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Light Vehicle Crash Avoidance Needs and Countermeasure Profiles for Safety Applications Based on Vehicle-to-Vehicle Communications

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13. ABSTRACT This report discusses light-vehicle crash countermeasure profiles and functions for five target pre-crash scenario groups based on vehicle-to-vehicle (V2V) communications. Target pre-crash scenario groups include rear-end, lane change, opposite direction, junction crossing, and left turn across path from opposite direction (LTAP/OD) crashes involving at least one light vehicle (e.g., passenger car, van, minivan, sport utility vehicle, or light pickup truck with a gross vehicle weight rating of 10,000 pounds or less). There are 10 pre-crash scenarios in these groups to be addressed by V2V-based crash countermeasures. Kinematic equations are presented for the time-to-collision and avoidance maneuvers to identify information needs for these crash countermeasures. Information needs are translated into countermeasure functional requirements based on relevant safety applications devised in two prior research projects dealing with cooperative V2V communications and autonomous vehicle-based sensing systems. This report identifies two target pre-crash scenarios that would require new safety applications not developed in prior projects, including the LTAP/OD and “opposite direction/no vehicle maneuver” pre-crash scenarios.			
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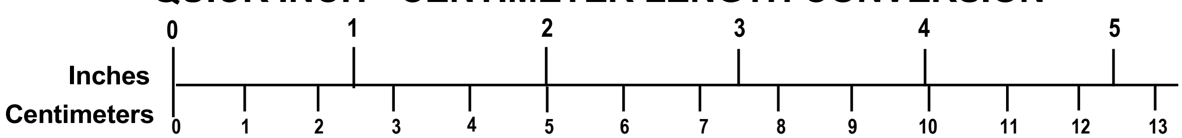


Table of Contents

EXECUTIVE SUMMARY vii
1. INTRODUCTION 1
2. SCENARIO DEPICTIONS AND COUNTERMEASURE FUNCTIONAL NEEDS 5
3. COUNTERMEASURE KINEMATIC PROFILES 7
3.1. Rear-End Pre-Crash Scenario Group 8
3.1.1. Lead Vehicle Stopped 8
3.1.2. Lead Vehicle Decelerating 10
3.1.3. Lead Vehicle Moving at Slower Constant Speed 12
3.1.4. Information Needs for Rear-End Crash Countermeasures 14
3.2. Lane Change Pre-Crash Scenario Group 15
3.2.1. Changing Lanes/Both Vehicles Traveling in Same Direction 15
3.2.2. Turning/Both Vehicles Traveling in Same Direction 16
3.2.3. Drifting/Both Vehicles Traveling in Same Direction 16
3.2.4. Information Needs for Lane Change Crash Countermeasures 17
3.3. Opposite Direction Pre-Crash Scenario Group 17
3.3.1. Opposite Direction/No Vehicle Maneuver 17
3.3.2. Opposite Direction/Vehicle Making a Maneuver 18
3.3.3. Information Needs for Opposite Direction Crash Countermeasures 19
3.4. LTAP/OD Pre-Crash Scenario Group 19
3.4.1. LTAP/OD Pre-Crash Scenario Avoidance Profile 19
3.4.2. Information Needs for LTAP/OD Crash Countermeasures 22
3.5. Junction Crossing Pre-Crash Scenario Group 23
3.5.1. Straight Crossing Paths at Non-Signalized Junctions 23
3.5.2. Information Needs for Junction Crossing Crash Countermeasures 25
4. COUNTERMEASURE FUNCTIONAL REQUIREMENTS 26
4.1. Information Needs for Pre-Crash Scenario Group Countermeasures 26
4.2. Functional and Performance Requirements of V2V-Based Safety Applications 27
4.2.1. VSC-A Safety Applications 27
4.2.2. IVBSS Safety Applications 27
4.2.3. Functional Requirements Based on VSC-A and IVBSS Safety Applications 28
4.2.4. Performance Requirements Based on VSC-A Safety Applications 30
4.3. Comprehensive Target Pre-Crash Scenario Countermeasures 32
5. CONCLUSIONS 35
6. REFERENCES 36

List of Figures

Figure 1. Overview of Selection of 10 Priority Light-Vehicle Pre-Crash Scenarios.......................4
Figure 2. Minimum Stopping Distance by Travel Speed and Braking Level in Rear-End/LVS Pre-Crash Scenario 10
Figure 3. Minimum Stopping Distance by Closing Speed and Braking Level in Rear-End/LVM Pre-Crash Scenario 14
Figure 4. Critical SCP Ranges for Selected Travel Speeds 25

List of Tables

Table 1. Societal Harm of Target Pre-Crash Scenario Groups..2
Table 2. Countermeasure Functional Needs Matrix 6
Table 3. Minimum Stopping Distance (ft) by Initial Velocity and Braking Level..........................9
Table 4. Rear-End/LVM Critical Range (ft) by Closing Speed and Braking Level......................13
Table 5. SCP Critical Range (ft)...24
Table 6. Pre-Crash Scenario Group Information Needs 26
Table 7. Performance Requirements of VSC-A Safety Applications..31
Table 8. VSC-A Safety Applications Mapped to Target Pre-Crash Scenarios..............................32
Table 9. Functional Requirements Pre-Crash Scenario Groups 33
Table 10. Vehicle Detection by Pre-Crash Scenario Groups...34

List of Acronyms

BSW	Blind Spot Warning
CAMP	Crash Avoidance Metrics Partnership
CDS	Crashworthiness Data System
DNPW	Do Not Pass Warning
EDR	Event Data Recorder
EEBL	Emergency Electronic Brake Light
FCW	Forward Collision Warning
GES	General Estimates System
IMA	Intersection Movement Assist
ITS	Intelligent Transportation System
IVBSS	Integrated Vehicle-Based Safety System
LCW	Lane Change Warning
LTAP/OD	Left Turn Across Path/Opposite Direction
LVA	Lead Vehicle Accelerating
LVD	Lead Vehicle Decelerating
LVM	Lead Vehicle Moving at slower constant speed
LVS	Lead Vehicle Stopped
MAIS	Maximum Abbreviated Injury Scale
NMVCCS	National Motor Vehicle Crash Causation Survey
SCP	Straight Crossing Paths
TCD	Traffic Control Device
ttc	Time-To-Collision
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VSC-A	Vehicle Safety Communications – Applications

List of Kinematic Equation Symbols

$\mathbf{A_i}$	Acceleration of vehicle i (1 = subject, 2 = other)
$\mathbf{D_0}$	Longitudinal gap between subject and host vehicles
$\mathbf{D_i}$	Initial distance of vehicle i from intersection
$\mathbf{L_i}$	Length of vehicle i
$\mathbf{S_0}$	Initial lateral gap between subject and host vehicles
$\mathbf{t_D}$	Summation of delays throughout countermeasures
$\mathbf{t_{signal}}$	Duration of signal before initiating turn
ttc	Time-to-collision
$\mathbf{V_i}$	Initial velocity of vehicle i
$\mathbf{W_i}$	Width of vehicle i
$\mathbf{Y}$	Lane width
$\boldsymbol{\alpha}$	Initial lateral acceleration of lane change maneuver
$\boldsymbol{\lambda_i}$	Initial distance from road centerline to edge of vehicle i
$\boldsymbol{\omega_i}$	Frequency of lane change maneuver of vehicle i
$\boldsymbol{\theta}$	Vehicle yaw angle
$\boldsymbol{\delta_i}$	Braking distance

EXECUTIVE SUMMARY

This report presents the results from the ongoing analysis in support of the U.S. Department of Transportation's Intelligent Transportation System initiative aimed at developing safety applications to increase situational awareness and reduce or eliminate crashes through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure communications. Specifically, this analysis covers Track 1 activities of the V2V research plan for the light-vehicle platform (e.g., passenger car, van, minivan, sport utility vehicle, or light pickup truck with a gross vehicle weight rating of 10,000 pounds or less). This research track establishes a key scenario framework by which the crash problem can be further defined and new crash avoidance capabilities identified and described. The framework connects pre-crash scenarios to crash avoidance safety applications and provides information that will enable the identification of safety application functions, performance, and initial effectiveness benchmarks.

This report identifies crash avoidance needs and countermeasure functional requirements for five pre-crash scenario groups of multiple-vehicle crashes that involve at least one light vehicle. The five groups include rear-end, lane change, opposite direction, left-turn-across-path/opposite direction (LTAP/OD), and junction crossing pre-crash scenarios. The last group encompasses straight crossing paths, turning left or right across the path or into the path of another vehicle approaching the junction from a perpendicular left or right direction. Overall, the five pre-crash scenario groups contribute to about 1,259,000 functional years lost and 180 billion dollars in comprehensive costs annually based on police-reported crashes involving at least one person with a Maximum Abbreviated Injury Scale (MAIS) level of one or more.

Crash avoidance needs for the V2V-based countermeasures are derived from kinematic equations that represent the time-to-collision and suitable avoidance maneuver for each target pre-crash scenario. These equations incorporate key parameters that the countermeasures must measure in order to decide on whether a crash is imminent in a specific scenario and to determine when to assist the driver. The list of parameters consists of, but not limited to, relative position and range rate between two principal vehicles, longitudinal and lateral accelerations, yaw rate, heading, velocity, vehicle size, location, and lane position. Countermeasures must also recognize driver intent to change lanes, merge, pass, turn left, turn right, or cross a junction. Based on this information, some equations are exercised using selected kinematic data from real world crash data to obtain estimates of the required communication range for the different safety applications. This type of analysis would help to establish minimum performance requirements for the various V2V-based safety applications.

This report also discusses the high-level functions that the countermeasures must perform to effectively prevent or reduce the severity of crashes belonging to the five pre-crash scenario groups. These countermeasure functions are determined from the information needs derived from kinematic equations representing the dynamically distinct pre-crash scenarios. Results

from a literature review of two prior research projects are presented, which identify countermeasure functional and performance requirements that are relevant to the countermeasures for the five pre-crash scenario groups. The Integrated Vehicle-Based Safety System (IVBSS) and Vehicle Safety Communications – Applications (VSC-A) projects are assessed to map their system functional requirements to the needs of the five target pre-crash scenario groups. This report focuses on countermeasure functional requirements that fall under the "sensing and perception" and "situation characterization and threat assessment" categories.

The IVBSS and VSC-A projects cover in great details the rear-end and lane change pre-crash scenario groups. The VSC-A project also tackles the junction crossing as well as the "opposite direction/vehicle making a maneuver" pre-crash scenarios. The two pre-crash scenarios, "opposite direction/no vehicle maneuver" and LTAP/OD, are not directly addressed by the VSC-A project. The IVBSS project deals with opposite direction crashes involving unintentional lane departure by the use of a lateral drift warning function that alerts the driver of unintentional drift to either side of the travel lane. Further development is recommended to build V2V-based safety applications for the LTAP/OD and "opposite direction/no vehicle maneuver" pre-crash scenarios.

1. INTRODUCTION

The U.S. Department of Transportation's Intelligent Transportation System (ITS) program 2010-2014 Strategic Research Plan describes an initiative aimed at developing safety applications to increase situational awareness and reduce or eliminate crashes through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) data transmission that supports driver advisories, driver warnings, and vehicle and/or infrastructure controls [1]. A multi-track research plan was conceived to promote V2V active safety applications that address the most critical crash scenarios [2]. Track 1 of this V2V research plan establishes a key scenario framework by which the crash problem can be further defined and new crash avoidance capabilities identified and described. The framework connects pre-crash scenarios to crash avoidance safety applications and provides information that will enable the identification of safety application functions, performance, and initial effectiveness benchmarks. This framework will contribute to determining requirements for safety applications and will also aid in the research and development of new crash avoidance technology and applications that will address the most pressing aspects of the crash problem.

This report presents the results from the ongoing analysis in support of the V2V research plan's Track 1 activities for the light-vehicle platform. Light vehicles encompass passenger cars, vans and minivans, sport utility vehicles, and light pickup trucks with gross vehicle weight rating less than or equal to 10,000 pounds. Following the identification of ten priority pre-crash scenarios, detailed profiles are described to provide the functional requirements for future V2V crash countermeasure systems to address these scenarios. Crash avoidance needs and countermeasure profiles will serve the development, testing, and safety benefits estimation of applicable V2V-based crash countermeasure systems.

The population of motor vehicle crashes involving at least one light vehicle was linked to a set of 37 pre-crash scenarios that describe vehicle movements and critical events immediately prior to a crash [3]. The statistics of the 37 pre-crash scenarios were updated based on crash data from the 2004-2008 National Automotive Sampling Systems (NASS) General Estimates System (GES), National Motor Vehicle Crash Causation Survey (NMVCCS), and event data recorder (EDR) databases [4]. The crash cases in the EDR database are a subset of the NASS Crashworthiness Data System (CDS) database. Further analysis was conducted which identified 17 target pre-crash scenarios for V2V-based safety applications. When considered as the primary countermeasure, V2V-based crash avoidance systems have the potential to deal with 76 percent of all light-vehicle crashes based on 2004-2008 GES statistics [5]. The 17 target scenarios were organized into six scenario groups by their pre-crash movement and relative positioning characteristics: Rear-End, Lane Change, Opposite Direction, Left Turn Across Path/Opposite Direction, Junction Crossing, and Traffic Control Device (TCD) Violation. Table 1 presents the complete list of the 17 target pre-crash scenarios[1] organized by their group assignments and societal harm. The measures of societal harm include comprehensive costs and functional years lost due to injured persons in the range of Maximum Abbreviated Injury Scale (MAIS) levels one through six. The six pre-crash scenario groups account for 73 percent of all comprehensive costs from police-reported crashes that could potentially be addressed by V2V technology; the remaining 27 percent is comprised of control loss, parking, backing up, and 'other' pre-crash scenarios.

Table 1. Societal Harm of Target Pre-Crash Scenario Groups

Target Pre-Crash Scenario Groups		Comprehensive Costs		Functional Years Lost	
		Total	Percentage	Total	Percentage
Rear-End	Rear-end/LVS	$ 29,716,000,000	10.8%	198,000	10.2%
	Rear-end/LVD	$ 12,215,000,000	4.4%	82,000	4.2%
	Rear-end/LVM	$ 10,342,000,000	3.8%	72,000	3.7%
	Rear-end/striking maneuver	$ 2,381,000,000	0.9%	16,000	0.8%
	Rear-end/LVA	$ 667,000,000	0.2%	5,000	0.3%
	Total	$ 55,321,000,000	20.1%	373,000	19.2%
Lane Change	Changing lanes/same direction	$ 8,414,000,000	3.1%	60,000	3.1%
	Turning/same direction	$ 6,176,000,000	2.2%	43,000	2.2%
	Drifting/same direction	$ 3,483,000,000	1.3%	25,000	1.3%
	Total	$ 18,073,000,000	6.6%	128,000	6.6%
Opposite Direction	Opposite direction/no maneuver	$ 29,558,000,000	10.8%	213,000	11.0%
	Opposite direction/maneuver	$ 3,500,000,000	1.3%	25,000	1.3%
	Total	$ 33,058,000,000	12.0%	238,000	12.2%
LTAP/OD	LTAP/OD @ non signal	$ 15,481,000,000	5.6%	111,000	5.7%
	LTAP/OD @ signal	$ 14,777,000,000	5.4%	105,000	5.4%
	Total	$ 30,258,000,000	11.0%	216,000	11.1%
Junction Crossing	SCP @ non signal	$ 41,095,000,000	14.9%	292,000	15.0%
	Turn @ non signal	$ 930,000,000	0.3%	6,000	0.3%
	Turn right @ signal	$ 908,000,000	0.3%	6,000	0.3%
	Total	$ 42,933,000,000	15.6%	304,000	15.6%
TCD Violation	Running red light	$ 18,274,000,000	6.6%	129,000	6.6%
	Running stop sign	$ 3,075,000,000	1.1%	22,000	1.1%
	Total	$ 21,349,000,000	7.8%	151,000	7

SCP ≡ Straight Crossing Paths LVS ≡ Lead Vehicle Stopped LVM ≡ Lead Vehicle Moving
LVD ≡ Lead Vehicle Decelerating LTAP/OD ≡ Left Turn Across Path/Opposite Directions
LVA ≡ Lead Vehicle Accelerating

[1] Refer to NHTSA report, *Description of Light Vehicle Pre-Crash Scenarios for Safety Applications Based on Vehicle-to-Vehicle Communications* by W.G. Najm et. al.[4] for descriptions of each scenario.

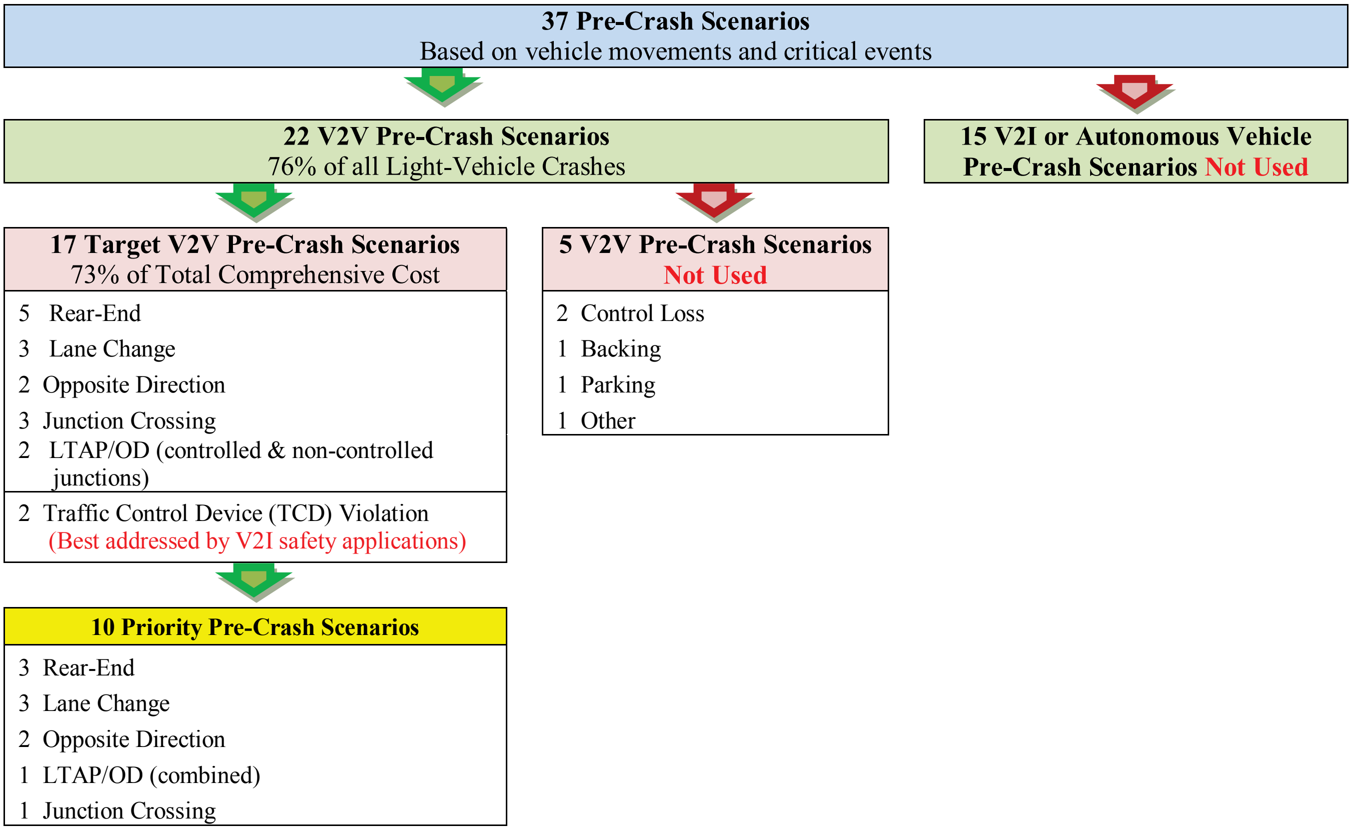
The target crash scenarios with the greatest societal harm were prioritized for further examination to gain the most benefit by reducing the occurrence of these crashes [6]. Figure 1 illustrates an overview of the pre-crash scenario prioritization. The 10 priority pre-crash scenarios in descending order of societal harm are:

1. Straight crossing paths (SCP) at non-signalized junctions
2. Left turn across path from opposite directions (LTAP/OD), includes both signal and non-signalized junctions.
3. Rear-end crash/lead vehicle stopped (LVS)
4. Opposite direction/no vehicle maneuver[2]
5. Rear-end crash/lead vehicle decelerating (LVD)
6. Rear-end crash/lead vehicle moving at slower constant speed (LVM)
7. Changing lanes/both vehicles traveling in same direction
8. Turning/both vehicles traveling in same direction
9. Opposite direction/vehicle making a maneuver
10. Drifting/both vehicles traveling in same direction

The six remaining target pre-crash scenarios are:

- Running red light: Host vehicle is going straight and runs a red light while crossing an intersection and collides with another straight crossing vehicle from a lateral direction.
- Running stop sign: Host vehicle is going straight and then runs a stop sign at an intersection.
- Rear-end/striking maneuver: Host vehicle is changing lanes or passing and closes on a lead vehicle.
- Turn at non signal: Host vehicle stops at a stop sign and then proceeds to turn left against lateral crossing traffic.
- Turn right at signal: Host vehicle is turning right at a signalized intersection and then turns into the same direction of another vehicle crossing initially from a lateral direction.
- Rear-end/LVA: Host vehicle is going straight at an intersection-related location and then closes in on an accelerating lead vehicle.

[2] Vehicle maneuver denotes passing, parking, turning, changing lanes, merging, or successful corrective action to a previous critical event



*Note that the numbers in the boxes above refer to the scenario totals

Figure 1. Overview of Selection of Ten Priority Light-Vehicle Pre-Crash Scenarios

It must be noted that the LTAP/OD pre-crash scenario combines crashes that occur at signalized and non-signalized junctions because of the very close similarities between the crash kinematics and circumstances between the two scenarios. In the LVS pre-crash scenario, the following vehicle is usually going straight and then closes in on a stopped lead vehicle. The following vehicle may also be decelerating or starting in its traffic lane and closes in on a stopped lead vehicle. In some of these crashes, the lead vehicle first decelerates to a stop and is subsequently struck by the following vehicle. This typically happens either in the presence of a traffic control device or when the lead vehicle is slowing down to turn.

2. SCENARIO DEPICTIONS AND COUNTERMEASURE FUNCTIONAL NEEDS

Pre-crash scenarios are depicted to present and compare the data that each countermeasure will require to be effective in reducing the occurrence and severity of multiple-vehicle collisions. A matrix of the data needed that will be used by each countermeasure was assembled as a tool to identify functional groups of performance. Table 2 shows the Functional Needs Matrix that was derived from the kinematic depictions of five target pre-crash scenario groups based on the framework established in [6]. This matrix addresses five pre-crash scenario groups and excludes the TCD Violation group since crashes involving traffic violations at three-color signals or stop signs are more appropriately mitigated by V2I countermeasure systems.

The Functional Needs Matrix presents the logical information needed for each pre-crash scenario organized by crash kinematics, driver intent, and demographic data. The kinematic and driver intent needs were derived from the pre-crash scenario depictions [6]. Time-to-collision equations led directly to the selection of the kinematic needs. Driver intent needs were identified to classify pre-crash circumstances and assess the threat of crash imminent situations. Examination of updated pre-crash scenario statistics resulted in the demographic data needs [4].

The five groups in Table 2 consolidate the priority pre-crash scenarios into functional countermeasure areas that may be addressed by V2V-based safety applications. The rear-end pre-crash scenario group is comprised of multiple-vehicle crashes that occur longitudinally while traveling in the same lane in the same direction. This group includes the LVS, LVM, and LVD priority V2V scenarios. The lane change group is characterized by predominantly laterally oriented multiple-vehicle crashes between vehicles traveling in the same direction in adjacent lanes, encompassing the changing lanes, drifting, and turning priority scenarios. The opposite direction pre-crash scenarios involve two vehicles approaching each other from opposite directions, either in the same lane or adjacent lanes prior to the critical event, including opposite direction collisions that were preceded by a vehicle making a maneuver or drifting. The LTAP/OD pre-crash scenario group consists of crashes involving two vehicles approaching each other from opposite directions, initially in adjacent lanes, with one vehicle initiating a left turn maneuver across the path of the other. This group includes crashes that occur at signalized and non-signalized junctions. The junction crossing group incorporates all crossing path pre-crash scenarios in which the two vehicles approach each other from perpendicular directions at mostly non-signalized junctions. The SCP at non-signalized junction scenario is the sole priority scenario included in this group.

Table 2. Countermeasure Functional Needs Matrix

		Rear-End Group	Opposite Direction Group	LTAP/OD Group	Junction Crossing Group	Lane Change Group
Crash Kinematics	RELATIVE POSITION	✓	✓	✓	✓	✓
	RANGE RATE	✓	✓	✓	✓	✓
	VELOCITY	✓	✓	✓	✓	✓
	HEADING	✓	✓	✓	✓	✓
	POSITION IN LANE	✓	✓			✓
	LONGITUDINAL ACCELERATION	✓	✓			
	LATERAL ACCELERATION		✓			✓
	YAW RATE			✓		✓
Driver Intent	TURN SIGNAL USE		✓	✓	✓	✓
	BRAKE USE	✓	✓	✓	✓	✓
	THROTTLE POSITION	✓	✓	✓	✓	✓
Demographic Data	INATTENTION	✓				
	FOLLOWING TOO CLOSELY	✓				
	SPEEDING	✓				
	MOVING VIOLATIONS	✓				
	DRIVER DISTRACTION		✓	✓	✓	✓
	FATIGUE		✓			
	INADEQUATE EVASIVE ACTION		✓	✓		
	INADEQUATE SURVEILLANCE		✓		✓	✓
	MISJUDGEMENT				✓	
					✓	

3. COUNTERMEASURE KINEMATIC PROFILES

The kinematics of the ten priority pre-crash scenarios are described in this section to define the conditions and specifications for the critical parameters representing the vehicle-to-vehicle collisions that may be avoided with the assistance of communications-based countermeasure systems. Sections 3.1 through 3.5 provide detailed calculations that can be used to determine how a V2V system should react in each of the pre-crash scenarios. For each of these sections, crash avoidance needs and countermeasure profiles are gleaned from the following questions that address the encounter and response to a crash imminent situation:

1. Will a collision occur given the initial conditions of the driving situation?
2. Can the collision be prevented given the imminence of the crash?
3. What is the countermeasure supposed to do to assist the driver in this situation?
4. How well should the functions of the countermeasure system perform?

The first two questions above are directly tied to the subject vehicle's range and range rate to the other vehicle(s), which are calculated from the position and velocity of all vehicles involved. The detection of crash imminent circumstances enables the system to identify the pre-crash scenario type and assess the threat. The response to the second question about the opportunity for crash prevention helps to determine when to intervene by warning the driver or applying automatic controls. The most recent statistical data for the 37 pre-crash scenarios have been updated to include EDR information about travel speed, brake activation, and deceleration levels reported from actual crash data [4]. The EDR data were examined to quantify the real world crash kinematics that should be dealt with by V2V-based countermeasures. The resultant 5th, 50th, and 95th percentile travel speeds and deceleration levels from EDR data were entered into the crash avoidance equations to derive the initial range between vehicles needed to avoid a crash.

The answer to the third question above determines the high-level system functions that must be performed to assist the driver in preventing or mitigating the severity of the collision. Time-to-collision and crash avoidance equations, along with the understanding of crash characteristics and circumstances, allow the identification of the different crash countermeasure functions. The last remaining question about performance levels of the crash countermeasure systems is not tackled in this report. Instead, this report covers a literature review that was conducted of project results dealing with functional requirements and minimum performance specifications for crash avoidance systems by the Crash Avoidance Metrics Partnership (CAMP) team and the Integrated Vehicle-Based Safety System (IVBSS) initiative [7-10].

3.1. Rear-End Pre-Crash Scenario Group

3.1.1. Lead Vehicle Stopped

The critical event that determines if a rear-end crash will be imminent is the presence of another vehicle in the same lane, facing the same direction, and stopped. In the LVS pre-crash scenario, the subject vehicle is typically traveling at constant speed while the other (lead) vehicle is standing still in the same lane. The subject vehicle might also be accelerating or decelerating.

Crash countermeasures must determine that a crash between the subject vehicle and another vehicle within the immediate vicinity is imminent. To ensure that there is sufficient range between vehicles to avoid a crash, rear-end/LVS pre-crash scenario countermeasures must continuously measure the range and closing speed between vehicles. The time-to-collision (ttc) shall serve as the indicator of imminent crash circumstances. When the subject vehicle is travelling at a constant velocity, the ttc can be calculated for rear-end/LVS crashes from the following equation:

$$\mathrm{ttc} = \frac{D_0}{V_1} \qquad (1)$$

ttc	=	Time-to-collision
D_0	=	Gap between front of subject vehicle and rear of lead vehicle
V_i	=	Vehicle *i* initial speed, (1 = subject vehicle, 2 = other vehicle)

Based on Equation (1), the countermeasure must recognize that the other vehicle is stopped in the same lane forward of the subject vehicle while continuously measuring the gap between vehicles and the subject vehicle's speed.

The recommended avoidance maneuver in the LVS scenario is braking by the following vehicle. Rear-end/LVS crashes occur if the initial gap between the vehicles is shorter than the actual braking distance of the following vehicle. The braking distance is calculated from the following vehicle's initial velocity and braking level. The distance traveled by the subject vehicle while braking, δ_1, is further dependent upon the combined delay between the time of critical event when a collision is likely to occur and the actual onset of the avoidance maneuver. This combined system delay, t_D, includes the time delay of the communication link between the two vehicles, the countermeasure system delay, the driver's reaction time, and the time for the subject vehicle to decelerate to the final effective deceleration level, A_1. The braking distance can therefore be calculated as:

$$\delta_1 = \frac{{V_1}^2}{2 \cdot A_1} + (t_D \cdot V_1) \qquad (2)$$

Table 3 presents the minimum stopping distances calculated from the following vehicle's initial velocity at brake onset and the effective braking level. Although the equation for braking distance incorporates a summation of driver reaction time, system delays, and vehicle delays, the data in Table 3 result when the delay is set to zero in order to calculate the actual braking distance of the subject vehicle only.

Table 3. Minimum Stopping Distance (ft) by Initial Velocity and Braking Level

Following Vehicle Initial Velocity (mph)	Brake Level (g)							
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
75	1,880	940	627	470	376	313	269	235
70	1,637	819	546	409	327	273	234	205
65	1,412	706	471	353	282	235	202	176
60	1,203	602	401	301	241	201	172	150
55	1,011	505	337	253	202	168	144	126
50	835	418	278	209	167	139	119	104
45	677	338	226	169	135	113	97	85
40	535	267	178	134	107	89	76	67
35	409	205	136	102	82	68	58	51
30	301	150	100	75	60	50	43	38
25	209	104	70	52	42	35	30	26
20	134	67	45	33	27	22	19	17
15	75	38	25	19	15	13	11	9
10	33	17	11	8	7	6	5	4
5	8	4	3	2	2	1	1	1

The data in Table 3 present a wide range of velocity and braking levels to capture the most complete cross-section of possible crash circumstances that may be addressed by V2V countermeasures. However, it is more practical to examine a smaller cross-section of the complete data set that portrays the conditions most likely to be present in real-world countermeasure applications. The updated EDR pre-crash statistics of the LVS crash scenario indicate travel speeds of 10, 30, and 50 mph respectively for the 5th, 50th, and 95th percentiles. Figure 2 plots the minimum required stopping distances as calculated from a subject vehicle's actual deceleration for these three initial velocity profiles.

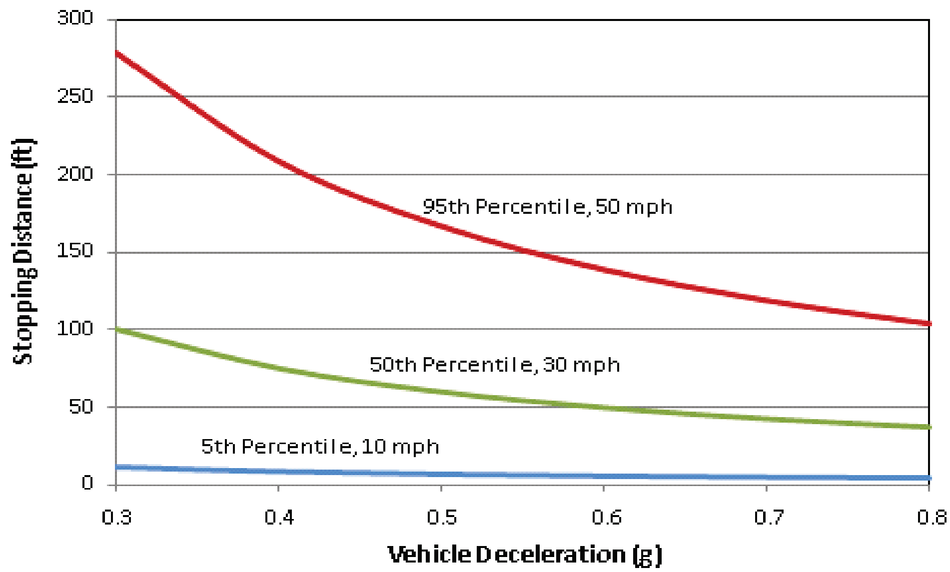


Figure 2. Minimum Stopping Distance by Travel Speed and Braking Level in Rear-End/LVS Pre-Crash Scenario

LVS crashes can be potentially prevented if the range of the countermeasure is greater than the minimum stopping distance of the following vehicle. From Figure 2, a crash can be avoided if the following vehicle brakes at least 278 feet from the lead stopped vehicle when initially traveling at 50 mph and applying a constant deceleration level of 0.3g. Similarly, vehicles traveling slower and/or braking harder require less warning distance to avoid a crash; for example, a vehicle initially traveling at 30 mph and braking at .8g requires just 38 feet to avoid a rear-end/LVS crash without accounting for delays.

3.1.2. Lead Vehicle Decelerating

The critical event that determines if a rear-end crash will be imminent is the presence of another vehicle in the same lane, heading in the same direction, and decelerating. In LVD crashes, the subject vehicle is typically traveling at constant speed when the other vehicle suddenly decelerates. The two vehicles are initially in a following mode (i.e., closing speed near zero) at a specific gap or headway. The two vehicles might also be initially decelerating or accelerating before the lead vehicle starts to brake or brake harder.

Crash countermeasures must measure the initial headway, closing speed, and brake level of all vehicles before activation. The time-to-collision equation for a rear-end/LVD collision is conditional upon the braking level of the lead vehicle. The time for the lead vehicle to stop, ttc_{stop}, is calculated from Equation (3) and the distance traveled by that vehicle while stopping, δ_2, is obtained from Equation (4) below.

$$\mathrm{ttc}_{\mathrm{stop}} = \frac{\mathrm{V}_2}{\mathrm{A}_2} \tag{3}$$

$$\delta_2 = \frac{(V_2)^2}{2 \cdot A_2} \tag{4}$$

A_2 = Vehicle i initial deceleration
δ_i = Vehicle i stopping distance

The stopping time and distance of the lead vehicle can then be used to determine the time-to-collision for the subject vehicle. If the distance traveled by the following vehicle while the other vehicle is braking is less than the stopping distance of the lead vehicle, then the vehicles will collide after the lead vehicle stops; ttc is expressed in Equation (5). Otherwise, the lead vehicle is struck during the deceleration state as expressed in Equation (6):

Collision after stopping:

$$ttc = \frac{D_0 + \delta_2}{V_1} \tag{5}$$

Collision during braking:

$$ttc = \frac{-1 \cdot (V_2 - V_1) + \sqrt{(V_2 - V_1)^2 + (2 \cdot A_2 \cdot D_0)}}{A_2} \tag{6}$$

From Equations (3-6), the system must measure the subject and lead vehicles' velocities, their initial separation distance, and the vehicles' deceleration levels.

The recommended avoidance maneuver for a rear-end/LVD crash is braking by the following vehicle. Rear-end/LVD crashes occur if the sum of the initial gap plus the distance required by the lead vehicle to stop is less than or equal to the braking distance of the following vehicle. The braking distance is calculated from the subject vehicle's initial velocity, braking level, and the summation of delays throughout the system, as in the braking equation for the LVS scenario. Rear-end/LVD scenarios incorporate the addition of the stopping distance of the lead vehicle to the determination if a crash can be avoided. To avoid a rear-end/LVD crash, the subject vehicle's countermeasure system must trigger a driver alert when the gap between vehicles approaches the minimum braking distance required.

The avoidance equation for LVD crashes is resolved by setting the final distance between vehicles, D_F, in Equations (7-8) below to zero to solve for the initial range between vehicles.

$$D_F = D_0 + \delta_2 - \delta_1 \tag{7}$$

When D_F is set to zero, the resulting equation is:

$$D_0 = \left(\frac{(V_1)^2}{2 \cdot A_1} + t_D \cdot (V_1) \right) - \frac{(V_2)^2}{2 \cdot A_2} \tag{8}$$

The EDR dataset was polled to identify the range of velocities that best represent the actual crash population of real-world driving circumstances. Subject vehicle velocities of 20 mph, 50 mph, and 70 mph were identified to best represent the 5th, 50th, and 95th travel speed percentiles. Based on the analysis of naturalistic driving data collected from the IVBSS field operational test, the lead vehicle was observed to decelerate at an average of 0.1g (5th percentile) to 0.35g (95th percentile) per braking event in pre-defined LVD near crashes.

3.1.3. Lead Vehicle Moving at Slower Constant Speed

The critical event that determines if a rear-end/LVM crash will be imminent is the presence of another vehicle in the same lane, in the same direction, traveling at a slower constant speed. In LVM collisions, the subject vehicle is typically traveling at constant speed when approaching the slower lead vehicle. The subject vehicle might also be decelerating or accelerating during the approach.

Crash countermeasures must take into account the distance and closing speed between the vehicles. The system must continuously calculate the following time-to-collision of the subject vehicle in order to alert the driver of impending collisions as early as possible:

$$\mathrm{ttc} = \frac{D_0}{(V_1 - V_2)} \tag{9}$$

Based on Equation (9), the system must measure the initial gap, D_0, and the range rate representing the difference between the subject vehicle speed, V_1, and the lead vehicle speed, V_2.

The recommended avoidance maneuver for a rear-end/LVM crash is braking by the subject vehicle to match the speed of the lead vehicle. Rear-end/LVM crashes occur if the initial gap between the vehicles is less than the distance traveled during braking by the following vehicle. The braking distance is calculated from the range rate (difference between subject and lead vehicles' speeds) and braking levels of the subject vehicle.

Equation (10) expresses the subject vehicle's braking distance as a function of the initial closing speed (V_1-V_2) and braking level of the subject vehicle assuming the lead vehicle's speed remains constant.

$$\delta_1 = \frac{(V_1 - V_2)^2}{2 \cdot A_1} + (V_1 - V_2) \cdot (t_D) \qquad (10)$$

Table 4 presents the critical range data established from the potential closing speeds and brake levels of the subject vehicle. The data represent the critical range for rear-end/LVM crashes, which is the minimum initial distance required between vehicles to potentially avoid the crash. Figure 3 plots the data in Table 4. It should be noted that crash data collected from a small sample of EDR cases indicate that the travel speed by the following vehicle was 7.5 mph for the 5th percentile and 40 mph for the 95th percentile in rear-end/LVM pre-crash scenarios.

Table 4. Rear-End/LVM Critical Range (ft) by Closing Speed and Braking Level

Range Rate (mph)	Brake Level (g)							
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
40	535	267	178	134	107	89	76	67
30	301	150	100	75	60	50	43	38
20	134	67	45	33	27	22	19	17
10	33	17	11	8	7	6	5	4

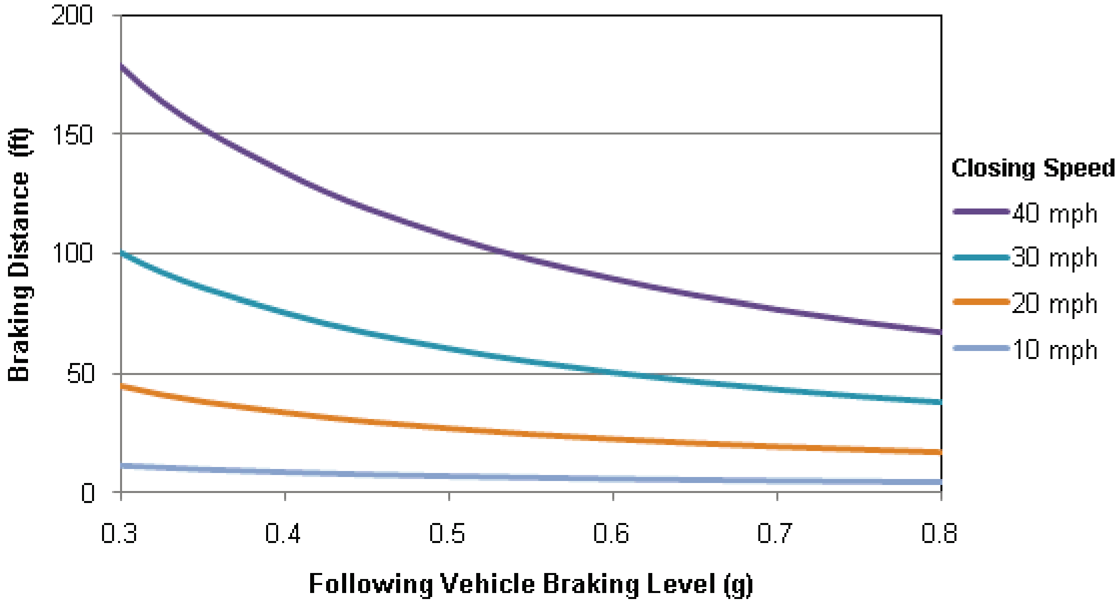


Figure 3. Minimum Stopping Distance by Closing Speed and Braking Level in Rear-End/LVM Pre-Crash Scenario

To avoid rear-end/LVM crashes, countermeasures must alert the driver or affect control over the vehicle when the range between vehicles is sufficient for the subject vehicle to slow to the lead vehicle's speed. From Figure 3, most LVM crashes can be avoided if the range of V2V-based countermeasures is greater than 200 feet. In a worst case scenario, where the subject vehicle is approaching a slower vehicle with a speed differential of 40 mph, the subject vehicle must brake at 178 feet from the lead vehicle given the average braking level of the avoidance maneuver is 0.3g. The distance required to brake is shorter if the range rate is less, or the subject vehicle decelerates harder, or combinations of both.

3.1.4. Information Needs for Rear-End Crash Countermeasures

Effectively reducing the occurrence of rear-end crashes through the use of V2V-based countermeasures requires gathering information from multiple vehicles, the environment, and the driver. The identified information needs will allow the countermeasures to recognize that a rear-end crash is imminent, to account for environmental and driver factors, and to identify the point when an avoidance maneuver or decision must be initiated to avoid the crash. Rear-end crash countermeasures must measure vehicles' kinematic data including position, heading, velocity, and acceleration information. The kinematic data serve to calculate the range, range rate, and time-to-collision by the countermeasure to identify if a crash will potentially occur and if it can be avoided. Additionally, since the effective braking level is dependent upon the road surface condition (i.e., dry, wet, or icy), the system should collect data from the vehicle to ascertain such environmental factors. To do so, vehicle information including the use of windshield wipers or defrosters and outside temperature should be monitored as a consideration for the effective braking level.

3.2. Lane Change Pre-Crash Scenario Group

3.2.1. Changing Lanes/Both Vehicles Traveling in Same Direction

The critical event that determines if a lane change crash will be imminent is the line crossing of an adjacent lane by the subject vehicle in the presence of another vehicle in close proximity in the same adjacent lane and traveling in the same direction. In lane change crashes, the subject vehicle and the other vehicle are both typically traveling at the same longitudinal speed, while the subject vehicle encroaches onto an adjacent lane and strikes the other vehicle. One variation of the close proximity scenario is the other vehicle in the adjacent lane fast approaching the subject vehicle from behind during the lane change maneuver.

Lane change crash countermeasures must determine that a crash between the subject vehicle and another vehicle within the immediate vicinity is imminent. The other vehicle is either to the left or right side of the subject vehicle in the adjacent lane. In the changing lanes/same direction pre-crash scenario, countermeasures must measure the lateral range between vehicles and the corresponding range rate (i.e., speed at which the subject vehicle is approaching the other vehicle laterally). The time-to-collision serves as the indicator of imminent crash circumstances. The ttc parameter can be calculated for the changing lanes/same-direction scenario by setting the instantaneous distance between vehicles to zero and solving for time.

$$0 = S_0 - \frac{\alpha}{\omega_1} \cdot \left(ttc - \frac{sin(\omega_1 \cdot ttc)}{\omega_1} \right) \tag{11}$$

S_0 = Initial lateral gap between vehicles
α = Initial lateral acceleration of lane change maneuver
ω_i = Initial frequency of lane change maneuver

To avoid a crash with an adjacent vehicle when a lane change maneuver has already been initiated, counter-steering by the subject vehicle is recommended to stop the lateral motion. Lane change crashes occur if the gap between the two vehicles is smaller than the required lateral distance to reduce the subject vehicle's lateral speed to zero. Lane change crashes can also be avoided by warning the subject vehicle not to initiate a lane change maneuver in the first place when another vehicle is present in close proximity in an adjacent lane.

Due to the small lateral distance between the two vehicles traveling in adjacent lanes, lane change crash countermeasures must detect the presence of other vehicles in close proximity to either side of the subject vehicle so as to advise or issue alerts to the driver. The countermeasures must also monitor the lateral range and range rate between the two vehicles.

Moreover, the system must recognize the intent of the driver in the subject vehicle who is about to initiate a lane change maneuver. In a fast approaching lane change pre-crash scenario, the countermeasure must also track the longitudinal range and range rate between the subject vehicle and the other vehicle closing in from behind in the adjacent lane.

3.2.2. Turning/Both Vehicles Traveling in Same Direction

The critical event that determines if a turning/same direction crash will be imminent is the encroachment of the turning subject vehicle onto an adjacent lane where the other vehicle is traveling in the same direction. Turning/same direction crashes are characterized by vehicles initially traveling in the same direction in adjacent lanes, the subject vehicle then initiates the crash by turning and crossing into the lane of the other vehicle. The subject vehicle might initiate the turning maneuver from a stop, constant speed, or during deceleration. Moreover, the other vehicle might be in close proximity or fast approaching from behind at constant speed. This pre-crash scenario encompasses turning maneuvers by the subject vehicle in either direction.

Turning/same direction crash countermeasures must determine that a crash between the turning subject vehicle and another vehicle is imminent. Countermeasures must recognize the intent to turn by the driver of the subject vehicle and detect the presence of the other vehicle in the intended direction. In addition, range and range rate between the two vehicles must be tracked. The ttc parameter is calculated from the time required for the subject vehicle to cross into the path of the other vehicle:

$$\mathrm{ttc} = \frac{S_0}{\sin(\theta) \cdot V_1} \qquad (12)$$

$\theta =$ Subject vehicle's initial yaw

The recommended maneuver to avoid a turning/same direction crash is for the driver of the subject vehicle to abort the ongoing turning maneuver by counter-steering or to simply wait for a clear path before turning. This avoidance decision applies directly to situations where the other vehicle is initially adjacent to the subject vehicle only. An additional condition is needed to address "fast-approach" scenarios in which the other vehicle is approaching from the rear. In such cases, countermeasures must account for vehicles initially adjacent, and those that will be directly adjacent when the subject vehicle crosses into the approaching vehicle's lane.

3.2.3. Drifting/Both Vehicles Traveling in Same Direction

The drifting/same direction pre-crash scenario is similar to the changing lanes/same direction scenario except that the adjacent lane encroachment is unintentional. The critical event that determines if a drifting/same direction crash will be imminent is the encroachment of the subject vehicle into an adjacent lane where another vehicle is present in close proximity or fast approaching.

To avoid drifting/same direction crashes, the driver of the subject vehicle must be warned of the unintentional drift and the presence of another vehicle in the adjacent lane. Counter-steering is the recommended avoidance action by the driver to keep the subject vehicle from unintentionally leaving its travel lane.

3.2.4. Information Needs for Lane Change Crash Countermeasures

To effectively reduce the occurrence of lane change crashes through the implementation of V2V-based countermeasures, information must be gathered from multiple vehicles about their relative positions and dynamic states as well as the intent of their drivers to make a lane change or turn. The identified information needs should allow V2V-based countermeasures to recognize imminent lane change crashes circumstances including lane change, turning, and drifting. The countermeasures should also account for environmental and driver factors. Moreover, countermeasures should identify the point when an avoidance maneuver must be initiated or a decision must be made to avoid the crash.

Lane change crash countermeasures must primarily recognize the relative position and motion between two adjacent vehicles in the longitudinal and lateral directions. Countermeasures must gather kinematic data including position, heading, velocity, and acceleration information from each vehicle. The kinematic data serve to calculate the range, range rate, and time-to-collision by the countermeasure to identify if a crash will potentially occur. Additionally, since the majority of lane change crashes is attributed to combinations of driver error and/or inadequate surveillance of the adjacent lanes, driver intent to change lanes or turn to either side should be recognized using measures such as turn signal use and/or steering wheel input.

3.3. Opposite Direction Pre-Crash Scenario Group

3.3.1. Opposite Direction/No Vehicle Maneuver

The critical event that determines if an “opposite direction/no vehicle maneuver” crash will be imminent is the determination that the subject vehicle is crossing the line of an adjacent opposing lane and encroaching onto the path of an oncoming vehicle. Both vehicles are typically traveling at constant speed. The subject vehicle might be going straight or negotiating a curve at a non-junction, and then drifts and encroaches into another vehicle traveling in the opposite direction. Thus, this pre-crash scenario results from an unintentional movement by the subject vehicle from its current travel lane to an adjacent, opposing lane.

Opposite direction crash countermeasures must determine that a crash between the subject vehicle and the other vehicle within the immediate vicinity is imminent. Such countermeasures must measure the longitudinal and lateral ranges between the two vehicles as well as their travel speeds. The time-to-collision serves as the indicator of imminent crash circumstances, which can be calculated for the “opposite direction/ no vehicle maneuver” crash scenario as follows:

$$ttc = \frac{D_0}{\frac{V_1 \cdot D_0}{\sqrt{{D_0}^2 + (S_0)^2}} + V_2} \tag{13}$$

"Opposite direction/no vehicle maneuver" collisions can be prevented by a counter-steering avoidance maneuver by the subject vehicle to clear the path of the other vehicle after the subject vehicle has crossed onto the adjacent lane. A collision occurs if the required longitudinal range by the subject vehicle to clear the path of the other vehicle is less than the distance covered by the both vehicles in the same period. The worst case circumstance would be characterized by the subject vehicle having completely crossed onto the opposing lane. In most "opposite direction/no vehicle maneuver" crashes, the longitudinal gap between the two vehicles is relatively very short after the encroachment. Consequently, the driver of the other vehicle does not have enough time to react and avoid the subject vehicle. The best countermeasure then would be to detect that the subject vehicle is about to depart its travel lane and pose threat to an oncoming vehicle, and warn the driver of the subject vehicle to remain within the boundaries of the current travel lane.

3.3.2. Opposite Direction/Vehicle Making a Maneuver

The critical event that determines if an "opposite direction/vehicle making a maneuver" crash will be imminent is the determination that the subject vehicle intends to cross the line of an adjacent opposing lane onto the path of an oncoming vehicle. Typically, the subject vehicle is passing another vehicle in front at a non-junction and encroaches into another vehicle traveling in the opposite direction. The subject vehicle might also be in the middle of a corrective maneuver in response to a prior crash imminent event. In this scenario, the other vehicle would be approaching the passing subject vehicle from a relatively long distance or would be obscured from the driver of the subject vehicle due to geometric roadway profiles or environmental conditions.

Opposite direction crash countermeasures must determine that a crash between the subject vehicle and the other opposing vehicle is imminent. Such countermeasures must measure the longitudinal and lateral ranges between the two vehicles as well as their travel speeds. Moreover, the countermeasures must recognize the intent to pass by the driver of the subject vehicle. Assuming that the critical event has occurred and the subject vehicle is already in the opposing lane, the time-to-collision is expressed as follows:

$$ttc = \frac{D_0}{(V_1 + V_2)} \tag{14}$$

The "opposite direction/vehicle making a maneuver" collisions can be prevented by a counter-steering avoidance maneuver by the subject vehicle to clear the path of the other vehicle after the subject vehicle has initiated the passing maneuver. A collision occurs if the required longitudinal range by the subject vehicle to clear the path of the other vehicle is less than the distance covered by the opposing vehicle in the same period. A more appropriate correction maneuver would be to warn the driver of the subject vehicle from initiating a passing maneuver in the first place given that the intent to pass is recognized and the gap between the two opposing vehicles is not sufficient for a safe passing maneuver.

3.3.3. Information Needs for Opposite Direction Crash Countermeasures

Effective V2V-based opposite direction crash countermeasures must gather information from multiple vehicles traveling in the same and opposing lanes about their relative positions and dynamic states as well as the intent of drivers to pass a vehicle in front. The countermeasures should account for roadway profiles and environmental factors. Moreover, the countermeasures should detect when an encroachment by the subject vehicle onto an opposing, occupied lane is about to happen, and identify the point when an avoidance maneuver must be initiated or a decision must be made to avoid the crash.

Opposite direction crash countermeasures must primarily recognize the relative position and motion between two adjacent vehicles in opposing lanes in the longitudinal and lateral directions. Countermeasures must gather kinematic data including position, heading, velocity, and acceleration information from each vehicle in the vicinity. The kinematic data serve to detect an impending critical encroachment event and calculate the range, range rate, and time-to-collision by the countermeasure to identify if an opposite direction crash will potentially occur. Additionally, driver intent to pass another vehicle in the same lane ahead should be recognized using measures such as turn signal use, yaw rate, and/or steering wheel input. Similar to drifting/same direction crashes, opposite direction crash countermeasures should monitor the lane keeping behavior of the subject vehicle in order to predict an unintentional drift onto an adjacent lane occupied by oncoming traffic.

3.4. LTAP/OD Pre-Crash Scenario Group

3.4.1. LTAP/OD Pre-Crash Scenario Avoidance Profile

The critical event for the LTAP/OD pre-crash scenario is the encroachment of the subject vehicle when executing the left turn maneuver onto the travel lane and path of another vehicle coming from the opposite direction at junctions. Typically, the subject vehicle is slowing down to make the turn at constant speed or is initially at rest before accelerating in a left turn. The other vehicle is generally traveling at constant speed. This pre-crash scenario happens at three-color signal and stop sign controlled junctions and at non-controlled junctions including intersections and driveways. At controlled junctions, the subject vehicle generally obeys the traffic control device before making the left turn maneuver. In crash cases where the subject vehicle violates the traffic control device, LTAP/OD crashes fall under the TCD violation pre-crash scenario group.

LTAP/OD crash countermeasures must take into account the position, distance, and speed of the other vehicle approaching from the opposite direction to determine whether or not to act. The system may need to calculate and compare four separate time intervals to decide on the imminent crash threat: times for the subject vehicle to reach and to clear the travel lane of the oncoming vehicle, and times for the opposing vehicle to reach and to clear the subject vehicle's travel path. A collision would occur if there were any overlap between the two vehicles in the crash zone that is defined by the intersecting area of the opposing lane and the arc of the subject vehicle's path. Equations (15-20) derive these times for the subject vehicle under two distinct dynamic situations and times for the other vehicle. The times for the opposing other vehicle to reach and clear the subject vehicle's path are the same for both dynamics situations.

When the subject vehicle slows down and then turns left at constant speed, the time for the front of the subject vehicle (Vehicle 1) to reach the path of the other opposing vehicle (Vehicle 2) is:

$$T_{1(r)} = \frac{(V_1) - \sqrt{(V_1)^2 - 2 \cdot A_1 \cdot D_1}}{A_1} + \frac{cos^{-1}\left(\frac{Y - \lambda_2}{Y + \lambda_1}\right) \cdot (Y + \lambda_1)}{\sqrt{{V_1}^2 - 2 \cdot A_1 \cdot D_1}} \tag{15}$$

Under the same dynamic situation, the time for the rear of the subject vehicle to clear the path of the other vehicle is:

$$T_{1(c)} = \frac{(V_1) - \sqrt{(V_1)^2 - 2 \cdot A_1 \cdot D_1}}{A_1} + \frac{L_1 + \cos^{-1}\left(\frac{\mathrm{Y} - \lambda_2 - \mathrm{W}_2}{\mathrm{Y} + \lambda_1 + \mathrm{W}_1}\right) \times (Y + \lambda_1 + W_1)}{\sqrt{{V_1}^2 - 2 \cdot A_1 \cdot D_1}} \tag{16}$$

When the subject vehicle accelerates from a stop and turns left, the time for the front of the subject vehicle to reach the path of the other vehicle is:

$$T_{1(r)} = \sqrt{\frac{2 \cdot \left(cos^{-1}\left(\frac{Y - \lambda_2}{Y + \lambda_1}\right) \cdot (Y + \lambda_1)\right)}{A_1}} \tag{17}$$

Under the same dynamic situation, the time for the rear of the subject vehicle to clear the path of the other vehicle is:

$$T_{1(c)} = \sqrt{\frac{2 \cdot \left((\cos^{-1}\left(\frac{\mathrm{Y} - \lambda_2 - \mathrm{W}_2}{\mathrm{Y} + \lambda_1 + \mathrm{W}_1}\right) \times ((Y + \lambda_1) + W_1)) + L_1\right)}{A_1}} \tag{18}$$

Under the two distinct dynamic situations of the subject vehicle, the time for the front of the other vehicle (Vehicle 2) to reach the path of the subject vehicle (Vehicle 1) is:

$$T_{2(r)} = \frac{D_2 + 2 \cdot Y - (Y + \lambda_1 + W_1) \cdot \sin\left(\cos^{-1}\left(\frac{Y - \lambda_2 - W_2}{Y + \lambda_1 + W_1}\right)\right)}{V_2} \quad (19)$$

The time for the rear of the other vehicle to clear the path of the subject vehicle is:

$$T_{2(c)} = \frac{D_2 + L_2 + 2 \cdot Y - (Y + \lambda_1) \cdot \sin\left(cos^{-1}\left(\frac{Y - \lambda_2}{Y + \lambda_1}\right)\right)}{V_2} \quad (20)$$

L_i = Length of vehicle i
W_i = Width of vehicle i
Y = Width of lane
λ_i = Initial lateral distance from left side of vehicle i to center line
D_i = Initial distance from front of vehicle i to intersection

A crash occurs if the subject vehicle time-to-clear the intersection is: greater than the time for the other vehicle to reach the intersection, and less than the other vehicle's time-to-clear the intersection. A crash also occurs if the other vehicle's time-to-clear the intersection is: greater than the subject vehicles time-to-reach the intersection, and less than the subject vehicle's time-to-clear the intersection.

The avoidance maneuver for the LTAP/OD pre-crash scenario is either for the subject vehicle to slow to a complete stop if it is initially moving, or to not begin the left turn if initially stopped. In the scenario where the subject vehicle is initially slowing, the brake level must be increased proportionally to the distance from the intersection to allow the vehicle to stop before entering the intersection zone. In the scenario where the subject vehicle is about to begin the left turn maneuver, the decision of whether or not to initiate the turn is dependent upon the opposing vehicle's initial lane position, speed, and distance to intersection.

If a 17-foot long subject vehicle is initially stopped before accelerating at 0.1g through a four-lane intersection, the subject vehicle will travel an estimated 48 feet, across three lanes longitudinally and one lane laterally. The range of the countermeasure is defined by the distance traveled by the other vehicle in the time it takes the subject vehicle to clear the intersection. Assuming the subject vehicle accelerates at 0.1g from rest, the subject vehicle clears the path of the other vehicle in 6.35 seconds. The parameter, D_2 in Equation (21), the initial distance from the intersection of the other vehicle, defines the critical range of the countermeasure.

$$D_2 = V_2 \cdot \sqrt{\frac{2 \cdot (D_1 + \lambda_1)}{A_1}} = V_2 \cdot 6.35 \quad (21)$$

The EDR data show travel speeds of 10 mph (5th percentile), 45 mph (50th percentile), and 60 mph (95th percentile) for the other vehicle's speed, which translates into ranges of 93, 420, and 560 feet, respectively.

The critical range between vehicles shall be greater when the subject vehicle initially slows to a constant speed to execute the left turn than is the case when the subject velocity is initially at rest. The distance traveled by the other vehicle, D_2 is expressed in Equation (22). This equation includes the time for the subject vehicle to traverse the intersection in addition to the time necessary to approach the intersection after the driver uses the signals before the turn. Normal driving rules establish turn-signal use for 100 feet before turning at intersections. Assuming a subject vehicle's final turning speed of 15 mph, after a 0.1g deceleration, the subject vehicle travels the 100-feet warning range in 3.6 seconds, t_{signal}.

$$D_2 = V_2 \cdot \left(\frac{D_1 + \lambda_1}{V_1} + t_{signal}\right) \tag{22}$$

The critical range of the countermeasure for a vehicle slowing at .1g that intends to turn left through a four-lane intersection at 15 mph is a function of the other vehicle's speed. Using the previously established EDR 5th, 50th, and 95th speed percentile data, the critical ranges for LTAP/OD crashes are respectively 196, 533, and 677 feet.

LTAP/OD crashes may be prevented if the V2V-based countermeasures warn the driver of the subject vehicle early enough to brake and stop completely before entering the intersection or remain stopped and not enter the intersection. The relative distance between the two vehicles is greater in situations where the subject vehicle is initially slowing down before the turn, which will define the range at which LTAP/OD crash countermeasures must function.

3.4.2. Information Needs for LTAP/OD Crash Countermeasures

Effective V2V-based LTAP/OD crash countermeasures must gather information from multiple vehicles approaching junctions about their relative positions and dynamic states as well as the intent of drivers to turn left. The countermeasures should account for the presence of a junction and its traffic controls. Moreover, the countermeasures should detect when an encroachment by the subject vehicle into the intersection zone is about to happen in the path of an oncoming vehicle and identify the point when an avoidance maneuver must be initiated or a decision must be made to avoid the crash.

LTAP/OD crash countermeasures must primarily recognize the relative position and motion between the subject vehicle and other vehicles in opposing lanes in the longitudinal and lateral directions. Countermeasures must gather kinematic data including position, heading, velocity, and acceleration information from each vehicle approaching the intersection. The kinematic data serve to detect an impending critical encroachment event and calculate the time-to-collision by the countermeasure to identify if an LTAP/OD crash will potentially occur. Additionally, driver intent to turn left at a junction should be recognized using measures such as turn signal use, yaw rate, and/or steering wheel input. It would also be helpful for the countermeasure to know the location of the subject vehicle relative to a junction and its presence in a left turn only lane. Moreover, the type of traffic control device present at the junction could be considered to enhance the capability of LTAP/OD crash countermeasures.

3.5. Junction Crossing Pre-Crash Scenario Group

This pre-crash scenario group encompasses the straight crossing paths, left turn across path, left turn into path, and right turn into path pre-crash scenarios that involve at least two vehicles approaching each other from perpendicular or lateral directions at non-signalized junctions. This group also includes the right turn into path at signalized junctions. The focus of this analysis is on the SCP pre-crash scenario since it is the most dominant in terms of annual frequency and societal harm among the other pre-crash scenarios in this group.

3.5.1. Straight Crossing Paths at Non-Signalized Junctions

The critical event that determines if a SCP crash will occur is the encroachment of the subject vehicle into the travel lane of an approaching vehicle traveling in a perpendicular direction. Typically, the subject vehicle is initially at rest before accelerating across an intersection and then cutting across the path of another vehicle laterally approaching from either side of the subject vehicle.

SCP crash countermeasures must take into account the position, distance, and speed of the other vehicle approaching from the cross street to decide whether or not to act. The system must calculate and compare four separate time intervals as illustrated in Equations (23-26). A collision would occur if there were any overlap between the two vehicles in the crash zone defined by the intersecting area of the perpendicular lanes. The time for the front of the subject vehicle (Vehicle 1) to reach the path of the other vehicle (Vehicle 2) is expressed as:

$$\mathrm{T}_{1(\mathrm{r})} = \sqrt{\frac{2 \cdot (Y - W_2 - \lambda_2)}{A_1}} \tag{23}$$

The time for the rear of the subject vehicle to clear the path of the other vehicle is:

$$T_{1(\mathrm{c})} = \sqrt{\frac{2 \cdot (Y + L_1 - \lambda_2)}{A_1}} \tag{24}$$

The time for the front of the other vehicle to reach the path of the subject vehicle is:

$$T_{2(\mathrm{r})} = \frac{D_2 + Y + \lambda_1}{V_2} \tag{25}$$

The time for the rear of the other vehicle to clear the path of the subject vehicle is:

$$T_{2(\mathrm{c})} = T_{2(\mathrm{r})} + \frac{W_1 + L_2}{V_2} \tag{26}$$

As in LTAP/OD, a crash occurs if the subject vehicle time-to-clear the intersection is: greater than the time for the other vehicle to reach the intersection, and less than the other vehicle's time-to-clear the intersection. A crash also occurs if the other vehicle's time-to-clear the intersection is: greater than the subject vehicles time-to-reach the intersection, and less than the subject vehicle's time-to-clear the intersection.

The recommended avoidance action by the subject vehicle is to decide whether or not to enter the intersection. SCP crash countermeasures must calculate the relative distance and closing speed between the subject vehicle waiting at the intersection and the approaching vehicle. The lane position, distance, and speed of the approaching vehicle define a range from the intersection within which the subject vehicle should not "go" and the countermeasure should act. The system should account for the capability of the subject vehicle to accelerate from a stop and the time it would take to cross the intersection or clear the path of the approaching vehicle.

To find the critical range, the system must calculate the time required for the subject vehicle to fully clear the intersection. The distance, D_2 (ft), is the criterion for countermeasure action and is expressed mathematically by Equation (27) below. If the actual range of the approaching on-coming vehicle were less than D_2, then the subject vehicle should not enter the intersection.

$$D_2 = (V_2) \cdot \sqrt{\frac{2 \cdot (Y + L_1 - L_2)}{A_1}} \tag{27}$$

Table 5 presents the tabulated critical ranges of the other vehicle at which the subject vehicle should not enter the intersection, as a function of the approaching vehicle's speed and the subject vehicle's likely acceleration from a stop. The data are further plotted in Figure 4 for three selected travel speeds of the other vehicle and acceleration levels between 0.1g and 0.5g by the subject vehicle. For an approaching vehicle traveling at 70 mph and an acceleration level of 0.2g by the subject vehicle from a stop, the subject vehicle would safely traverse the intersection if the approaching vehicle were at least 280 feet away from the intersection.

Table 5. SCP Critical Range (ft)

Range Rate	Subject Vehicle Acceleration (g)				
(mph)	0.1	0.2	0.3	0.4	0.5
10	57	40	33	28	25
20	113	80	65	57	51
30	170	120	98	85	76
40	227	160	131	113	101
50	283	200	164	142	127
60	340	240	196	170	152
70	396	280	229	198	177

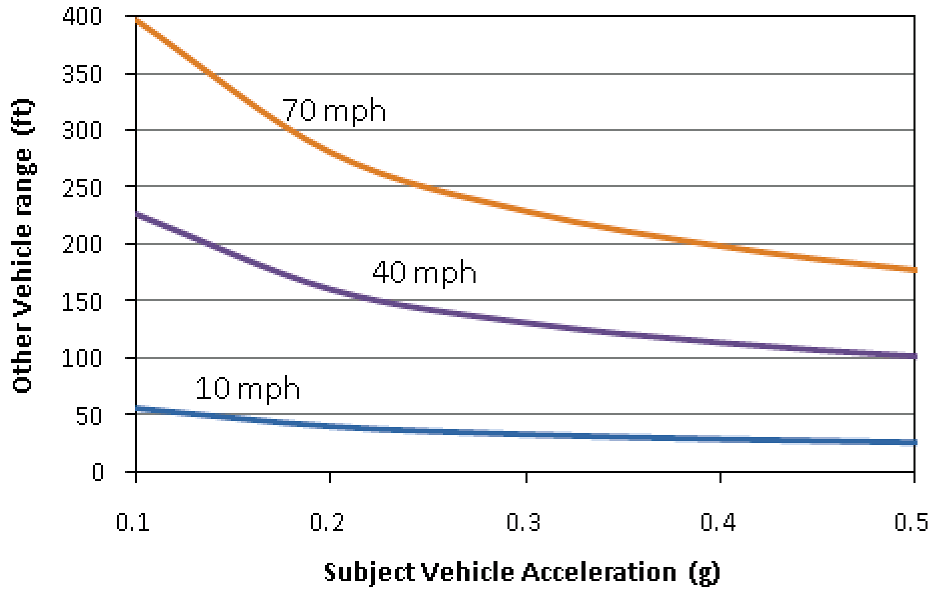


Figure 4. Critical SCP Ranges for Selected Travel Speeds

3.5.2. Information Needs for Junction Crossing Crash Countermeasures

Effectively reducing the occurrence of junction crossing crashes through the use of V2V-based countermeasures would require gathering information from multiple vehicles, the environment, and the drivers. The identified information needs would allow the V2V-based crash countermeasures to recognize that a junction crossing crash is imminent, to account for environmental and driver factors, and to identify the point when an avoidance maneuver or decision must be initiated to avoid the crash.

Junction crossing crash countermeasures must measure vehicles' kinematic data including position, heading, velocity, and acceleration. The kinematic data serve to calculate the relative range, range rate, and time-to-collision to identify if a crash will potentially occur and if it can be avoided. Additionally, countermeasures must collect vehicle specific details including vehicle length and width as well as its acceleration capability, and intersection geometry to feed into the kinematic profile. Other factors that may influence the vehicle's probable acceleration should also be recognized, which may be inferred from vehicle type and the use of vehicle controls that indicate weather precipitation and road surface conditions such as the use of windshield wipers or defrosters and outside temperature. Anticipating the intended maneuver of the subject vehicle would also enhance the capability of the junction crossing crash countermeasures since these pre-crash scenarios include different maneuvers by the subject vehicle such as straight crossing, turning left, and turning right. Moreover, the knowledge of the intended travel path and maneuver of the other vehicle would also help improve the capability of the countermeasures.

4. COUNTERMEASURE FUNCTIONAL REQUIREMENTS

The overall information needs of the light vehicle V2V-based crash countermeasures are presented for the five target pre-crash scenario groups. In addition, this section presents functional and performance requirements of relevant crash countermeasures as defined by the Vehicle Safety Communications – Applications (VSC-A) [7-9] and Integrated Vehicle-Based Safety System (IVBSS) [10] projects. This section also discusses whether or not VSC-A applications address all five pre-crash scenario groups as well as the various elements of their countermeasure profiles.

4.1. Information Needs for Pre-Crash Scenario Group Countermeasures

In Section 3, information needs were derived from the kinematic profile of each of the ten pre-crash scenarios. A summation of all needs is presented below. Table 6 shows the information needs that are specific to each of the pre-crash scenario groups.

Information Needs from Profile:

- Vehicle position
- Velocity
- Longitudinal acceleration
- Lateral acceleration
- Heading
- Position in lane
- Yaw rate

Calculated

- Range
- Range rate
- Time-to-collision

Other Information Needs:

- Wiper state, temperature, etc.
- Turn signal use
- Throttle position
- Brake activation
- Vehicle size

Table 6. Pre-Crash Scenario Group Information Needs

Information Needs	Pre-Crash Scenario Group				
	Rear-End	Opposite Direction	LTAP/OD	Junction Crossing	Lane Change
Relative Position	✓	✓	✓	✓	✓
Velocity	✓	✓	✓	✓	✓
Longitudinal Acceleration	✓	✓	✓	✓	✓
Lateral Acceleration	✓	✓	✓	✓	✓
Heading	✓	✓	✓	✓	✓
Yaw rate			✓		✓
Range Rate	✓	✓	✓	✓	✓
Position in Lane	✓	✓			✓
Other: Wiper state, temperature, turn signal status, throttle, brake, etc.	✓	✓	✓	✓	✓

4.2. Functional and Performance Requirements of V2V-Based Safety Applications

This section presents a description of two previous research projects, VSC-A and IVBSS, in terms of V2V-based safety applications. It also includes the functional and performance requirements associated with these projects. Note that these requirements are related to the current V2V communication research and are for research prototyping being done under the V2V research program.

4.2.1. VSC-A Safety Applications

The VSC-A project developed and tested six safety applications for autonomous vehicles to work in conjunction with vehicle positioning systems. It was an extension of prior research that proposed numerous safety applications based on V2V and V2I communications [11]. The following is a brief description of five of these related safety applications that were selected for a test bed in the VSC-A project:

- *Emergency Electronic Brake Light (EEBL)*: This application enables a host vehicle to broadcast a self-generated emergency brake event to surrounding remote vehicles. Upon receiving such event information, the remote vehicle determines the relevance of the event and provides a warning to the driver if appropriate.
- *Forward Collision Warning (FCW)*: This application warns the driver of the host vehicle in case of an impending rear-end collision with a remote vehicle ahead in traffic in the same lane and direction of travel.
- *Intersection Movement Assist (IMA)*: This application warns the driver of a host vehicle when it is not safe to enter an intersection due to high collision probability with other remote vehicles at stop sign controlled and uncontrolled intersections.
- *Blind Spot Warning (BSW) + Lane Change Warning (LCW)*: This application warns the driver of the host vehicle during a lane change attempt if the blind spot zone into which the host vehicle intends to switch is, or will soon be, occupied by another vehicle traveling in the same direction. The application also provides the driver of the host vehicle with advisory information that a vehicle in an adjacent lane is positioned in the blind spot zone when a lane change is not being attempted.
- *Do Not Pass Warning (DNPW)*: This application warns the driver of the host vehicle during a passing maneuver attempt when a slower moving vehicle, ahead and in the same lane, cannot be safely passed using a passing zone that is occupied by vehicles in the opposite direction of travel. The application also provides the driver of the host vehicle with advisory information that the passing zone is occupied when a passing maneuver is not being attempted.

Mapping of these VSC-A applications to the ten priority pre-crash scenarios that comprise the five target pre-crash scenario groups will be addressed in Section 4.3.

4.2.2. IVBSS Safety Applications

The purpose of the IVBSS project was to evaluate the safety benefits and driver acceptance of integrated vehicle-based crash warning technologies to aid drivers in recognizing and avoiding crashes through system alerts and advisories. Two distinct systems were developed and evaluated for light vehicle and heavy truck platforms. These systems were designed to address road departure crashes due to unintended lateral drift and excessive speeds while negotiating a curve, rear-end crashes, and lane change/merge crashes due to unsafe lane movements. Thus, four safety applications were implemented including lateral drift warning, curve speed warning, FCW, and LCW+BSW functions. The latter two IVBSS applications dealt with rear-end and lane change pre-crash scenario groups targeted for V2V-based crash countermeasures.

The IVBSS project identified four major functional activities that might be applicable to V2V-based crash countermeasure systems. The following is a list of items related to each activity:

1. **Sensing and Perception**
    - Monitor vehicle
    - Perceive roadway
    - Perceive obstacles

2. **Situation Characterization and Threat Assessment**
    - Determine road conditions
    - Integrate data: vehicle, target, roadway, and road conditions
    - Assess threats
    - Arbitrate threats
    - Determine driver conditions
    - Identify false alarms

3. **Presentation of Crash-Avoidance Information**
    - Commands to vehicle
    - Cues and displays to driver

4. **System Management**
    - Driver inputs
    - Data integrity, diagnostics, raw data
    - System status messages

Functional requirements about the presentation of "crash avoidance information" and "system management" activities are not included in this report since these requirements are related to the driver-vehicle interface.

4.2.3. Functional Requirements Based on VSC-A and IVBSS Safety Applications

In order to reduce the occurrence and severity of crashes, V2V-based crash countermeasures must be able to detect vehicles within a specified distance in order to provide alerts or warnings to the driver. These systems must evaluate subject vehicle information, other vehicles and objects, roadway data, intended driver maneuvers, and other vehicle's motion to assess whether it is appropriate to alert the driver for crash avoidance. The data are retrieved from remote vehicle sensors including wireless communications, GPS, map matching, and on-board computer systems, etc.

The functional requirements related to the sensing and perception category include the measurement or retrieval of data about the subject vehicle, roadway, nearby vehicles, and other obstacle information. The following is a list of items that are necessary for V2V-based crash countermeasure systems in terms of the vehicle and the roadway:

1. ***Vehicle***:

   Subject and Other Vehicle information:
   - Vehicle type/class
   - Vehicle size (length, width, height)
   - GPS antenna offset (relative XYZ)

   Driver inputs to the vehicle controls:
   - Brake position
   - Throttle position
   - Turn signal status
   - Steering wheel angle or angular rate

   Predict vehicle paths
   - Vehicle speed
   - Vehicle acceleration
   - Time stamp
   - Vehicle heading
   - Vehicle yaw-rate
   - GPS coordinates

2. ***Roadway***:

   - Roadway geometry
   - Heading of the road relative to the vehicle axes and road curvature
   - Functional class of the road
   - Number of travel lanes in the subject vehicle's direction of travel
   - Surface conditions (ambient temperature, wiper state, etc.)

The IVBSS defined category "Situation Characterization and Threat Assessment" includes the activities of assessing and arbitrating threats. These actions integrate the sensing and perception data to determine if it becomes necessary to issue crash alerts or warnings to the driver. The following are some general items which are important for ensuring the proper functioning of V2V-based crash countermeasures in this category:

- Identify if earlier crash alerts are warranted due to road conditions such as ice and snow on the road.

- Identify if earlier crash alerts are warranted due to driver behaviors such as fatigue or inattentiveness.
- Detect vehicles at ample distances that have the most potential to cause a crash.
- Determine when and where vehicles may intersect and suppress alerts if there is no potential for a collision.
- Distinguish between same-direction, opposite-direction, and lateral-direction vehicles.
- Eliminate threats that do not pose a hazard such as lead vehicles in adjacent lanes traveling in the same direction as the subject vehicle.
- Arbitrate threats based on the information about the crash alert circumstances.
- Issue timely crash alerts or warnings to the driver for crash avoidance.

4.2.4. Performance Requirements Based on VSC-A Safety Applications

Table 7 includes the performance requirements as related to V2V-based crash countermeasures. The requirements presented describe the minimum conditions in terms of operational speed, vehicle detection, weather, etc. that the system must satisfy in order to function in the intended manner. These requirements are presented for the VSC-A safety applications addressed previously.

Table 7. Performance Requirements of VSC-A Safety Applications

Performance Parameter	VSC-A Safety Applications				
	EEBL	FCW	DNPW	BSW + LCW	IMA
Operational Speed:					
Minimum Operational Speed Range	11.4 – 30 m/s (25-67 mph)			10-30 m/s	0-30 m/s - host vehicle 7-30 m/s - remote vehicle
Minimum Operational Delta Speed Range			11.4-60 m/s		
Vehicle Detection:					
Zone Definition	Same direction traffic, ahead (same lane), ahead-left, and ahead-right (left and right immediate adjacent lanes)	Same direction traffic, ahead (same lane)	Same direction traffic: ahead (same lane) with a speed delta dependent longitudinal time gap that is measured from the front bumper of the host vehicle to rear bumper of the ahead remote vehicle. Opposite direction traffic: adjacent left lane with a longitudinal detection distance at the extent of DSRC communication range.	Blind spot: Immediate adjacent left or right lane up to 20 meters behind the center of the host vehicle; Zone width - 4 meters. LCW: If vehicle is predicted to be in blind spot within 5 sec.	Intersecting left or intersecting right cross direction traffic out to a length of 300 meters from the projected intersection point
Excluded Vehicles within Zone	Vehicle not traveling in same direction	Vehicle not oriented in the same travel direction	Oncoming vehicle in lane not immediately ajacent to travel lane	Vehicle not traveling in same direction; vehicle traveling in the same lane; vehicle in right blind spot for a left lane warning, and vice versa	Vehicle not oriented such that the paths of the subject vehicle and the remote vehicle intersect
Longitudinal Detection Distance	No greater than 300 m from the front bumper of the host vehicle to the rear bumper of the remote vehicle		See zone definition	See zone definition	No greater than 300 meters for clear line-of-sight between the front bumpers of the host vehicle and the remote vehicle
Lateral Detection Distance	See zone definition	One-half of a lane width about each side of the host vehicle's center	See zone definition	See zone definition	One-half of a vehicle length to the left and right of the longitudinal axis through the center of the vehicle
Dimensions of an Obstructing Vehicle between Host and Remote Vehicle	Length ≤ 7.3 m; height ≤ 2.2 m; width ≤ 2.4 m				
Weather Conditions:					
Ambient Temperature	1 - 38 ^{o}C				
Other:					
Hard Brake Status	> .4 g				

4.3. Comprehensive Target Pre-Crash Scenario Countermeasures

Functional requirements from the VSC-A and IVBSS applications are used to translate the information needs of the five group countermeasures into potential countermeasure functions. Table 8 shows the mapping of the ten priority pre-crash scenarios to the safety applications addressed in the VSC-A and IVBSS projects. Generally, V2V-based crash countermeasures would perform similar functions as the VSC-A safety applications. Two scenarios (LTAP/OD and opposite direction/no vehicle maneuver) do not match directly to the VSC-A and IVBSS applications. It is noteworthy that the IVBSS project instead addresses “opposite direction/no vehicle maneuver” crashes through the lateral drift warning function to the left side of the lane.

Table 8. VSC-A Safety Applications Mapped to Target Pre-Crash Scenarios

Target Pre-Crash Groups and Scenarios		VSC-A Safety Applications				
		EEBL	FCW	IMA	DNPW	BSW+LCW
Rear-End	Lead Vehicle Stopped		✓			
	Lead Vehicle Moving		✓			
	Lead Vehicle Decelerating	✓	✓			
Junction Crossing	SCP @ Non Signal			✓		
LTAP/OD	LTAP/OD					
Opposite Direction	Opposite Direction/No Maneuver					
	Opposite Direction/Maneuver				✓	
Lane Change	Changing Lanes/Same Direction					✓
	Turning/Same Direction					✓
	Drifting/Same Direction					✓

A comprehensive summary of the functional requirements of the pre-crash scenario groups mapped to the VSC-A safety applications is presented in Table 9. The functional requirements for the two pre-crash scenarios that do not directly map to the VSC-A applications are also shown. Some of the functional requirements are not applicable to the various scenarios and are colored gray as noted in Table 9. VSC-A safety applications would require some further development to deal with the different crash characteristics and kinematics of the pre-crash scenarios already addressed by these applications especially in the alert decision making area by considering distinct dynamic states of the vehicles. There are no additional functional requirements resulting from the two remaining scenarios than have already been represented by the other eight target pre-crash scenarios.

Table 9. Functional Requirements Pre-Crash Scenario Groups

Functional Requirements	Pre-Crash Scenario Groups Adressed by VSC-A					Pre-Crash Scenario Groups Not Addressed by VSC-A	
	Rear-End		Junction Crossing	Opposite Direction (Maneuver)	Lane Change	Opposite Direction (No Maneuver)	LTAP/OD
	EEBL	FCW	IMA	DNPW	BSW + LCW	N/A	N/A
Vehicle Type/Class	✓	✓	✓	✓	✓	✓	✓
Vehicle Size (length, width, height)	✓	✓	✓	✓	✓	✓	✓
GPS antenna offset (relative XYZ)	✓	✓	✓	✓	✓	✓	✓
Brake Position	✓	✓	✓	✓	✓	✓	✓
Throttle Position	✓	✓	✓	✓	✓	✓	✓
Turn Signal Status			✓	✓	✓		✓
Steering Wheel Angle or Angular Rate	✓	✓	✓	✓	✓	✓	✓
Vehicle Speed	✓	✓	✓	✓	✓	✓	✓
Vehicle Acceleration - longitudinal	✓	✓		✓		✓	✓
Vehicle Acceleration - lateral				✓	✓	✓	✓
Time Stamp	✓	✓	✓	✓	✓	✓	✓
Vehicle Heading	✓	✓	✓	✓	✓	✓	✓
Vehicle Yaw-rate			✓		✓		✓
GPS coordinates	✓	✓	✓	✓	✓	✓	✓
Roadway geometry	✓	✓	✓	✓	✓	✓	✓
Heading of the road and road curvature	✓	✓	✓	✓	✓	✓	✓
Functional class of the road	✓	✓	✓	✓	✓	✓	✓
Number of travel lanes	✓	✓	✓	✓	✓	✓	✓
Surface conditions (temp., wiper state, etc.)	✓	✓	✓	✓	✓	✓	✓

In addition to the functional requirements listed in Table 9, specific vehicle tracking requirements are necessary for each of the pre-crash scenario groups and relevant VSC-A safety applications. The vehicles that each pre-crash scenario countermeasure and related VSC-A safety application are specifically designed to monitor are presented in Table 10. In addition, the vehicle tracking requirements for the two pre-crash scenarios that do not directly map to the VSC-A applications are shown.

Table 10. Vehicle Detection by Pre-Crash Scenario Groups

Vehicle Location	Pre-Crash Scenario Groups Adressed by VSC-A					Pre-Crash Scenario Groups Not Addressed by VSC-A	
	Rear-End		Junction Crossing	Opposite Direction (Maneuver)	Lane Change	Opposite Direction (No Maneuver)	LTAP/OD
	EEBL	FCW	IMA	DNPW	BSW + LCW	N/A	N/A
Same lane vehicles ahead	✔	✔					
Stopped vehicles ahead	✔	✔					
Moving vehicles ahead	✔	✔				✔	✔
Crossing and oncoming traffic			✔				✔
Vehicles in adjacent lanes				✔	✔	✔	✔
Lane change vehicles					✔	✔	✔
Merging vehicles					✔		
Same direction vehicle in driver's blind spot				✔	✔		

5. CONCLUSIONS

This report identified crash avoidance needs and countermeasure functional requirements for five light-vehicle pre-crash scenario groups that were targeted for safety applications based on dedicated short-range V2V communications. The five groups include rear-end, lane change, opposite direction, LTAP/OD, and junction crossing pre-crash scenarios. The first two groups deal with vehicles traveling in the same direction in the same or adjacent lanes. The third group involves vehicles moving in the opposite direction in the same or adjacent lanes. The last two groups occur at junctions such as intersections and driveways. The LTAP/OD pre-crash scenario consists of multiple vehicles approaching the junction from opposite directions. The junction crossing scenarios entail multiple vehicles approaching the junction from perpendicular directions.

Crash avoidance needs for the V2V-based countermeasures were derived from kinematic equations that represent the time-to-collision and suitable avoidance maneuver for each target pre-crash scenario. These equations incorporated key parameters that the countermeasures must measure in order to decide on whether a crash is imminent in a specific scenario and to determine when to assist the driver. Based on this information, some equations were exercised using selected kinematic data from real world crash data and IVBSS field operational test to obtain estimates of the required communication range for the different safety applications. This type of analysis would help to establish minimum performance specifications for the various V2V-based safety applications.

This report discussed the high-level functions that the countermeasures must perform to effectively prevent or reduce the severity of crashes belonging to the five light-vehicle pre-crash scenario groups. These countermeasure functions were determined from the information needs derived from kinematic equations representing the dynamically distinct pre-crash scenarios. A literature review was conducted to identify countermeasure functional and performance requirements that are directly related to the countermeasures for the five pre-crash scenario groups. Results from the IVBSS and VSC-A projects were assessed to identify the functional requirements that meet the needs of these groups. The IVBSS and VSC-A projects covered in a comprehensive way the rear-end and lane change pre-crash scenario groups. The VSC-A project also tackled the junction crossing as well as the "opposite direction/vehicle making a maneuver" pre-crash scenarios. The two pre-crash scenarios, "opposite direction/no vehicle maneuver" and LTAP/OD, were not directly addressed by the VSC-A project. On the other hand, the IVBSS project dealt with the opposite direction scenario by the lateral drift warning function that alerts the driver of unintentional drift to either side of the travel lane. Further development is recommended to build V2V-based safety applications for the LTAP/OD and "opposite direction/no vehicle maneuver" pre-crash scenarios.

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