver on on-coming vehicles either in or out-of-path. The mental model that is being developed is that the FCW system only warn on the rear-end of in-path vehicles.

***Crossing-Path Traffic* –** It is reasonable that the naïve driver would expect the forward-looking, rear-end collision warning system to provide warnings on in-path crossing-path threats that present an imminent collision threat. Such as left turn across path and vehicles stalled in the host vehicle travel lane. If a tradeoff exists between warning the driver of imminent crossing-path collision conditions and not warning the driver on crossing-path non-imminent collision conditions, then the FCW system should not warn the driver on crossing-path conditions.

***Secondary Vehicle Warning* –** The forward-looking, rear-end collision warning system may be able to provide warnings on vehicles that are not the closest in-path vehicle dependent upon the sensing technology utilized. Such as stopped vehicles in-front of lead vehicles in aggressive lead vehicle lane change scenarios. It is not understood if the driver can comprehend a warning on a collision threat that is not the closest in-path vehicle. The FCW system may or may not provide a warning under these circumstances.

***Atmospheric Conditions / Weather* –** It is reasonable that the naïve driver would expect the forward-looking, rear-end collision warning system to be operational in degraded atmospheric conditions. As the weather conditions worsen, some or complete degradation will occur dependent upon the technology implemented. The value of this event is contrary to expectations for ACC system operation where the degradation would be desirable as long as the ability exists to shift longitudinal control from the ACC system to the driver under degraded weather conditions. It is advantageous for the forward-looking, rear-end collision warning system to remain operational under a great many atmospheric conditions. It may also be necessary that if the forward-looking, rear-end collision warning system cannot function due to atmospheric conditions that this condition be sensed and relayed to the driver. If weather related shutdown of the forward-looking, rear-end collision warning system occurs frequently then the driver may consider it a nuisance and driver reliance on the system may be reduced.

***Driver Impairment* –** It is possible that forward-looking, rear-end collision warning system can be used by drivers that are in various stages of impairment such as under the influence of drugs or alcohol. These types of systems could promote risk taking behavior by encouraging drivers to drive while impaired. This may be an unavoidable result of FCW systems deployment.

***Curves* –** The naïve driver would reasonably expect the forward-looking, rear-end collision warning system to work on all types of curves. However, a typical system has limitations in horizontal and vertical fields of regard and therefore cannot operate effectively in all turn and curved roadway scenarios.

***Special Roadway Environments* –** There are obviously special roadway environments that may cause the forward-looking, rear-end collision warning system to be temporarily unable to detect objects in the forward path and warn the driver. Under these conditions, the forward-looking, rear-end collision warning system must not provide false alarms to the driver and the system must be perceived by the driver as reliable.

Special Vehicles – There are a wide range of on-road vehicles which the forward-looking, rear-end collision warning system must detect and potentially warn the driver, including passenger cars and trucks. It is reasonable to expect that certain types of vehicles, such as small motorcycles and bicycles, may cause detection problems for the FCW system. These occurrences are considered false alarms (or misses) and should be minimized..

Damage – It is possible that the forward-looking, rear-end collision warning system can become damaged and/or out of alignment with the vehicle which would cause errant operation. This damage may be undetectable by the FCW system.

Obscured Vehicle – It is possible that the sensing technology employed may be temporarily unable to determine if a collision threat exists. An example of this is when a vehicle in the forward path is stopped below an overhead object that the sensor is detecting. It is advisable in these conditions that the FCW system exclude the overhead object even though it would mask warnings to the driver for the vehicle stopped underneath. The goal is to eliminate false alarms and it is anticipated that overhead objects will be encountered more often than the particular situation where a vehicle is stopped below an overhead object. This applies to other scenarios where an out-of-path roadside object masks a collision threat in the forward path.

7 QUALIFICATION TESTS

7.1 INTRODUCTION

The tests described in this section are designed to evaluate the FCW system performance in a non-invasive manner. The tests described are based on the anticipated capabilities of a mass marketed FCW system and may not be adequate for FCW systems that do not meet the goals of these guidelines. The FCW systems are anticipated to be installed on passenger vehicles instead of being stand-alone units due to the high level of system integration for proper function. Special FCW units are not desired to perform these tests, but rather standard production units should be used. Special interfacing may be required, however, to record and correlate the test data.

The tests described herein include a set of simple scenarios that are representative of the types of conditions likely to be encountered in normal driving. They are divided into the following categories: Collision Warnings, False Warnings, Situational Awareness, Human Factors, and Environmental categories. A statistical database will need to be developed to evaluate the relative performance of FCW systems from multiple manufacturers. Each test described should be performed a minimum number of times in order to obtain a statistical sampling. The suggested numbers of repetitions for different types of tests are described in section 7.1.1 below.

The tests can be performed in normal and adverse weather conditions. Performance in adverse weather conditions is a crucial issue for FCW systems; however, it is not anticipated that reliable weather conditions will always be available to perform the required testing so manufacturer data may need to be relied upon for adverse weather condition performance. Any adverse weather conditions need to be monitored and recorded to provide adequate data comparisons to test standards and for unit qualification. It is unlikely that a set of tests can be developed to comprehensively test the FCW system for all known performance issues. As a result, these tests evaluate and quantify performance in a limited number of conditions in order to correlate the information with widespread deployment. The FCW system should perform according to the guidelines specified herein for the ideal environment. An ideal environment is defined as an open, flat, dry, clean, smooth, paved asphalt roadway with unobstructed line-of-sight from the test vehicle to the lead vehicle, under moderate temperature and humidity conditions in daylight hours.

It should be noted that these tests are a first to attempt to qualitatively and quantitatively evaluate the performance of an FCW system. It is possible that the focus of the suggested tests will change as capable FCW systems are developed. As experience with the testing of these systems is gained, properly designed tests, consistent with the sound principles of experimental design, may increase the precision and fidelity of the estimates while decreasing the total effort of the test procedures.

7.1.1 Performance Tests

The following tests are designed to verify the FCW system compliance to the performance guidelines specified in this document. No adjustments to the system under test or to the recording equipment are allowed once the test has begun. These tests are designed for professional drivers and no naïve driver testing is included. Each test should be performed multiple times under the same conditions to collect a statistical sample.

7.1.2 Test Facility

All tests are performed on an asphalt (bituminous) surface under normal conditions. The roadway surface is expected to be dry except where indicated. All driving lanes are of standard width. All roadway and roadside features must be accurately placed. The goal is to provide a set of tests which are repeatable and which provide an accurate comparison of all FCW systems tested.

A possible option to on-road testing is a target or object simulator that allows the tests to be conducted at multiple facilities in a more timely and cost effective manner. This object simulator should not to be confused with a driving simulator. The object simulator must simulate vehicle and roadside objects for the FCW sensor under test. From the sensor's standpoint, the object simulator appears to be the same as real-world driving. All roadside clutter and object characterizations must be built into the simulator. The advantages of a target or object simulator is the ability to perform many tests in many configurations to build a statistical data base and characterize the system as much as possible for much less expense than performing the same tests on a test track. Additionally, the object simulator allows exact repeatability of the tests compared to execution on-road. The disadvantages of the object simulator are that it would be sensor specific, very complex and may require access to the FCW developer's proprietary information regarding the sensor. In order for a single simulator to operate all types of sensors, a different front-end attachment specific to the sensor would be required. The test controller should be able to be used for all sensors. The object simulator would need calibration and the operating parameters required to develop the simulator may be considered proprietary by the sensor developer, thus, possibly making the simulator not feasible. However, there are sufficient justifications to consider the possibility of a simulator for the major contenders.

7.1.3 Standard Test Vehicles

Standard test vehicles and objects will be used to eliminate variations due to different test vehicles/objects and for comparison of different types of FCW systems.

The following vehicle types require standardization: motorcycle, midsize passenger car and a large truck. These vehicle types are intended to be used for this testing. However, all licensed vehicles that are found on-roadway are of interest. As long as the test vehicles meet US standards they should be appropriate for testing. These standard vehicles must be detected and tracked in their original factory condition without special reflectors or modifications to make them more visible to the FCW sensor under test unless the FCW system under, test is designed to only work with such devices. Use of specially modified lead vehicles is discouraged and should be noted in the test report.

7.1.4 Standard Test Objects

Roadside objects will be used to determine the capability of the FCW system to eliminate false alarms. The roadway and roadside objects can be created specifically for these tests, or representative roadways can be utilized. The roadside objects requiring standardization include the following: a pole, mailbox, guardrail, traffic lights, street lights, road signs and overhead bridge. The pole should be representative of a common street light and should be located approximately one meter from the lane edge. The mailbox is the standard size US Postal Service street side drop box for US Mail and its closest side should be approximately one meter from the lane edge. The guardrail is the standard metal guardrail found on curves on US roadways and shall be approximately 30 meters in length and located 1/3 meter from the lane edge. One standard traffic light shall be mounted on the pole and over each lane in which the subject vehicle is traveling. Street lights shall consist of a mounting pole with an overhanging arm that is in the middle of the lane at the US minimum height. The standard road signs shall consist of a square sign turned on its corners that is equivalent to standard roadway signage. The standard overhead bridge shall be US minimum height above the roadway.

7.1.5 Roadways

Straight, curved and curved with straight approach roadways need to be standardized for repeatable testing. By conducting the tests at a single facility this requirement is satisfied. Rather than develop a roadway at a test facility, it may be beneficial to have restricted access to representative roadways that are equivalent to the test roadways described.

7.1.6 Installation of the Test Unit on the Subject Vehicle

It is anticipated that the FCW system under test will be delivered already installed on a subject vehicle. If the FCW system under test requires installation then it should be installed according to manufacturer specifications. All interfaces to the subject vehicle shall be connected and the FCW system should be operating within the FCW manufacturers specifications. It is preferred that the system under test be furnished already installed on a passenger vehicle.

7.1.7 Recorded Data / Test Equipment

In order to properly evaluate performance, an independent measurement of range to the lead vehicle or other objects, speed of the lead and subject vehicles, warning occurrences (visual, haptic, auditory, etc.) and a time standard must be recorded. The time standard shall serve to time-correlate all recorded data. A video image of the drivers view and any visual warning indicators with text overlay of the recorded data and the time standard shall be recorded. Driver warnings shall be recorded by modality specific instrumentation. The measurement accuracy of all recorded data shall be equivalent to the video frame rate of 30 Hz.

The data measured should be the same from system test to system test. The data acquisition shall include:

- Independent measuring equipment shall monitor the separation distance between the subject and lead vehicles (range) and the speeds of the subject and all lead vehicles.
- A video camera shall be mounted to capture the driver's forward view.
- Display modality specific instrumentation shall record all driver warnings (visual, auditory, haptic).
- A 3-dimensional accelerometer shall record any brake applications and other physical dynamics of the vehicle.

7.1.8 Setup

Unless otherwise noted, the subject vehicle is initially placed at a distance from the lead vehicle(s)/object(s) that is beyond the system under test's acquisition range and far enough to allow time for the subject vehicle to reach the test speed before entering the acquisition range of the system under test.

7.1.9 Statistically Significant Sample Size

In order to provide a statistical sample of the tests performed, they are required to be executed a minimum number of times to quantify the error bound on the measurement. Three statistical tests are included: estimating the variance of a normally distributed random variable (NDRV), estimating the mean of a normally distributed random variable, and the mean of a binomial distributed random variable (BDRV).

7.1.9.1 Variance of NDRV

The variance of a normally distributed random variable relies on tables for the Chi-Square distribution to estimate the error bounds. If 30 independent samples are taken from a normally distributed random variable, then error bounds on the true variance (tvar) can be related to the sample variance (svar). The true variance can be shown to be 90% certain to lie within:

tvar = [0.68,1.9]*svar.

That is, the actual variance will probably not be more than 60% greater or 32% less than the measured sample variance. More samples could be collected if one desired a higher confidence (e.g. 95%) or a narrower error bound. This implies that all collision warning and situational awareness tests be executed a minimum of 30 times.

7.1.9.2 Mean of NDRV

The mean of n samples of a normally distributed random variable is itself a normally distributed random variable with standard deviation sigma/sqrt(n), where sigma is the true standard deviation. For a 90% confidence interval, we take the 2-sigma point:

true_mean = sample_mean +/- 2*true_sigma/sqrt(30)

Re-writing the above confidence interval, based on the confidence interval on the standard deviation,

true_mean = sample_mean +/- 2*sqrt(1.9)*sample_sigma/sqrt(30)

true_mean = sample_mean +/- 0.5*sample_sigma

7.1.9.3 Mean of BDRV

A binomial distributed random variable is one that can take on one of 2 values, usually 0 or 1, for example a false alarm in the driver warning system. It can be shown that the RMS error (or 1-sigma error bound) is

sigma = sqrt(p*(1-p)/n)

where p is the probability of the event and n is the number of times the test is repeated. As a good rule of thumb,

n = 4/p (or greater)

So, for example, if we expect that the false alarm rate is 1% (p=0.01) then we need about 400 tests. The n = 4/p rule gives about e^{-4} or about 2% chance that zero false alarms will be recorded.

7.2 COLLISION WARNING TESTS

The collision warning tests are performed to determine if and when the FCW provides a warning to a driver. The output of the collision warning tests can be considered as a distance or a time-to-collision, for a given subject vehicle current speed and deceleration level. The performance limits for the collision warning tests are shown in Table 3 for two values of subject vehicle current speed. The performance limits chosen here are based on the required deceleration to stop once the warning has been issued. The deceleration (or warning distance) of the system is used to establish a characterization of the system type as follows: nuisance, conservative, moderate, aggressive and dangerous. The nuisance category is defined as a warning that is given on a real threat but is given so early that the driver could have easily reacted to it on his own. See the definition section for nuisance alarm. The dangerous category is defined as a situation where the vehicle is not capable of stopping at the deceleration rates required to avoid a collision. The conservative, moderate and aggressive categories were established from simulations and testing. Additional driver information is necessary to establish a correlation between the tests and drivers.

Speed (m/s)	Deceleration ($g\alpha$) (m/s²)	Warning Distance (WD) (m)	Type
16	$g\alpha < 3.0$	$60.1 \le WD$	Nuisance
16	$3.0 \le g\alpha < 4.5$	$46.0 \le WD < 60.1$	Conservative
16	$4.5 \le g\alpha < 6.0$	$38.9 \le WD < 46.0$	Moderate
16	$6.0 \le g\alpha < 8.0$	$33.6 \le WD < 38.9$	Aggressive
16	$8.0 \le g\alpha$	$WD < 33.6$	Dangerous
34	$g\alpha < 3.0$	$230.1 \le WD$	Nuisance
34	$3.0 \le g\alpha < 4.5$	$165.8 \le WD < 230.1$	Conservative
34	$4.5 \le g\alpha < 6.0$	$133.7 \le WD < 165.8$	Moderate
34	$6.0 \le g\alpha < 8.0$	$109.7 \le WD < 133.7$	Aggressive
34	$8.0 \le g\alpha$	$WD < 109.7$	Dangerous

Table 3 Collision Warning Distance Test Criteria

The warning distances were calculated from the following standard collision equation.

$$WD = \frac{(v - v_f)^2}{2g\alpha} + t_d(v - v_f)$$

Where

WD = warning distance (meters)
v = subject vehicle current speed (meters/second)
v_f = subject vehicle final speed (0 meters/second)
t_d = Time delay = 1.1 seconds
g = 9.8 meters/second^2
α = deceleration (g's)

7.2.1 Lead Vehicle Stopped Warning Distance - Straight Road

The purpose of this test is to characterize the warning generated by the FCW system under test on a straight roadway and determine if the system provides adequate warnings. The standard vehicles used are the motorcycle, midsize passenger car and large truck.

Place a stationary lead vehicle on a straight roadway. Drive the subject vehicle toward the lead vehicle at 5 m/s (11 mph). Record the subject vehicle speed and the range at which the warning occurred. Repeat the test multiple times. Repeat with the subject vehicle at 16 m/s, 25 m/s and 34 m/s (35, 56, 75 mph).

In the interest of safety, it may not be possible to perform these tests with actual lead vehicles, because it would require driving at a high rate of speed toward another vehicle and stopping or swerving soon before impact. There is the risk that a driver error during testing could generate an actual collision. If this is the case, alternative approaches to accomplish the same testing should be investigated. The use of standard targets that represent the vehicles in question for the FCW sensor under test is acceptable but not desirable.

Compare the recorded warning ranges to the standard algorithm warning ranges given above in Table 3. Average the results over the trials for each speed. Classify the system for each speed.

7.2.2 Lead Vehicle Stopped Warning Distance - Curved Road

The purpose of this test is to characterize the warning generated by the FCW system under test on curved roadways and determine if the FCW system provides adequate warnings. The standard vehicles used are the motorcycle, midsize car and large truck.

Place a stationary lead vehicle in the right hand lane of the curve at the ¾ point through the curve, refer to Figure 33. The curve radius should be 250 ± 25 meters at a test speed of 16 m/s (35 mph). The subject vehicle is driven toward the lead vehicle, following the curve, at 16 m/s (35 mph). Record the range to the lead vehicle at which the warnings occur and the subject vehicle speed. Repeat the test multiple times. Repeat the test at 34 m/s (75 mph) on a 950 ± 50 meter radius curve.

Note, it is unlikely that this test can be executed using actual lead vehicles. Therefore, it may be necessary to use standard targets that represent the vehicles in question for the FCW sensor under test. These standard targets should be constructed to allow the subject vehicle to impact them without damage, or drive over or under them without damage. For example, in testing a radar system a target can be constructed of a reflecting piece of aluminum foil sandwiched between 2 pieces of soft foam. The size and shape could be chosen to give a radar cross section equivalent to a passenger car. Similar mock targets could be created to test lasers or other sensors while minimizing risk to the test drivers.

Compare the recorded warning ranges to the standard algorithm warning ranges given above in Table 3. Average the results over the trials for each speed. Classify the system for each speed according to conservative, moderate, aggressive, etc., as defined in table 3.

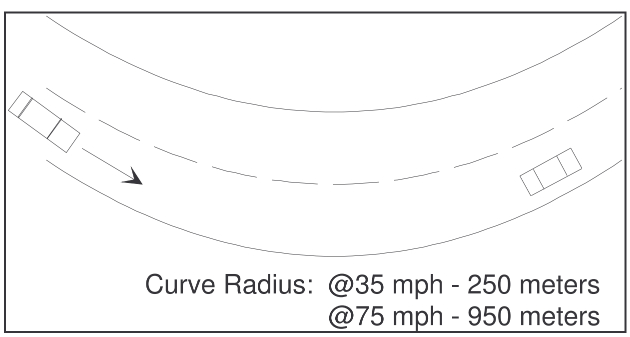

Figure 33 Curved Road Warning Distance Test Setup

7.2.3 Adjacent Lane Vehicles

The purpose of this test is to characterize the warnings generated by the FCW system under test in the presence of adjacent out-of-path objects and determine if the system provides the appropriate warning. The standard vehicles used are the motorcycle, midsize car and large truck. Adjacent lane vehicles may be combined with the in lane vehicle to form an object that appears to the system to be centered between lanes which may cause a warning to not be issued or the two vehicles can appear to be a single large object that may be too large to be classified as a vehicle for the system under test.

On a straight roadway, an in lane and an adjacent lane vehicle are placed with sufficient spacing to be outside the acquisition range of the sensor and sufficient headway to achieve the test speed before entering the acquisition range of the sensor. The adjacent lane vehicle will be placed 1/3 meter from the right lane line. The lead vehicle will be place 1/3 meter from the left lane line such that both vehicles are separated by 2/3-1 meter. See Figure 34. The subject vehicle is driven toward the in lane stationary lead vehicle at 16 m/s (35 mph). The warning range to the lead vehicle is recorded. Repeat the test multiple times. Repeat the test at 34 m/s (75 mph).

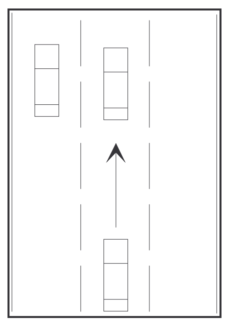

Figure 34 Adjacent Lanes Test Setup

Compare the recorded warning ranges to the standard algorithm warning ranges given above in Table 3. Average the results over the trials for each speed. Classify the system for each speed, according to conservative, moderate, aggressive, etc., as described in table 3.

7.2.4 Small Target Detection with Large Background Target

The purpose of this test is to characterize the warning generated by the FCW system when two closely spaced vehicles, one small and one large, are placed in the forward path of the lead vehicle. A motorcycle and large truck are used for this test.

The test is divided into 3 cases as shown in Figure 35.

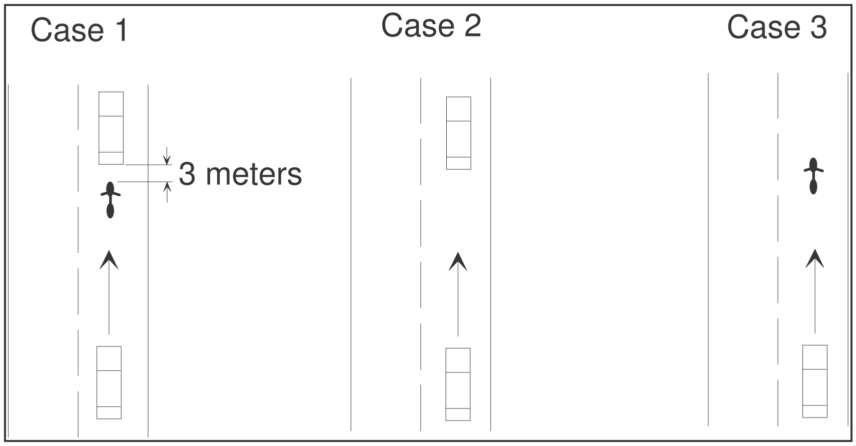

Figure 35 Small Target with Large Background Target Test Setup

Case 1: Large truck and motorcycle aligned longitudinally with the drivers line-of-sight and in-path with the system under test. The separation distance between the truck and motorcycle is set to 3 meters. The subject vehicle is placed beyond the acquisition range where the truck and/or motorcycle could be detected.

Case 2: The Motorcycle is removed leaving the larger truck aligned longitudinally with the drivers line-of-sight and in-path with the system under test. The subject vehicle is placed as in case 1.

The subject vehicle is driven toward the lead vehicles at 16 m/s (35 mph). Record the warning range and speed of the subject vehicle. Repeat multiple times to obtain a statistical sample. Repeat at 34 m/s (75 mph).

The lead vehicles are changed to the case 2 scenario. The subject vehicle is driven toward the lead vehicle at 16 m/s (35 mph). Record the warning distance and speed of the subject vehicle. Repeat multiple times to obtain a statistical sample. Repeat at 34 m/s (75 mph).

The lead vehicle setup is now changed to the case 3 scenario. The subject vehicle is driven toward the lead vehicle at 16 m/s (35 mph). Record the warning distance and speed of the subject vehicle. Repeat multiple times to obtain a statistical sample. Repeat at 34 m/s (75 mph).

Average the results over the trials for each speed and for each case. If the warning distance for case 1 is the same for case 2, then the FCW system will not provide the driver with protection under those circumstances. The warning distance for case 2 should be different from case 1 by the length of the motorcycle and the gap distance. The warning distance for case 3 should be the same for case 1.

7.2.5 Moving Lead Vehicle

The purpose of this is to repeat the warning testing with a moving lead vehicle. In this case, the lead vehicle should be moving at 5 m/s (10 mph), 16 m/s (35 mph) and 25 m/s (55 mph). The subject vehicle should approach the lead vehicle at approximately a 5 m/s (10 mph) and 10 m/s (20 mph) speed differentials on a straight roadway. The warning distance should be measured in each case. The test should be repeated multiple times at each speed and compared to the baseline algorithm.

7.3 FALSE ALARM TESTS

False alarms are warnings that occur because the FCW system does not exclude non-threatening objects as threats such as warning on roadside objects. Not only does elimination of false alarms aid user acceptance, but it also allows more intrusive driver warning display modalities to be chosen that will increase overall system effectiveness. The tests subject the FCW system to a series of driving scenarios that may produce false alarms. For each test, no collision threats are present and any warnings to the driver will be considered false. After all of the tests have been performed, the total number of false alarms for all of the tests is used to assign a false alarm rating for the FCW system.

7.3.1 Lead Vehicle Stopped

Pulling up behind a stopped lead vehicle may cause false warnings. The purpose of these tests is to determine if the system generates false alarms when out of lane vehicles are present in the system's field of view. The test consists of pulling up behind a stationary lead vehicle from various speeds and deceleration rates of 2.0 m/s^2 and 3.5 m/s^2. The driver should not coast prior to applying the brakes and a reasonable accelerator to brake transition time should be utilized. The accelerator to brake transition time could be determined by human factors testing, and is expected to be around 0.5 seconds. The lead vehicle stopped test should be performed at speeds of 5 m/s (10 mph), 16 m/s (35 mph) and 34 m/s (75 mph). The test should be repeated multiple times at each speed

7.3.2 Vehicles in Adjacent lanes

The purpose of these tests is to determine if the system generates false alarms when out of lane vehicles are present in the system's field of view.

7.3.2.1 Vehicles in the Left Lane

A stationary midsize passenger car should be placed in the left lane approximately 1/3 meter from the right most lane marker. The subject vehicle is placed in the right lane. See Figure 36. The traffic lanes should be of standard width. The subject vehicle is driven past the adjacent lane lead vehicle at 16 m/s (35 mph) and 34 m/s (75 mph). The tests at each speed should be repeated multiple times. Record any warnings as false alarms.

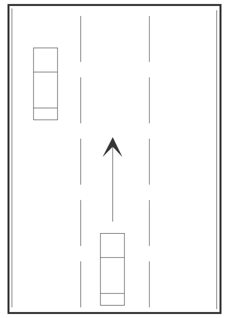

Figure 36 Adjacent Lane False Alarm Test Setup

7.3.2.2 Vehicles in the Left and Right Lanes

A stationary midsize passenger car should be place in the left lane approximately 1/3 meter from the right most lane marker and a stationary midsize passenger car should be placed in the right lane approximately 1/3 meter (1 foot) from the left most lane marker. Both vehicles should be coincident in cross range. The subject vehicle should be traveling in the middle lane. See Figure 37. The traffic lanes should be of standard width. The subject vehicle is driven past the adjacent lane vehicles at 16 m/s (35 mph) and 34 m/s (75 mph). The tests at each speed should be repeated multiple times. Record any warnings as false alarms. The test should be repeated at 16 m/s (35 mph) with a 250 meter radius curve, and at 34 m/s (75 mph) with a 950 meter radius curve. These curvatures are designed to produce a lateral acceleration of approximately 1.0 m/sec^2.

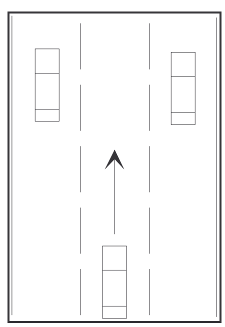

Figure 37 Adjacent Lanes False Alarm Test Setup

7.3.3 Overhead Objects

The purpose of this test is to determine if the system under test will generate false warnings on overhead objects as shown in Figure 38. The subject vehicle is driven under the objects at 16 m/s (35 mph) and 34 m/s (75 mph) The test should be conducted with a standard traffic light, overhead road sign and bridge deck as shown below. These objects should be spaced at least 200 meters apart and should be at a legal minimum height above the road surface.

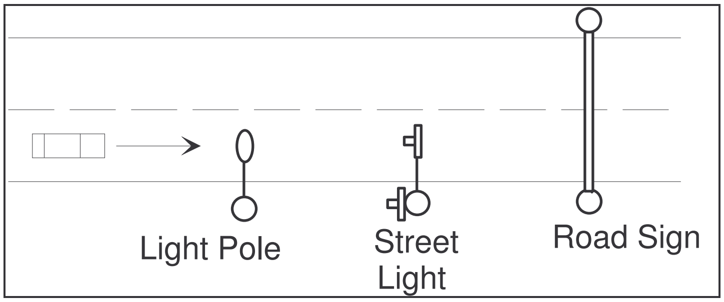

Figure 38 Overhead Objects

No warnings should be generated by any of the overhead objects. The tests at each speed should be repeated multiple times. Record any warnings as false alarms.

7.3.4 Roadside Objects - Straight Road

This test consists of a subject vehicle driving on a straight roadway at 16 m/s (35 mph) and 34 m/s (75 mph) past a variety of roadside objects shown in Figure 39. Roadside objects include light poles, trees, bushes, mailboxes, and signs. The FCW system should reject all roadside objects as threats and provide no warnings. These objects should be approximately one meter from the road edge. If available, a representative roadway can be used to perform the tests. In this case, the particular roadside objects should be tested.

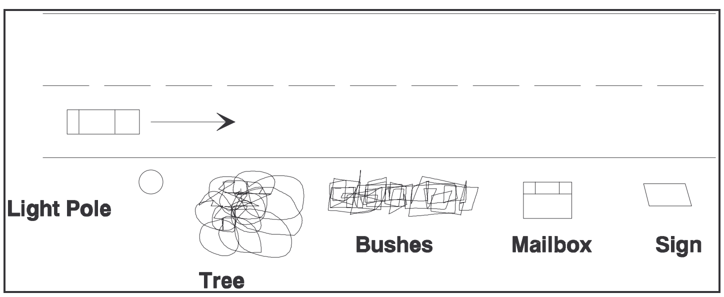

Figure 39 Straight Roadway False Alarm Setup

The tests at each speed should be repeated multiple times. Record any warnings as false alarms.

7.3.5 Roadside Objects - Curved Road

In this test, the subject vehicle is driven along a curved section of roadway that includes roadside objects. Various roadside objects including light poles, trees, bushes, guardrails, mailboxes, and signs should be along the roadside as shown in Figure 40. These objects should be approximately one meter from the road edge. The test should be performed at 16 m/s (35 mph) with a 250 meter radius curve, and at 34 m/s (75 mph) with a 950 meter radius curve. These curvatures are designed to produce a lateral acceleration of approximately 1.0 m/sec^2.

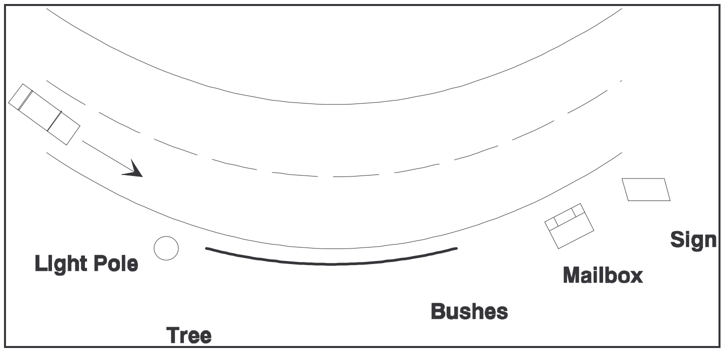

Figure 40 Curved roadway False Alarm Setup

The tests at each speed should be repeated multiple times. Record any warnings as false alarms. Each occurrence of a warning should be counted as a false alarm so multiple false alarms are possible for each test.

7.3.6 Roadside Objects - Curve Entry and Exits

This test is designed to evaluate the FCW system's ability to exclude false alarms at curve entry / exit points. This test can be performed in conjunction with the previous test. The subject vehicle should be driven on a straight section of roadway through a curve and then out to another straight section of roadway as shown in Figure 41. Roadside objects should be present at the curve entry / exit points and should include a light pole, a guardrail, a sign, trees and bushes, etc. A representative roadway with applicable roadside objects.

The roadside objects should be approximately one meter from the lane edge. Roadside objects must be present at the entry and exit points of the curve. The radius of curvature is a function of speed. The test should be performed at 16 m/s (35 mph) with a 250 meter radius curve, and at 34 m/s (75 mph) with a 950 meter radius curve. The road curvature should produce an angular change in direction of at least 70 degrees. The radius should produce a lateral acceleration of approximately 1.0 m/sec^2.

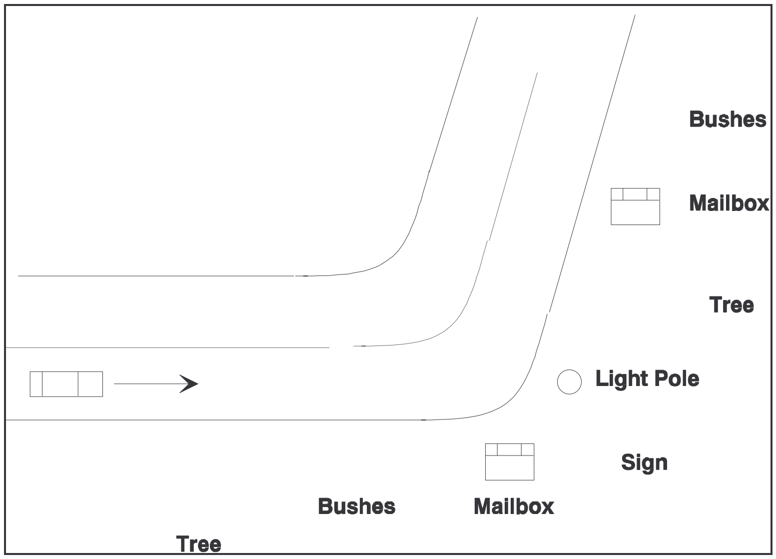

Figure 41 Curve Entry/Exit False Alarm Setup

The tests at each speed should be repeated multiple times. Record any warnings as false alarms. Each occurrence of a warning should be counted as a false alarm so multiple false alarms are possible for each test.

7.3.7 Debris in the Roadway

This test evaluates the FCW system's ability to reject debris in the roadway as a collision threat. The subject vehicle should be driven on a straight level road that has debris in the forward path. This debris should include aluminum cans (upright and horizontal), glass bottles (upright and horizontal), small cardboard boxes or milk cartons (upright and horizontal), and small tree branches (less than 1" diameter) as shown in Figure 42. This debris should be spaced at 30 meter intervals along the roadway. The FCW system should not generate false alarms on this roadway debris. This test should be performed at speeds of 16 m/s (35 mph) and 34 m/s (75 mph).

False warnings due to debris in the roadway does not prohibit an FCW system from performing its intended function. Rather it may cause a reduction in driver acceptance and an overall reduction in system effectiveness. This test is for informational purposes only.

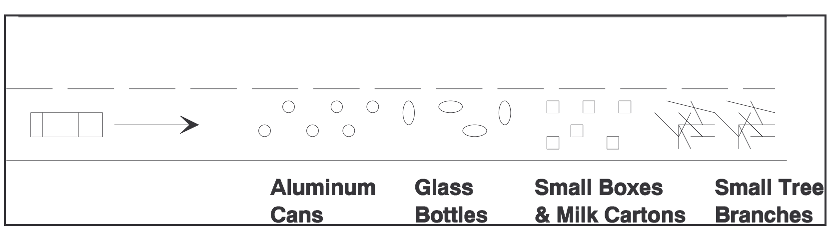

Figure 42 Debris in Roadway Setup

The tests at each speed should be repeated multiple times. Record any warnings as false alarms. Each occurrence of a warning should be counted as a false alarm so multiple false alarms are possible for each test.

7.3.8 Lane-Change / Merging / Cut-In

The ability to not provide false warnings on lane change and cut-in scenarios will be evaluated as part of this test as well as any dynamic lag that may be present under these conditions.

7.3.8.1 Lane Change

For this test, the subject vehicle will merge behind a moving lead vehicle on a straight section of roadway. The merging will occur at two points, both inside and outside the warning distance. It should be established if the FCW system under test provides a stable display for this lane change condition. The lane change itself will be performed gradually so that lateral acceleration is negligible. This test should be performed at speeds of 5 m/s (10 mph), 16 m/s (35 mph) and 34 m/s (75 mph). The test should be repeated multiple times at each speed.

7.3.8.2 Cut-In

For this test, the lead vehicle will cut-in in front of the subject vehicle on a straight section of roadway. The cut-in will occur at two points, both inside and outside the warning distance. It should be established if the FCW system under test provides a stable display for this cut-in condition. This test should be performed at speeds of 5 m/s (10 mph), 16 m/s (35 mph) and 34 m/s (75 mph). The test should be repeated multiple times at each speed.

7.3.9 Aggressive Merging

The performance of the FCW system in aggressive merging scenarios will be evaluated as part of this test. The subject vehicle will be behind a lead vehicle that is traveling 5 m/s (10 mph) slower than the subject vehicle. An adjacent lane vehicle will be place two subject vehicle car lengths behind the lead vehicle in the adjacent left lane. The subject vehicle will merge between the lead vehicle and adjacent lane vehicle. This test should be performed at speeds of 16 m/s (35 mph) and 34 m/s (75 mph). The test should be repeated multiple times at each speed.

7.3.10 Left Turn Across Path

Left turn across path represents situations in which vehicles are moving in near perpendicular directions and is a source of false alarms. This includes left turn across path and approaching cross traffic at intersections. The left turn across path should occur at or inside the warning distance. This test should be performed at speeds of 16 m/s (35 mph) and 34 m/s (75 mph). The test should be repeated multiple times at each speed.

7.3.11 Approaching Traffic

A typical FCW system can exclude approaching traffic as threats. This test evaluates the FCW system's ability to not provide false warnings on approaching traffic. The test should be executed on a curved section of roadway where the sensor is momentarily pointing directly at the on-coming traffic. This test should be performed at speeds of 5 m/s (10 mph), 16 m/s (35 mph) and 34 m/s (75 mph). The approaching vehicle should be moving at approximately the same speed as the subject vehicle. The test should be repeated multiple times at each speed.

7.3.12 Random Drive

It is difficult if not impossible to evaluate an FCW system without some long term exposure in real-world riving environments. This test is intended to allow evaluators to measure false alarms under real-world circumstances. A drive around a predetermined route that exposes the FCW to a variety of roadway and traffic situations is desirable. False alarms should be noted as well as the potential causes. The test should be performed at normal speeds and any correct warnings should be ignored. While it is impossible to exactly repeat such a test, it can nevertheless be made valid if it is long enough that any statistical aberrations are averaged out.

7.4 SITUATIONAL AWARENESS TESTS

The situational awareness tests are performed to evaluate the FCW system in coupled headway, following-too-closely (tailgating) situations. The FCW system must be equipped with a situational awareness display in order to perform these tests. The headway time rating of the system is used to establish a characterization of the system type as follows: nuisance, conservative, moderate, aggressive and dangerous. These are arbitrary categories used for evaluation and comparison. The dangerous category is defined as a situation where the vehicle is not capable of stopping at the deceleration rates required to avoid a collision. The conservative, moderate and aggressive categories were established from simulations and test performed with this algorithm. The performance limits are shown in Table 4.

Speed	Deceleration - %g's			Warning Distance - meters			Type
m/s	Sec		sec	m		m	
16	2.5	< t	-	39.11	< WD	-	Nuisance
16	1.8	<= t <	2.5	28.16	<= WD <	39.11	Conservative
16	0.7	<= t <	1.8	10.95	<= WD <	28.16	Moderate
16	0.3	<= t <	0.7	4.69	<= WD <	10.95	Aggressive
16	-	t <	0.3	-	WD <	4.69	Dangerous
34	2.5	< t	-	83.81	< WD	-	Nuisance
34	1.8	<= t <	2.5	60.35	<= WD <	83.81	Conservative
34	0.7	<= t <	1.8	23.47	<= WD <	60.35	Moderate
34	0.3	<= t <	0.7	10.06	<= WD <	23.47	Aggressive
34	-	t <	0.3	-	WD <	10.06	Dangerous

Table 4 Tailgate Warning Distance Test Criteria

The warning distances were calculated from the standard coupled headway equation shown below.

$$WD = Vf\left(0.01Vf + 0.5\right)$$

Where:

WD = Warning distance
Vf = Following or Subject Vehicle speed

7.4.1 Following-too-Closely Warning Distance on Straight Roads

This test is intended to characterize and evaluate proper performance of the FCW system in following-too-closely situations on straight roadways. The standard vehicles used are the motorcycle, midsize car and large truck.

The subject vehicle is initially positioned with a separation distance such that there is a 3.0 second headway or the FCW system is not generating warnings, which ever is greater, see Figure 43. Both vehicles are traveling at 16 m/s (35 mph). The subject vehicle then closes on the lead vehicle at a rate of 1 m/s (2 mph) until a warning is generated. The warning distance, lead and subject vehicle speeds are recorded. Repeat the test multiple times. Repeat the test at 34 m/s (75 mph).

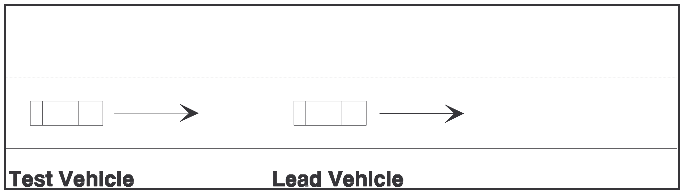

Figure 43 Tailgating Warnings on Straight Roads Test Setup

Compare the recorded warning ranges to the standard tailgating algorithm warning ranges given above in Table 4. Average the results over the trials for each speed. Classify the system accordingly for each speed.

7.4.2 Following-too-Closely Warnings on Curved Roads

This test is intended to characterize and evaluate proper performance of the FCW system in tailgating situations. The standard vehicles used are the motorcycle, midsize car and large truck.

The subject vehicle is initially positioned with a separation distance such that there is a 3.0 second headway or the FCW system is not generating warnings, which ever is greater, see Figure 44. Both vehicles are traveling at 16 m/s (35 mph). The subject vehicle then closes on the lead vehicle at a rate of 1 m/s (2 mph) until a warning is generated. The warning distance, lead and subject vehicle speeds are recorded. Repeat the test multiple times. Repeat the test at 34 m/s (75 mph).

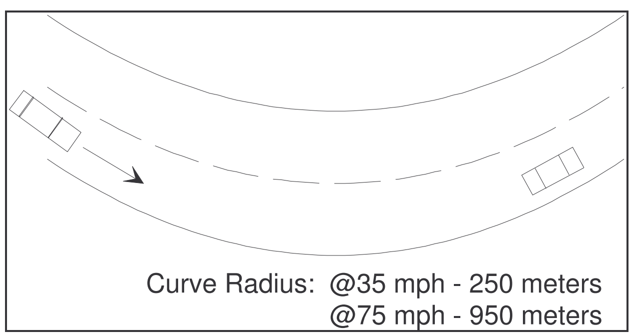

Figure 44 Tailgating Warnings on Curved Roads Test Setup

Compare the recorded warning ranges to the standard following-too-closely algorithm warning ranges given above in Table 4. Average the results over the trials for each speed. Classify the system for each speed.

7.4.3 Stop-and-Go Test - Low Speed System Operation

The stop and go test is intended to evaluate the system's situational awareness performance in stop-and-go traffic.

Drive the subject vehicle in a stop-and-go pattern such that the subject vehicle stops at intervals after attaining a maximum speed of 2 m/s (5 mph) with adjacent lane vehicles even with the subject vehicles. The spacing between vehicles should vary from 0.5 to 4 meters, see Figure 45. Record the occurrence of any warnings and the distance between the lead and subject vehicle. Repeat the test multiple times.

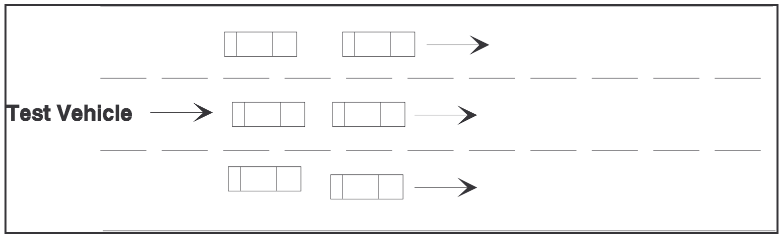

Figure 45 Stop and Go Setup

Average the results over the trials. Classify the system according to Table 4.

Low	Moderate	High
0-1	2-3	>3

Table 5 Stop & Go Traffic Nuisance Criteria, number of nuisance alarms

7.4.4 Interference and Safety

7.4.4.1 Interference from Other Collision Warning Systems

The FCW system shall not interfere with the operation of other, similar warning systems which are in the system's field of view. Compliance will be tested by simultaneously operating two identical vehicle mounted systems. An identical stationary FCW system is placed in the adjacent lane to and facing the subject vehicle. The lead vehicle is placed adjacent and even with the identical FCW system and in the same lane as the subject vehicle. The subject vehicle is placed at sufficient range so that it is out of acquisition range of the lead vehicle and up to speed prior to the identical FCW system being within the acquisition range of the subject vehicle FCW system. See Figure 46.

Both FCW systems should be on and functional. The subject vehicle approaches the stationary lead vehicle at 16 m/s (35 mph). Record the subject vehicle warning distance. Record any warnings from the identical FCW system. Repeat multiple times. Repeat the test at 34 m/s (75 mph).

Repeat the test with the identical FCW system traveling toward the subject vehicle. Record the subject vehicle warning distance. Record any warnings from the identical FCW system.

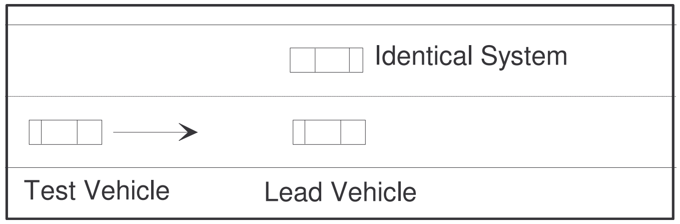

Figure 46 Interference Warning Distance Test Setup

Compare the recorded warning ranges to the standard algorithm warning ranges given above in Table 4. Average the results over the trials for each speed. Classify the system for each speed with the identical FCW system stationary and moving.

7.4.4.2 Interference from Other Sources

The FCW system should not be significantly affected by external interference sources. The FCW system shall be tested to be in compliance with all applicable interference standards and regulations. The specific standards and regulations are not listed here. The particular technology of the system under test will determine which standards and regulations shall be applied.

7.4.4.3 Safety

The FCW system shall not pose any threat to human safety. The system under test will be tested for compliance with all applicable safety standards and regulations. Any emitted energy shall be measured to be in compliance with applicable standards and regulations. Specific standards and regulations are not listed here. The particular technology of the system under test will determine which standards and regulations shall be applied.

7.5 DISPLAY TESTING

These display tests are more subjective and qualitative in nature and difficult to control. In the interest of obtaining a greater statistical sampling the test in this section should be performed by many different drivers. This data may be obtained from the system manufacturer. It is included here not so much as human factors, but to establish a clear record of driver interface issues for effectiveness determination

7.5.1 Driver Interface

In order to evaluate and compare FCW systems, it is necessary to record the unique features of the driver warning interface. This shall include the placement within the vehicle, aesthetics, and interaction with other systems in the vehicle. Record the warning modality utilized.

The drivers should answer the following questions in determining their rating:

- Is the display aesthetically pleasing?
- Does the display seem to provide reliable information?
- Does the display distract from normal driving responsibilities?
- Is the display interpretable under all conditions?
- Are the controls/displays intuitive?
- Are the controls/displays confusing?

7.5.2 Driver Response

Ideally, it would be beneficial to allow drivers to experience the warning from the FCW system. This would typically require the driver to be involved in an imminent collision situation and is considered beyond the scope of this research. The next best approach is to evaluate the driver's response to the system under normal operating conditions. This assesses nuisance and false alarms for individual drivers. To perform this test, multiple drivers would drive the system and evaluate performance qualitatively. This information could be used to compare FCW systems. The drivers shall answer the following questions in determining their rating:

The drivers should answer the following questions in determining their rating:

1. Does the FCW system provide warnings when there are no threats?
2. Were there occasions when there should have been a warning and there was none?
3. Were there noticeable delays in warning?
4. Does the FCW system effect changes in following distance?
5. Does the information provided by the FCW system seem reliable?
6. Overall rating of the FCW system?

7.6 ENVIRONMENTAL TESTING

Environmental testing should be performed to evaluate FCW system performance in representative driving environments. It may be impossible to test and evaluate the FCW system under these environments and, as a result, information from the manufacturer may be utilized.

7.6.1 Rain

Collision Warning tests, Situational Awareness tests, and False Alarm tests should be conducted in rain and road spray conditions. Data should be recorded that compares performance against the baseline. Additional testing is expected to be performed by the system manufacturer to verify system operation under rain and road spray environments. False alarms due to rain or road spray should be tabulated. Reductions in system effectiveness due to decreased sensor range or increased stopping distance are possibly acceptable. The system should provide a failure indicator to the driver if system performance degrades due to environmental conditions. High speed tests may be omitted for safety reasons.

7.6.2 Operation in Various Light Levels

Collision Warning tests, Situational Awareness tests, and False Alarm tests should be conducted in night light level conditions. Data should be recorded that compares performance against the baseline. Additional testing is expected to be performed by the system manufacturer to verify system operation under various light levels. False alarms due to light level should be eliminated.

7.6.3 Other Environments

It is the requirement of the system developer to ensure that the FCW system performs adequately under other environments such as temperature, humidity, dust, snow, ice, etc. False alarms due to other environments should be eliminated. Reductions in system effectiveness due to decreased sensor range or increased stopping distance are possibly acceptable. The benefits curves for crash mitigation versus acquisition range could be used for a cost/benefit analysis in determining if the decreased range were acceptable.

7.6.4 Summary

At this point in the evolution of FCW systems, there is no pass / fail criteria for the tests. As more is learned regarding driver acceptance and system effectiveness, pass / fail criteria can be delineated. The tests have been developed in anticipation of what the naïve driver expects from the FCW system. Systems that perform poorly in some of these tests will likely have low driver acceptance and ultimately low system effectiveness.

8 ADAPTIVE CRUISE CONTROL

8.1 INTRODUCTION

This section presents guidelines for ACC systems as they relate to FCW systems. The guidelines are operating performance parameters that should be considered as part of the system requirements. ACC systems are an extension of the conventional (speed control only) cruise control systems, found in passenger vehicles today. ACC systems track moving vehicles in the forward path and automatically maintain a safe headway. When no vehicles are present, the ACC system maintains the drivers' set speed. If the headway between the host vehicle and the lead vehicle falls below the safe headway, the ACC system initiates control actions to slow the host vehicle and reestablish a safe headway. ACC systems utilize similar technology to FCW systems and FCW systems may be considered a superset of ACC systems.

8.2 DEFINITION OF ADAPTIVE CRUISE CONTROL

ACC systems are also known as Intelligent Cruise Control (ICC) or Autonomous Intelligent Cruise Control (AICC) systems. A representative block diagram of an ACC system is shown in Figure 47. The ACC system combines a headway sensor that detects vehicles in the forward path along with a longitudinal control algorithm that automatically controls the speed of the host vehicle to either the "set" speed or to maintain a safe headway, whichever is less. Details of the overall system are described in subsequent sections.

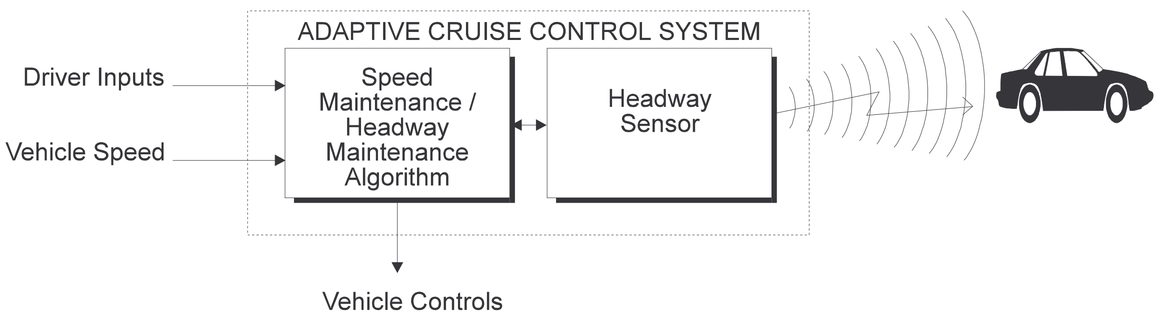

Figure 47 Adaptive Cruise Control System Block Diagram

ACC systems have been designated by system developers as convenience devices which are on-demand devices under direct supervision of the driver; moreover manufacturers typically do not consider ACC as a safety system. This notion of ACC systems as only a convenience feature is acceptable as long as the resultant extended system of ACC and driver does not promote the occurrence of rear-end collisions. ACC systems may provide an opportunity to introduce technology similar to FCW systems, and may aid the deployment of forward-looking, rear-end collision warning systems.

8.3 MENTAL MODEL

The mental model refers to the system performance that would reasonably be anticipated by a naïve (untrained) driver of the ACC system. Drivers would reasonably expect an ACC system to provide smooth longitudinal control of the host vehicle. This includes accelerations, decelerations, and following distances similar to the preferences of the typical driver.

8.4 SYSTEM GUIDELINES

The system guidelines are those guidelines that are key to bounding the overall system operating environment. ACC systems can be bounded, in general, by acquisition range, approach speed, deceleration authority, acceleration authority, curve performance and warning requirement.

8.4.1 ACC versus Conventional Cruise Control

There is a large population of drivers familiar with conventional cruise control found in passenger vehicles today and it is likely that the drivers' expectations for ACC systems will be based on their knowledge of conventional cruise control. As a result, ACC systems should be an extension of conventional cruise control in interface and functionality.

8.4.2 Operating Modes

While the ACC system has two internal modes, a headway maintenance mode and a speed maintenance mode, the transitions between the two modes are made automatically. It is believed that the automatic transition between modes increases the safety of the system. It is recommended that the ACC system not provide a speed maintenance only (conventional cruise control) mode. If the headway function were allowed to be disabled, the driver may turn it off, either accidentally or intentionally, and fail to turn it back on. This could create a situation where the driver incorrectly thinks that the headway separation is turned on and could potentially cause the host vehicle to collide with vehicles in the forward path. It should be noted that a person that routinely drives, and is comfortable with, an ACC equipped vehicle and then transitions to a non-ACC equipped vehicle may have problems due to the "negative transfer of training" from one vehicle to another. This has the potential to lead to collisions where the driver of the non-ACC equipped vehicle expects the headway to be maintained to vehicles in the forward path.

8.4.3 Slowly Moving and Stationary Vehicles

ACC systems studied to date have generally ignored slowly moving and stationary objects in order to provide smooth longitudinal control of the host vehicle and to eliminate nuisance alarms due to roadside objects that are difficult for a basic system to identify and classify. Vehicles in the forward path that are slowly moving or stopped and the response of naïve drivers to the operation of an ACC system faced with such objects could lead to a safety problem[48]. Therefore, while the longitudinal control of the ACC vehicle may require eliminating such objects, it may be necessary for the driver to be alerted when stopped or slowly moving vehicles are in the forward path. In this context, a driver alert is used to denote when the ACC system has reached the limits of its control authority, whereas a warning is for potential collisions.

[48] Ervin, B., UMTRI, "Adaptive Cruise Control Deployment and Operational Performance Issues", ITS America Eighth Annual Meeting, May 1998.

8.4.4 Acquisition Range, Deceleration Authority, and Approach Speed

The acquisition range is defined as the maximum sensor range at which the vehicle in the forward path can be reliably detected while allowing for system operation. Proper system operation requires accounting for system processing delay, system deceleration authority, the relative speed between the vehicles, and the selected headway. Upper and lower limits in acquisition range must take into account the amount of control authority that the ACC system has as well as upper and lower set speed boundaries. Under normal driving conditions, the ACC system requires an acquisition range on the order of 70 meters (assuming 0.1 g deceleration, 0.5 seconds delay, and a 11 m/s (25 mph) approach speed). However, this acquisition range does not provide the driver adequate protection for lead vehicles that are stopped or moving slowly. In order to accommodate stopped and slow moving lead vehicles, the ACC system may require an acquisition range that is equivalent to the recommended FCW system acquisition range of 130 meters.

Deceleration authority is the ACC system's ability to slow the host vehicle to maintain a safe headway, or to react to changes in lead vehicle deceleration. Approach speed is the speed differential between the ACC equipped vehicle and the vehicle in the forward path.

ACC systems require deceleration authority to maintain headway to a lead vehicle. This is accomplished in a number of ways: First, by allowing the host vehicle to "coast", using engine braking. Dependent on vehicle type, weight, tires, road friction, wind resistance, etc., coasting provides a deceleration varying between approximately 0.01 and 0.1 g's. Second, by allowing the ACC system to down-shift the transmission, deceleration between approximately 0.05 and 0.15 g's can be obtained dependent on vehicle type, gear ratio, etc. Third, by allowing the ACC system active control of vehicle braking, decelerations up to the braking limit of the host vehicle can be obtained.

Figure 48 shows a graph of ACC system acquisition range (vertical axis) versus ACC system deceleration authority (horizontal axis) required for various approach speeds. The acquisition range is calculated using the following formula:

$$AR = \frac{(v_s - v_l)^2}{2 * \alpha} + (v_s - v_l)t_d + v_l(v_l t_{sl} + t_{so})$$

where

AR = Acquisition Range (meters)
v_s = Subject vehicle speed (m/s)
v_l = Lead vehicle speed (m/s)
α = ACC system deceleration (m/s²)
t_d = System delay (seconds) assumed to be on the order of 0.3 seconds
t_{sl} = Slope of standoff time as a function of speed on the order of 0.01 (s²/m)
t_{so} = Minimum standoff headway time (seconds) on the order of 0.5 seconds

It should be noted that acquisition range as shown in this figure is based on a simplistic control algorithm. It is assumed that the full level of deceleration authority is used at once, rather than a more gradual climb to the full level of deceleration to allow for comfort. The gradual onset of deceleration would require increased acquisition range. The range is based on a minimum standoff time on the order of 0.5 seconds, when a value of 1.0 seconds might be more appropriate for a driver-selected value of headway, to allow for a conservative estimation of acceleration range.

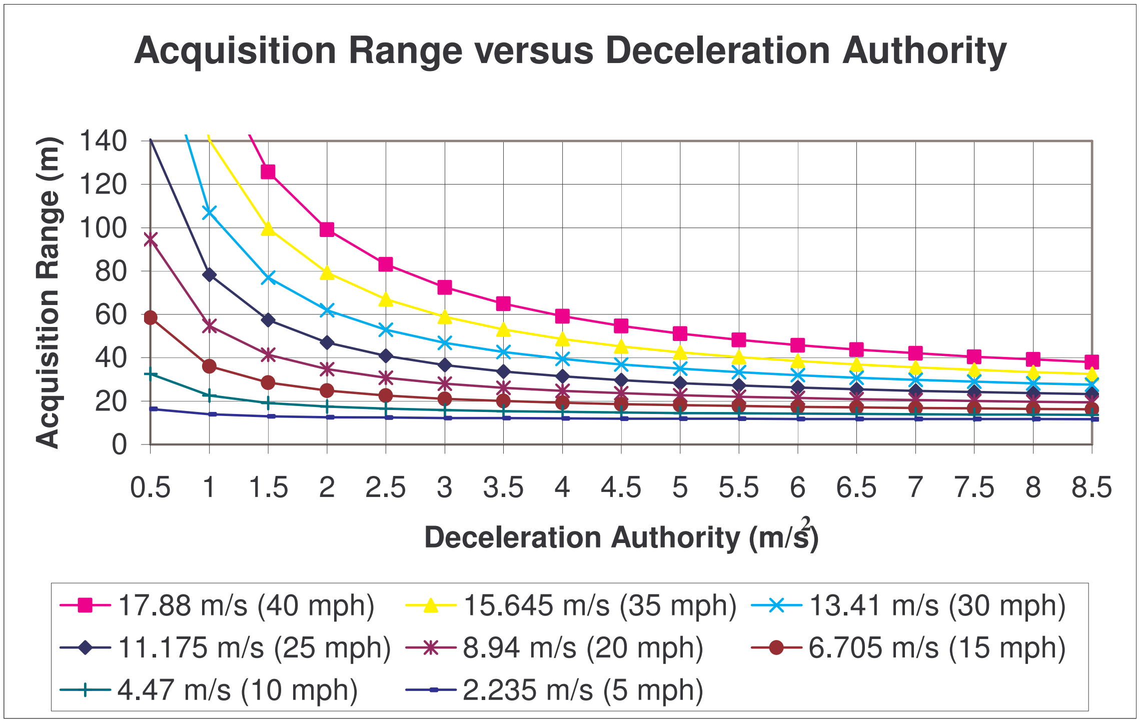

Figure 48 Acquisition Range versus Deceleration Authority

As an example of interpreting this figure, an ACC system with 2 m/s² of deceleration authority and an acquisition range of 100 meters can handle closing velocities in excess of 17 m/s. Typical 5th-95th percentile approach speeds for rural interstates are 11 m/s (25 mph)[49].

It should be noted that acquisition ranges that are too short may not provide enough control and warning time. While, deceleration authorities that are too high may startle or be uncomfortable for the driver. Although Figure 48 shows deceleration authorities of 0.5 – 8.5 m/s², it is believed that an appropriate range for ACC is 0.5 – 2.0 m/s². The deceleration authority however, must take into account lane change, merge and cut-in scenarios where a vehicle may be in relatively close proximity to the subject vehicle.

[49] A policy on Geometric Design of Highways and Streets, AASHTO, 1994

8.4.5 Performance on Curves

ACC systems are required to detect, acquire, track, and maintain headway to vehicles in the forward path on curves. A significant operational problem with curves is the tendency for a basic ACC system to not exclude adjacent lane vehicles. The tracking of an adjacent lane vehicle on a curve in the absence of a legitimate in-lane lead vehicle is a nuisance to the driver but does not necessarily render the ACC system incapable of performing its task. To increase user acceptance of these types of systems, the ACC system should identify adjacent lane vehicles and not provide any control response to the host vehicle.

8.4.6 Driver Alerts

As previously stated a driver may not operate the vehicle appropriately in all situations that the ACC system encounters (e.g., when stopped or slowly moving vehicles are in the forward path) unless the ACC system can provide some type of alert to the driver for those scenarios that exceed the ACC system's deceleration authority. If no driver alert is issued, even attentive drivers may hesitate momentarily while they determine if the system has the capability to correct the situation. The alert needs to be separate and unique from any warning associated with normal ACC system operation.

8.4.7 Headway

For the purposes of this document, headway time is defined as the range between the host and lead vehicles divided by the absolute speed of the lead vehicle. A minimum headway time needs to be established by the system developers and the system should not be adjustable below the minimum headway time. If the ACC system allows the driver to select the headway times, it is desirable that additional headway times beyond the minimum be available for safety and convenience. ACC headway times may need to be greater than the warning times used for FCW applications to compensate for the fact that the driver has given up longitudinal control to the system and requires more time to take back control from the ACC system.

8.4.8 Acceleration Limit

The ACC system controls both the deceleration and acceleration of the host vehicle. There may be significant acceleration by the ACC system, typically when the host vehicle resumes the set speed after maintaining headway on a slower moving lead vehicle. A reasonable limit on the acceleration of the host vehicle should be established (1.0-1.5 mph/s)[50]. If the ACC system loses track of a lead vehicle due to roadway curvature, or to allow other traffic to merge, then it may be desirable to limit the positive acceleration of the ACC system until the system can determine that the roadway ahead is clear. This is to prevent acceleration by the ACC equipped vehicle toward a vehicle that is not out of path, but rather is out of the forward field of regard. It may be better for user acceptance to limit or delay significant positive accelerations under all scenarios.

[50] On-Road Investigation of Driver Preferences for Automatic Acceleration Levels for an Adaptive Cruise Control (ACC) System. NHTSA Contract Number DTNH22-94-H-27016, December 1997.

8.4.9 Vehicle Types

The requirements on the type of vehicles that must be detected and tracked by the ACC system should be the same as the FCW system requirements. The driver would reasonably expect that the ACC system operate on any vehicle that can maintain highway, or near highway speeds. This includes some possibly small cross section vehicles such as motorcycles. The naïve driver will expect all moving vehicles that may be in the forward path to be detected and tracked by the ACC system.

8.5 DRIVER DISPLAYS

Standard driver displays are desirable to prevent confusion by the driver when using systems from different manufacturers.

8.5.1 ACC Icon

As with FCW systems, to aid in reinforcing of the driver's mental model and to identify vehicles equipped with ACC systems, some type of standardized symbolic icon is recommended. One particular note is that the acronym "ACC" is already associated with "Accessories" in vehicles so ICC may be considered. The ACC icon should be separate and unique from the FCW icon unless it is determined that an ACC system requires an FCW system.

Initial exposure to ACC systems will be unique for drivers not familiar with the technology. It is expected that a "standard" associated icon can assist driver's curiosity toward ACC systems by identifying those vehicles properly equipped.

Additionally there is the consideration that drivers, through force of habit, will expect any system to behave like their system. This implies that drivers who own ACC systems will rely on it and may become victims of this habit when operating a vehicle not equipped with ACC. The Icon and display will serve as necessary indications of the performance that the driver may expect from an unfamiliar vehicle, see section 8.6.1.

8.5.2 Set Speed Indication

As an aid to the driver in understanding the ACC system it may be desirable to provide an indication of the current set speed of the ACC system. A display of the set speed would be beneficial to drivers not familiar with ACC technology and would assist these drivers in system operation. The set speed indication may be necessary for those vehicles that have very aggressive acceleration associated with ACC system performance to remind the driver of the speed that will be resumed following operation in the headway maintenance mode.

8.5.3 Headway Maintenance Mode Indication

As an aid to the driver in understanding and verifying ACC system operation, it may be desirable to provide an indication of vehicles in the forward path. This indication tells the driver that the system is operating correctly and is currently tracking a vehicle in the forward path.

8.5.4 Driver Alert Display

As previously stated ACC systems may require the ability to issue an alert to the driver regarding stopped or very slow moving vehicles in the forward path or when the ACC system exceeds its control authority. The alert needs to be separate and unique from any warning associated with normal ACC system operation. Any collision warning should follow the FCW performance guidelines.

8.5.5 Brake Light Illumination

As a means of providing braking and deceleration cues to following drivers, if the ACC system employs active braking or downshifting to maintain headway, then the brake lights should be illuminated during deceleration.

8.5.6 Fault Indication

The ACC system should provide feedback to the driver for fault indications. Fault indications could range from system or subsystem failure to degradation in the sensor that causes inoperability.

8.6 DRIVER CONTROLS

Standard driver controls shall be used to avoid confusing the driver when using systems from different manufacturers. A system flow diagram is shown in Figure 49.

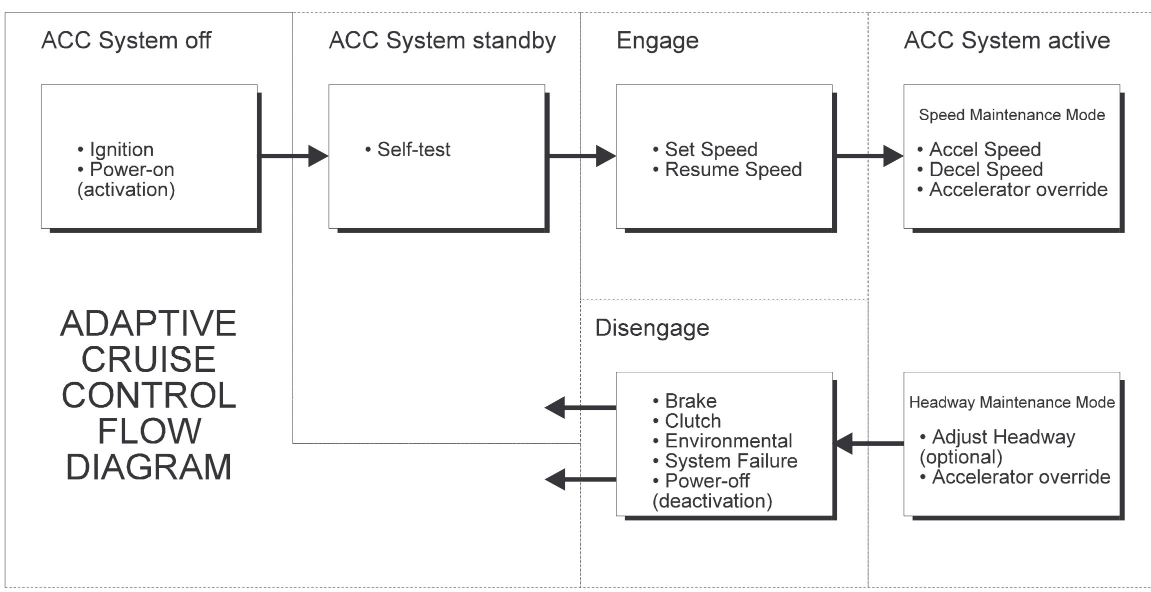

Figure 49 Adaptive Cruise Control Flow Diagram

8.6.1 Power-On Activation

Unlike forward-looking collision warning systems that must activate with the ignition, adaptive cruise control systems can use a secondary switch to be turned on and off by the driver. Power-on activation applies power to the ACC system and causes the ACC system to perform any power-on diagnostics. Power-on activation places the ACC system into a standby mode from which the system can be engaged into ACC mode. Conventional cruise control typically provides an ON switch with or without an indication of system activation. Because of the longitudinal control authority (acceleration and deceleration) it is recommended that ACC systems provide an indication of system activation.

8.6.2 Power-Off Deactivation

A method for power-off deactivation of the ACC system should be provided. This power-off activation can be through the ignition or a secondary switch as with conventional cruise control. Power-off deactivation removes power from the ACC system and causes the ACC to disengage and power down from either the standby or ACC modes.

8.6.3 Set Speed / System Engage

When the ACC system is engaged and no vehicles are present in the forward path, the host vehicle automatically maintains the set speed. The ACC system should provide the driver a means to select the set speed. The preferred method for selecting the set speed is to use the vehicle speed at the time of the setting, care should be taken if some other means is used.

8.6.3.1 Minimum Set Speed

There may be a set speed below which the driver is unable to engage the ACC system. This minimum set speed may cause the ACC system to disengage if the driver commands the set speed below this value. If the headway is less than the minimum and the driver attempts to engage the system, the system can engage, engage and provide an alert, or simply not engage.

How the ACC system responds while in the headway maintenance mode and the lead vehicle decelerates below the minimum speed is dependent upon ACC system control strategy, assuming that the driver does not intervene prior to the vehicle going below the minimum speed. First, the ACC system may simply disengage. However if active braking is being employed disengaging the system may cause a positive acceleration toward the lead vehicle, putting the driver at risk of a collision. Second, the ACC system may continue to maintain the selected headway even as the lead vehicle decelerates to a stop. In any of these scenarios, an alert would inform the driver that the system has reached a boundary where it will no longer function. Problems may arise if the driver expects the ACC system to maintain headway to a stop and it cannot, or if systems developed by different manufacturers vary significantly in the minimum speed. These guidelines favor issuing some type of an alert at a speed typical of the minimum engagement speed for conventional cruise control, say 15 m/s. This allows the ACC system to be simpler but maximizes protection to the driver. Additional research is necessary to determine typical driver response to these issues.

8.6.3.2 Maximum Set Speed

The ACC system may need a maximum allowable set speed to prevent drivers from driving beyond the capability of the ACC system. The maximum set speed is dependent upon the vehicle platform and the ACC system design and is left to the system developer.

8.6.4 System Disengage

Various methods can cause the ACC system to disengage from the ACC mode to the standby mode.

The ACC system may disengage when the driver activates the brake as with conventional cruise control systems currently deployed in the U.S. If the ACC system employs active braking to maintain headway, then any active braking should not interfere with the driver providing additional braking.

The ACC system may disengage when the driver activates the clutch pedal (manual transmission systems only). In other words, the ACC system must be compatible with the vehicle on which it is installed and operating.

The ACC system may disengage when a fault is detected in the proper operation of the ACC system. This includes disengaging the ACC system when the sensor subsystem can no longer reliably detect vehicles in the forward path due to atmospheric (rain, sleet, snow, etc.) or roadway (road spray) conditions. If the ACC system is controlling the headway through active braking, then it may be necessary for the ACC system to continue braking until driver intervention is detected. From a human factors standpoint, it is desirable that the driver be given an indication of the fault condition. The fault condition should be unique to the failure mode of the ACC system.

The ACC system may need to disengage if the driver is in the speed maintenance mode and commands the set speed below the minimum set speed. The ACC system may also need to disengage if the ACC system drops below the minimum set speed while in the headway maintenance mode. However if active braking is being employed disengaging the system may cause a positive acceleration toward the lead vehicle, putting the driver at risk of a collision. It may be necessary to require the ACC system to continue to decelerate until the driver intervenes.

8.6.5 Set Speed Increase Command

As with conventional cruise control, the ACC system may provide the driver the ability to increase the set speed. If the subject vehicle is in the headway maintenance mode then commands to increase the set speed will not change the headway. This may necessitate an indication to the driver of the current speed setting for the ACC system independent of the speedometer.

8.6.6 Set Speed Decrease Command

As with conventional cruise control, the ACC system may provide the driver the ability to decrease the set speed. If the host vehicle is in the speed maintenance mode, then commands to the set speed decelerate will incrementally decrease the speed down to the minimum speed setting. At the minimum speed setting the ACC system may disengage. If the subject vehicle is in the headway maintenance mode and is employing active braking to maintain headway on the lead vehicle then commands to decrease the set speed below the minimum set speed should not cause the system to disengage, however a warning or dialog may be appropriate.

8.6.7 Accelerator Override

In order to maintain compatibility with the naïve drivers' mental model, it may be necessary to provide the capability for the driver to override the accelerator while the ACC system is operating. Conventional cruise control systems currently allow this option, and unless compelling reasons can be given to show that drivers will not expect this to be the case with ACC systems it should remain similar in order to avoid possible safety issues.

If the ACC system employs active braking to maintain headway, then accelerator override may need to inhibit active deceleration. It may also be necessary to inhibit collision warnings to the driver if this condition occurs. It may be possible to disengage the ACC system if this condition occurs, but this may be considered a nuisance to the driver since conventional cruise control systems do not function in this manner.

8.6.8 Braking Override

ACC systems that employ active braking to maintain headway must not decrease the capability and response for driver override.

8.6.9 Headway Adjustment

A minimum headway time needs to be established by the system developers and regulators and no ACC systems should be adjustable below the minimum headway time. The intent of the headway adjustment is to allow drivers of differing abilities and comfort levels to adjust the headway between the subject and lead vehicles.

The headway adjustment time may need to return to a nominal value each time the system is powered off to prevent drivers with conservative abilities from using aggressive headway times, although it may be considered a nuisance by the driver if they must reset the headway setting to their preferred value every time the system is started.

8.7 CONCLUSION

There is a large population of US drivers familiar with conventional cruise control; therefore ACC systems should be an extension of these systems. Drivers must under all circumstances be able to override the system with the accelerator and brake pedal. There should be automatic transition between the speed and headway maintenance modes. Slow and stopped lead vehicles must be accommodated. Warnings and alerts should occur when the longitudinal authority of the ACC system is exceeded or is going to be exceeded. An identifying icon or display must alert the driver to the presence of an ACC system (rather than a conventional cruise control) so that the driver may anticipate either the relinquishing of speed control to the ACC or perhaps more importantly the need for individual control in the absence of ACC. The ACC may ideally be deployed as a subset of an FCW system and as an aid to deployment of both systems.

Two issues are extremely important to consider regarding the deployment of ACC systems. First, does the ACC system have the potential to increase the likelihood of rear-end collisions through promotion of driver inattention, or by potentially placing the driver in collision situations due to limitations in the design of the ACC system (such as stopped object detection)? Second, can ACC systems being developed for mass-market deployment support future FCW functions?

9 SUMMARY

The need for a forward-looking collision warning system is based on driver inattention and following-too-closely. Therefore, the guidelines presented herein recommend an inattentive driver warning system that warns the driver of potential rear-end collision situations and a following-too-closely warning system that provides situational awareness to the driver for coupled headway situations.

Testing, modeling, surveys, simulations and statistics have been employed to determine the range of “best” values for FCW systems. The guidelines presented represent a minimum performance level for mass marketed FCW systems. The driver warning algorithm presented is considered a starting point (baseline) for the development of a real-world system. The work on this program did not have access to the normative driver data necessary to determine a complete driver warning algorithm.

The key to driver acceptance of a forward-looking, rear-end collision warning system may be not when to warn the driver, but when not to warn the driver. In order for the system to reduce collisions it must be deployed, and in order to be bought and used it will have to maximize warnings of potentially dangerous conditions while truly minimizing the occurrence of nuisance alarms (this includes both false alarms and nuisance alarms from the drivers’ perspective).

This document provides guidelines for performance related issues of a forward-looking collision warning system. The driving environment is extremely complex and a competent FCW system must be capable of eliminating false alarms to the driver. If false alarms are eliminated under all driving scenarios, then nuisance alarms can be managed through system adaptation and driver warning display modality configuration. The guidelines discussed within this document relate to a minimum acceptable mass marketed FCW system for passenger vehicles and light trucks. Other advanced features may be necessary to fully satisfy the naïve driver’s expectations.

As long as there are no perceived limitations by the driver then the FCW system might be significantly scaled back, for cost or other reasons. This would include, only warning the driver on vehicles that are directly in the forward path, no cut-in / lane change / merge warnings, and no curve performance (which equates to a reduction in effectiveness for curved roadways). All of this hinges on the ability to preprocess the sensor inputs and completely remove false alarms. This is the burden of the system developer.

These guidelines also anticipate that the forward-looking collision warning system is closely related to an Adaptive Cruise Control system.

10 CONCLUSION

These guidelines support a forward-looking collision warning system that is intended to warn the driver to avoid a collision with the rear-end of vehicles in the forward path. These guidelines were developed to include all manner of driving environment, all vehicular speeds and vehicular encounters. These guidelines show that false alarms are the greatest impediment to deployment of an FCW system. Nuisance alarms are manageable, but may require an added level of sophistication over systems being developed today.

It should be noted that this report is based on an initial system level study of FCW. System elements that were addressed were sensor systems, collision warning algorithms, and the driver warning/display interface. Other areas covered by this study included user acceptance and system benefits. While much was learned during the course of this study, including that a FCW system is technically feasible, the project did not include real-world driving of FCW systems. Many complex issues associated with FCW systems need further study and refinement prior to the deployment of systems.

Some of the results of this program are:

- Forward-Looking Collision Warning is technically achievable
- The end user (driver) with ultimately define the success or failure of FCW systems. Systems must be developed to the extended system
- The three primary FCW system issues are performance, cost & reliability. Each of these must be evaluated in light of the end user (driver).
- False alarms are the primary technical issue, and must be eliminated for user acceptance
- Lost time must be managed by the resultant driver warning algorithm to reduce nuisance alarms
- Scene processing is necessary for the system to perform the task. The key to scene processing is high angular and range resolution
- The testbed performs at a level acceptable for FCW
- In order to make the remaining decisions regarding FCW system issues, it will be necessary to gather information on the "science of driving". This normative driver behavior is necessary to make further progress to development of an acceptable warning algorithm methodology.

There appears to be some safety related issues with the introduction of ACC systems. It is unknown what risks ACC systems present to the naïve driver, but recent research has shown a high percentage of improper understanding regarding system operation[51]. Although ACC systems are marketed as convenience devices with no inherent safety features, the studies suggest that ACC systems could be unsafe leading to an overall increase in collisions. As a result, FCW may be required to play a more important role in ACC development and deployment.

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[51] Ervin, B., UMTRI, "Adaptive Cruise Control Deployment and Operational Performance Issues", ITS America Eighth Annual Meeting, May 1998.

ACC systems are considered an aid to FCW deployment through introduction of the technology, cost, market penetration, etc. However, it is often overlooked that ACC system design may be so short sighted, that deployed ACC systems cannot support FCW. This is a concern especially when the underlying goal is the deployment of FCW systems.

These guidelines stand as a conclusion to volumes of research into the requirements for FCW systems. Many complex issues remain to be resolved prior to deployment of acceptable systems.