U.S. Department
of Transportation
**National Highway
Traffic Safety
Administration**

NHTSA
www.nhtsa.gov

DOT HS 811 732

April 2013

Depiction of Priority Light-Vehicle Pre-Crash Scenarios for Safety Applications Based on Vehicle-to-Vehicle Communications

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 2013	August 2009 – February 2011

4. TITLE AND SUBTITLE
Depiction of Priority Light-Vehicle Pre-Crash Scenarios for Safety Applications Based on Vehicle-to-Vehicle Communications

5. FUNDING NUMBERS
Inter-Agency Agreement
HS-60A1
DTNH22-09-V-00030

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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Research and Innovative Technology Administration
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Cambridge, MA 02142

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
John Harding
U.S. Department of Transportation
National Highway Traffic Safety Administration
1200 New Jersey Avenue SE.
Washington, DC 20590

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
DOT HS 811 732
DOT-VNTSC-NHTSA-11-12

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Document is available to the public from the National Technical Information Service
www.ntis.gov

12b. DISTRIBUTION CODE

13. ABSTRACT

A template of pre-crash scenarios is presented to depict national crash statistics and kinematic information of time-to-collision for the design of appropriate crash countermeasures based on vehicle-to-vehicle (V2V) communications. This template serves the development of functional requirements, performance specifications, test procedures, and benefits estimation for potential light-vehicle V2V safety applications. A set of ten pre-crash scenarios is suggested as a priority list to be addressed by V2V technology for light vehicles (i.e., passenger cars, vans and minivans, sport utility vehicles, and light pickup trucks with gross vehicle weight ratings of 10,000 pounds or less). This report presents the time-to-collision equations as well as the crash statistics for each of the ten priority scenarios based on data available in the General Estimates System, National Motor Vehicle Crash Causation Survey, and Event Data Recorder databases.

14. SUBJECT TERMS
Safety Applications, Intelligent Transportation Systems, light vehicles, vehicle-to-vehicle communications, crash avoidance, General Estimates System, National Motor Vehicle Crash Causation Survey, Event Data Recorder, pre-crash scenarios, crash causes, crash contributing factors, and kinematic data.

15. NUMBER OF PAGES
79

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

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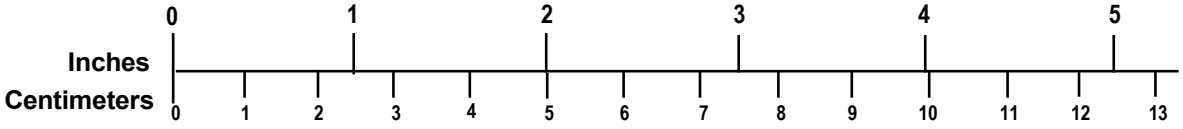
QUICK INCH - CENTIMETER LENGTH CONVERSION



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LIST OF ACRONYMS

AV	Autonomous vehicle
BSW	Blind Spot Warning
CICAS-V	Cooperative Intersection Collision Avoidance System for Violations
CLW	Control Loss Warning
DNPW	Do Not Pass Warning
EDR	Event Data Recorder
EEBL	Emergency Electronic Brake Light
FCW	Forward Collision Warning
FYL	Functional Years Lost
GES	General Estimates System
IMA	Intersection Movement Assist
LCW	Lane Change Warning
LTAP/OD	Left Turn Across Path/Opposite Directions
LVA	Lead Vehicle Accelerating
LVD	Lead Vehicle Decelerating
LVM	Lead Vehicle Moving
LVS	Lead Vehicle Stopped
NASS	National Automotive Sampling System
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*
$\mathbf{D_0}$	Longitudinal gap between subject and other vehicles
$\mathbf{D_i}$	Initial distance from front of vehicle *i* to stop line
ILCD	Intended lane change distance
$\mathbf{L_i}$	Length of vehicle *i*
S(t)	Lateral gap between subject and other vehicles at time *t*
$\mathbf{S_0}$	Lateral gap between subject and other vehicles
t	time
$\mathbf{T_{i(c)}}$	Time for vehicle *i* to clear the path of the other vehicle
$\mathbf{T_{i(r)}}$	Time for vehicle *i* to reach the path of the other vehicle
TLC	Time to complete lane change
ttc	Time-to-collision
$\mathbf{V_i}$	Velocity of vehicle *i* (1 = subject, 2 = other)
$\mathbf{V_{i(s)}}$	Velocity of vehicle *i* at stop line
$\mathbf{W_i}$	Width of vehicle *i*
Y	Lane width
$\boldsymbol{\theta}$	Vehicle yaw/drift angle
$\boldsymbol{\lambda_i}$	Distance from road centerline to edge of vehicle *i*

EXECUTIVE SUMMARY

This report presents a template that describes pre-crash scenarios involving at least one light vehicle for potential safety applications based on vehicle-to-vehicle (V2V) communications. The light-vehicle platform encompasses passenger cars, vans and minivans, sport utility vehicles, and light pickup trucks with gross vehicle weight ratings of 10,000 pounds or less. The goal of the template is to support the development of functional requirements, performance specifications, objective test procedures, and safety benefits for crash avoidance systems using V2V technology. The template consists of representative crash statistics from national crash databases as well as kinematic description of the time-to-collision equations. National crash databases such as the General Estimates System, National Motor Vehicle Crash Causation Survey, and Event Data Recorder provide the necessary variables to depict the characteristics of pre-crash scenarios. Crash elements include:

- Driving environment
- Driver characteristics
- Driver contributing factors
- Driver causal factors
- Vehicle contributing factors
- Kinematic information

From a list of 17 target pre-crash scenarios involving multi-vehicle crashes, a subset of ten pre-crash scenarios is suggested as priority scenarios for V2V-based safety applications. The 10 priority pre-crash scenarios are grouped into 5 distinct categories for consideration as V2V-based safety application packages:

- Junction crossing: Straight crossing paths (SCP) at non-signalized junctions
- Left turn across path/opposite directions (LTAP/OD) at controlled and non-controlled junctions
- Rear-end:
    - Lead vehicle stopped
    - Lead vehicle decelerating
    - Lead vehicle moving at constant speed
- Opposite direction:
    - One vehicle attempting a maneuver such as passing
    - No maneuvering involved such as drifting
- Lane change/same direction:
    - Changing lanes
    - Turning at a junction
    - Drifting

The ten priority pre-crash scenarios account for about 87 percent of the comprehensive economic cost and functional years lost of all V2V pre-crash scenarios involving multiple vehicles with at least one light vehicle.

The 10 priority pre-crash scenarios listed above were mapped to potential V2V-based safety applications under development by the Crash Avoidance Metrics Partnership through the Vehicle Safety Communications – Applications (VSC-A) project. The LTAP/OD and opposite direction/no maneuver pre-crash scenarios were not addressed by V2V-based crash countermeasures. It should be noted that further development of the VSC-A applications would be required to deal with the different crash characteristics and kinematics of the pre-crash scenarios already addressed by these applications.

1. INTRODUCTION

The Intelligent Transportation System program's 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 function, performance, and initial effectiveness benchmarks. This framework will contribute to determining requirements for safety applications and will 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 results from ongoing analyses in support of the V2V research plan's Track 1 activities for the light-vehicle platform that includes passenger cars, vans and minivans, sport utility vehicles, and light pickup trucks with gross vehicle weight rating of 10,000 pounds or less. Detailed depiction of priority pre-crash scenarios is delineated to help understand their individual characteristics and dynamics, which provides a basis to assess the capabilities required to develop suitable crash avoidance systems to address these scenarios. Moreover, scenario depictions serve the development of crash countermeasure profiles, functional requirements, minimum performance specifications, objective test procedures, and safety benefits estimation.

1.1. Target Light Vehicle Pre-Crash Scenarios

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 recently updated based on crash data from the 2004-2008 General Estimates System (GES), National Motor Vehicle Crash Causation Survey (NMVCCS), and event data recorder (EDR) databases [4]. Further analysis was conducted to identify 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 following 17 pre-crash scenarios were deemed as target crashes for V2V-based safety applications:

1. Rear-end crash/lead vehicle stopped (LVS)
2. Rear-end crash/lead vehicle moving at slower constant speed (LVM)
3. Rear-end crash/lead vehicle decelerating (LVD)
4. Rear-end crash/lead vehicle accelerating (LVA)
5. Rear-end crash/following vehicle making a maneuver
6. Opposite direction/no vehicle maneuver
7. Opposite direction/vehicle making a maneuver
8. Left turn across path from opposite directions (LTAP/OD) at signalized junctions
9. LTAP/OD at non-signalized junctions
10. Straight crossing paths (SCP) at non-signalized junctions
11. Turning at non-signalized junctions
12. Turning right at signalized junctions
13. Running red light
14. Running stop sign
15. Changing lanes/both vehicles traveling in same direction
16. Drifting/both vehicles traveling in same direction
17. Turning/both vehicles traveling in same direction

Table 1 lists and ranks the 17 target pre-crash scenarios in terms of average annual crash frequency, comprehensive economic costs, and functional years lost based on 2004-2008 GES light-vehicle crash statistics.

Table 1. Societal Harm of Target Light Vehicle V2V Pre-Crash Scenarios

Pre-Crash Scenario	Crash Frequency		Comprehensive Costs		Functional Years Lost	
	Value	Rank	Value	Rank	Value	Rank
SCP @ non signal	647,000	2	41,095,000,000	1	292,000	1
Rear-end/LVS	942,000	1	29,716,000,000	2	198,000	3
Opposite direction/no maneuver	118,000	10	29,558,000,000	3	213,000	2
Running red light	237,000	5	18,274,000,000	4	129,000	4
LTAP/OD @ non signal	184,000	9	15,481,000,000	5	111,000	5
LTAP/OD @ signal	204,000	6	14,777,000,000	6	105,000	6
Rear-end/LVD	398,000	3	12,215,000,000	7	82,000	7
Rear-end/LVM	202,000	7	10,342,000,000	8	72,000	8
Changing lanes/same direction	336,000	4	8,414,000,000	9	60,000	9
Turning/same direction	202,000	7	6,176,000,000	10	43,000	10
Opposite direction/maneuver	11,000	17	3,500,000,000	11	25,000	11
Drifting/same direction	105,000	11	3,483,000,000	12	25,000	11
Running stop sign	41,000	14	3,075,000,000	13	22,000	13
Rear-end/striking maneuver	83,000	12	2,381,000,000	14	16,000	14
Turn @ non signal	45,000	13	930,000,000	15	6,000	15
Turn right @ signal	31,000	15	908,000,000	16	6,000	15
Rear-end/LVA	21,000	16	667,000,000	17	5,000	17

1.2. V2V-Based Safety Applications

The Vehicle Safety Communications – Applications (VSC-A) project developed and tested communications-based vehicle safety systems to determine if dedicated short-range communications at 5.9 GHz, in combination with vehicle positioning, can improve upon autonomous vehicle (AV) based safety systems and enable new communications-based safety applications [6]. The VSC-A project was an extension of a prior research effort that originally proposed numerous safety applications based on V2V and vehicle-to-infrastructure communications [7]. Six safety applications were selected for the VSC-A system test bed:

1. Emergency Electronic Brake Light (EEBL): Enables a host (subject) vehicle to broadcast a self-generated emergency brake event to surrounding remote (other) vehicles. Upon receiving such event information, the remote vehicle determines the relevance of the event and provides a warning to the driver if appropriate.
2. Forward Collision Warning (FCW): 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.
3. Intersection Movement Assist (IMA): 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.
4. Blind Spot Warning + Lane Change Warning (BSW+LCW): 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.
5. Do Not Pass Warning (DNPW): 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.
6. Control Loss Warning (CLW): Enables a host vehicle to broadcast a self-generated control loss 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.

Table 2 maps target V2V pre-crash scenarios to VSC-A safety applications. It should be noted that the control loss pre-crash scenarios are excluded from the target V2V scenarios because they mostly involve a single-vehicle crash. Moreover, the CLW application provides situational awareness information about upcoming surface condition hazard and not necessarily about a crash imminent condition between two vehicles. Thus, the focus of target V2V pre-crash scenarios is on driving scenarios that involve at least two vehicles on an imminent collision path. The three pre-crash scenarios that do not map directly to any of the safety applications defined within the scope of the VSC-A project are LTAP/OD at signalized junctions, turning right at signalized junctions, and running red light. Although these three scenarios are addressed

primarily by V2V communications in multiple vehicle incidents, they may also be addressed at the vehicle level with vehicle-to-infrastructure communications.

Table 2. Mapping of Target Light-Vehicle Pre-Crash Scenarios to VSC-A Applications

Target Pre-Crash Scenarios	VSC-A Safety Applications				
	EEBL	FCW	IMA	BSW+LCW	DNPW
Rear-end crash/LVS		√			
Rear-end crash/LVM		√			
Rear-end crash/LVD	√	√			
Rear-end crash/LVA		√			
Rear-end crash/following vehicle making a maneuver		√			
Opposite direction/no vehicle maneuver					√
Opposite direction/vehicle making a maneuver					√
LTAP/OD at signalized junctions					
LTAP/OD at non-signalized junctions			√		
SCP at non-signalized junctions			√		
Turning at non-signalized junctions			√		
Turning right at signalized junctions					
Running red light					
Running stop sign			√		
Changing lanes/both vehicles traveling in same direction				√	
Drifting/both vehicles traveling in same direction				√	
Turning/ both vehicles traveling in same direction				√	

1.3. Target Pre-Crash Scenario Groups

The 17 target V2V pre-crash scenarios were organized into six target pre-crash scenario groups [4]. These groups were logically organized by their crash characteristics including movement and relative positioning between vehicles prior to impact. The six groups are:

1. Rear-end
2. Lane change
3. Opposite direction
4. LTAP/OD
5. Junction crossing
6. Traffic control device (TCD) violation

Table 3 presents the six pre-crash scenario groups with their combined comprehensive economic costs and functional years lost. In total, the six groups account for approximately 73 percent of the comprehensive costs and functional years lost of all multiple-vehicle V2V crashes involving at least one light vehicle. The remaining 27 percent of the total societal cost is attributed to control loss, parking, backing up, and 'other' pre-crash scenarios. The most frequent collisions occur in the rear-end pre-crash scenario group, followed by the junction crossing group.

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. Four of the five scenarios differ only in the velocity and acceleration of the lead vehicle. Lane change crashes are

characterized by predominantly laterally oriented multiple-vehicle crashes between vehicles traveling in the same direction in adjacent lanes. 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, typically away from road junctions. The LTAP/OD pre-crash scenarios consist of 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. 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 last group, TCD Violation, is different from the other five groups as it requires a specific driver violation at junctions controlled by 3-color signals or stop signs.

Table 3. 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	7.8%

In this report, a subset of the 17 target pre-crash scenarios is selected as priority scenarios for V2V-based safety applications. A priority scheme is established using the relative contribution of each pre-crash scenario to the total societal harm produced by the 17 target pre-crash scenarios. Priority scenarios are then described in terms of crash characteristics and physical equations following a template that has been developed to depict the key elements of each group of scenarios so as to aid system designers in quantifying essential aspects of the driving situation.

2. FRAMEWORK OF PRE-CRASH SCENARIO DEPICTIONS

Pre-crash scenarios are depicted to convey information that will be helpful in the development of functional requirements, performance specifications, objective test procedures, and estimation of safety benefits for V2V-based safety applications. A depiction framework is presented below to characterize each group of priority V2V pre-crash scenarios using a template that meets these objectives. This depiction supplements the pre-crash scenario template based on national crash statistics found in the GES, NMVCCS, and EDR databases as presented in [4]. The template consists of the following elements:

- Driving environment (GES):
    - Roadway alignment × roadway surface condition × atmospheric condition
    - Relation to junction × traffic control device
    - Lighting condition
    - Posted speed limit
- Driver characteristics (GES):
    - Age
    - Gender
- Driver contributing factors (GES):
    - Alcohol
    - Drugs
    - Physical impairment
    - Violation
    - Speeding
    - Vision obscured
    - Distraction
- Driver causal factors (NMVCCS):
    - Fatigued
    - Inattention
    - Conversing
    - Misjudgment of distance/speed
    - False assumption
    - Inadequate evasive action
    - Inadequate surveillance
    - Following too closely
- Vehicle contributing factors (GES)
- Corrective action attempted (GES)
- Kinematic information (EDR):
    - Travel speed
    - Brake activation
    - Deceleration level

2.1. Elements of Pre-Crash Scenario Depictions

The depiction of pre-crash scenarios consists of the following four key elements as described below in Sections 2.1.1 through 2.1.4. These are general crash characteristics, relative location and motion of vehicles, supporting demographic data, and kinematic crash depiction.

2.1.1. General Crash Characteristics

- *Typical Scenario*: Each pre-crash scenario group is depicted in a typical configuration to illustrate the common kinematic and time-dependent elements. A generic illustration is provided, which shows the simplest roadway geometry and defines the critical quantitative physical parameters.
- *Critical Event*: Each pre-crash scenario group is linked to a primary critical event that made the crash imminent [8]. There are three primary critical events:

    1. Lane departure leading to encroachment onto the travel lane of another vehicle. The two vehicles may be traveling in the same or opposite directions.
    2. Approaching a vehicle in the same lane. The two vehicles may be traveling in the same or opposite directions.
    3. Encroaching onto the travel lane of another vehicle at junctions including turning across the path or straight crossing paths. In turning across the path, the two vehicles may be initially traveling from the same or opposite directions.

2.1.2. Relative Location and Motion of Vehicles

The location and trajectory of the subject vehicle and other relevant vehicles are the essence of the mathematical description for the time-to-collision (ttc) variable. The initial state of the vehicles must be understood and the potential influence of other driving factors must be estimated in order to predict possible intersection of their paths. In addition to the subject vehicle, other vehicles of interest include target vehicles located ahead, behind, and to either side of the subject vehicle. Moreover, the front or rear offset of target vehicles must be considered. V2V-based safety applications must be able to ascertain each vehicle's: relative position (including elevation), velocity, heading, range rate, position in lane, acceleration (longitudinal and lateral), and yaw rate. Elevation can be especially crucial at overpasses and underpasses where two-dimensional representations of the trajectories would generate numerous false alerts.

2.1.3. Supporting Demographic Data

Where available, the template will include supporting demographic data from the GES and NMVCCS databases [4]. Such information provides insight into the most common crash contributing factors.

2.1.4. Kinematic Crash Depiction

The three key elements described above are provided for each pre-crash scenario group. In contrast, the kinematic crash depiction element is delineated for each individual pre-crash scenario in the various groups. This fourth element consists of the following:

- *Scenario Configuration*: A figure is provided, which illustrates an essential description of the specific scenario.
- *Crash Timeline*: An illustrative timeline depicts the velocities and the gap between vehicles as a function of time, to the point of impact.
- *Mathematical Description*: A series of mathematical equations are derived to determine whether a collision will occur and the concomitant ttc variable.

2.2. Universal Crash Characteristics

While the generic scenario descriptions capture the essence of the events, there can be numerous complicating and confounding factors that need to be considered for a more complete pre-crash scenario depiction. Many of these factors are common to all crash modes. A multitude of crash characteristics may influence the ttc value other than simple range and range rate between vehicles. Where possible, all relevant crash characteristics should be considered in the calculation of the ttc variable. The alert logic of V2V-based safety applications depends on accurate detection and measurements of these crash characteristics. The following are some crash characteristics that can form part of the alert logic of any V2V system.

2.2.1. Scenario Crash Characteristics

The depictions of the pre-crash scenarios become more complex as real world considerations are taken into account. In particular, detection of vehicles beyond topographical features such as hills or sloped terrain can be augmented by V2V-based safety systems, and may be recognized by measuring vehicle inclination, throttle position, engine RPM, brake use, and GPS data. Vehicle path determination can be enhanced by measuring steering input, yaw rate, and GPS data. Consideration should be given to obstructions to the driver's line of sight such as hills, buildings, and vegetation.

2.2.2. Environmental Crash Characteristics

There are several environmental factors that may contribute to crashes. These include reduced visibility either by darkness at night or sun glare during the day. Precipitation and vehicle window condensation can negatively impact the driver's ability to recognize and react to crash circumstances. Further, precipitation and icing can contribute to reduce traction between the vehicle and the road surface.

Environmental factors can often be inferred through the use of equipment such as headlights and fog lights, windshield wiper, window defrosters, turn signals, and hazard lights. Their use can

indicate reduced visibility, for example. Similarly, the activation of traction control systems or anti-lock brake systems may indicate poor braking performance and thus may serve as measures of the road surface condition.

2.2.3. Driver Crash Characteristics

Driver conditions and errors are a contributing factor in almost every crash to some degree. These factors include misjudging other vehicle behavior and false assumptions of other drivers' behavior, distraction, fatigue, aggressiveness, and impairment (e.g., alcohol or drug use). Potential measurements of driver factors may include blood alcohol content sensors and eye-tracking cameras. Vehicle positioning within lane may indicate fatigue or distraction.

Driver aggressiveness, misjudgment, and false assumptions of other driver's intent present the greatest challenge to measure and quantify due to the subjective nature and effect of the behavior. It may be possible to utilize an extended GPS system track of the vehicle's behavior to highlight aggressiveness over an extended period of time. Repeated occurrences of high accelerations followed quickly by heavy braking, frequent lane changes (augmented by turn signal use during lane change), relative position to other vehicles, frequent passing and horn use may serve as measures of such aggressive behavior. Indicators of aggressive driving behavior may be gleaned from traffic violation citations handed out by State and local police.

2.2.4. Additional Crash Depiction Elements

- *Non-Vehicle Obstructions*: The presence of non-vehicle obstructions such as pedestrians, pedalcyclists, animals, and road debris may trigger unexpected maneuvers by some or all of the vehicles. Non-vehicle obstructions appear as a critical event in some multi-vehicle crashes. These road obstacles must be considered even though they may not be picked up by V2V communications.
- *Traffic Control Devices*: Specific TCDs, including road signs, generally serve to minimize the risk of vehicle crashes. Nonetheless, assumptions and ambiguities about their position, status, and intended audience can result in crashes.
- *Miscellaneous Ambiguities*: Beyond poorly orientated or placed TCDs, there may be other situational ambiguities (e.g., optical illusions regarding relative approach velocity) that can contribute to the critical event of pre-crash scenarios.

3. SELECTION OF PRIORITY PRE-CRASH SCENARIOS

Table 4 presents statistics about the annual societal harm of the 17 target light vehicle pre-crash scenarios in terms of the comprehensive economic costs and functional years lost (FYL). The pre-crash scenarios are arranged by the six target pre-crash scenario groups. The absolute values in Table 4 are similar to those provided in Table 3 in Section 1. The percentage values, however, are computed from the proportions relative to the total societal harm attributed to the 17 target pre-crash scenarios as opposed to the total harm from all light-vehicle, multi-vehicle, police reported crashes. It should be noted that the societal harm is derived from persons who were injured in police reported crashes involving at least one light vehicle, excluding crashes not reported to the police.

Table 4. Societal Harm of Target Pre-Crash Scenarios

Target Pre-Crash Scenario Groups		Comprehensive Costs		Functional Years Lost	
		Total	Percentage	Total	Percentage
Rear-End	Rear-end/LVS	$ 29,716,000,000	14.8%	198,000	14.0%
	Rear-end/LVD	$ 12,215,000,000	6.1%	82,000	5.8%
	Rear-end/LVM	$ 10,342,000,000	5.1%	72,000	5.1%
	Rear-end/striking maneuver	$ 2,381,000,000	1.2%	16,000	1.1%
	Rear-end/LVA	$ 667,000,000	0.3%	5,000	0.4%
	Total	$ 55,321,000,000	27.5%	373,000	26.5%
Lane Change	Changing lanes/same direction	$ 8,414,000,000	4.2%	60,000	4.3%
	Turning/same direction	$ 6,176,000,000	3.1%	43,000	3.0%
	Drifting/same direction	$ 3,483,000,000	1.7%	25,000	1.8%
	Total	$ 18,073,000,000	9.0%	128,000	9.1%
Opposite Direction	Opposite direction/no maneuver	$ 29,558,000,000	14.7%	213,000	15.1%
	Opposite direction/maneuver	$ 3,500,000,000	1.7%	25,000	1.8%
	Total	$ 33,058,000,000	16.4%	238,000	16.9%
LTAP/OD	LTAP/OD @ non signal	$ 15,481,000,000	7.7%	111,000	7.9%
	LTAP/OD @ signal	$ 14,777,000,000	7.4%	105,000	7.4%
	Total	$ 30,258,000,000	15.1%	216,000	15.3%
Junction Crossing	SCP @ non signal	$ 41,095,000,000	20.4%	292,000	20.7%
	Turn @ non signal	$ 930,000,000	0.5%	6,000	0.4%
	Turn right @ signal	$ 908,000,000	0.5%	6,000	0.4%
	Total	$ 42,933,000,000	21.4%	304,000	21.6%
TCD Violation	Running red light	$ 18,274,000,000	9.1%	129,000	9.1%
	Running stop sign	$ 3,075,000,000	1.5%	22,000	1.6%
	Total	$ 21,349,000,000	10.6%	151,000	10.7%
Total		$ 200,992,000,000	100.0%	1,410,000	100.0%

Pre-crash scenario groups deemed as priority for V2V-based safety applications are limited to the following five: rear-end, lane change, opposite direction, LTAP/OD, and junction crossing. The TCD violation group is excluded since its pre-crash scenarios are best addressed with V2I-based safety applications. A cooperative intersection collision avoidance system for violations

(CICAS-V), involving communications between the infrastructure and in-vehicle elements, was developed by the Crash Avoidance Metrics Partnership to reduce the number of violation crashes at controlled intersections [9]. In its basic concept, a CICAS-V equipped vehicle approaching a CICAS-V equipped intersection receives messages about the intersection geometry and type and status of the traffic control device (i.e., stop sign or 3-color signal). A warning is issued if equipment in the vehicle determines that a violation of the stop sign or red light will occur given the current vehicle operating conditions.

The 15 pre-crash scenarios in the five priority pre-crash scenario groups are selected down to a total of ten priority pre-crash scenarios for V2V-based safety applications as listed in Table 5. This reduced selection excludes target pre-crash scenarios that contributed to less than 1.5 percent of the annual societal harm. In addition, the two LTAP/OD pre-crash scenarios are combined as one since they have similar kinematics. Figure 1 illustrates the ranking of the priority pre-crash scenarios based on their relative contribution to the annual societal harm.

Table 5. Priority V2V Pre-Crash Scenarios

No	Pre-Crash Scenario	Group	Cost	FYL
1	SCP @ non signal	Junction Crossing	20.4%	20.7%
2	LTAP/OD	LTAP/OD	15.1%	15.3%
3	Rear-end/LVS	Rear-End	14.8%	14.0%
4	Opposite direction/no maneuver	Opposite Direction	14.7%	15.1%
5	Rear-end/LVD	Rear-End	6.1%	5.8%
6	Rear-end/LVM	Rear-End	5.1%	5.1%
7	Changing lanes/same direction	Lane Change	4.2%	4.3%
8	Turning/same direction	Lane Change	3.1%	3.0%
9	Opposite direction/maneuver	Opposite Direction	1.7%	1.8%
10	Drifting/same direction	Lane Change	1.7%	1.8%
Total			86.9%	87.0%

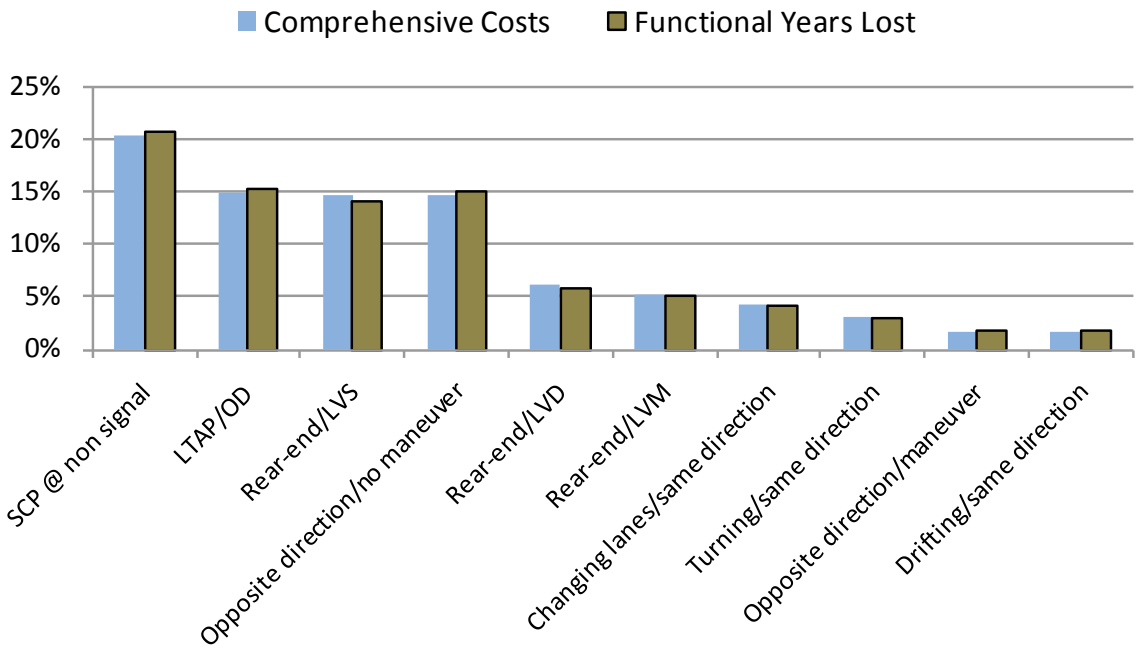


Figure 1. Ranking of V2V Priority Pre-Crash Scenarios

4. DEPICTION OF PRIORITY PRE-CRASH SCENARIOS

Depictions of the five priority pre-crash scenario groups are presented following the framework as described in Section 2. The kinematic depictions include general descriptions of the pre-crash circumstances for all vehicles involved, as well as the critical event that must be addressed by a primary V2V-based crash countermeasure. Universal crash characteristics discussed in Section 2 regarding the subject vehicle's driver and local environment characteristics are applicable to all crash scenarios. A selection of these universal elements that are of special interest to each pre-crash scenario is also presented. These secondary crash elements do not directly indicate or lead to a critical event but may influence the probability of a critical event or the severity of the crash.

For each priority pre-crash scenario, the pre-crash kinematics leading to the moment of impact are illustrated graphically and plotted to illustrate the relationship between the vehicles' velocities and the closing gap between them. The plots show the crash timeline that occurs in the absence of a V2V-based crash countermeasure. Each depiction includes the ttc equation for the vehicle of interest if no crash countermeasure is applied. Appendix A provides relevant crash statistics as reported in [4] including the driving environment, driver characteristics, driver contributing and causal factors, vehicle contributing factors, corrective action attempted, and kinematic information.

4.1. Depiction of Rear-End Pre-Crash Scenario Group

Typical Scenario: A rear-end crash scenario is characterized by front-to-rear impacts between vehicles traveling in the same lane in the same direction as shown in Figure 2. They are typically differentiated by type based upon the velocity and acceleration of the lead vehicle.

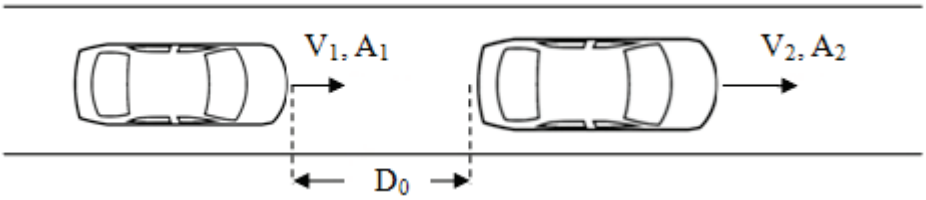


Figure 2. Typical Rear-End Pre-Crash Scenario

Critical Event: The critical event for all rear-end pre-crash scenarios is a following vehicle approaching a lead vehicle in the same lane and in the same path. The lead vehicle may be characterized as stopped, decelerating, accelerating, or simply moving at slower constant speed.

Primary Crash Elements: The relative position of vehicles ahead and offset ahead of the following vehicle is the primary positioning element for all rear-end pre-crash scenarios. Crash countermeasures must record the following metrics for vehicle(s) ahead and offset ahead to determine if a rear-end crash critical event has occurred:

- Relative position, including elevation
- Range rate
- Velocity
- Heading
- Position in lane
- Longitudinal acceleration

Supporting Demographic Data: Driver inattention, following too closely, speeding, and moving violations are main contributing factors to rear-end crashes. Driver distraction, following too closely, and false assumption are cited as primary causal factors in rear-end crashes.

4.1.1. Lead Vehicle Stopped

Scenario Configuration: The following vehicle is typically going straight at constant speed, and then closes in on a stopped lead vehicle as depicted in Figure 3.

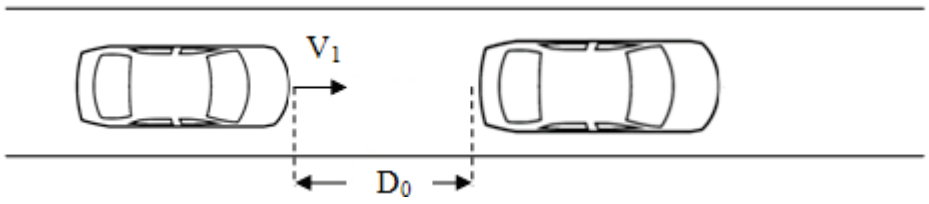


Figure 3. Rear-End/Lead Vehicle Stopped Pre-Crash Scenario Configuration

Crash Timeline: The following vehicle is moving at constant speed and the gap between the two vehicles decreases linearly with time until the vehicles collide as seen in Figure 4. The following vehicle may also be accelerating or decelerating on a straight road or curve.

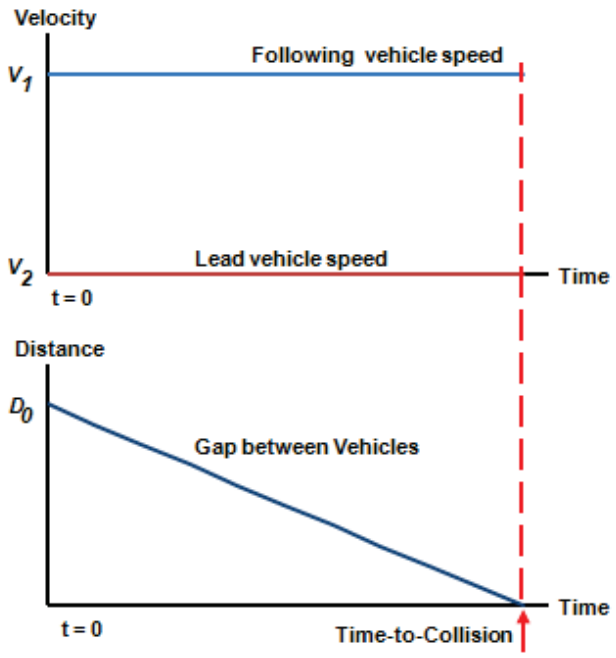


Figure 4. Crash Timeline of Rear-End/Lead Vehicle Stopped Pre-Crash Scenario

Mathematical Description

ttc = Time-to-collision
D_0 = Gap between front of following vehicle and rear of lead vehicle
V_i = Vehicle i speed

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

4.1.2. Lead Vehicle Decelerating

Scenario Configuration: The following vehicle is typically going straight at constant speed and following another lead vehicle that slows down in traffic lane as shown in Figure 5.

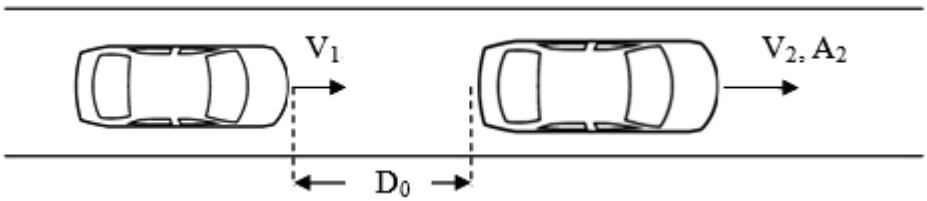


Figure 5. Rear End/Lead Vehicle Decelerating Pre-Crash Scenario Configuration

Crash Timeline: In an LVD scenario in which the following vehicle is traveling at constant speed, the gap between the two vehicles decreases at an ever increasing rate with time until the two vehicles collide as illustrated in Figure 6.

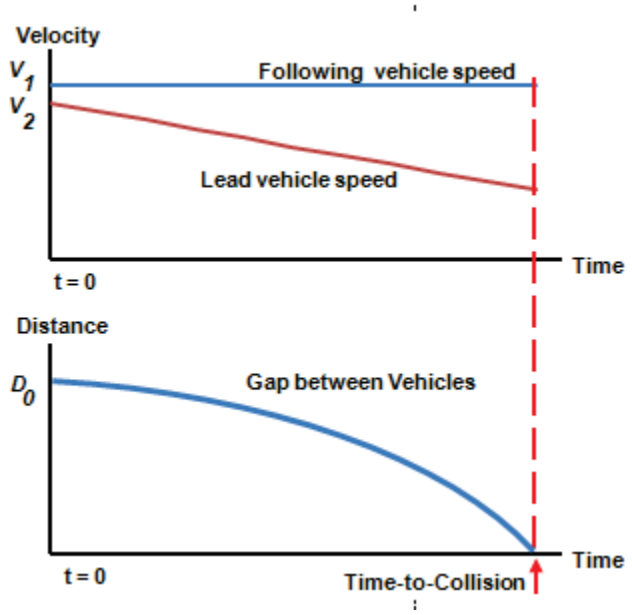


Figure 6. Crash Timeline of Rear-End/Lead Vehicle Decelerating Pre-Crash Scenario

Mathematical Description

ttc = Time-to-collision
D_0 = Initial gap between front of following vehicle and rear of lead vehicle
V_i = Vehicle i speed
A_i = Vehicle i deceleration

The lead vehicle may be struck by the following vehicle after stopping or during braking. The lead vehicle begins braking when t=0. If $\left\{V_1 \times \frac{V_2}{A_2}\right\} \leq \left\{D_0 + \frac{(V_2)^2}{2 \times A_2}\right\}$ then the lead vehicle is struck after stopping. The ttc when the two vehicles collide at the moment the lead vehicle is stopped is calculated from Equation (2) below:

$$ttc_{stopped} = \frac{\left(D_0 + \frac{(V_2)^2}{2 \times A_2}\right)}{V_1} \qquad (2)$$

Otherwise, the lead vehicle is struck during the deceleration state and the ttc may be calculated from:

$$ttc_{moving} = \frac{-1 \times (V_2 - V_1) + \sqrt{(V_2 - V_1)^2 + (2 \times A_2 \times D_0)}}{A_2} \quad (3)$$

4.1.3. Lead Vehicle Moving

Scenario Configuration: Vehicle is typically going straight at constant speed and then closes in on a lead vehicle moving at lower constant speed as shown in Figure 7.

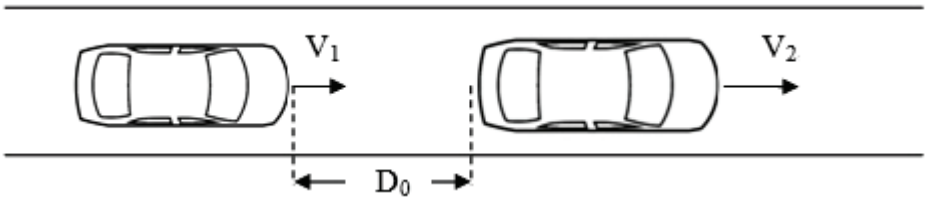


Figure 7. Rear-End/Lead Vehicle Moving Pre-Crash Scenario Configuration

Crash Timeline: In this scenario where the following vehicle is traveling at constant speed, the gap between the two vehicles decreases linearly with time until impact as depicted in Figure 8.

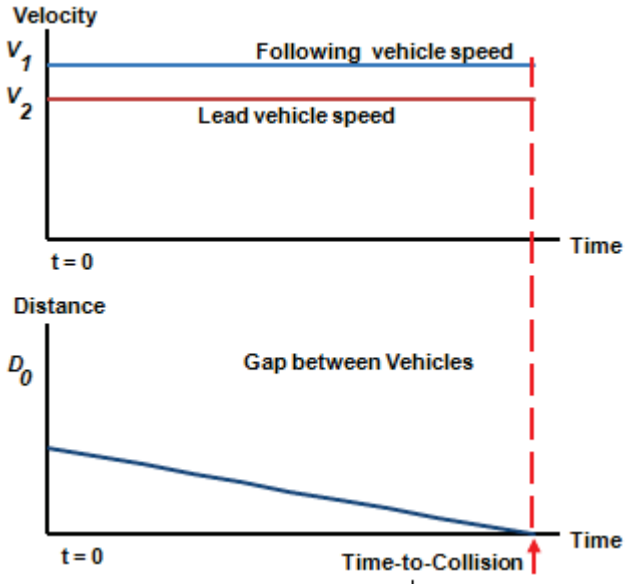


Figure 8. Crash Timeline of Rear-End/Lead Vehicle Moving Pre-Crash Scenario

Mathematical Description

ttc = Time-to-collision
D_0 = Initial gap between front of following vehicle and rear of lead vehicle

V_i = Vehicle *i* speed

$$ttc = \frac{D_0}{(V_1 - V_2)} \quad (4)$$

4.2. Depiction of Opposite Direction Pre-Crash Scenario Group

Typical Scenario: An opposite direction pre-crash scenario is characterized by at least one vehicle encroaching onto an oncoming traffic lane resulting in a front-to-front impact. Figure 9 illustrates the pre-crash location and movement of each vehicle. This encroachment scenario may involve a vehicle drifting out of its travel lane or passing another vehicle in front prior to impact.

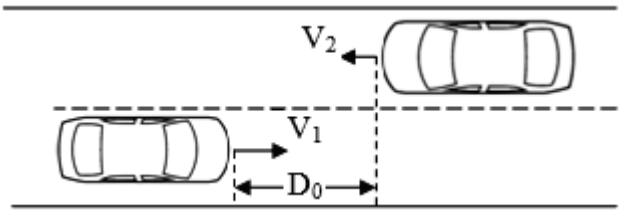


Figure 9. Typical Opposite Direction Pre-Crash Scenario

Critical Event: The critical event for the opposite direction pre-crash scenario group is one vehicle approaching another in the same lane when the two vehicles are initially traveling in the opposite directions.

Primary Crash Elements: The relative position of vehicles to either side and in front of the host vehicle is the primary positioning element for opposite direction pre-crash scenarios. Crash countermeasures must record the following variables to determine if an opposite direction crash critical event has occurred:

- Relative position, including elevation
- Range rate
- Velocity
- Heading
- Position in lane
- Lateral acceleration

Supporting Demographic Data: Driver distraction, fatigue, inadequate evasive action, and inadequate surveillance are cited as causal factors in opposite direction crashes.

4.2.1. Opposite Direction/No Maneuver

Scenario Configuration: Vehicle is going straight, and then drifts and encroaches into another vehicle traveling in the opposite direction. Figure 10 illustrates the scenario.

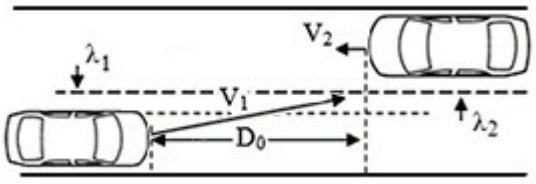


Figure 10. Opposite Direction/No Maneuver Pre-Crash Scenario Configuration

Crash Timeline: Figure 11 traces the time history of an opposite direction/no maneuver crash scenario in which both vehicles are traveling along the same general axis at constant speeds in opposing directions. The longitudinal gap between the two vehicles decreases linearly with time until the two vehicles collide.

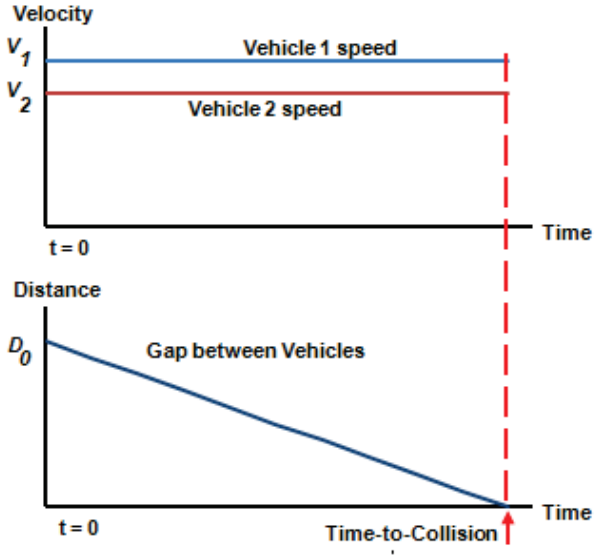


Figure 11. Crash Timeline of Opposite Direction/No Maneuver Pre-Crash Scenario

Mathematical Description

ttc = Time-to-collision
D_0 = Initial gap between the front of Vehicle 1 and the front of Vehicle 2
V_i = Vehicle i speed
λ_i = Distance from left side of Vehicle *i* to the road center line

$$ttc = \frac{D_0}{\frac{V_1 \cdot D_0}{\sqrt{{D_0}^2 + (\lambda_1 + \lambda_2)^2}} + V_2} \tag{5}$$

4.2.2. Opposite Direction/Maneuver

Scenario Configuration: Subject vehicle (V_1) is initially following or closing in on a lead vehicle in the same lane. The subject vehicle then makes a passing maneuver around the lead vehicle and encroaches into another vehicle (V_2) traveling in the opposite direction as illustrated in Figure 12.

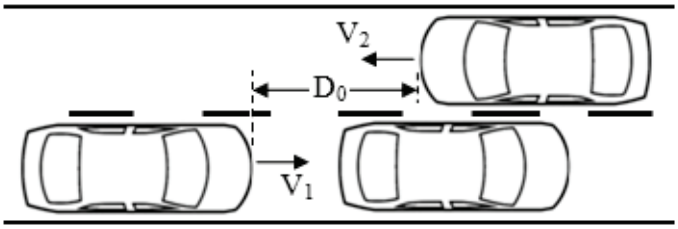


Figure 12. Opposite Direction/Maneuver Pre-Crash Scenario Configuration

Crash Timeline: In an opposite direction/maneuver pre-crash scenario, the colliding vehicles are initially traveling in opposite directions in separate lanes. The critical event occurs when the subject vehicle crosses onto the oncoming lane to maneuver around a lead vehicle. Assuming the subject vehicle (V_1) and the opposing vehicle (V_2) remain in the same lane traveling along the same path in opposite directions, the crash timeline is represented by Figure 11.

Mathematical Description

Assuming that the critical event has occurred and Vehicle 1 is already in the opposing lane, the time-to-collision is expressed as follows:

ttc = Time-to-collision
D_0 = Initial gap between the front of Vehicle 1 and the front of Vehicle 2
V_i = Speed of Vehicle *i*

$$ttc = \frac{D_0}{(V_1 + V_2)} \quad (6)$$

4.3. Depiction of Left Turn Across Path/Opposite Direction Pre-Crash Scenario Group

Typical Scenario: An LTAP/OD pre-crash scenario is characterized by a vehicle turning left across the path of an oncoming vehicle at a junction, both initially traveling in opposite directions, resulting in a front-to-front or front-to-side impact. The two pre-crash scenarios in this group are only differentiated by the presence of a traffic signal at the scene of the crash. Figure 13 illustrates a general configuration of this pre-crash scenario group. It should be noted that the left turning vehicle may initially travel at constant speed, decelerate, or start from a stop before making the left turn. Moreover, there are crash cases that involve both vehicles making a left turn in this pre-crash scenario group. Driver intent to turn left is typically indicated by the use of the turn signal or the presence of the subject vehicle in a left-turn-only lane.

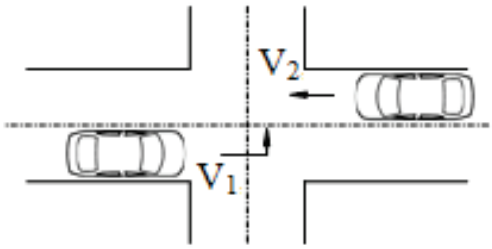


Figure 13. Typical LTAP/OD Pre-Crash Scenario

Critical Event: The critical event for the LTAP/OD pre-crash scenario is the encroachment of the subject vehicle onto the travel lane and path of another vehicle at junctions when executing the left turn maneuver.

Primary Crash Elements: The primary positioning element for all LTAP/OD pre-crash scenarios is the relative position of vehicles' lateral offset, with both vehicles initially traveling in the opposite directions. Crash countermeasures must record the following parameters to determine if the critical event of an LTAP/OD crash has occurred:

- Relative position, including elevation
- Range Rate
- Heading
- Velocity
- Yaw Rate

Supporting Demographic Data: Driver distraction and inadequate surveillance measures are primary causal factors in LTAP/OD crashes.

4.3.1. LTAP/OD at Non-Signalized or Signalized Junctions

Scenario Configuration: In Figure 14, one vehicle is turning left at an intersection without traffic controls or controlled by a 3-color signal (shown) and then cuts across the path of another vehicle traveling from the opposite direction.

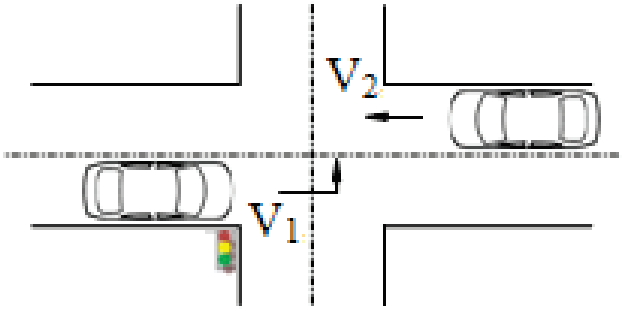


Figure 14. LTAP/OD Pre-Crash Scenario Configuration

Crash Timeline: In an LTAP/OD pre-crash scenario, the subject vehicle approaches a perpendicular junction at a constant speed intending to turn left. The subject vehicle then slows, but does not stop, to execute the left turn at a constant speed and is struck by a vehicle traveling at constant speed from the opposite direction in the opposing lane as depicted in Figure 15. The subject vehicle may also come to a full stop first before proceeding with the left turn maneuver as illustrated in Figure 16.

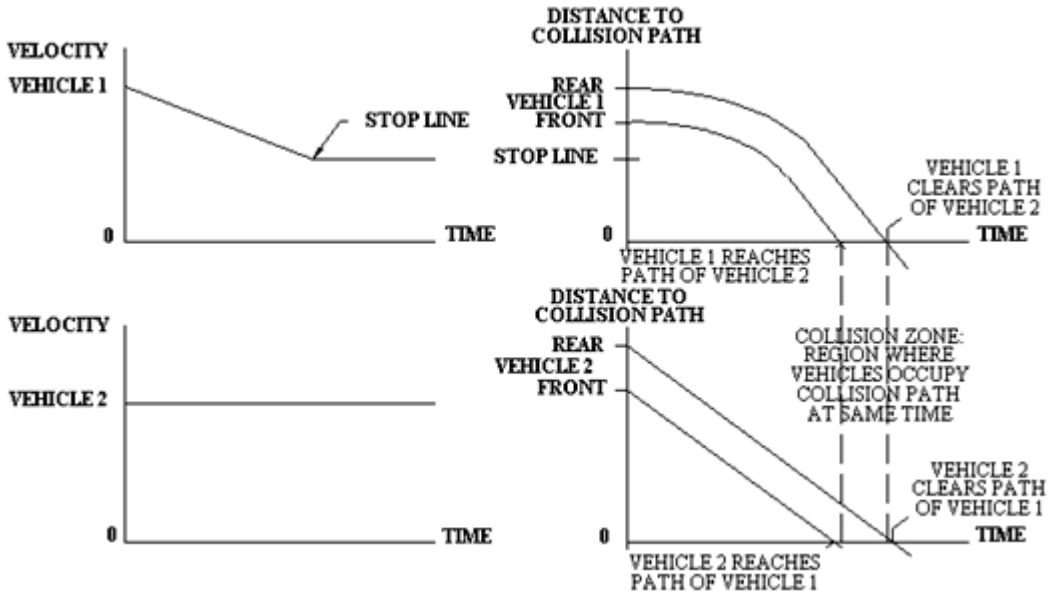


Figure 15. Crash Timeline of LTAP/OD Pre-Crash Scenario (Vehicle 1 Slows/Turns)

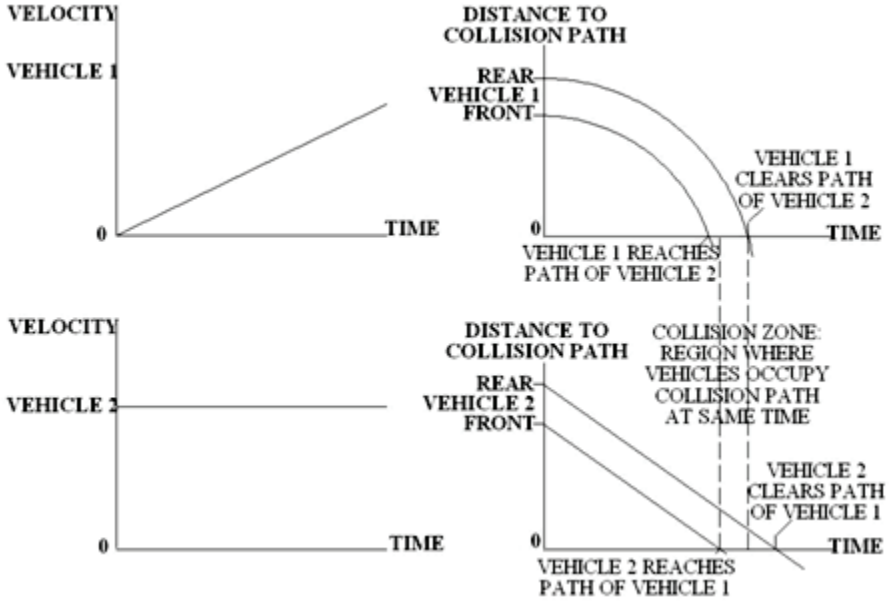


Figure 16. Crash Timeline of LTAP/OD Pre-Crash Scenario (Vehicle 1 Starts from Stop/Turns)

Mathematical Description

Vehicle 1 Slows Down and Turns Left at Constant Speed

Figure 17 is presented below to explain the different variables used in the mathematical description of this particular LTAP/OD pre-crash scenario.

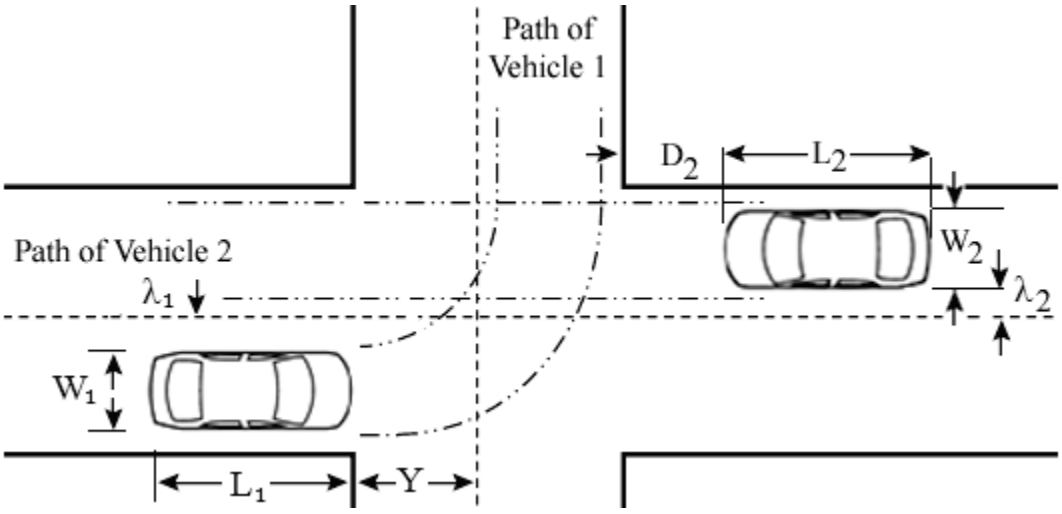


Figure 17. Schematic of LTAP/OD Pre-Crash Scenario

L_i = Length of Vehicle *i*
W_i = Width of Vehicle *i*
λ_i = Lateral distance from side of Vehicle *i* to center line
D_i = Initial distance from front of Vehicle *i* to stop line
V_i = Initial velocity of Vehicle *i* at D_i
$V_{i(s)}$ = Velocity of Vehicle *i* at stop line
A_i = Acceleration of Vehicle *i*
Y = Width of lane

Time for front of Vehicle 1 to reach path of Vehicle 2 is:

$$T_{1(r)} = \frac{V_1 - \sqrt{V_1^{\,2} - 2 \cdot A_1 \cdot D_1}}{A_1} + \frac{cos^{-1}\left(\frac{Y - L_2}{Y + L_1}\right) \cdot (Y + L_1)}{V_{1(s)}} \quad (7)$$

Time for rear of Vehicle 1 to clear path of Vehicle 2 is:

$$T_{1(c)} = \frac{V_1 - \sqrt{V_1^{\,2} - 2 \cdot A_1 \cdot D_1}}{A_1} + \frac{L_1 + \left\{\cos^{-1}\left(\frac{Y - L_2 - W_2}{Y + L_1 + W_1}\right) \times (Y + \lambda_1 + W_1)\right\}}{V_{1(s)}} \quad (8)$$

Time for front of Vehicle 2 to reach path of Vehicle 1 is:

$$T_{2(r)} = \frac{D_2 + 2 \cdot Y - (Y + \lambda_1 + W_1) \cdot \sin\left(\cos^{-1}\left(\frac{Y - L_2 - W_2}{Y + L_1 + W_1}\right)\right)}{V_2} \quad (9)$$

Time for rear of Vehicle 2 to clear path of Vehicle 1 is:

$$T_{2(c)} = \frac{D_2 + L_2 + 2 \cdot Y - (Y + \lambda_1) \cdot \sin\left(\cos^{-1}\left(\frac{Y - \lambda_2}{Y + \lambda_1}\right)\right)}{V_2} \quad (10)$$

A crash would occur if $T_{2(r)} \leq T_{1(c)} \leq T_{2(c)}$ or $T_{1(r)} \leq T_{2(c)} \leq T_{1(c)}$.

Vehicle 1 Accelerates from a Stop and Turns Left

L_i = Length of Vehicle *i*
W_i = Width of Vehicle *i*
λ_i = Lateral distance from side of Vehicle *i* to center line
D_i = Initial distance from front of Vehicle *i* to stop line
V_i = Initial velocity of Vehicle *i* at D_i
A_i = Acceleration of Vehicle *i*
Y = Width of lane

Time for front of Vehicle 1 to reach path of Vehicle 2 is:

$$T_{1(r)} = \sqrt{\frac{2 \cdot \cos^{-1}\left(\frac{Y - L_2}{Y + L_1}\right) \cdot (Y + \lambda_1)}{A_1}} \quad (11)$$

Time for rear of Vehicle 1 to clear path of Vehicle 2 is:

$$T_{1(c)} = \sqrt{\frac{2 \cdot \left(\cos^{-1}\left(\frac{Y - L_2 - W_2}{Y + L_1 + W_1}\right) \times (Y + L_1 + W_1) + L_1\right)}{A_1}} \quad (12)$$

Time for front of Vehicle 2 to reach path of Vehicle 1 is:

$$T_{2(r)} = \frac{D_2 + 2 \cdot Y - (Y + L_1 + W_1) \cdot \sin\left(\cos^{-1}\left(\frac{Y - L_2 - W_2}{Y + L_1 + W_1}\right)\right)}{V_2} \quad (13)$$

Time for rear of Vehicle 2 to clear path of Vehicle 1 is:

$$T_{2(c)} = \frac{D_2 + L_2 + 2 \cdot Y - (Y + L_1) \cdot \sin\left(cos^{-1}\left(\frac{Y - L_2}{Y + L_1}\right)\right)}{V_2} \quad (14)$$

A crash would occur if $T_{2(r)} \leq T_{1(c)} \leq T_{2(c)}$ or $T_{1(r)} \leq T_{2(c)} \leq T_{1(c)}$.

4.4. Depiction of Junction Crossing Pre-Crash Scenario Group

Typical Scenario: A junction crossing pre-crash scenario is characterized by the subject vehicle stopping and then proceeding straight across the path of another vehicle at a stop sign or turning right into the same direction of the other vehicle at a stop sign or traffic signal, resulting mostly in front-to-side impacts. Figure 18 illustrates straight crossing paths at a stop-sign-controlled intersection, which does not involve any violation of the stop sign. The vehicle in the horizontal direction first stops at the stop line and then proceeds against the path of the vehicle in the vertical direction. In most cases, the driver of the vehicle in the horizontal direction misjudges the gap and speed of the other vehicle.

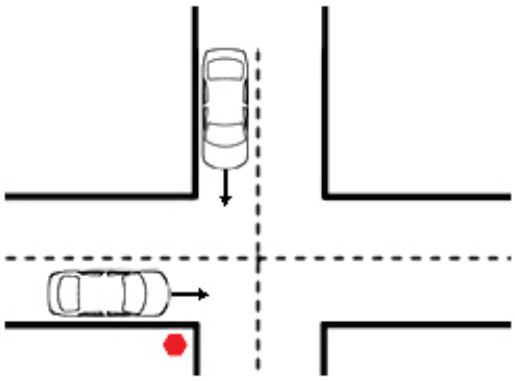


Figure 18. Typical Junction Crossing Pre-Crash Scenario

Critical Event: The critical event for the junction crossing pre-crash scenario group is the encroachment of the subject vehicle onto the travel lane of an oncoming vehicle traveling from a perpendicular direction. The subject vehicle intends to cut across or turn into the other vehicle's travel lane.

Primary Crash Elements: The primary positioning element for all junction crossing pre-crash scenarios is the relative position of vehicles to either side of the subject vehicle. Crash countermeasures must record the following parameters to determine if the critical event of the junction crossing scenario has occurred:

- Relative position, including elevation
- Range rate

- Velocity
- Heading

Supporting Demographic Data: Driver distraction, misjudgment, false assumptions, and inadequate surveillance are associated with junction crossing crashes.

4.4.1. Straight Crossing Paths at Non-Signalized Junctions

Scenario Configuration: Figure 19 presents a schematic of an SCP pre-crash scenario at a stop sign controlled intersection where the subject vehicle first stops at the stop line, and then proceeds by accelerating and traveling straight across the path of another vehicle approaching at a constant speed from a perpendicular direction.

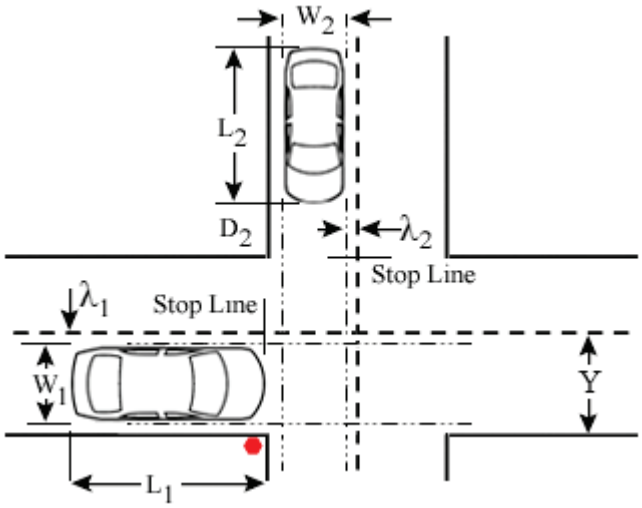


Figure 19. SCP at Non-Signalized Junction Pre-Crash Scenario Configuration

Crash Timeline: Figure 20 illustrates the time history of distance and speed of both vehicles. Vehicle 1 comes to a halt at the stop line and later accelerates to cross the intersection into the path of an oncoming lateral Vehicle 2 whose path is not controlled by a stop sign.

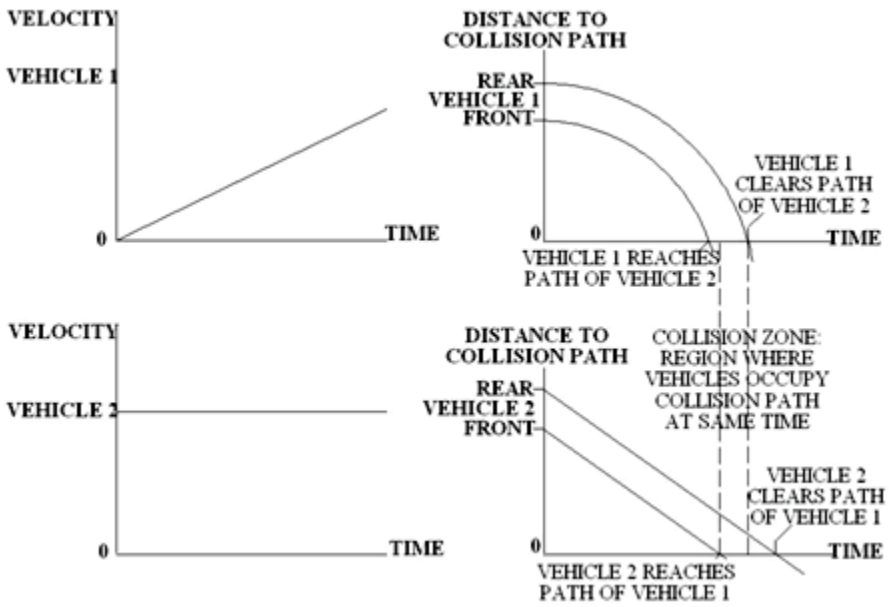


Figure 20. Crash Timeline of SCP Pre-Crash Scenario (Vehicle 1 Stops/Proceeds against Traffic)

Mathematical Description

L_i = Length of Vehicle *i*
W_i = Width of Vehicle *i*
λ_i = Lateral distance from side of Vehicle *i* to center line
D_i = Initial distance from front of Vehicle *i* to stop line
V_i = Initial velocity of Vehicle *i*
A_i = Acceleration of Vehicle *i*
Y = Width of intersection

Time for front of Vehicle 1 to reach path of Vehicle 2 is:

$$T_{1(r)} = \sqrt{\frac{2 \cdot (Y - W_2 - \lambda_2)}{A_1}} \quad (15)$$

Time for rear of Vehicle 1 to clear path of Vehicle 2 is:

$$T_{1(c)} = \sqrt{\frac{2 \cdot (Y + L_1 - \lambda_2)}{A_1}} \quad (16)$$

Time for front of Vehicle 2 to reach path of Vehicle 1 is:

$$T_{2(r)} = \frac{D_2 + Y + \lambda_1}{V_2} \quad (17)$$

Time for rear of Vehicle 2 to clear path of Vehicle 1 is:

$$T_{2(c)} = T_{2(r)} + \frac{W_1 + L_2}{V_2} \quad (18)$$

A crash would occur if $T_{2r} \leq T_{1c} \leq T_{2c}$ or $T_{1r} \leq T_{2c} \leq T_{1c}$.

4.5. Depiction of Lane Change Pre-Crash Scenario Group

Typical Scenario: A lane change crash scenario is characterized by lateral impacts when a vehicle encroaches onto an adjacent lane and impacts a second vehicle with a primarily side-to-side contact as illustrated in Figure 21. They are typically differentiated by type based upon the actions and velocity of the vehicle changing lanes immediately before impact.

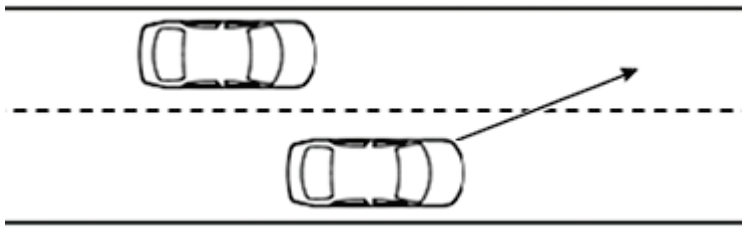


Figure 21. Typical Lane Change Pre-Crash Scenario

Critical Event: The critical event for lane change pre-crash scenarios is the intended or unintended lane departure by one vehicle leading to encroachment onto the travel lane of another vehicle, both traveling in the same direction in adjacent lanes.

Primary Crash Elements: The relative position of vehicles to either side and behind the subject vehicle is the primary positioning element for all lane change pre-crash scenarios. Crash countermeasures must record the following metrics for vehicle(s) to each side and offset behind to determine if a lane change critical event has occurred:

- Relative position, including elevation
- Velocity
- Heading
- Range rate
- Yaw rate
- Position in lane
- Lateral acceleration

Supporting Demographic Data: Driver distraction and inadequate surveillance factors are cited as contributing factors in lane change crashes.

4.5.1. Changing Lanes/Same Direction

Scenario Configuration: One vehicle is going straight and then changes lanes into an adjacent vehicle, both traveling at a constant speed as shown below in Figure 22.

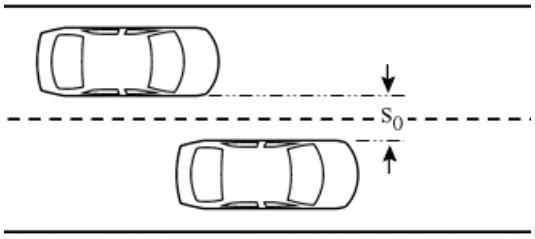


Figure 22. Changing Lanes/Same Direction Pre-Crash Scenario Configuration

Crash Timeline: In this changing lane scenario, the subject vehicle exhibits lateral acceleration as it moves laterally to the adjacent lane, gradually closing the lateral gap with the adjacent vehicle over time until collision as seen in Figure 23.

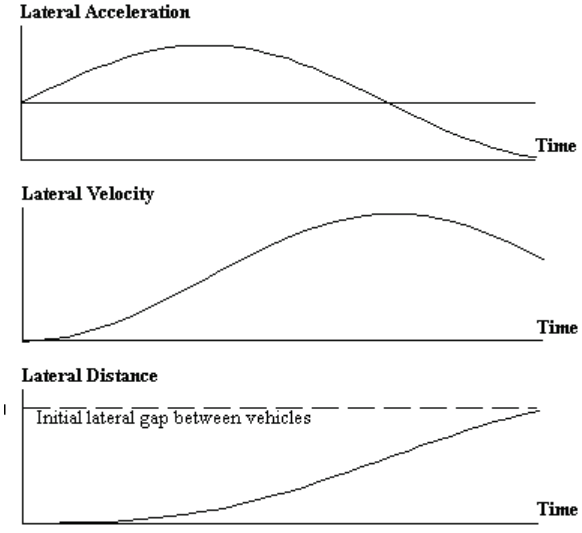


Figure 23. Crash Timeline of Changing Lanes/Same Direction Pre-Crash Scenario

Mathematical Description

S_0 = Initial lateral gap between vehicles
S(t) = Instantaneous lateral gap between vehicles
ILCD = Intended lane change distance
t = time
TLC = Time to complete lane change

Vehicles 1 and 2 are assumed to be traveling side-by-side at the same longitudinal speed. The lateral distance between vehicles is expressed in Equation (19) below:

$$S(t) = S_0 - \frac{ILCD}{TLC} \times \left(t - \frac{sin(\frac{2\pi}{TLC} \times t)}{Y} \right) \quad (19)$$

The time it takes Vehicle 1 to close the lateral gap is determined by setting Equation (19) to zero and solving for time.

4.5.2. Turning/Same Direction

Scenario Configuration: One vehicle is turning left at an intersection, and then cuts across the path of another vehicle initially traveling in the same direction as illustrated in Figure 24.

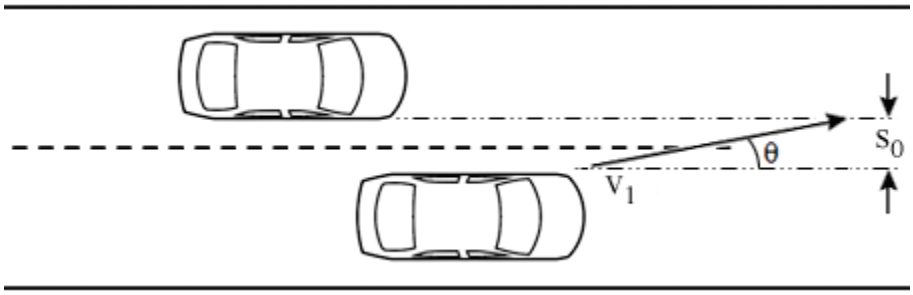


Figure 24. Changing Lanes/Same Direction Pre-Crash Scenario Configuration

Crash Timeline: On a multi-lane road, a vehicle in the right lane attempts to cut across the left adjacent lane to execute a left turn and is struck by a vehicle in the left lane traveling at a constant speed during the turn maneuver, as seen in Figure 25.

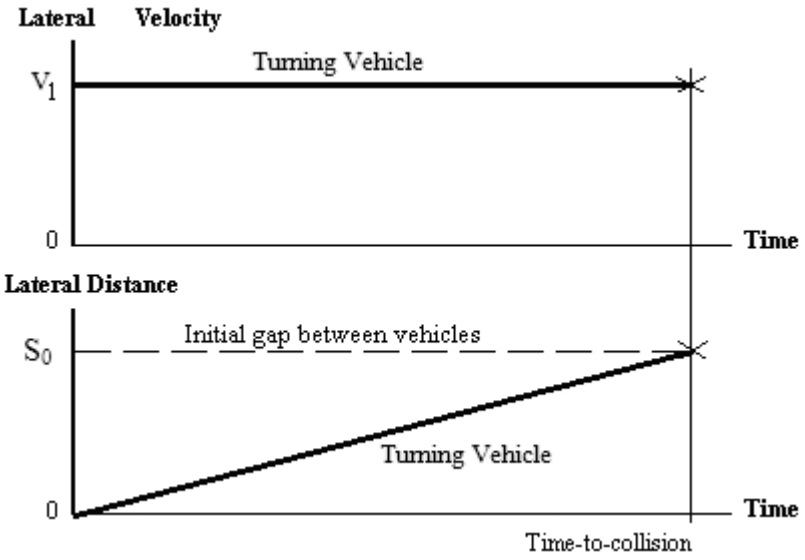


Figure 25. Crash Timeline of Turning/Same Direction Pre-Crash Scenario

Mathematical Description

S_0 = Initial lateral gap between vehicles
V_i = Velocity of Vehicle *i*
θ = Turn (drift) angle of Vehicle 1

Vehicles 1 and 2 are assumed to be traveling side-by-side at the same longitudinal speed. The time for Vehicle 1 to close lateral gap and strike Vehicle 2, ttc, is expressed in Equation (20):

$$ttc = \frac{S_0}{V_1 \cdot \sin(\theta)} \quad (20)$$

4.5.3. Drifting/Same Direction

Scenario Configuration: One vehicle is going straight and then drifts onto an adjacent lane and strikes another vehicle traveling in the same direction, similar to the representation in Figure 24.

Crash Timeline: On a multi-lane road where two vehicles are traveling in the same direction, the subject vehicle drifts across the lane marker and collides with the vehicle in the adjacent lane as seen in Figure 25 (turning vehicle becomes drifting vehicle).

Mathematical Description

The mathematical description of the drifting/same direction pre-crash scenario is also represented by Equation 20 derived for the turning/same direction pre-crash scenario.

5. CONCLUDING REMARKS

A template was presented to completely depict pre-crash scenarios deemed as priority for V2V-based safety applications. The template consists of representative crash statistics from national crash databases as well as kinematic descriptions of the time-to-collision equations. From a list of 17 target pre-crash scenarios, a subset of ten pre-crash scenarios were suggested as priority scenarios for V2V-based safety applications. The ten priority pre-crash scenarios were also grouped into five distinct categories for consideration as V2V-based safety application packages. The pre-crash scenario template provides a basis for the development of functional requirements, performance specifications, objective test procedures, and safety benefits for V2V-based safety applications.

The ten priority pre-crash scenarios were mapped to potential VSC-A applications as shown in Table 6. The LTAP/OD and opposite direction/no maneuver pre-crash scenarios remain to be addressed by V2V-based crash countermeasures. It should be noted that the VSC-A applications would require further development to deal with the different crash characteristics and kinematics of the pre-crash scenarios already addressed by these applications.

Table 6. Mapping of Priority Pre-Crash Scenarios to VSC-A Applications

			VSC-A Safety Applications				
No	**Group**	**Pre-Crash Scenario**	**EEBL**	**FCW**	**IMA**	**BSW+LCW**	**DNPW**
1	Junction Crossing	SCP @ non signal			√		
2	LTAP/OD	LTAP/OD					
3	Rear-End	Rear-end/LVS		√			
4		Rear-end/LVD	√	√			
5		Rear-end/LVM		√			
6	Opposite Direction	Opposite direction/maneuver					√
7		Opposite direction/no maneuver					
8	Lane Change	Changing lanes/same direction				√	
9		Turning/same direction				√	
10		Drifting/same direction				√	

If V2V-based crash countermeasures are to prove effective in reducing the frequency and severity of light-vehicle crashes, systems must rapidly, accurately, and continually assess the likelihood of a crash in each of the ten priority pre-crash scenarios. Systems must determine whether a crash is imminent with sufficient lead time to allow the countermeasure to either prevent the crash or to reduce the harm to all persons involved. A critical element of a pre-crash depiction is the determination of the range and range rate between the vehicle of interest and all other similarly equipped vehicles in the vicinity. At all times, communications between two vehicles' systems must determine the potential time-to-collision that will in turn determine

whether to deploy the countermeasures, and to what degree. To determine ttc, systems must be able to determine subject vehicle position, velocity, longitudinal and lateral acceleration, as well as its in-lane position and yaw rate, and its relation in each of these measures to other vehicles in close proximity. As vehicles approach one another, the ttc may approach zero. A series of thresholds may be crossed that can be used to trigger varying countermeasure interventions. Finally, systems must be able to discriminate between crash imminent driving situations and benign driving conditions so as to minimize the occurrence of false positive interventions.

6. REFERENCES

[1] *ITS Strategic Research Plan, 2010-2014: Transforming Transportation Through Connectivity*. (2010). (Report No. FHWA-JPO-10-028). Washington, DC: U.S. Department of Transportation, Research and Innovative Technology Administration, ITS Joint Program Office.

[2] *USDOT IntelliDrive^{SM} Program: Vehicle to Vehicle Safety Application Research Plan.* (2009). Washington, DC: National Highway Traffic Safety Administration; and Research and Innovative Technology Administration.

[3] Najm, W. G., Smith, J. D. & Yanagisawa, M. (2007). *Pre-Crash Scenario Typology for Crash Avoidance Research*. (Report No. DOT HS 810 767). Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.

[4] Najm, W. G., Ranganathan, R., Srinivasan, G., Smith, J. D., Toma, S., Swanson, E., & Burgett, A. (In review). *Description of Pre-Crash Scenarios for Safety Applications Based on Vehicle-to-Vehicle Communications*. Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.

[5] Najm, W. G., Koopmann, J., Smith, J. D., & Brewer, J. (2010). *Frequency of Target Crashes for IntelliDrive^{SM} Safety Systems*. (Report No. DOT HS 811 381). Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.

[6] Farid, A. Z. & Carter, A. (2009). *Vehicle Safety Communications – Applications First Annual Report*. (Report No. DOT HS 811 073). Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.

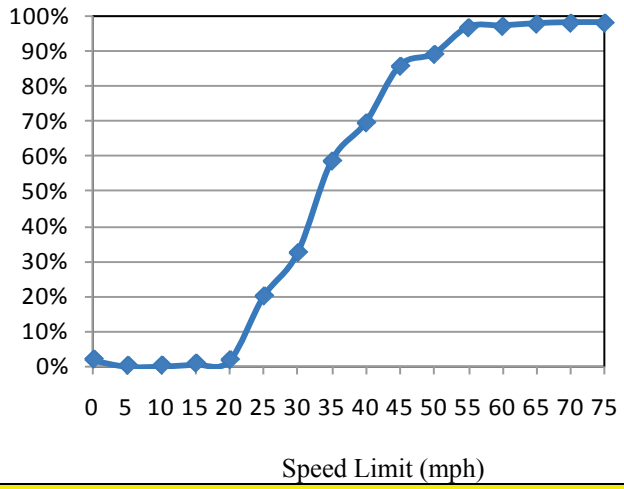
[7] Crash Avoidance Metrics Partnership. (2006). *Vehicle Safety Communications Project – Final Report*. (Report No. DOT HS 810 591). Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.

[8] National Center for Statistics and Analysis. (2009). *National Automotive Sampling System (NASS) General Estimates System (GES) Analytical User's Manual 1988-2008*. Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.

[9] Crash Avoidance Metrics Partnership. (2007). *Cooperative Intersection Collision Avoidance System Limited to Stop Sign and Traffic Signal Violations (CICAS-V) – Concept of Operations*. (Report No. DTFH61-01-X-00014). Washington, DC: U.S. Department of Transportation, Federal Highway Administration.

APPENDIX A. CRASH CHARACTERISTICS OF PRIORITY PRE-CRASH SCENARIOS

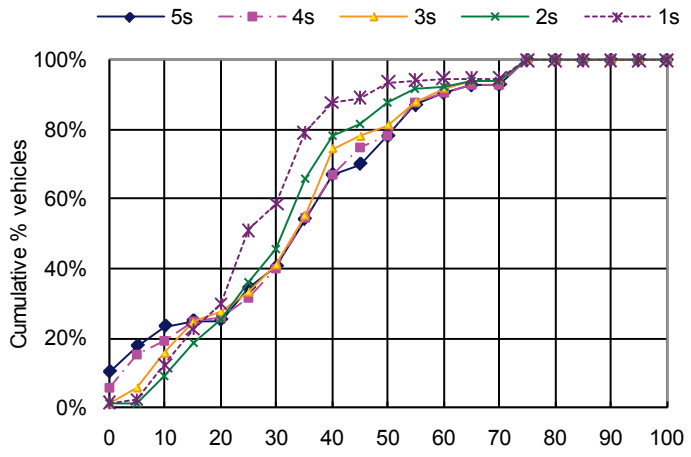
A1. Straight Crossing Paths at Non-Signal

Driving Environment[1]	
Roadway Alignment × Roadway Surface Condition × Atmospheric Condition	77% - Straight, dry road surface with no adverse weather 11% - Straight, slippery road surface with adverse weather
Relation to Junction × Traffic Control Device	52% - Intersection or intersection related at stop sign 25% - Driveway, alley, etc. without traffic controls
Lighting Condition	80% - Daylight 12% - Dark but lighted
Posted Speed Limit	
Driver Characteristics	
Age	28% - 0 to 24 years 61% - 25 to 64 years 10% - 65 years or above
Gender	53% - Male 47% - Female
Driver Contributing Factors	
Alcohol	2% - Alcohol use
Drugs	< 1% - Drug use
Physical Impairment	< 1% - Physical impairment
Violation Cited	27% - Violation cited
Speeding	2% - Speeding
Vision Obscured	8% - Obstruction
Distraction	13% - Distracted
Vehicle Contributing Factors	
Contributing Factors	< 1% - Contributing Factors

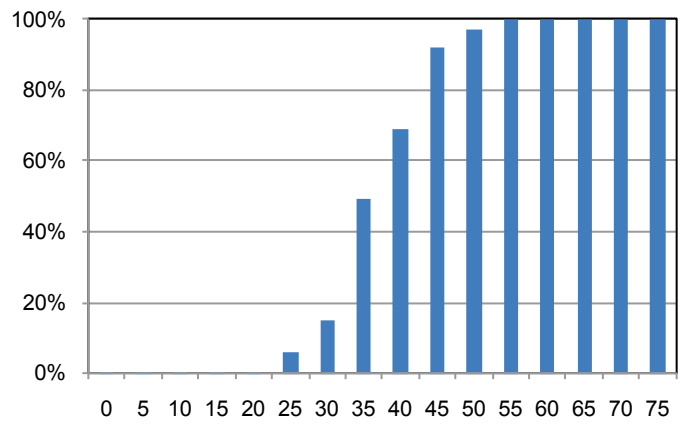
[1] The data in Appendix A presents the most significant values only, the data not shown is divided across multiple entries that are not individually significant though they appear significant when summed.

Corrective Action Attempted	
Corrective Action	6% - Braking (No lockup) 9% - Braking (Lockup) 7% - Braking (Lockup Unknown) 11 % - Steering Left 6% - Steering Right 2% - Braking and Steering Left 1% - Braking and Steering Right 1% - Unspecified action
Causal Factors (NMVCCS)	
	(Combined SCP & Turn at Non-Signal)
Driver Fatigued	9% - Driver fatigued
Inattention	13% - Inattention factors
Driver Conversing	16% - Conversing
Misjudgment of Distance/Speed	6% - Misjudgment of distance/speed factors
False Assumption	13% - False assumption factors
Inadequate Evasive Action	4% - Inadequate evasive action factors
Critical Reason	21% - No critical reason 0% - Sleepy 0% - Ill/blackout 76% - Driver error 1% - Vehicle issues 2% - Weather /road /sign-signal issues
Inadequate Surveillance	69% - Inadequate surveillance factors
Other Driver Recognition Factors	14% - Other recognition factors
Following Too Closely	0% - Following too closely factors
Other Driver Decision Factors	29% - Other decision factors

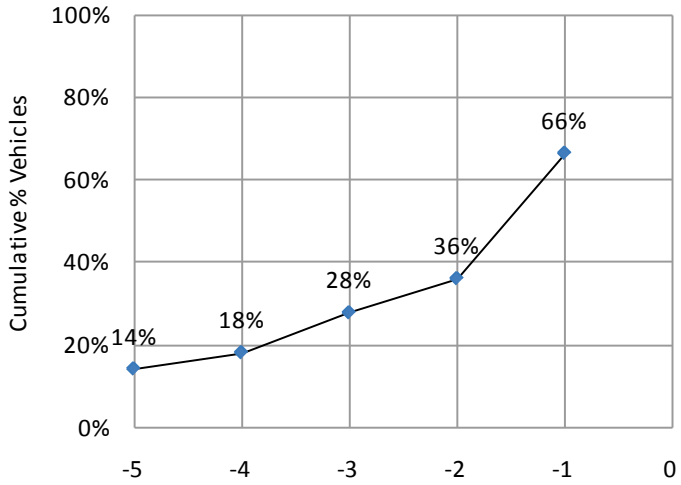
Kinematic Data (126 EDR Cases) **SCP at Non-Signal**



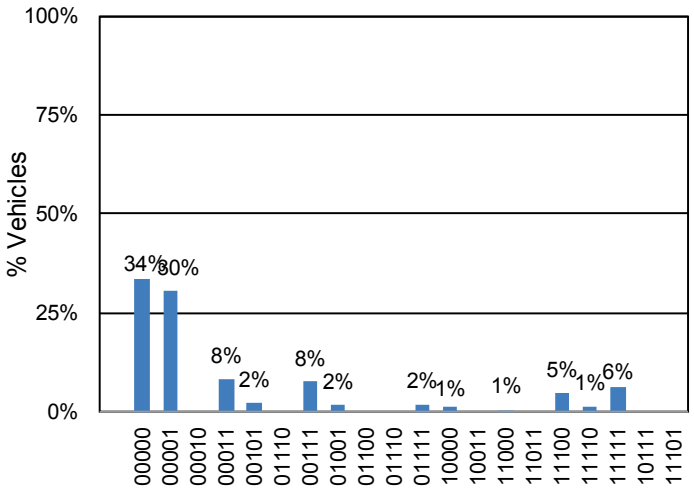
Vehicle Travel Speed (mph)



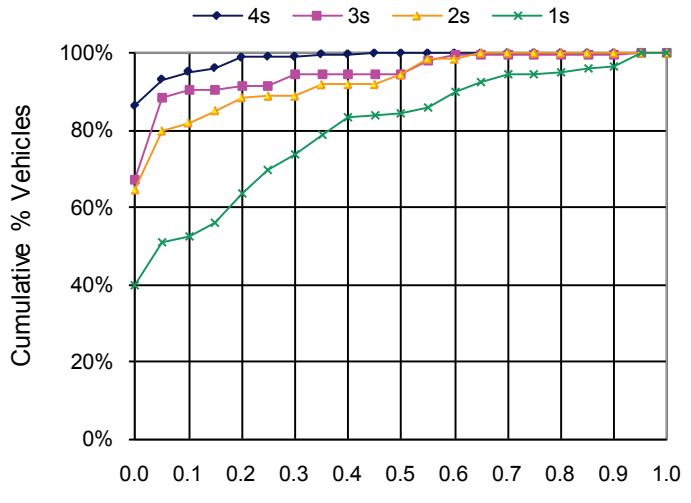
Vehicle Speed Limit (mph) , 04-08 GES



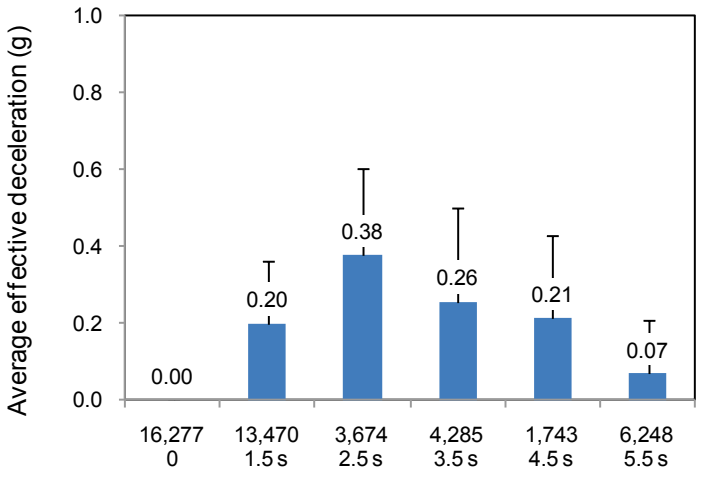
Brake Frequency at Time to Collision (s)



Detailed Brake Application Frequency



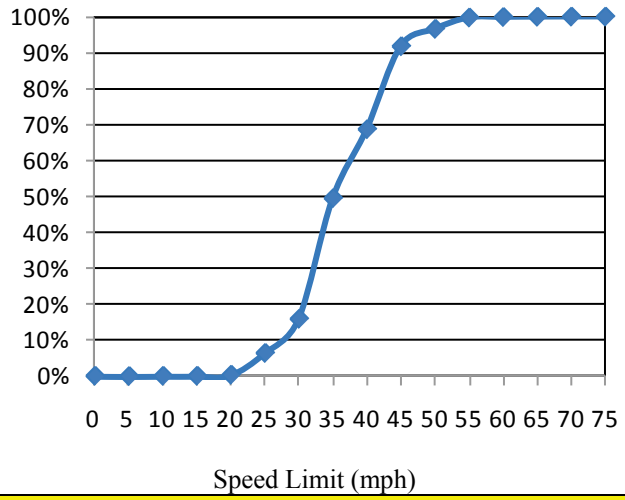
Braking Deceleration (g)



Effective Deceleration at TTC (s) with Frequency

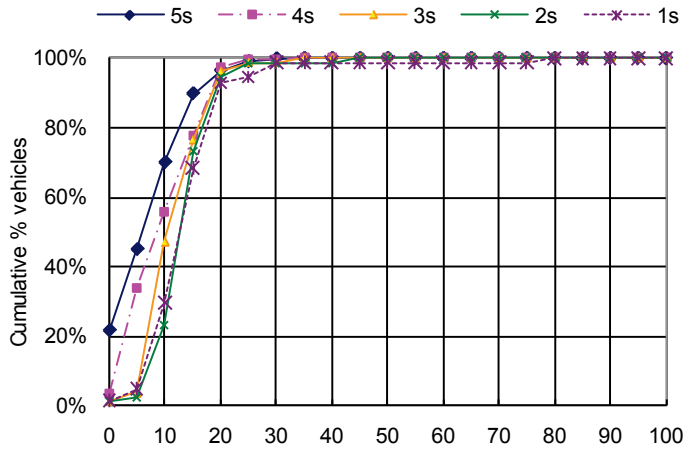
A2. Left Turn Across Path/Opposite Direction

A2.1. LTAP/OD at Signal

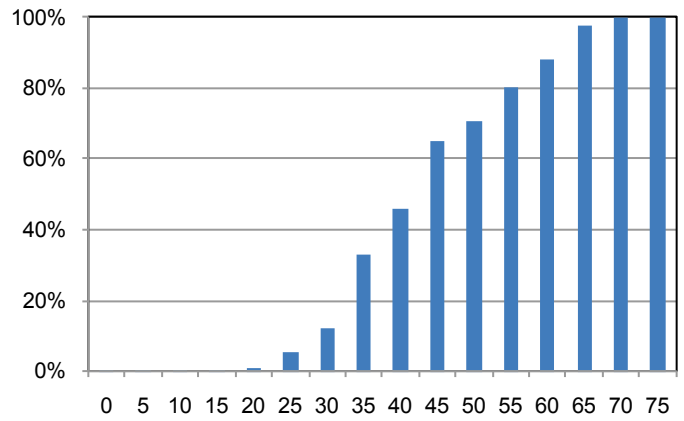
Driving Environment		
Roadway Alignment × Roadway Surface Condition × Atmospheric Condition	81% - Straight, dry road surface with no adverse weather 11% - Straight, slippery road surface with adverse weather	
Relation to Junction × Traffic Control Device	97% - Intersection or intersection related at RGY traffic signal	
Lighting Condition	66% - Daylight 26% - Dark but lighted	
Posted Speed Limit		
Driver Characteristics		
	Left Turning Vehicle	**Non-Left Turning Vehicle**
Age	34% - 0 to 24 years 52% - 25 to 64 years 14% - 65 years or above	28% - 0 to 24 Years 64% - 25 to 64 Years 7% - 65 Years or above
Gender	52% - Male 48% - Female	56% - Male 44% - Female
Driver Contributing Factors		
	Left Turning Driver	**Non-Left Turning Driver**
Alcohol	3% - Alcohol use	1% - Alcohol use
Drugs	< 1% - Drug use	< 1% - Drug use
Physical Impairment	< 1% - Physical impairment	< 1% - Physical impairment
Violation Cited	51% - Violation cited	13% - Violation cited
Speeding	1% - Speeding	2% - Speeding
Vision Obscured	6% - Obstruction	3% - Obstruction
Distraction	21% - Distracted	4% - Distracted
Vehicle Contributing Factors		
	Left Turning Vehicle	**Non-Left Turning Vehicle**
Contributing Factors	< 1% - Contributing Factors	< 1% - Contributing Factors

Corrective Action Attempted	**LTAP/OD at Signal**	
	Left Turning Vehicle	**Non-Left Turning Vehicle**
Corrective Action	3% - Braking (No lockup) 2% - Braking (Lockup) 1% - Braking (Lockup Unknown) 1% - Steering Left 3% - Accelerating	12% - Braking (No lockup) 13% - Braking (Lockup) 10% - Braking (Lockup Unknown) 5% - Steering Left 10% - Steering Right 1% - Braking and Steering Left 3% - Braking and Steering Right 2% - Unspecified action
Causal Factors (NMVCCS)		
	Left Turning Vehicle	**Non-Left Turning Vehicle**
Driver Fatigued	6% - Driver fatigued	5% - Driver fatigued
Inattention	8% - Inattention factors	5% - Inattention factors
Driver Conversing	13% - Conversing	10% - Conversing
Misjudgment of Distance/Speed	13% - Misjudgment of distance/speed factors	11% - Misjudgment of distance/speed factors
False Assumption	23% - False assumption factors	44% - False assumption factors
Inadequate Evasive Action	1% - Inadequate evasive action factors	1% - Inadequate evasive action factors
Critical Reason	0% - No critical reason 0% - Sleepy 0% - Ill/blackout 99% - Driver error 0% - Vehicle issues 1% - Weather /road /sign-signal issues	1% - No critical reason 0% - Sleepy 2% - Ill/blackout 98% - Driver error 0% - Vehicle issues 0% - Weather /road /sign-signal issues
Inadequate Surveillance	69% - Inadequate surveillance factors	49% - Inadequate surveillance factors
Other Driver Recognition Factors	10% - Other recognition factors	4% - Other recognition factors
Following Too Closely	0% - Following too closely factors	0% - Following too closely factors
Other Driver Decision Factors	25% - Other decision factors	24% - Other decision factors

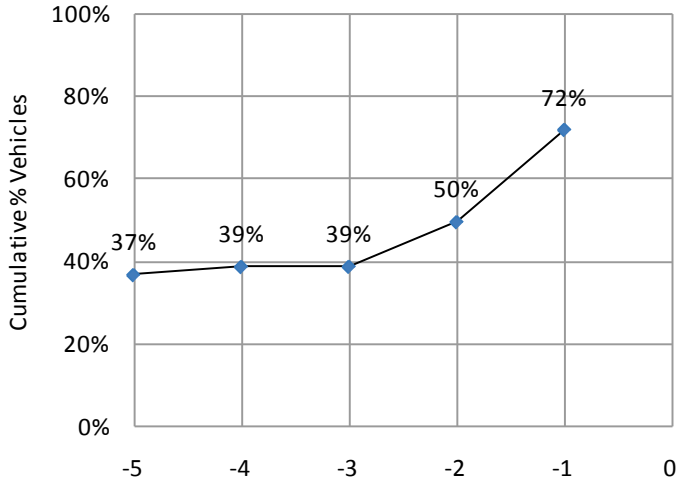
Kinematic Data of Turning Vehicle (89 EDR Cases) **LTAP/OD at Signal**



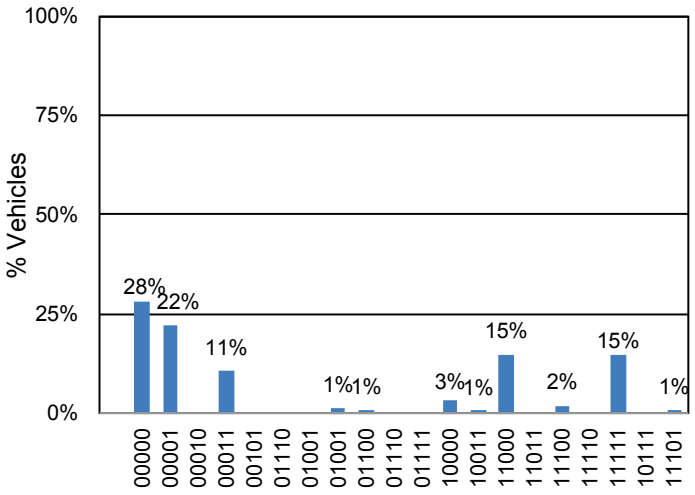
Vehicle Travel Speed (mph)



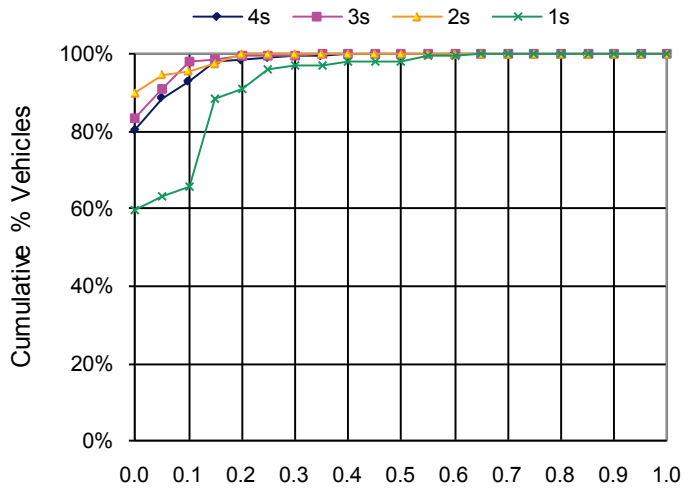
Vehicle Speed Limit (mph) , 04-08 GES



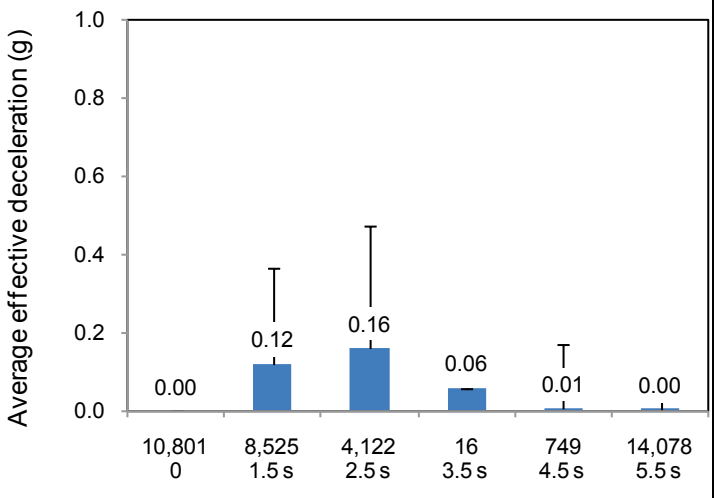
Brake Frequency at Time to Collision (s)



Detailed Brake Application Frequency

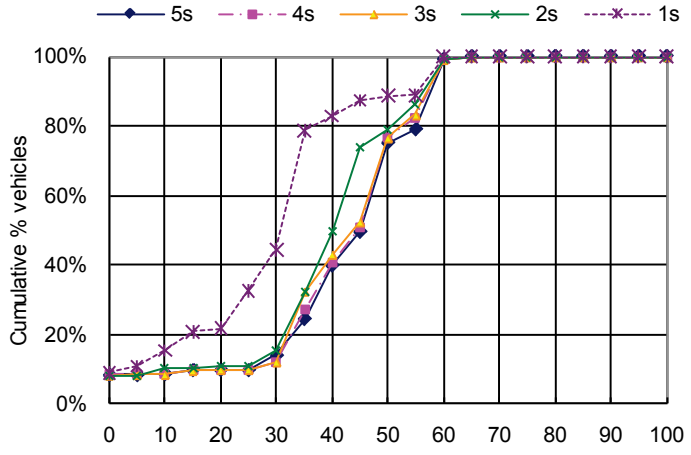


Braking Deceleration (g)

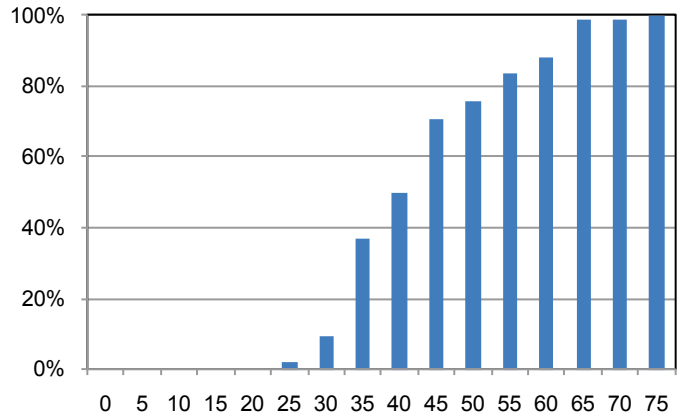


Effective Deceleration at TTC (s) with Frequency

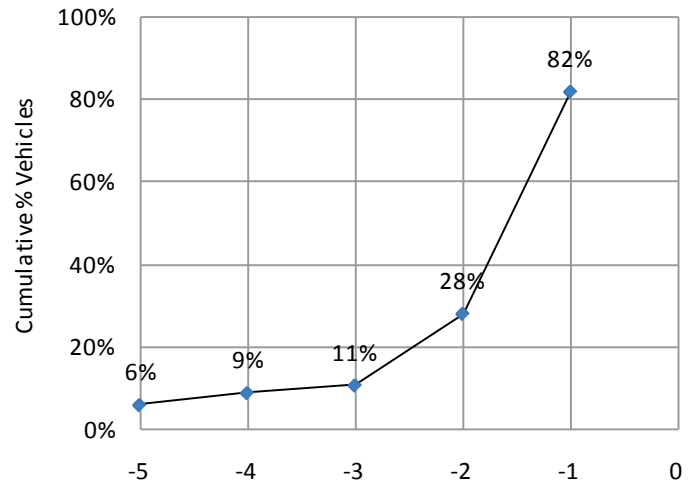
Kinematic Data of Non-Turning Vehicle (78 EDR) **LTAP/OD at Signal**



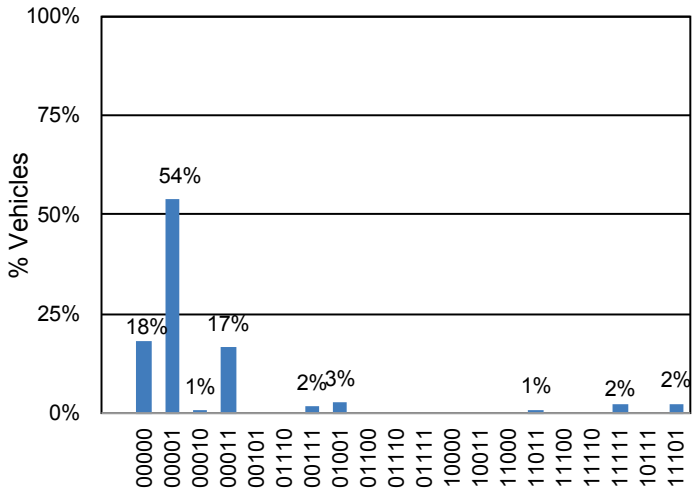
Vehicle Travel Speed (mph)



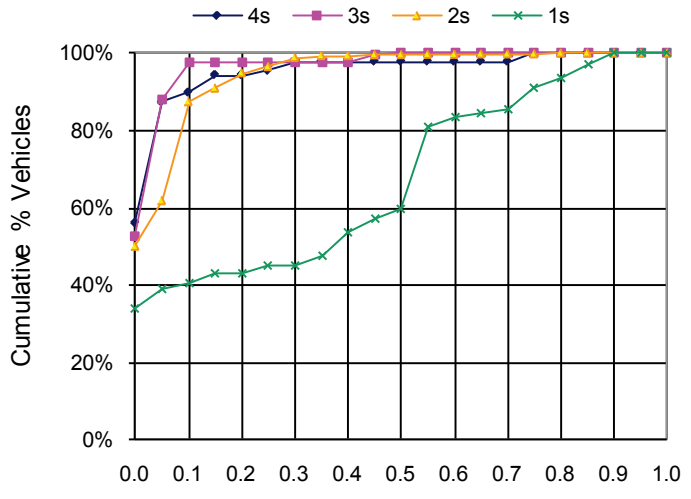
Vehicle Speed Limit (mph) , 04-08 GES



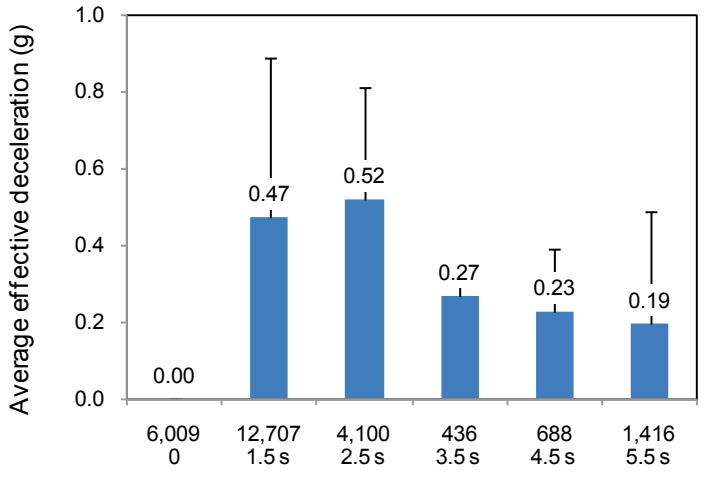
Brake Frequency at Time to Collision (s)



Detailed Brake Application Frequency

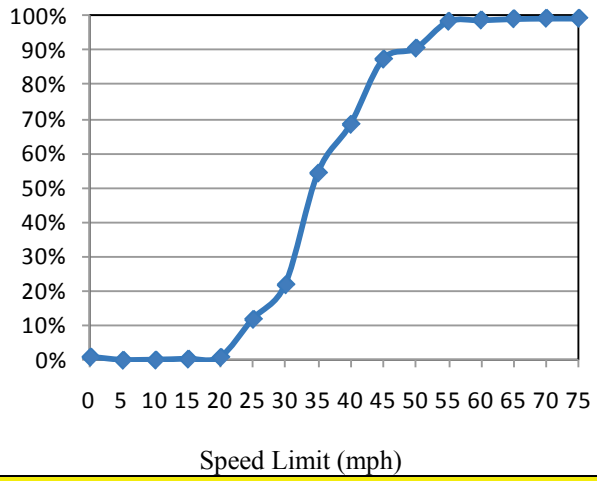


Braking Deceleration (g)



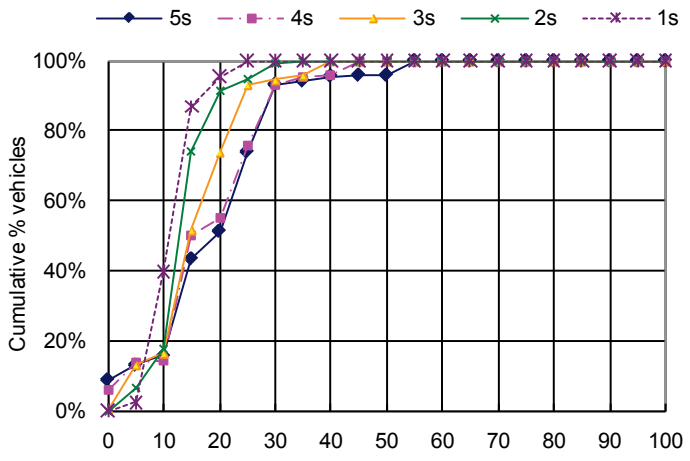
Effective Deceleration at TTC (s) with Frequency

A2.2. LTAP/OD at Non-Signal

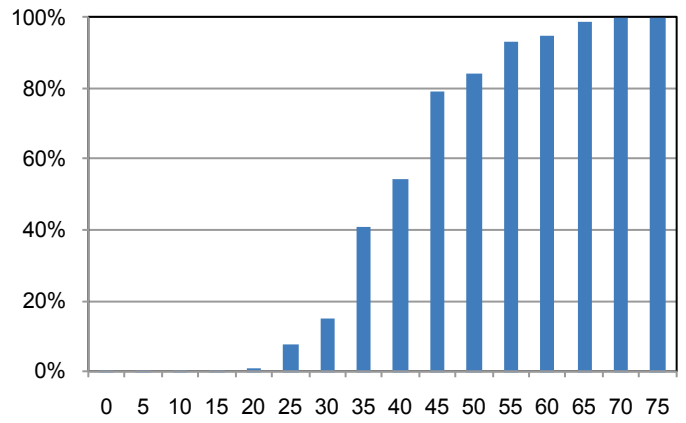
Driving Environment		
Roadway Alignment × Roadway Surface Condition × Atmospheric Condition	80% - Straight, dry road surface with no adverse weather	
Relation to Junction × Traffic Control Device	41% - Intersection or intersection related without traffic controls 35% - Driveway, alley, etc. without traffic controls	
Lighting Condition	79% - daylight 13% - dark but lighted	
Posted Speed Limit		
Driver Characteristics		
	Left Turning Vehicle	**Non-Left Turning Vehicle**
Age	30% - 0 to 24 years 55% - 25 to 64 years 15% - 65 years or above	26% - 0 to 24 years 67% - 25 to 64 years 7% - 65 years or above
Gender	54% - Male 46% - Female	55% - Male 45% - Female
Driver Contributing Factors	**LTAP/OD at Non-Signal**	
	Left Turning Vehicle	**Non-Left Turning Vehicle**
Alcohol:	3% - Alcohol use	1% - Alcohol use
Drugs	< 1% - Drug use	< 1% - Drug use
Physical Impairment	< 1% - Physical impairment	< 1% - Physical impairment
Violation Cited	56% - Violation cited	10% - Violation cited
Speeding	1% - Speeding	2% - Speeding
Vision Obscured	18% - Obstruction	9% - Obstruction
Distraction	29% - Distracted	4% - Distracted
Vehicle Contributing Factors		
	Left Turning Vehicle	**Non-Left Turning Vehicle**
Contributing Factors	< 1% - Contributing Factors	< 1% - Contributing Factors

Corrective Action Attempted	**LTAP/OD at Non-Signal**	
	Left Turning Vehicle	**Non-Left Turning Vehicle**
Corrective Action	3% - Braking (No lockup) 2% - Accelerating	13% - Braking (No lockup) 12% - Braking (Lockup) 11% - Braking (Lockup Unknown) 6% - Steering Left 9% - Steering Right 1% - Braking and Steering Left 4% - Braking and Steering Right 1% - Unspecified action
Causal Factors (NMVCCS)		
Driver Fatigued	6% - Driver fatigued	
Inattention	8% - Inattention factors	
Driver Conversing	9% - Conversing	
Misjudgment of Distance/Speed	16% - Misjudgment of distance/speed factors	
False Assumption	5% - False assumption factors	
Inadequate Evasive Action	0% - Inadequate evasive action factors	
Critical Reason	1% - No critical reason 0% - Sleepy 0% - Ill/blackout 98% - Driver error 0% - Vehicle issues 1% - Weather /road /sign-signal issues	
Inadequate Surveillance	77% - Inadequate surveillance factors	
Other Driver Recognition Factors	14% - Other recognition factors	
Following Too Closely	0% - Following too closely factors	
Other Driver Decision Factors	40% - Other decision factors	

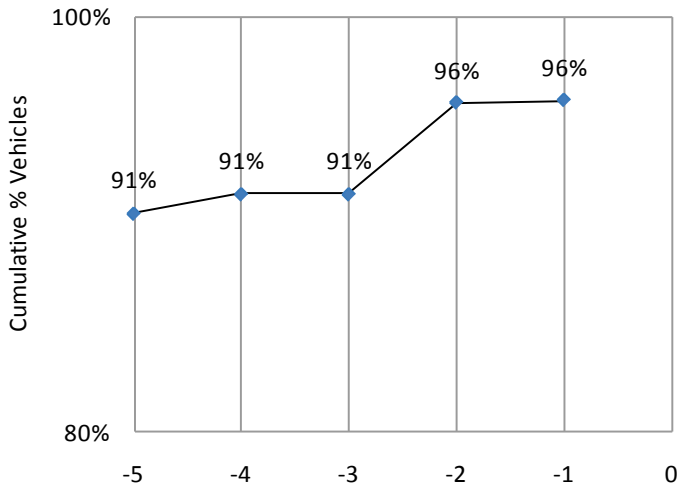
Kinematic Data of Turning Vehicle (44 EDR Cases) **LTAP/OD at Non-Signal**



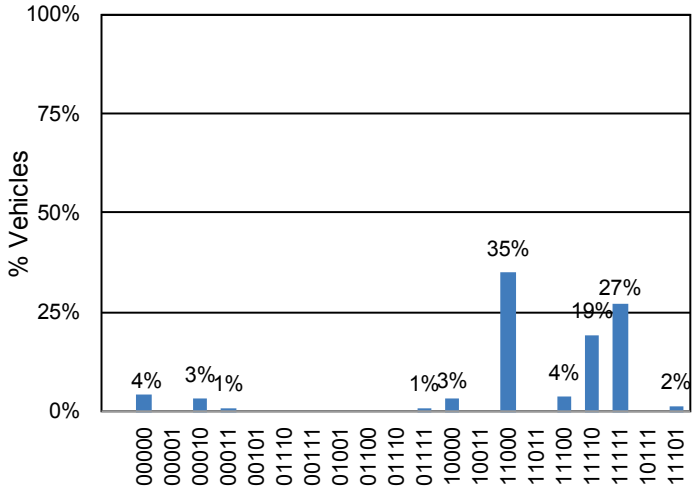
Vehicle Travel Speed (mph)



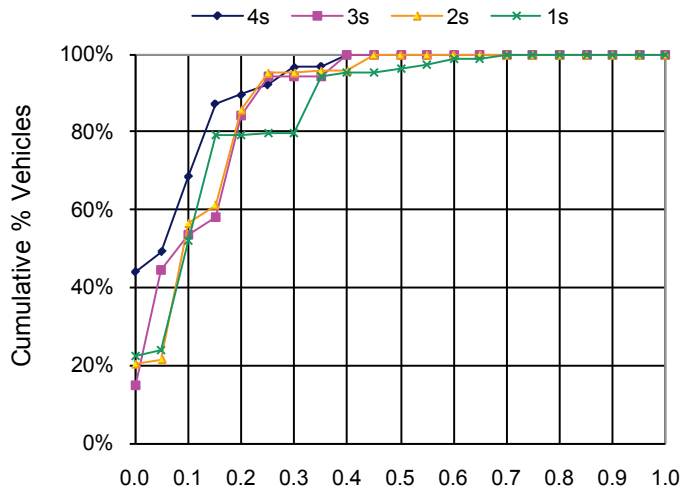
Vehicle Speed Limit (mph) , 04-08 GES



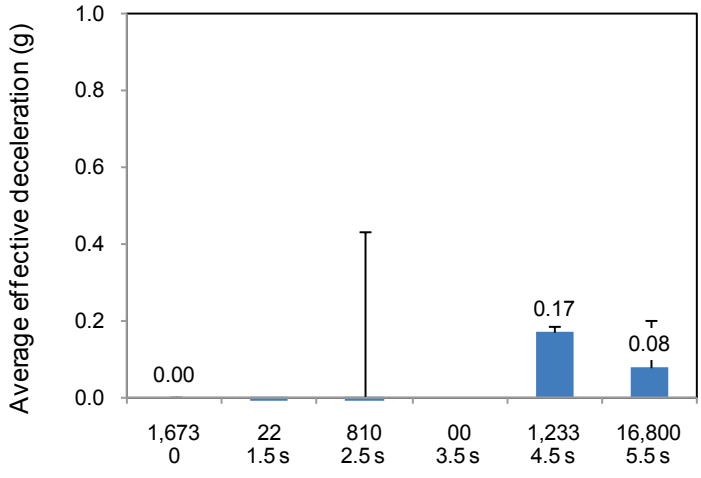
Brake Frequency at Time to Collision (s)



Detailed Brake Application Frequency

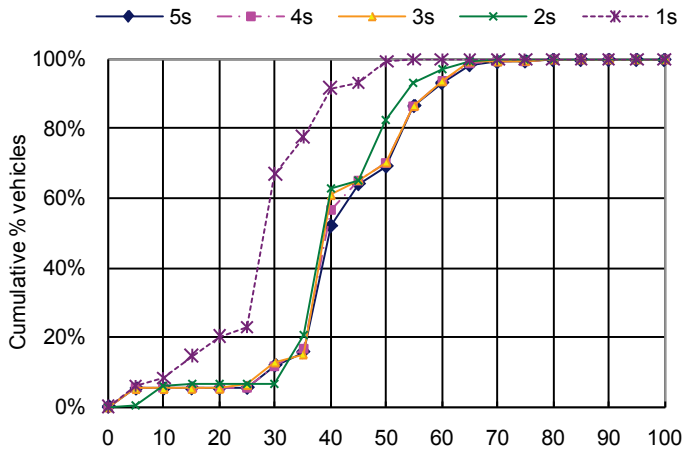


Braking Deceleration (g)

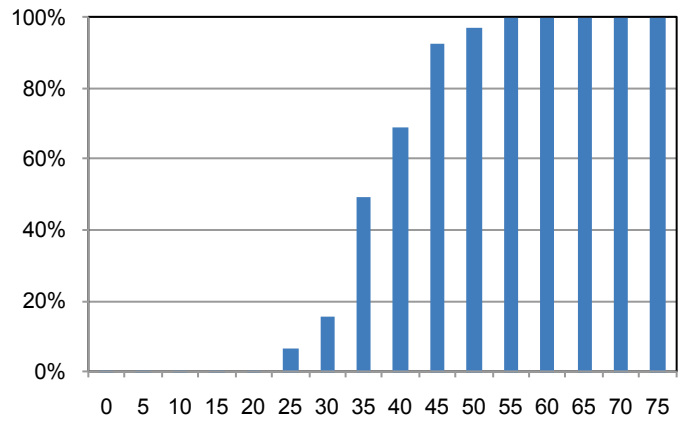


Effective Deceleration at TTC (s) with Frequency

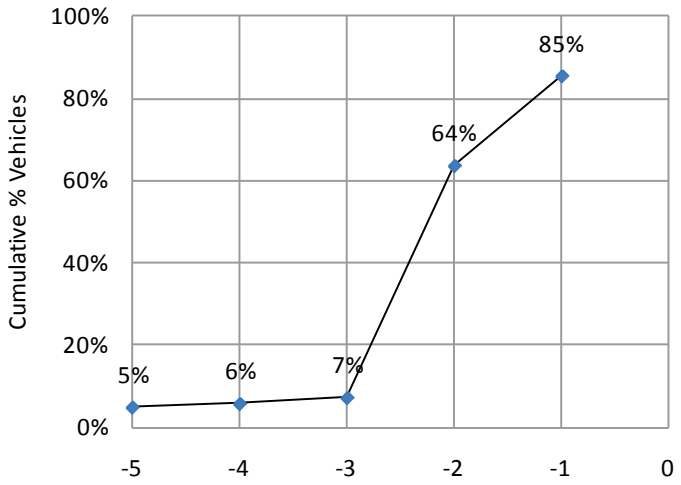
Kinematic Data of Non-Turning Vehicle (44 EDR Cases) **LTAP/OD at Non-Signal**



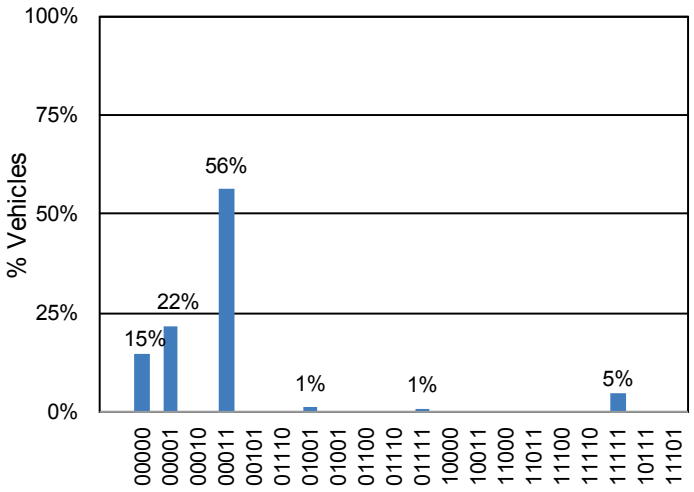
Vehicle Travel Speed (mph)



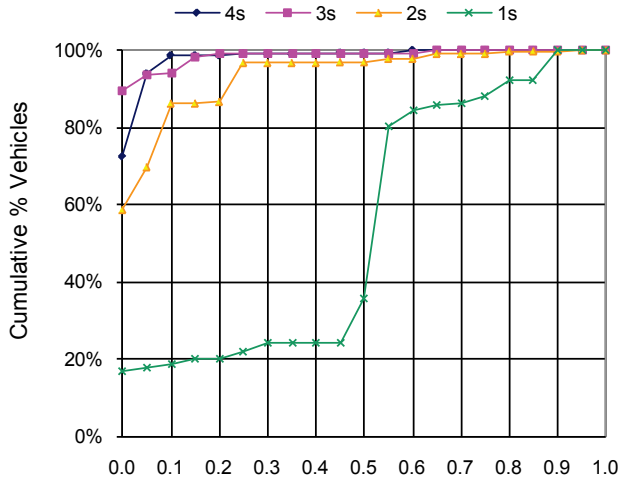
Vehicle Speed Limit (mph) , 04-08 GES



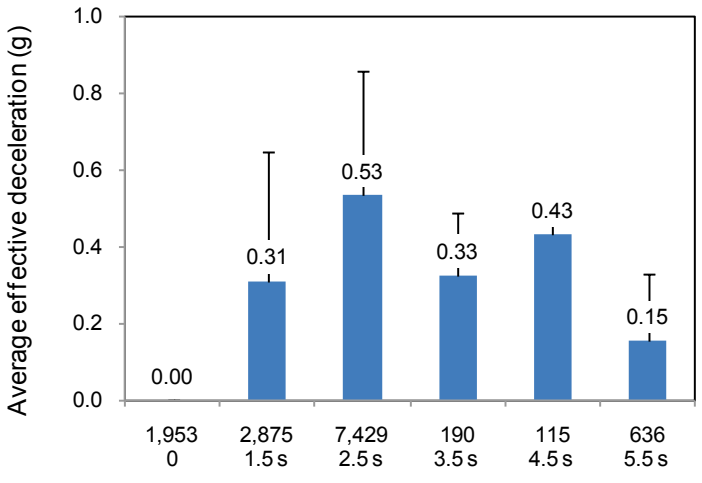
Brake Frequency at Time to Collision (s)



Detailed Brake Application Frequency

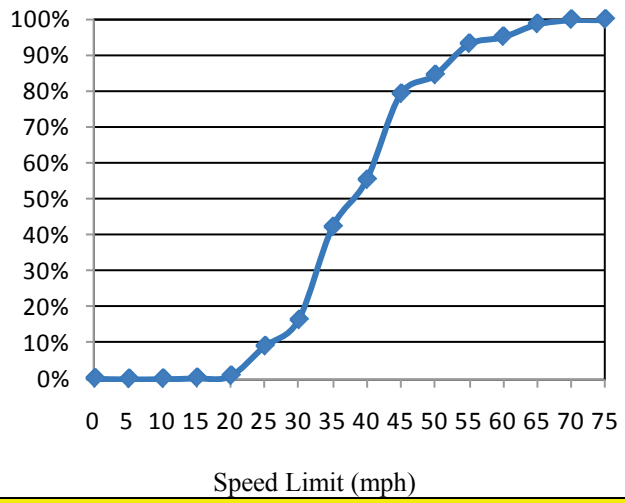


Braking Deceleration (g)



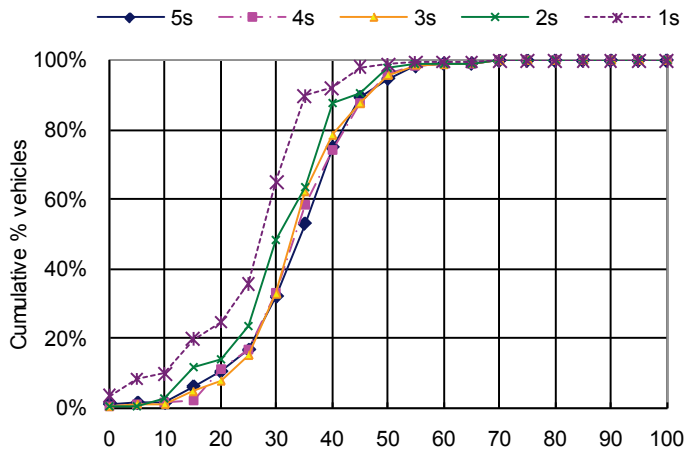
Effective Deceleration at TTC (s) with Frequency

A3. Rear-End/Lead Vehicle Stopped

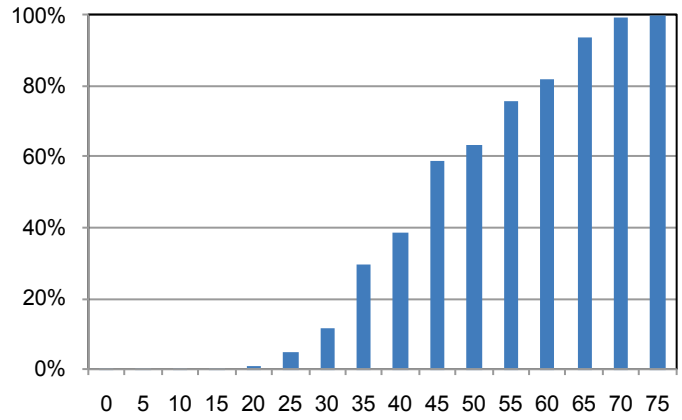
Driving Environment	
Roadway Alignment × Roadway Surface Condition × Atmospheric Condition	74% - Straight, dry road surface with no adverse weather 13% - Straight, slippery road surface with adverse weather
Relation to Junction × Traffic Control Device	37% - Intersection or intersection related at RGY traffic signal 29% - Non-Junction without traffic controls
Lighting Condition	81% - Daylight 12% - Dark but lighted
Posted Speed Limit	
Driver Characteristics	
Age	35% - 0 to 24 years 59% - 25 to 64 years 7% - 65 years or above
Gender	56% - Male 44% - Female
Driver Contributing Factors	
Alcohol	4% - Alcohol use
Drugs	< 1% - Drug use
Physical Impairment	< 1% - Physical impairment
Violation Cited	55% - Violation cited
Speeding	31% - Speeding
Vision Obscured	2% - Obstruction
Distraction	47% - Distracted 1% - Sleepy
Vehicle Contributing Factors	
Contributing Factors	1% - Contributing Factors

Corrective Action Attempted	**Rear-End/Lead Vehicle Stopped**
Corrective Action	20% - Braking (No lockup) 13% - Braking (Lockup) 13% - Braking (Lockup Unknown) 3% - Steering Left 5% - Steering Right 2% - Braking and Steering Right 2% - Accelerating
Causal Factors (NMVCCS)	
Driver Fatigued	13% - Driver fatigued
Inattention	23% - Inattention factors
Driver Conversing	11% - Conversing
Misjudgment of Distance/Speed	15% - Misjudgment of distance/speed factors
False Assumption	25% - False assumption factors
Inadequate Evasive Action	13% - Inadequate evasive action factors
Critical Reason	4% - No critical reason 1% - Sleepy 1% - Ill/blackout 91% - Driver error 1% - Vehicle issues 2% - Weather /road /sign-signal issues
Inadequate Surveillance	52% - Inadequate surveillance factors
Other Driver Recognition Factors	8% - Other recognition factors
Following Too Closely	9% - Following too closely factors
Other Driver Decision Factors	4% - Other decision factors

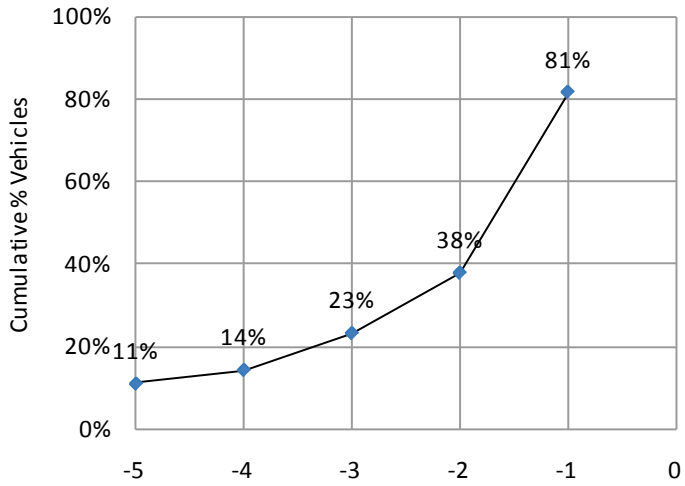
Kinematic Data (99 EDR Cases) **Rear-End/Lead Vehicle Stopped**



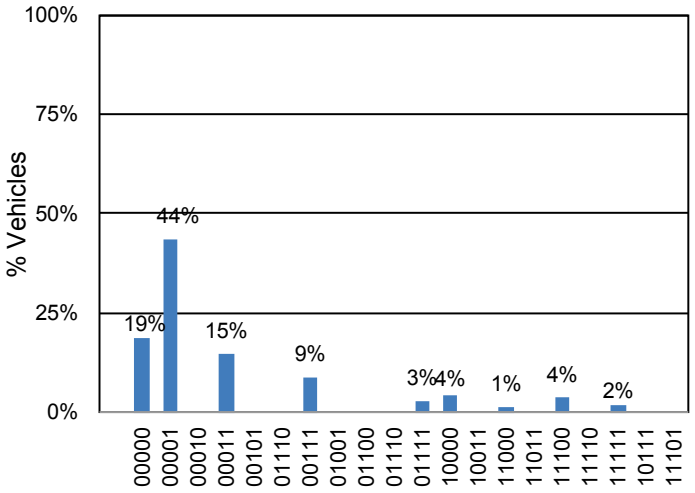
Vehicle Travel Speed (mph)



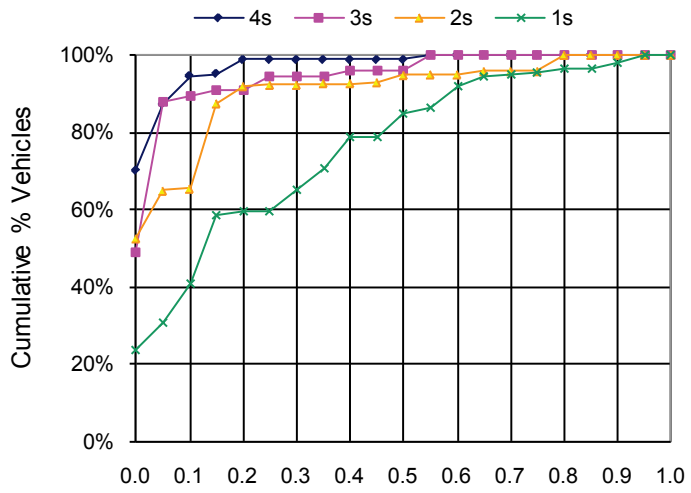
Vehicle Speed Limit (mph) , 04-08 GES



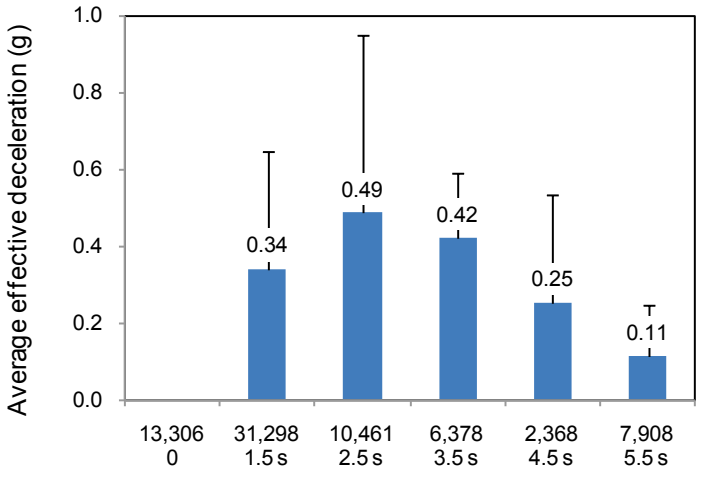
Brake Frequency at Time to Collision (s)



Detailed Brake Application Frequency

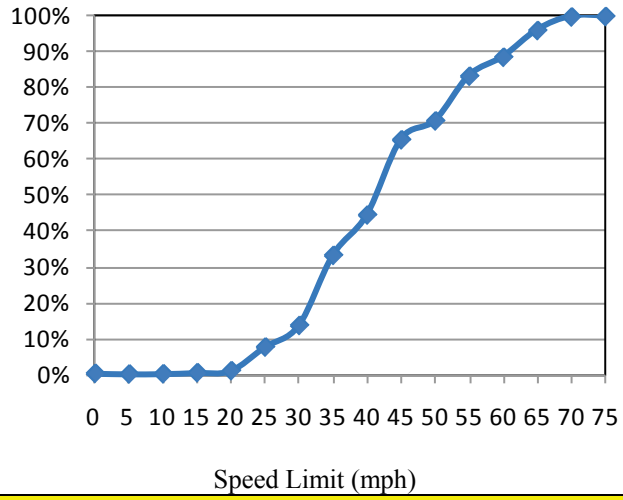


Braking Deceleration (g)



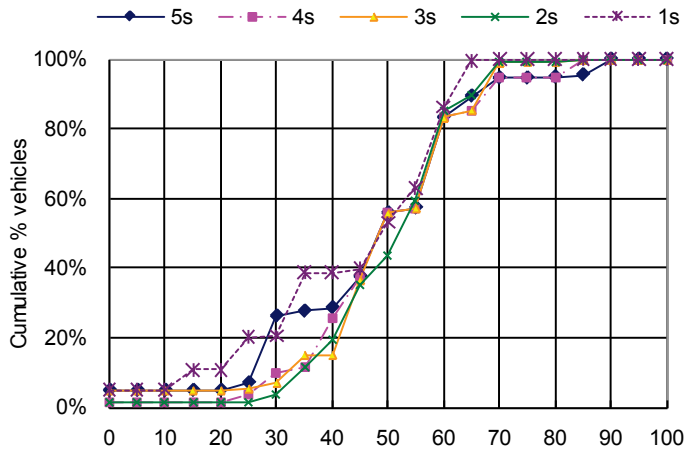
Effective Deceleration at TTC (s) with Frequency

A4. Rear-End/Lead Vehicle Decelerating

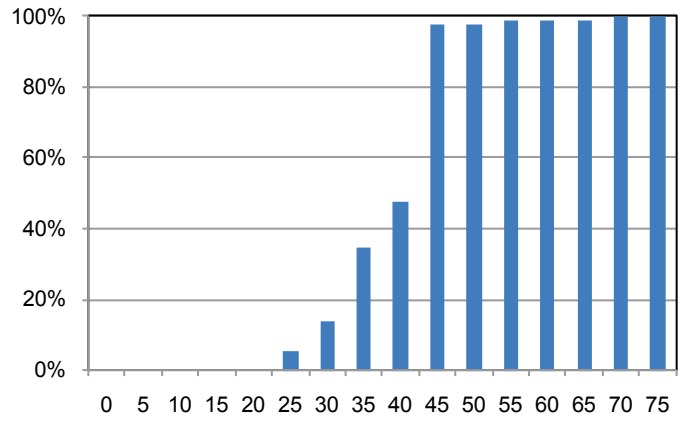
Driving Environment	
Roadway Alignment × Roadway Surface Condition × Atmospheric Condition	74% - Straight, dry road surface with no adverse weather 13% - Straight, slippery road surface with adverse weather
Relation to Junction × Traffic Control Device	47% - Non-Junction without traffic controls 19% - Intersection or intersection related at RGY traffic signal 11% - Intersection or intersection related without traffic controls
Lighting Condition	82% - Daylight 10% - Dark but lighted
Posted Speed Limit	
Driver Characteristics	
Age	38% - 0 to 24 years 58% - 25 to 64 years 4% - 65 years or above
Gender	58% - Male 42% - Female
Driver Contributing Factors	
Alcohol	2% - Alcohol use
Drugs	< 1% - Drug use
Physical Impairment	< 1% - Physical impairment
Violation Cited	51% - Violation cited
Speeding	34% - Speeding
Vision Obscured	2% - Obstruction
Distraction	38% - Distracted
Vehicle Contributing Factors	
Contributing Factors	< 1% - Contributing Factors

Corrective Action Attempted	**Rear-End/Lead Vehicle Decelerating**
Corrective Action	23 % - Braking (No lockup) 14 % - Braking (Lockup) 12 % - Braking (Lockup Unknown) 4 % - Steering Left 6 % - Steering Right 2 % - Braking and Steering Left 3 % - Braking and Steering Right
Causal Factors (NMVCCS)	
Driver Fatigued	13% - Driver fatigued
Inattention	18% - Inattention factors
Driver Conversing	8% - Conversing
Misjudgment of Distance/Speed	8% - Misjudgment of distance/speed factors
False Assumption	12% - False assumption factors
Inadequate Evasive Action	3% - Inadequate evasive action factors
Critical Reason	51% - No critical reason 0% - Sleepy 1% - Ill/blackout 47% - Driver error 0% - Vehicle issues 1% - Weather /road /sign-signal issues
Inadequate Surveillance	29% - Inadequate surveillance factors
Other Driver Recognition Factors	3% - Other recognition factors
Following Too Closely	20% - Following too closely factors
Other Driver Decision Factors	3% - Other decision factors

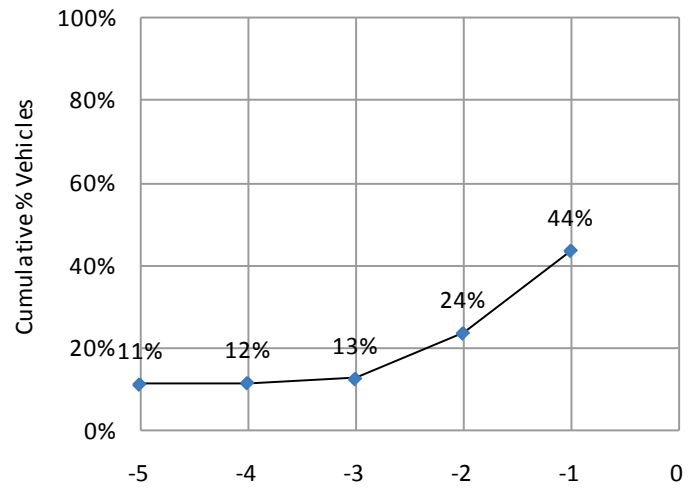
Kinematic Data (27 EDR Cases) **Rear-End/Lead Vehicle Decelerating**



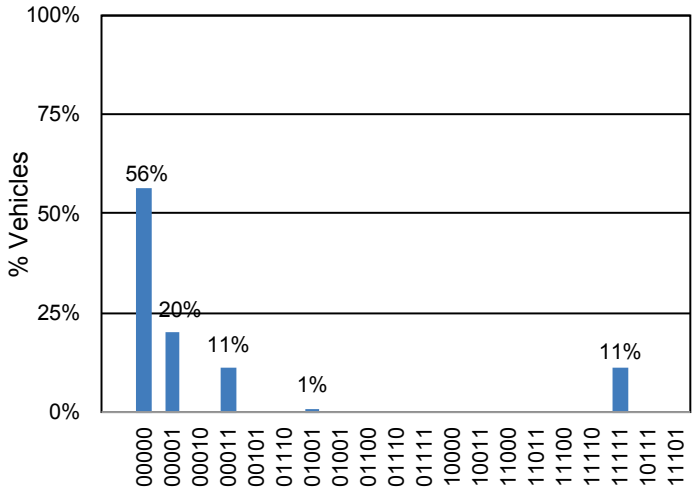
Vehicle Travel Speed (mph)



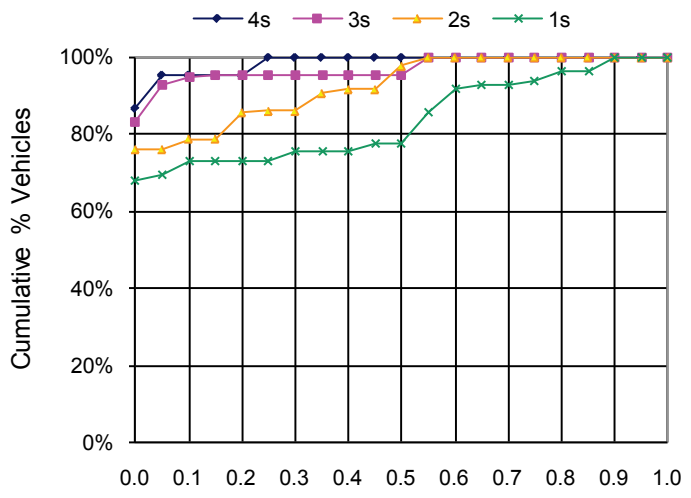
Vehicle Speed Limit (mph) , 04-08 GES



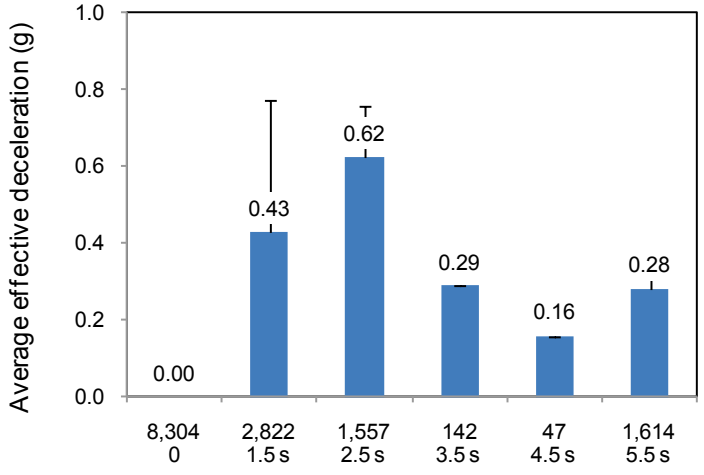
Brake Frequency at Time to Collision (s)



Detailed Brake Application Frequency

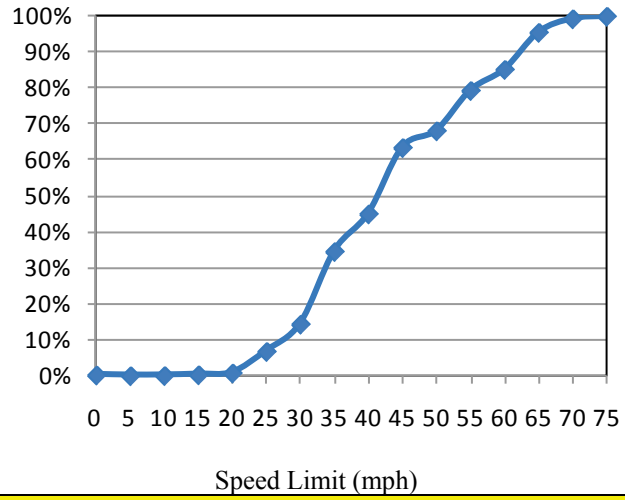


Braking Deceleration (g)



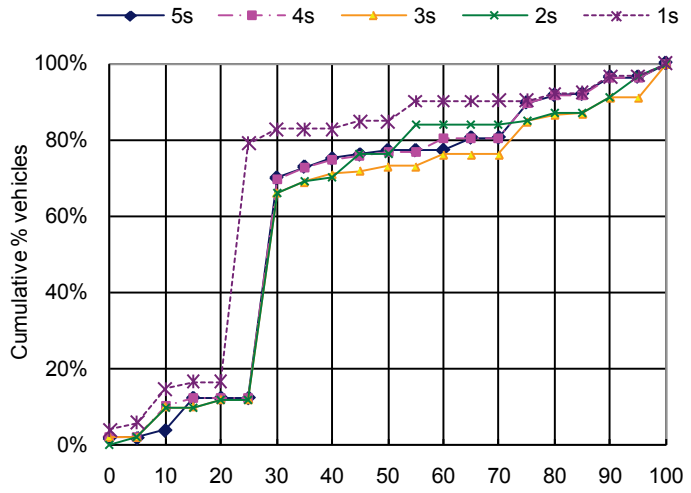
Effective Deceleration at TTC (s) with Frequency

A5. Rear-End/Lead Vehicle Moving at Slower Constant Speed

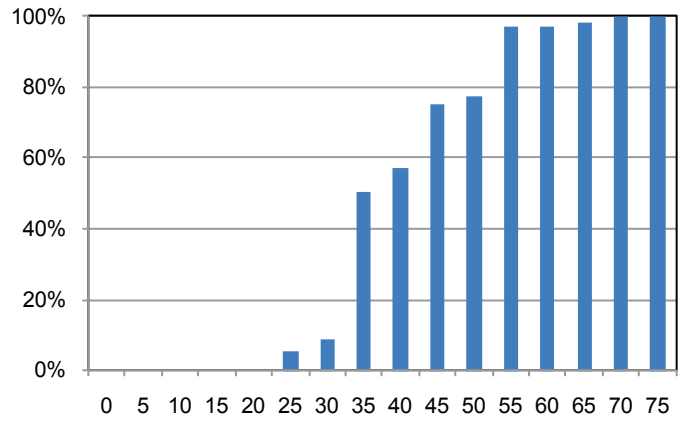
Driving Environment	
Roadway Alignment × Roadway Surface Condition × Atmospheric Condition	76% - Straight, dry road surface with no adverse weather 12% - Straight, slippery road surface with adverse weather
Relation to Junction × Traffic Control Device	58% - Non-Junction without traffic controls 18% - Intersection or intersection related at RGY traffic signal
Lighting Condition	75% - Daylight 14% - Dark but lighted
Posted Speed Limit	
Driver Characteristics	
Age	36% - 0 to 24 years 59% - 25 to 64 years 5% - 65 years or above
Gender	61% - Male 39% - Female
Driver Contributing Factors	
Alcohol	7% - Alcohol use
Drugs	< 1% - Drug use
Physical Impairment	2% - Sleepy
Violation Cited	51% - Violation cited
Speeding	32% - Speeding
Vision Obscured	2% - Obstruction
Distraction	36% - Distracted
Vehicle Contributing Factors	
Contributing Factors	< 1% - Contributing Factors

Corrective Action Attempted	**Rear-End/Lead Vehicle Moving**
Corrective Action	31% - Braking (No lockup) 11% - Braking (Lockup) 13% - Braking (Lockup Unknown) 5% - Steering Left 5% - Steering Right 2% - Braking and Steering Left 3% - Braking and Steering Right
Causal Factors (NMVCCS)	
Driver Fatigued	5% - Driver fatigued
Inattention	8% - Inattention factors
Driver Conversing	17% - Conversing
Misjudgment of Distance/Speed	5% - Misjudgment of distance/speed factors
False Assumption	5% - False assumption factors
Inadequate Evasive Action	2% - Inadequate evasive action factors
Critical Reason	60% - No critical reason 1% - Sleepy 1% - Ill/blackout 37% - Driver error 0% - Vehicle issues 1% - Weather /road /sign-signal issues
Inadequate Surveillance	15% - Inadequate surveillance factors
Other Driver Recognition Factors	4% - Other recognition factors
Following Too Closely	9% - Following too closely factors
Other Driver Decision Factors	2% - Other decision factors

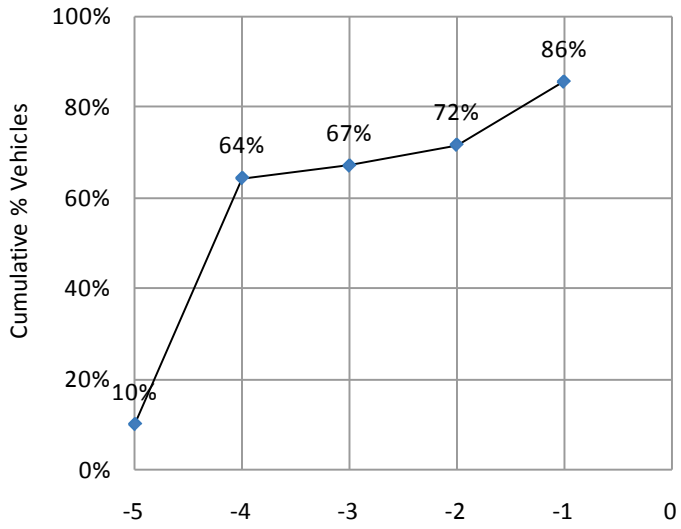
Kinematic Data (21 EDR Cases) **Rear-End/Lead Vehicle Moving**



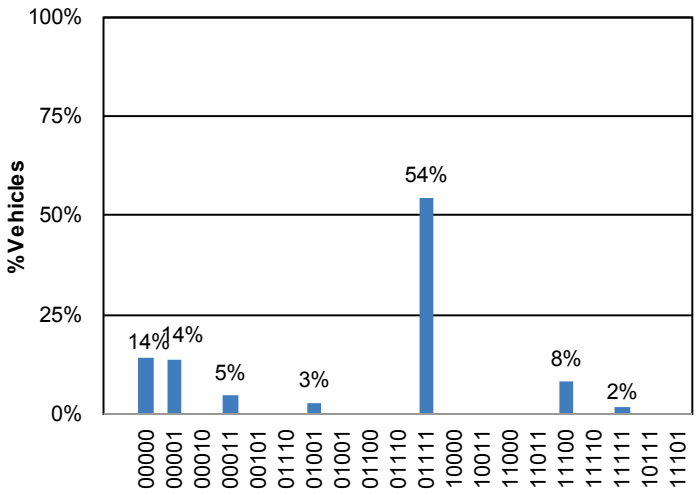
Vehicle Travel Speed (mph)



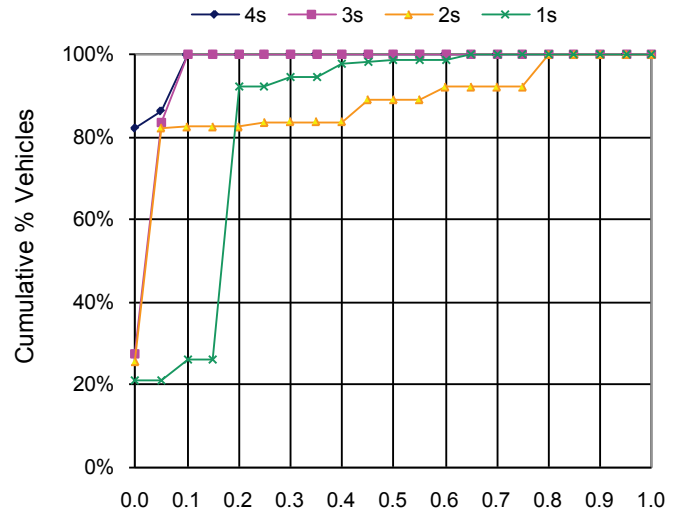
Vehicle Speed Limit (mph) , 04-08 GES



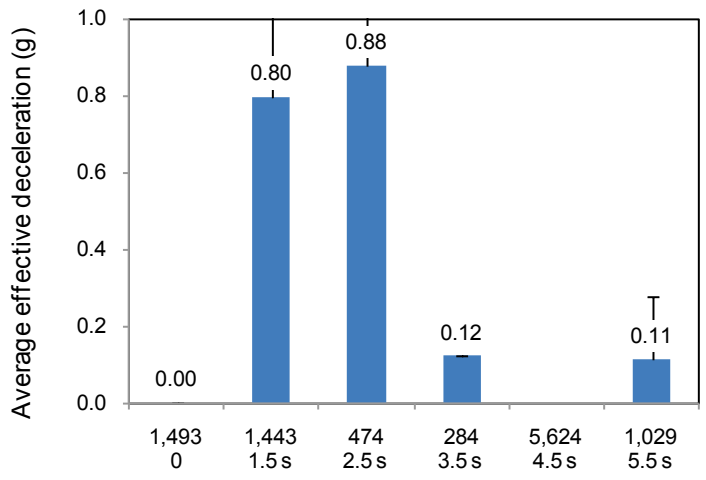
Brake Frequency at Time to Collision (s)



Detailed Brake Application Frequency

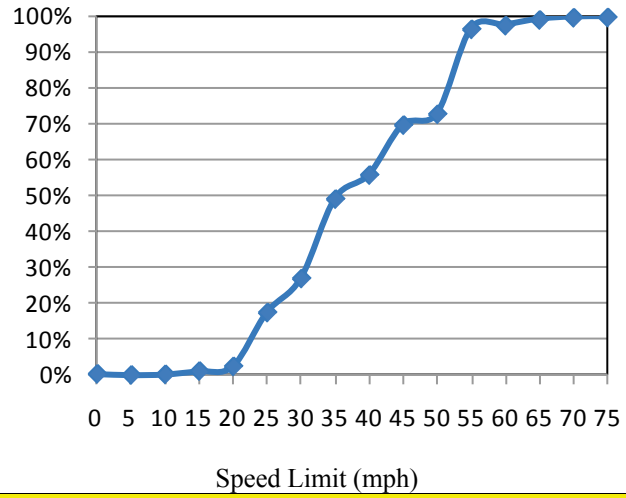


Braking Deceleration (g)



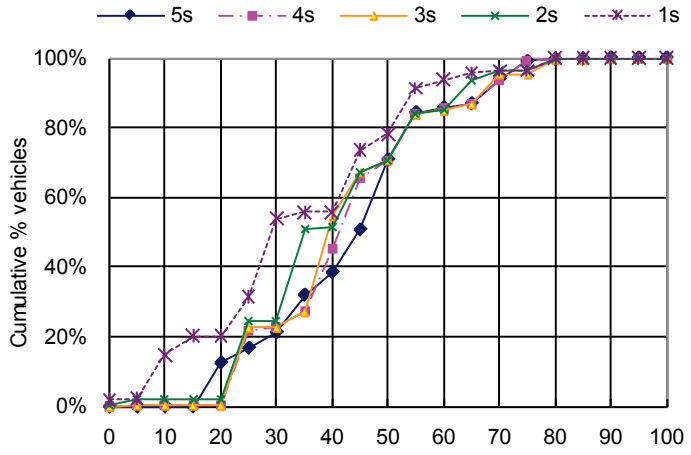
Effective Deceleration at TTC (s) with Frequency

A6. Opposite Direction/No Maneuver

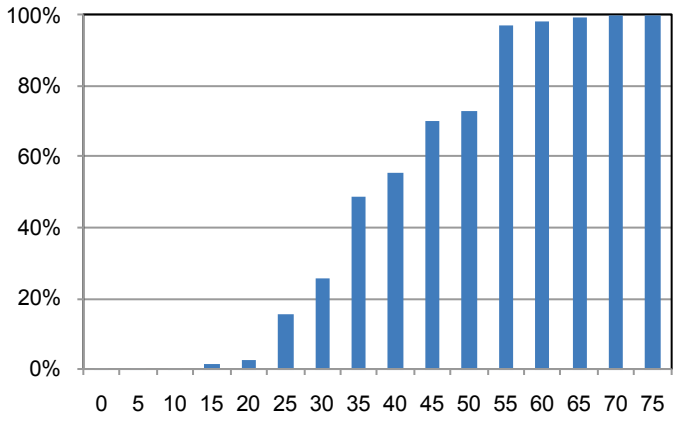
Driving Environment	
Roadway Alignment × Roadway Surface Condition × Atmospheric Condition	47% - Straight, dry road surface with no adverse weather 26% - Curve, dry road surface with no adverse weather 10% - Straight, slippery road surface with adverse weather
Relation to Junction × Traffic Control Device	78% - Non-Junction without traffic controls
Lighting Condition	67% - Daylight 16% - Dark 13% - Dark but lighted
Posted Speed Limit	
Driver Characteristics	
Age	33% - 0 to 24 years 60% - 25 to 64 years 7% - 65 years or above
Gender	65% - Male 35% - Female
Driver Contributing Factors	
Alcohol:	12% - Alcohol use
Drugs	2% - Drug use
Physical Impairment	4% - Sleepy 1% - Ill, blackout
Violation Cited	39% - Violation cited
Speeding	10% - Speeding
Vision Obscured	5% - Obstruction
Distraction	24% - Distracted
Vehicle Contributing Factors	
Contributing Factors	1% - Contributing Factors

Corrective Action Attempted	**Opposite Direction / No Maneuver**
Corrective Action	2% - Braking (No lockup) 5% - Braking (Lockup) 3% - Braking (Lockup Unknown) 17% - Steering Left 49% - Steering Right 2% - Braking and Steering Left 3% - Braking and Steering Right 1% - Unspecified action
Causal Factors (NMVCCS)	
(Combined values for Opposite Direction/Maneuver and No Maneuver)	
Driver Fatigued	26% - Driver fatigued
Inattention	10% - Inattention factors
Driver Conversing	14% - Conversing
Misjudgment of Distance/Speed	0% - Misjudgment of distance/speed factors
False Assumption	2% - False assumption factors
Inadequate Evasive Action	24% - Inadequate evasive action factors
Critical Reason	1% - No critical reason 6% - Sleepy 7% - Ill/blackout 84% - Driver error 1% - Vehicle issues 2% - Weather /road /sign-signal issues
Inadequate Surveillance	20% - Inadequate surveillance factors
Other Driver Recognition Factors	6% - Other recognition factors
Following Too Closely	0% - Following too closely factors
Other Driver Decision Factors	3% - Other decision factors

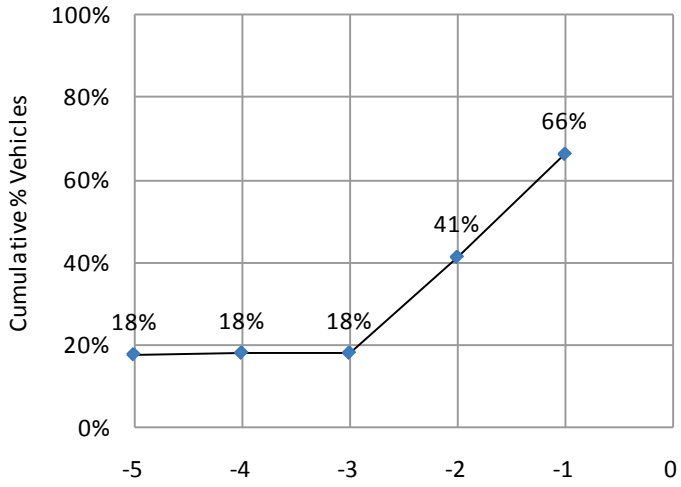
Kinematic Data (40 EDR Cases) **Opposite Direction/No Maneuver**



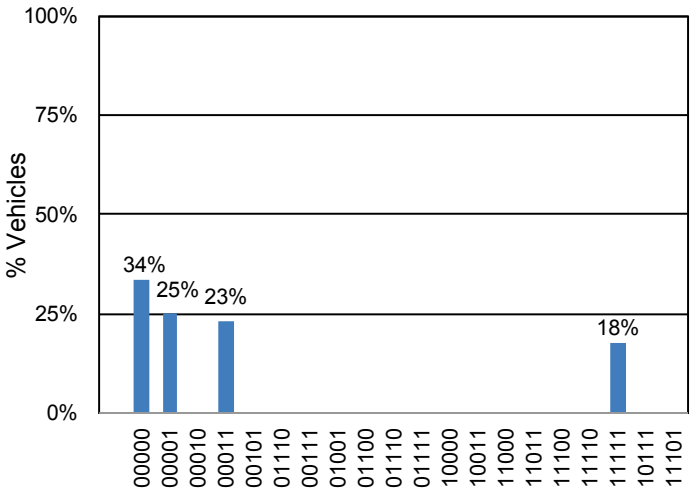
Vehicle Travel Speed (mph)



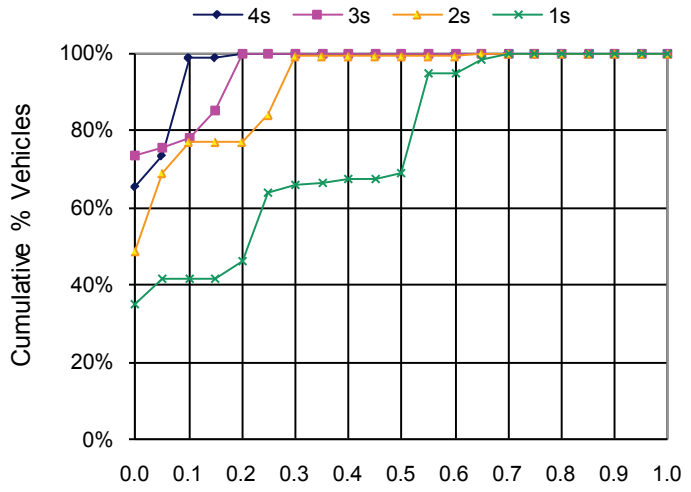
Vehicle Speed Limit (mph) , 04-08 GES



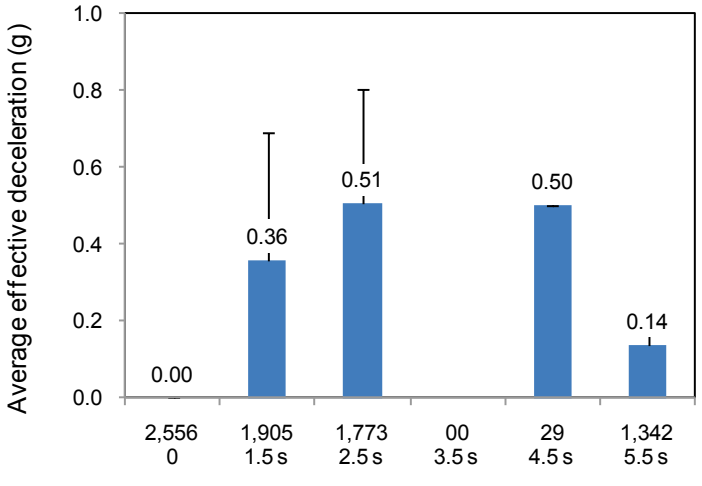
Brake Frequency at Time to Collision (s)



Detailed Brake Application Frequency

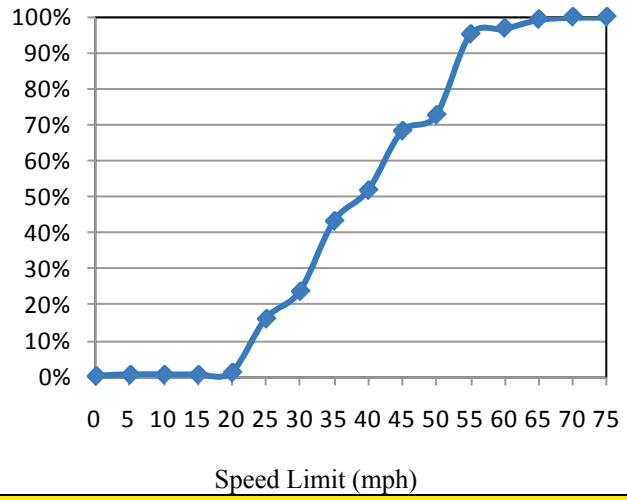


Braking Deceleration (g)



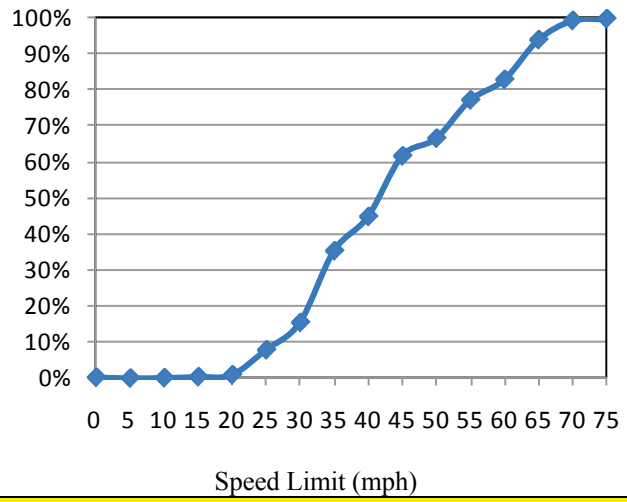
Effective Deceleration at TTC (s) with Frequency

A7. Opposite Direction/Maneuver

Driving Environment	
Roadway Alignment × Roadway Surface Condition × Atmospheric Condition	60% - Straight, dry road surface with no adverse weather 15% - Straight, slippery road surface with adverse weather 13% - Curve, dry road surface with no adverse weather
Relation to Junction × Traffic Control Device	70% - Non-Junction without traffic controls
Lighting Condition	62% - Daylight 18% - Dark but lighted 17% - Dark
Posted Speed Limit	
Driver Characteristics	
Age	38% - 0 to 24 years 56% - 25 to 64 years 7% - 65 years or above
Gender	70% - Male 30% - Female
Driver Contributing Factors	
Alcohol	13% - Alcohol use
Drugs	2% - Drug use
Physical Impairment	< 1% - Physical Impairment
Violation Cited	39% - Violation cited
Speeding	8% - Speeding
Vision Obscured	7% - Obstruction
Distraction	19% - Distracted
Vehicle Contributing Factors	
Contributing Factors	1% - Contributing Factor

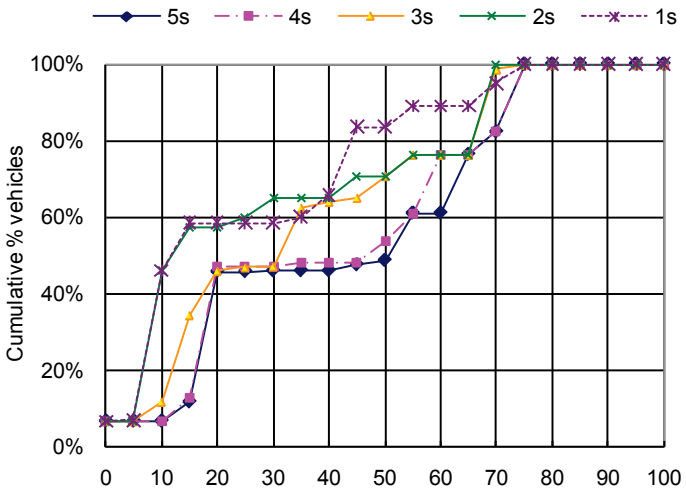
Corrective Action Attempted	**Opposite Direction/Maneuver**
Corrective Action	3% - Braking (Lockup) 36% - Steering Left 38% - Steering Right 3% - Braking and Steering Left 1% - Braking and Steering Right 1% - Accelerating
Causal Factors (NMVCCS)	
(Combined values for Opposite Direction/Maneuver and No Maneuver)	
Driver Fatigued	26% - Driver fatigued
Inattention	10% - Inattention factors
Driver Conversing	14% - Conversing
Misjudgment of Distance/Speed	0% - Misjudgment of distance/speed factors
False Assumption	2% - False assumption factors
Inadequate Evasive Action	24% - Inadequate evasive action factors
Critical Reason	1% - No critical reason 6% - Sleepy 7% - Ill/blackout 84% - Driver error 1% - Vehicle issues 2% - Weather /road /sign-signal issues
Inadequate Surveillance	20% - Inadequate surveillance factors
Other Driver Recognition Factors	6% - Other recognition factors
Following Too Closely	0% - Following too closely factors
Other Driver Decision Factors	3% - Other decision factors

A8. Changing Lanes/Same Direction

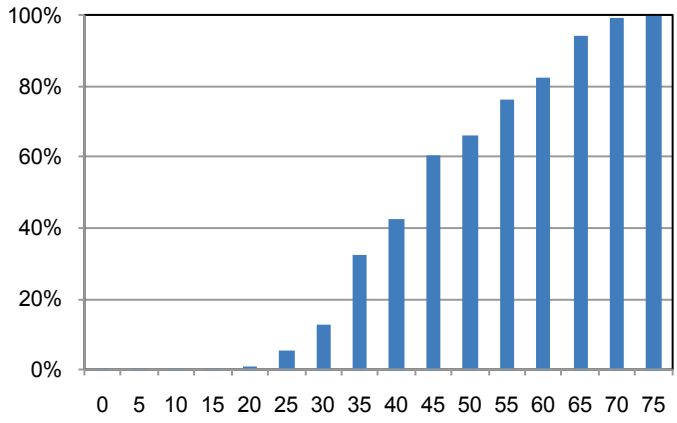
Driving Environment	
Roadway Alignment × Roadway Surface Condition × Atmospheric Condition	78% - Straight, dry road surface with no adverse weather 9% - Straight, slippery road surface with adverse weather
Relation to Junction × Traffic Control Device	65% - Non-Junction without traffic controls 11% - Intersection or intersection related at RGY traffic signal
Lighting Condition	75% - Daylight 15% - Dark but lighted
Posted Speed Limit	
Driver Characteristics	
Age	32% - 0 to 24 years 59% - 25 to 64 years 10% - 65 years or above
Gender	59% - Male 41% - Female
Driver Contributing Factors	
Alcohol	4% - Alcohol use
Drugs	< 1% - Drug use
Physical Impairment	< 1% - Physical Impairment
Violation Cited	42% - Violation cited
Speeding	4% - Speeding
Vision Obscured	2% - Obstruction
Distraction	28% - Distracted
Vehicle Contributing Factors	
Contributing Factors	< 1% - Contributing Factors

Corrective Action Attempted	**Changing Lanes/Same Direction**
Corrective Action	2% - Braking (Lockup) 20% - Steering Left 20% - Steering Right 2% - Braking and Steering Left 2% - Braking and Steering Right
Causal Factors (NMVCCS)	
(Combined values for Changing Lanes, Turning and Drifting Same Direction)	
Driver Fatigued	15% - Driver fatigued
Inattention	14% - Inattention factors
Driver Conversing	17% - Conversing
Misjudgment of Distance/Speed	8% - Misjudgment of distance/speed factors
False Assumption	17% - False assumption factors
Inadequate Evasive Action	5% - Inadequate evasive action factors
Critical Reason	6% - No critical reason 2% - Sleepy 2% - Ill/blackout 88% - Driver error 2% - Vehicle issues 0% - Weather /road /sign-signal issues
Inadequate Surveillance	59% - Inadequate surveillance factors
Other Driver Recognition Factors	5% - Other recognition factors
Following Too Closely	3% - Following too closely factors
Other Driver Decision Factors	14% - Other decision factors

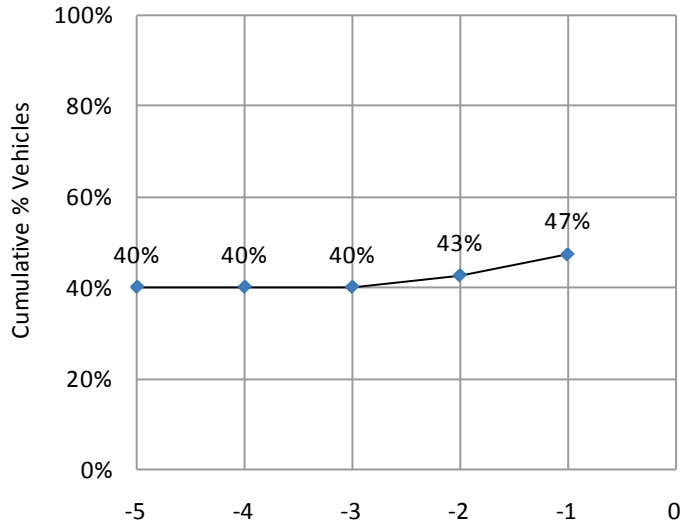
Kinematic Data (16 EDR Cases) **Changing Lanes/Same Direction**



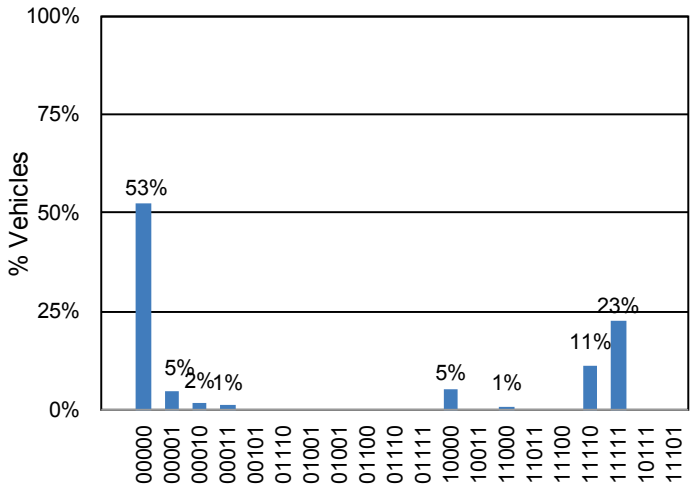
Vehicle Travel Speed (mph)



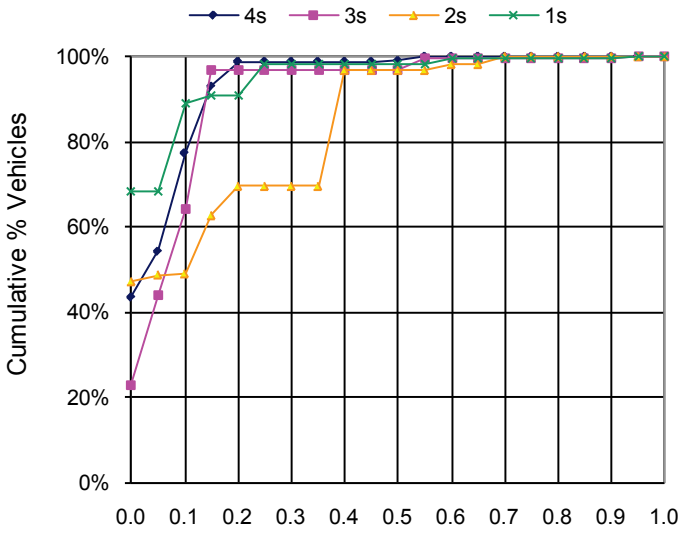
Vehicle Speed Limit (mph) , 04-08 GES



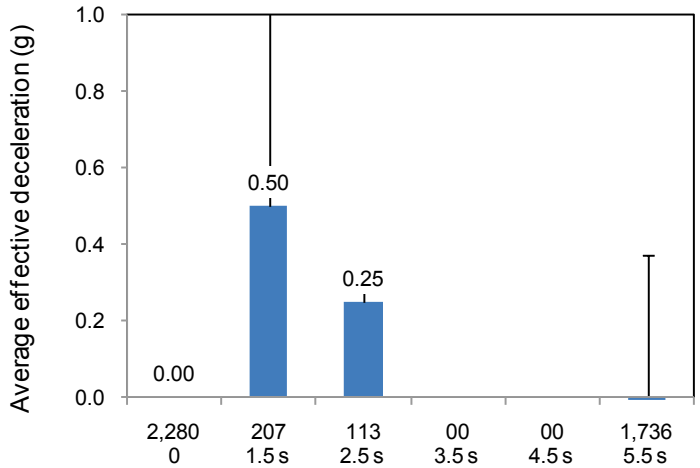
Brake Frequency at Time to Collision (s)



Detailed Brake Application Frequency

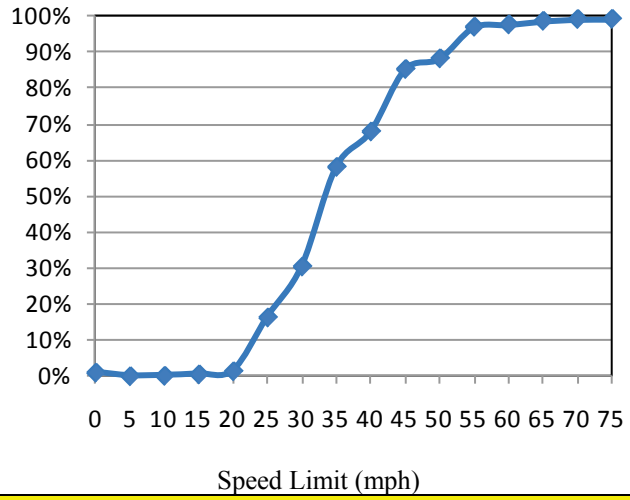


Braking Deceleration (g)



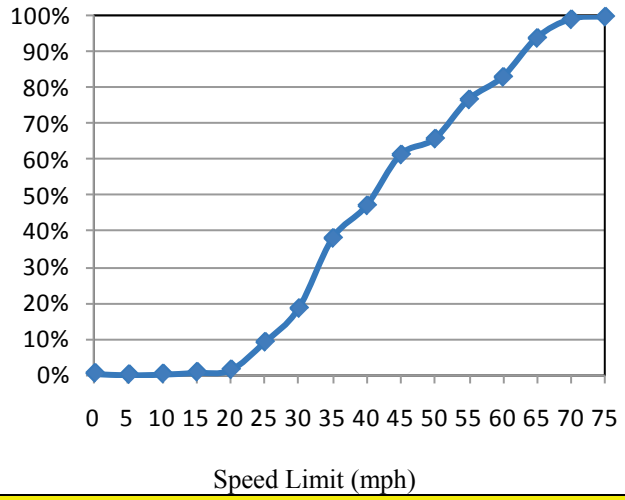
Effective Deceleration at TTC (s) with Frequency

A9. Turning/Same Direction

Driving Environment	
Roadway Alignment × Roadway Surface Condition × Atmospheric Condition	78% - Straight, dry road surface with no adverse weather 9% - Straight, slippery road surface with adverse weather
Relation to Junction × Traffic Control Device	26% - Intersection or intersection related at RGY traffic signal 25% - Intersection or intersection related without traffic controls 25% - Driveway, alley, etc. without traffic controls
Lighting Condition	80% - Daylight 13% - Dark but lighted
Posted Speed Limit	
Driver Characteristics	
Age	26% - 0 to 24 years 65% - 25 to 64 years 10% - 65 years or above
Gender	55% - Male 45% - Female
Driver Contributing Factors	
Alcohol	2% - Alcohol use
Drugs	< 1% - Drug use
Physical Impairment	< 1% - Physical Impairment
Violation Cited	28% - Violation cited
Speeding	1% - Speeding
Vision Obscured	1% - Obstruction
Distraction	17% - Distracted
Vehicle Contributing Factors	
Contributing Factors	< 1% - Contributing Factors

Corrective Action Attempted	**Turning/Same Direction**
Corrective Action	2% - Braking (No lockup) 2% - Steering Right
Causal Factors (NMVCCS)	
(Combined values for Changing Lanes, Turning and Drifting Same Direction)	
Fatigue	15% - Driver fatigued
Inattention	14% - Inattention factors
Conversing	17% - Conversing
Misjudgment of Distance/Speed	8% - Misjudgment of distance/speed factors
False Assumption of Others' Action	17% - False assumption factors
Inadequate Evasive Action	5% - Inadequate evasive action factors
Critical Reason	6% - No critical reason 2% - Sleepy 2% - Ill/blackout 88% - Driver error 2% - Vehicle issues 0% - Weather /road /sign-signal issues
Inadequate Surveillance	59% - Inadequate surveillance factors
Other Recognition Factors	5% - Other recognition factors
Following Too Close	3% - Following too closely factors
Other Decision Errors	14% - Other decision factors

A10. Drifting/Same Direction

Driving Environment	
Roadway Alignment × Roadway Surface Condition × Atmospheric Condition	71% - Straight, dry road surface with no adverse weather 12% - Straight, slippery road surface with adverse weather
Relation to Junction × Traffic Control Device	60% - Non-Junction without traffic controls 15% - Intersection or intersection related at RGY traffic signal
Lighting Condition	71% - Daylight 18% - Dark but lighted
Posted Speed Limit	
Driver Characteristics	
Age	27% - 0 to 24 years 63% - 25 to 64 years 9% - 65 years or above
Gender	66% - Male 34% - Female
Driver Contributing Factors	
Alcohol	9% - Alcohol use
Drugs	1% - Drug use
Physical Impairment	2% - Sleepy
Violation Cited	33% - Violation cited
Speeding	7% - Speeding
Vision Obscured	2% - Obstruction
Distraction	28% - Distracted
Vehicle Contributing Factors	
Contributing Factors	< 1% - Contributing Factors

Corrective Action Attempted	**Drifting/Same Direction**
Corrective Action	2% - Braking (No lockup) 3% - Braking (Lockup) 1% - Braking (Lockup Unknown) 9% - Steering Left 16% - Steering Right 2% - Braking and Steering Left 1% - Unspecified action
Causal Factors (NMVCCS)	
(Combined values for Changing Lanes, Turning and Drifting Same Direction)	
Driver Fatigued	15% - Driver fatigued
Inattention	14% - Inattention factors
Driver Conversing	17% - Conversing
Misjudgment of Distance/Speed	8% - Misjudgment of distance/speed factors
False Assumption	17% - False assumption factors
Inadequate Evasive Action	5% - Inadequate evasive action factors
Critical Reason	6% - No critical reason 2% - Sleepy 2% - Ill/blackout 88% - Driver error 2% - Vehicle issues 0% - Weather /road /sign-signal issues
Inadequate Surveillance	59% - Inadequate surveillance factors
Other Driver Recognition Factors	5% - Other recognition factors
Following Too Closely	3% - Following too closely factors
Other Driver Decision Factors	14% - Other decision factors

DOT HS 811 732
April 2013

U.S. Department
of Transportation
**National Highway
Traffic Safety
Administration**

9356-040813-v1c