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

www.nhtsa.gov

DOT HS 811 147 June 2009

Analysis of Lane-Change Crashes and Near-Crashes

REPORT DOCUMENTATION PAGE				*Form Approved OMB No. 0704-0188*
1. AGENCY USE ONLY (Leave blank) DOT HS 811 147	2. REPORT DATE June 2009			3. REPORT TYPE AND DATES COVERED Final Report
4. TITLE AND SUBTITLE Analysis of Lane-Change Crashes and Near-Crashes				5. FUNDING NUMBERS
6. AUTHOR(S) G. M. Fitch, S. E. Lee, S. Klauer, J. Hankey, J. Sudweeks, and T. Dingus				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Virginia Tech Transportation Institute 3500 Transportation Research Plaza (0536) Blacksburg, VA 24061				8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Human-Vehicle Performance Research Human Factors/Engineering Integration Division (NVS-331) National Highway Traffic Safety Administration, W46-424 1200 New Jersey Avenue SE. Washington, DC 20590				10. SPONSORING/MONITORING AGENCY REPORT NUMBER DTNH22-00-C-07007 Task Order 23
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT This document is available to the public through the National Technical Information Service, Springfield, VA 22161.				12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This report examines driver behaviors leading to lane-change crashes and near-crashes using data from the 100-Car Naturalistic Driving Study (Dingus, Klauer, Neale, et al., 2006) that unobtrusively examined 241 participants as they drove their personal vehicles during their daily commutes in the Northern Virginia/Washington, DC, area for a period of 12 to 13 months each. The study identified 135 lane-change events, of which 3 were crashes and the rest near-crashes. The analysis of these events found that 85 percent of the drivers used their turn signals during planned left-lane changes, while 24 percent used their turn signals when making unplanned left-lane changes to avoid a forward crash threat. The study found that 46 percent of the drivers looked toward their left mirrors, 50 percent looked toward their left windows, and 17 percent looked toward their center mirrors during the 3 s prior to performing planned left-lane changes. Furthermore, significantly fewer drivers sampled their mirrors when swerving into adjacent lanes to avoid forward crash threats. It was also found that drivers making planned left-lane changes took an average of 1.5 s to cross into the adjacent left lanes. An average of 2.3 s elapsed before these drivers encountered a lane-change near-crash. These findings suggest that drivers had little time to avoid an event once they started to change lanes. The majority of the near-crashes were resolved by drivers braking and steering away from the crash threat (compared to just braking, or just steering away). The 100-Car Study shows that safe driving requires drivers to concurrently monitor the forward roadway and surrounding traffic. However, drivers are limited in that they can visually attend to only one location at a time. Safely monitoring one’s surroundings may be difficult in dense traffic conditions. Systems that assist drivers in perceiving adjacent vehicles and recognizing crash threats while concurrently monitoring the forward roadway may mitigate this human factors dilemma.

14. SUBJECT TERMS 100-Car, eye-glance, mirror sampling, naturalistic, lane change, collision avoidance, intelligent vehicle initiative, driver behavior, human factors	15. NUMBER OF PAGES 88
	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		

NSN 7540-01-280-5500

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

GLOSSARY OF ACRONYMS

BRT	Brake Response Time
DAS	Data Acquisition System
EOR	Eyes Off Road
FARS	Fatality Analysis Reporting System
FAZ	Fast Approach Zone
GES	General Estimates System
GPS	Global Positioning System
LOS	Level of Service
NAS	Network Attached Storage
POV	Principal Other Vehicle
PZ	Proximity Zone
RE	Rear End
SUV	Sport Utility Vehicle
SV	Subject Vehicle
TTC	Time-to-Collision
VMT	Vehicle Miles Traveled
VTTI	Virginia Tech Transportation Institute

GLOSSARY OF TERMS USED IN THIS REPORT

Adjacent Vehicle
An adjacent vehicle is a vehicle located in a lane next to the SV's lane. This lane's direction of travel must be the same as that of the SV's lane.

Blind Spot The blind spot refers to the area around the vehicle that cannot be observed by the driver while he or she looks forward or through the rear-view or side mirrors. Blind spots can be checked by drivers when they turn their heads and look out the side windows. It should be noted that exact blind-spot measurement was not performed in this study. Rather, blind-spot checks are loosely assumed to have occurred when drivers glance out the side windows.

Brake Response Time
The BRT is operationally defined as the elapsed time from the lead vehicle action to the SV driver pressing the brake pedal.

Event An event refers to both crash and near-crash.

Eye-Glance An eye-glance was operationally defined as the time the driver's eyes fixated on a location around the vehicle. Specifically, an eye-glance began when the driver's eyes fixated on a point for two consecutive frames (at 10 Hz) and ended when the driver fixated on another point for two consecutive frames. Saccades were inherently included in eye-glance durations.

Fast Approach Zone
The FAZ is the area in the adjacent lane from 30 to 162 ft behind the rear bumper of the SV. At 100 ft/s (68.2 mph), a vehicle within this zone would have between 0.3 to 1.6 s of time headway. Both the PZ and the FAZ refer to areas that should be monitored before lane-change initiation.

Inattention to the Forward Roadway
A form of driver inattention identified in the 100-Car Study in which drivers do not attend to the forward roadway because they are actively looking to their side-view mirrors, side windows, or center mirror.

Lane Change A lane change is defined as a driving maneuver that moves a vehicle from one lane to another where both lanes have the same direction of travel. Events involving lateral motion onto the shoulder of the road or into an oncoming lane are not considered. The beginning of a lane change is defined using criteria adopted from Lee et al. (2004):

1. The driver initiates a steering input intended to change the direction of the vehicle relative to the lane. This criterion was predominantly used to establish lane-change initiation.

2. The vehicle begins to move laterally relative to the lane. This criterion was used when in-vehicle video footage was not available, during nighttime driving when the in-vehicle image contrast was low, and when the vehicle was performing a lane change on a curved highway segment.
3. The driver returns his/her gaze to the forward view upon glancing at his/her mirrors or side windows.

The lane change ends when the vehicle position in the adjacent lane normalizes. One analyst determined the beginning and end points of each lane change in this investigation. Since this report set out to investigate lane-change events with respect to struck and striking drivers, two types of lane-change maneuvers were identified: planned lane changes and unexpected lane changes.

Lane-Change Crash

A lane-change crash occurs when contact is made with an object during a lane-change maneuver and kinetic energy is measurably transferred or dissipated. A lane-change crash can occur at any speed. The object, which can be either moving or fixed, can be another vehicle, a roadside barrier, an object on the roadway, a pedestrian, a pedalcyclist, or an animal.

Lane-Change Near-Crash

A lane-change near-crash occurs when a rapid, evasive maneuver by the SV, or any other vehicle, is required to avoid an event that arises as a result of a lane change. The definition also includes events in which the SV performs an unexpected lane change to avoid a forward crash threat. A rapid, evasive maneuver is defined as steering, braking, or accelerating, or any combination of control inputs that approaches the limits of the vehicle's capabilities. The lane-change near-crash event time stamp was assessed to be the point in time where the two vehicles become the closest to each other. Distance cues were obtained from forward and side video footage recorded from cameras mounted in the SV.

Lane-Change Scenario

Three lane-change scenarios are investigated in this report. The first one involves the SV sideswiping a POV while making a lane change. The term sideswipe refers to an event that arises when a vehicle closes in on an adjacent vehicle during the execution of a lane change. This definition includes events in which a vehicle cuts in front of (i.e., changes lanes with little clearance) another vehicle, strikes or nearly strikes the side of another vehicle, and strikes or nearly strikes the closest rear corner of another vehicle. The second scenario involves a POV sideswiping the SV. The third scenario involves the SV performing an unexpected lane change to avoid an unforeseen forward crash threat, such as a decelerating lead vehicle. Unexpected lane changes are also referred to as swerves in this report.

LOS A: Free Flow

Individual users are virtually unaffected by the presence of others in the traffic stream. Freedom to select desired speeds and to maneuver within the traffic stream is extremely high. The general level of comfort and convenience provided to the motorist, passenger, or pedestrian is excellent.

LOS B: Flow With Some Restrictions

In the range of stable traffic flow, but the presence of other users in the traffic stream begins to be noticeable. Freedom to select desired speeds is relatively unaffected, but there is a slight decline in the freedom to maneuver within the traffic stream from LOS A, because the presence of others in the traffic stream begins to affect individual behavior.

LOS C: Stable Flow, Maneuverability and Speed Are More Restricted

In the range of stable traffic flow, but marks the beginning of the range of flow in which the operation of individual users becomes significantly affected by the interactions with others in the traffic stream. The selection of speed is now affected by the presence of others, and maneuvering within the traffic stream requires substantial vigilance on the part of the user. The general level of comfort and convenience declines noticeably at this level.

LOS D: Unstable Flow: Temporary Restrictions Substantially Slow Driver

Represents high-density but stable traffic flow. Speed and freedom to maneuver are severely restricted, and the driver or pedestrian experiences a generally poor level of comfort and convenience. Small increases in traffic flow will generally cause operational problems at this level.

LOS E: Flow Is Unstable; Vehicles Are Unable to Pass, Temporary Stoppages, etc.

Represents operating conditions at or near the capacity level. All speeds are reduced to a low, but relatively uniform value. Freedom to maneuver within the traffic stream is extremely difficult, and it is generally accomplished by forcing a vehicle or pedestrian to "give way" to accommodate such maneuvers. Comfort and convenience levels are extremely poor, and driver or pedestrian frustration is generally high. Operations at this level are usually unstable, because small increases in flow or minor perturbations within the traffic stream will cause breakdowns.

LOS F: Forced Traffic Flow Condition With Low Speeds and Traffic Volumes That Are Below Capacity. Queues Forming in Particular Locations

This condition exists whenever the amount of traffic approaching a point exceeds the amount that can traverse the point. Queues form behind such locations. Operations within the queue are characterized by stop-and-go waves, and they are extremely unstable. Vehicles may progress at reasonable speeds for several hundred feet or more, and then be required to stop in a cyclic fashion. LOS F is used to describe the operating conditions within the queue, as well as the point of the breakdown. It should be noted, however, that in many cases operating conditions of vehicles or pedestrians discharged from the queue may be quite good. Nevertheless, it is the point at which arrival flow exceeds discharge slow that causes the queue to form, and LOS F is an appropriate designation for such points.

Planned Lane Change

A planned lane change occurs when the driver decides to change lanes for positioning rather than in response to a forward threat, such as a slow or stopping lead vehicle. Examples of planned lane changes would be changing from the left lane to the right lane to prepare to exit a highway, changing from the right lane to the left lane on a highway to select a path of lesser resistance, and merging onto a highway.

Precipitating Event

The action of a driver that begins the chain of events leading up to the crash or near-crash.

Principal Other Vehicle

The POV refers to the vehicle with which the SV interacts in an event.

Proximity Zone

The PZ is the area in the adjacent lane from 4 ft in front of the front bumper of the SV to 30 ft behind the rear bumper of the SV. This area generally includes the blind spot and the area beside and behind the vehicle. The most common lane-change crashes appear to be those occurring in the PZ (Chovan et al., 1994). Both the PZ and the FAZ refer to areas that should be monitored before lane-change initiation.

Saccades A rapid irregular movement of the eye as it changes focus moving from one point to another (e.g., while reading).

Sideswipe A sideswipe describes an event that arises when a striking vehicle closes in on an adjacent POV during the execution of a lane change. This definition includes events in which the striking vehicle cuts in front of the POV (i.e., changes lanes with little clearance) and events in which the SV nearly strikes the POV's rear corner.

Striking vehicle

The SV is considered a striking vehicle when it creates a crash or near-crash event during the execution of a planned lane change, or when it swerves into an adjacent lane to avoid a forward threat.

Struck vehicle

The SV is considered to have been struck when it is involved in a crash or near-crash generated from another vehicle sideswiping the SV.

Unexpected Lane Change/Swerve

An unexpected lane change, which is also referred to as a swerve, results when the driver rapidly changes lanes to avoid a forward or lateral threat. Examples of unexpected lane changes are a driver swerving into an adjacent lane to avoid colliding with a rapidly decelerating lead vehicle, a driver swerving into an adjacent lane to avoid colliding with an object on the road, and a driver swerving into an adjacent lane to avoid being sideswiped by an adjacent vehicle.

EXECUTIVE SUMMARY

This report examines the driver behavior leading to lane-change crashes and near-crashes. The findings are derived from data collected in the 100-Car Naturalistic Driving Study (Dingus, Klauer, Neale, et al., 2006). The 100-Car Study unobtrusively observed 241 participants who resided in the Northern Virginia/Washington, DC area as they drove their personal vehicles for a period of 12 to 13 months. Both vehicular and driver behavior data (including driver eye-glance locations) were recorded.

Five research objectives were investigated in this analysis of lane-change crashes and near-crashes (hereafter referred to as lane-change events). The first objective was to classify the types of lane-change events recorded in the 100-Car Study. The severity and direction of the lane-change events, the precipitating events that occurred beforehand, as well as the avoidance maneuvers drivers performed, are all described. The second objective was to explore whether striking vehicle drivers' (i.e., drivers who initiated the lane-change events) rear- and side-view mirror use differed from struck vehicle drivers (i.e., drivers who encountered a vehicle changing into their lanes). Driver eye-glance locations were analyzed to determine the number of drivers who scanned their surroundings prior to and during the occurrence of the lane-change events. The third objective was to assess the vehicle control behavior (such as turn-signal use and lane-change duration) of striking vehicle drivers. The fourth objective was to analyze in a similar fashion the lane-change behavior of nearby vehicles that may have contributed to the lane-change events. Within this analysis, a fifth objective investigated the differences in driver responses to nearby vehicles entering the forward driving path according to their turn-signal use. The results obtained in pursuing these research objectives are summarized below.

Three event scenarios were used to classify 135 lane-change events (3 crashes and 132 near-crashes; lane-change events were categorized by lane-change direction within each scenario):

1) Subject vehicle (SV) striking or nearly striking an adjacent principal other vehicle (POV) during a planned lane change (termed the *SV Sideswipe POV* scenario).
2) SV swerving into an adjacent lane to avoid a forward crash threat (termed the *SV Swerve to Avoid Forward Crash Threat* scenario).
3) Adjacent POV striking or nearly striking the SV as the POV executed a lane change (termed the *POV Sideswipe SV* scenario).

The 51 near-crashes in the *SV Sideswipe POV* scenario (26 of these were left-lane changes, and 25 were right-lane changes) occurred at moderately high speeds (an average of 37 mph) in stable flow traffic conditions where maneuverability and speed were restricted. An analysis of drivers' eye-glance locations revealed that 17 percent of the drivers failed to check their left mirrors, left windows, and center mirrors during the last 8 seconds prior to initiating left-lane changes. Furthermore, 36 percent of the drivers failed to check their right mirrors, right windows, and center mirrors during the last 8 seconds prior to initiating a right-lane change. These results suggest that some SV drivers failed to adequately scan their surroundings prior to changing lanes. An analysis of SV driver behavior found that 85 percent of the drivers used their turn signals when making planned left-lane changes and 72 percent used their turn signals when making planned right-lane changes. Turn signals were activated on average for 3.4 s prior to left-lane changes and 3.9 s prior to right-lane changes. These results show that some drivers failed to give proper notice to surrounding vehicles regarding their intent to change lanes. This also suggests that turn-signal use may not be a reliable predictor of lane changes that lead to crashes or near-crashes. With respect to vehicle control, the average elapsed time from lane-change initiation to the SV crossing into the adjacent lane was 1.5 s for left-lane changes and 1.3 s for right-lane changes. Additionally, left-lane-change events occurred in an average of 2.3 s and right lane-change events occurred in an average of 1.9 s. These findings suggest that drivers had little time to respond to avoid a crash if a threat was present. The majority of lane-change events were resolved by drivers braking and steering in the opposite direction (compared to just braking or just steering away).

The 32 near-crashes in the *SV Swerve to Avoid Forward Crash Threat* scenario (17 were left-lane changes, and 15 were right-lane changes) occurred at moderately high speeds (an average of 41 mph for left-lane changes and 35 mph for right-lane changes) in stable flow traffic conditions where maneuverability and speed were restricted. An analysis of drivers' eye-glance locations found that 33 percent of the drivers failed to check their left mirror, left window, and center mirror during the last 8 seconds prior to swerving into an adjacent left lane. Furthermore, 43 percent of the drivers failed to check their right mirror, right window, and center mirror prior to swerving into an adjacent right lane. These results suggest that some SV drivers failed to adequately scan their surroundings prior to swerving into an adjacent lane in order to avoid a forward crash threat. This may have occurred because these drivers may have been focused on monitoring the forward crash threat as they prepared to perform an evasive lane change, or because they had previously performed a lane change and assumed that the adjacent lane would be vacant. With respect to vehicle control, 24 percent of the drivers activated their turn signal prior to swerving into a left lane, while 33 percent activated their turn signal prior to swerving into a right lane. Drivers activated their turn signals on average for 1.5 s prior to swerving into the left lane and 1.3 s prior to swerving into the right lane. The elapsed time from lane-change initiation to crossing the lane was 1.2 s for left evasive lane changes and 0.9 s for right evasive lane changes. The elapsed time from lane-change initiation to the event was 1.8 s for left evasive lane changes and 1.6 s for right evasive lane changes. These findings suggest that drivers performed rapid lane changes to avoid a forward crash threat. Overall, the relatively low number of drivers who glanced to their periphery and used their turn signals may have been a product of the increased time pressure to change lanes.

The 49 near-crashes in the *POV Sideswipe SV* scenario (22 were left-lane changes and 27 were right-lane changes) occurred at average moderate speeds of 45 mph when POVs made left-lane changes and 34 mph when POVs made right-lane changes. An analysis of SV drivers' eye-glance locations found that 100 percent of the drivers looked forward during the last 3 seconds prior to POVs making left-lane changes into the SVs' lane. Furthermore, 100 percent of the SV drivers looked forward during the last 3 seconds prior to POVs making right-lane changes into the SVs' lane. Perhaps lead SV drivers were able to avoid a crash because they were looking in the direction of the unfolding crash threat. In contrast, the striking SV drivers previously described may have instigated a crash threat by failing to adequately scan their surroundings prior to changing lanes. In analyzing POVs lane-change behavior, an average of 1.4 s elapsed from POVs initiating a left-lane change and crossing into the SV's lane, while an average of 1.3 s elapsed from POVs initiating a right-lane change and crossing into the SV's lane. Events resulting from POVs performing left-lane changes into the SV's lane occurred on average in 2.1 s, while events resulting from POVs performing right-lane changes into the SV's lane occurred on average in 2.2 s. It was found that 50 percent of the POV drivers used their turn signals when making left-lane changes, while 36 percent signaled when making right-lane changes. The majority of SVs elected to brake and steer away from the crash threat. Closer inspection revealed that SV driver brake-response times (BRTs) to POVs did not appear to differ by POV driver turn-signal use. SV drivers took on average 1.0 s to brake to a signaling POV making a left-lane change, and 1.8 s to brake to a signaling POV making a right-lane change. In contrast, SVs took on average 1.2 s to brake to a non-signaling POV making a left-lane change, and 1.5 s to brake to a non-signaling POV making a right-lane change. There appears to be a tendency for SV drivers' BRTs to be longer for POVs entering the SV's lane from the left compared to entering the lane from the right.

The 100-Car Study was the first study to establish a direct relationship between immediate, pre-event driving inattention and crash and near-crash involvement. Glances away from the forward roadway greater than 2 s were shown to increase crash risk by at least two times. This is because drivers looking away from the road stand to miss critical changes in the environment that affect where they can safely travel. Similarly, the current study found that a driver who nearly crashed with an adjacent vehicle when making a lane change failed to adequately monitor the side-view mirrors, side windows, and center mirror prior to changing lanes. It is possible that these drivers also failed to perceive changes in their environment, such as a fast-approaching POV in the adjacent lane prior to changing lanes. These events may have been avoided had these drivers monitored their surroundings more closely. The notion that monitoring one's surroundings is a protective driving behavior is supported by the 100-Car Study, which found that driving-related glances away from the forward roadway of less than 2 s reduce crash risk (odds ratio of .048). Taken as a whole, these findings exemplify a dilemma that drivers face between monitoring the forward roadway and monitoring the areas around them. For example, a driver checking the vehicle's blind spot in preparing to change lanes to pass a slow-moving lead vehicle may fail to notice when the lead vehicle suddenly decelerates. On the other hand, drivers closely attending to decelerating lead vehicles may fail to notice fast-approaching POVs in the adjacent lanes when attempting passing maneuvers. Being aware of surrounding traffic conditions may be a protective driving behavior, but surrounding traffic conditions may make it difficult to safely gather this information. Systems that assist drivers in perceiving the position of adjacent vehicles and recognizing when they become a crash threat, while they attend to the forward roadway, may mitigate this human factors dilemma. Systems such as blind spot notification systems (which typically display a visual icon when a POV is located in the SV's blind spot) and lane change warning systems (which generate an alert when an SV is about to crash with an adjacent vehicle during a lane change) may address this issue.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

This report provides an analysis of driver behavior prior to and during lane-change crashes and near-crashes. The findings are formulated from driving data collected in the 100-Car Naturalistic Driving Study (Dingus, Klauer, Neale, et al., 2006). The 100-Car Study examined 241 drivers as they performed their everyday driving in the Northern Virginia/Washington, DC, area for a period of 12 to 13 months. Data was collected by installing an unobtrusive data acquisition system (DAS) in each vehicle. Without an in-vehicle experimenter, drivers were free to drive as they normally would. Events where drivers crashed or nearly crashed with other vehicles while executing lane changes were identified from the recorded data. This data provides an unprecedented insight into lane-change crashes and near-crashes and increases our understanding of the factors contributing to these events.

Following an overview of the research objectives, the second chapter provides a review of the literature and outlines the scope of the lane-change events that were examined. A review of non-event lane-change driver behavior is provided. Brief overview information on the 100-Car Study is included. Chapter 3 explains the methods used to prepare the *100-Car Lane-Change Event Database*. The results of the study are presented in Chapter 4. Attention is given to lane-change event classification and driver eye-glance behavior prior to and during the event, as well as driver performance. Each analysis is reported by event scenario. Chapter 5 discusses the results as they relate to the stated research questions. Chapter 6 concludes the report, suggests how the results can be applied to improve transportation safety and lists the study's limitations.

OBJECTIVES

The overall objective of the current analyses is to quantify driver and vehicle performance to better understand lane-change crashes and near-crashes. This study has five research objectives.

Objective 1. Classify Lane-Change Events

An understanding of the types of lane-change events observed in the 100-Car Study will be gained by establishing a classification scheme. This classification scheme will also establish the severity of the lane-change events, lane-change direction frequencies, precipitating events, and avoidance maneuvers.

Objective 2. Explore the Differences Between Striking and Struck Vehicles With Regard to Rear- and Side-View Mirror Sampling Behavior

An understanding of the differences in rear- and side-view mirror use between striking and struck vehicles will be gained by analyzing driver eye-glance data. This approach provides insight on where drivers look when formulating spatial awareness prior to changing lanes, where drivers look when making their go/no-go decision to change lanes, and where drivers look when executing the lane-change maneuver.

Objective 3. Explore the Vehicle-Control Behavior of Striking Subject Vehicle Drivers.

An analysis of vehicle-control behavior will provide insight on the driving conditions present during the lane-change events, how fast the SVs were traveling prior to the events, how many SV drivers used their turn signals when changing lanes, how long the turn signals were used prior to changing lanes, the length of time that elapsed from the SV initiating a lane change to when it crossed into the POV's lane, the length of time that elapsed from the SV initiating the lane change to the event, and how hard SV drivers braked when responding to lane-change events.

Objective 4. Analyze the Relevant Lane-Change Behavior of Nearby Vehicles That May Have Contributed to Crash and Near-Crash Events
An analysis of actions of POVs that struck or nearly-struck SVs while changing lanes will yield insight on how many POVs used turn signals prior to changing lanes, how long the POVs used their turn signals prior to changing lanes, how much time elapsed from a POV initiating a lane change to crossing into the SV's lane, and how much time elapsed from a POV initiating a lane change to the lane-change event.

Objective 5. Analyze SV Response Behavior to Nearby Vehicles Entering the SV's Forward Driving Path by Turn-Signal Use
An analysis of SV response behavior to striking POVs will provide insight into how fast an SV driver traveled prior to a POV driver executing a lane change into the SVs' forward driving path. It will also reveal how quickly SV drivers braked in response to POV drivers executing lane changes into the SVs' forward driving paths. How SV drivers' brake-response times and level of deceleration differed according to the POV drivers' turn-signal use will also be examined.

CHAPTER 2: BACKGROUND

LITERATURE REVIEW

The development of countermeasures to reduce events associated with changing lanes and passing requires an understanding of drivers' behaviors, the timing of those behaviors, and the driving environment's influence on the chosen behaviors. A lane-change event occurs when a driver is in the process of maneuvering the vehicle laterally from one lane into another. Transportation researchers estimate that lane-change crashes account for 4 to 10 percent of all crashes (Barr & Najm, 2001; Eberhard et al., 1994; Wang & Knipling, 1994; Young et al., 1995). Annually, between 240,000 to 610,000 lane-change crashes are reported to the police; at least 60,000 people are injured and a significant amount of property is damaged (NHTSA, 2001; Wang & Knipling, 1994). It is estimated that another 386,000 lane-change crashes go unreported (Chovan et al., 1994; Wang & Knipling, 1994). In addition, lane-change crashes account for between 0.5 to 1.5 percent of all motor-vehicle fatalities (224 to 732 fatalities per year; NHTSA, 2001; Wang & Knipling, 1994). Crashes associated with lane changes account for almost 10 percent (41.2 million hours) of all crash-caused delays due to the high probability of multiple lane blockages when such crashes occur (Chovan et al., 1994).

Research has revealed that most drivers in lane-change crashes did not attempt an avoidance maneuver; this finding suggests that the drivers did not see or were unaware of the presence of another vehicle or crash hazard (Chovan et al., 1994; Eberhard et al., 1994; Tijerina, 1999). According to Knipling (1993), 75 percent of lane-change/merge crashes involve a recognition failure by the driver. To reduce lane-change crashes, drivers must be made aware of impending hazards before initiating a lane change (Chovan et al., 1994; Tijerina, 1999).

This literature review begins with a discussion of the various historical definitions and parameters important to understanding lane changes. It concludes with a discussion of an earlier naturalistic lane-change study (Lee, Olsen, & Wierwille, 2004). This earlier effort was focused primarily on lane changes, and used many of the same techniques used in the 100-Car Study. Nearly 9,000 lane changes were captured in the resulting dataset; 500 of these were studied in-depth, leading to an unprecedented understanding of driver behavior during such maneuvers.

Definition of a Lane Change

A lane change has been defined as a deliberate and substantial shift in the lateral position of a vehicle (Chovan et al., 1994). Worrall and Bullen (1970) described a lane change in three parts: the head portion is the time and distance required for a vehicle to move from a straight-ahead path to the first intercept of the lane line. The actual lane change starts when a vehicle first encroaches on the lane line between the original and destination lanes. The maneuver ends once the vehicle has completely crossed that line. The tail portion of the maneuver is the time and distance required for a vehicle to return to a straight-ahead path in the destination lane after crossing the lane line.

Another view, offered by Van Winsum et al. (1999), describes three sequential phases of the lane-change maneuver based on steering. The first phase is an initial turn of the steering wheel to a maximum angle. The second phase begins when the steering wheel is turned in the opposite direction and ends when the vehicle heading approaches a maximum that occurs when the steering wheel angle passes through zero (straight-ahead). During the third phase, the steering wheel is turned to a maximum angle in the opposite direction to stabilize the vehicle in the new lane. This definition is useful when only steering data is available. However, lane changes performed in curves may not be captured if the driver does not reverse the angle of the steering wheel. Consideration for road geometry is also required to operationally define a lane change.

Wierwille (1984) described a lane change in two parts. A heading deviation is introduced by a steering input that results in buildup of lateral deviation. As the vehicle approaches the correct lateral position in the adjacent lane, the heading deviation is removed by applying a steering correction in the direction opposite that of the initial steering input.

Lane changes can occur for a variety of reasons, such as entering the roadway (merging), preparing to exit the roadway, anticipating vehicles merging onto the roadway, anticipating a slowing lead vehicle, a change in the number of lanes available, and swerving to avoid a forward crash threat such as a rapidly decelerating lead vehicle. One of the most common types of lane change is a maneuver in which a driver changes lanes to pass a slower lead vehicle to maintain current speed (Fancher, 1999; Hetrick, 1997).

Lane-Change Crash Scenarios
There are two primary types of lane-change crashes in which a POV is approaching from behind the SV in the adjacent lane. In the fast-approach case, there is a longitudinal gap between the vehicles prior to the start of the lane change, and this gap is closed at a substantial velocity differential (Chovan et al., 1994). This crash case is potentially dangerous and severe due to the high velocity differential (e.g., between 15 to 30 mph) (Young et al., 1995). This scenario occurs infrequently.

The second case, in which the majority of lane-change crashes occur, is the proximity case. In this case there is little or no longitudinal gap and the velocity differential between vehicles is small (Chovan et al., 1994; Wang & Knipling, 1994). Young et al. (1995) found that 78 percent of lane-change collisions involve low closing speeds (i.e., relative speed < 15 mph).

Najm and Smith (2002) identified nine lane-change *pre-crash scenarios*. They are: encroaching from adjacent lane (34.9%), turning (13.9%), drifting (7.7%), both vehicles attempting (avoidance) maneuvers in an encroachment situation (7.6%), passing (4.0%), avoiding a rear-end crash (3.9%), parking (3.7%), losing control (3.7%), and merging (2.5%).

Monitoring Surrounding Areas
Changing lanes requires high attentional and visual demand compared to normal highway or freeway driving due to the need to continually monitor areas around the vehicle (Shinar, 1978). The driver must continually monitor areas in front of and behind the vehicle to maintain an awareness that is essential for safe driving. This increased attentional and visual demand makes lane changing one of the riskiest driving maneuvers, according to Jula, Kosmatopoulos, and Ioannou (1999). Drivers must straddle traffic flows and are exposed to two streams of vehicles; they must make rapid gap judgments, monitor vehicles approaching from behind and in the blind spot, and potentially disrupt the flow of following vehicles (Redelmeier & Tibshirani, 2000).

Forward Area
The forward area is the area in the same lane in front of the SV in which a POV is traveling. This area is discussed in terms of headway and concerns the area between a lead vehicle and a following vehicle, in terms of time headway or distance (Rockwell, 1972; Van Winsum & Heino, 1996). Time headway is the elapsed time between the front of the lead vehicle passing a point on the roadway and the front of the following vehicle passing the same point; it is calculated as the range between the two vehicles divided by the speed of the following vehicle (McLaughlin, 1998). For example, a vehicle moving at 100 ft/s at a range of 100 ft (100 ft ÷ 100 ft/s) would have a time headway of 1 s. Time headway can be thought of as a margin of safety. One convention states that headway should be at least 2 s (Evans, 1991), which is referred to as the "2-second rule" and is often taught in driver's education classes. Another rule is the National Research Council recommendation of "one car length for every 10 mph," which few drivers follow (Rockwell, 1972).

Four distinct headway zones have been described by Ohta (1993): the danger zone (within 0.6 s of the vehicle ahead), the critical zone (0.6 s to 1.0 s), the normal driving zone (1.1 s to 1.7 s), and the pursuit zone (> 1.7 s). Under normal circumstances, it appears that drivers travel with a time headway of between 0.5 s and 4.0 s and, in general, drivers attempt to maintain a minimum of 2.0 s (Rockwell, 1972).

Forward Adjacent Lane Area
The forward area in the destination lane is another area of concern. The available distance is very likely to influence the decision to change lanes. Jula et al. (1999) analyzed the kinematics of the vehicles involved in lane changing and studied the conditions under which crashes can be avoided. This approach is promising in that the minimum longitudinal spacing requirements can be calculated in preparation for a lane change

Rearward Adjacent Lane Area
Some drivers are willing to change lanes even when a vehicle is approaching from behind in the adjacent lane. This scenario is more likely to lead to a crash as the driver attempts to change lanes and strikes or is struck by a vehicle in the adjacent lane (Chovan et al., 1994). The rearward area is divided into rear zones related to the lane-change crash scenarios previously described. The zones include the proximity zone and the fast approach zone (Talmadge et al., 2000). The PZ is the area in the adjacent lane from 4 ft in front of the front bumper of the SV to 30 ft behind the rear bumper of the SV. This area generally includes the blind spot and the area beside and behind the vehicle. The most common lane-change crashes appear to be those occurring in the PZ (Chovan et al., 1994). The FAZ is the area in the adjacent lane from 30 to 162 ft behind the rear bumper of the SV. At 100 ft/s (68.2 mph), a vehicle within this zone would have between 0.3 to 1.6 s of time headway. Both the PZ and the FAZ are areas that should be monitored before lane-change initiation.

Lane Change Duration
In a literature review on lane changes, Finnegan and Green (1990) reported that lane changes take between 4.9 and 7.6 s (including visual search time). Tijerina et al. (1997) described a pilot study of both highway and city street driving. For the city streets, lane-change duration was between 3.5 and 6.5 s, with a mean of 5.0 s. For the highway, the range was 3.5 to 8.5 s with a

mean of 5.8 s. In a study by Hetrick (1997), the distribution of lane-change times ranged from 3.4 to 13.6 s with a reported mode of 6.0 s for 282 lane changes. In that study, 16 participants drove on city and highway segments for 1.5 h in an instrumented vehicle with an observer present. In another study, the influence of fatigue on local short-haul truck drivers was investigated (Hanowski, Wierwille, Garness, Dingus, Knipling, & Carroll, 2000). The majority of lane changes were made on local urban and suburban streets and roadways at relatively low speeds (e.g., < 45 mph). It was concluded that drivers who were fatigued spent more time looking at the center-forward direction and made significantly shorter lane changes (M = 3.73 s) as compared to those completed by non-fatigued drivers (M = 4.79 s). The average lane-change duration was 4.52 s for 260 lane-change events. Lane changes started when the wheel of the vehicle crossed the lane line and ended when the vehicle settled in the new lane, and did not include the head duration. If the average lane-change duration of 4.79 s is added to the Worrall and Bullen (1970) value of 1.25 (the head), the total lane-change duration would be 6.04 s, a value that falls within the range of previous findings (Chovan et al., 1994; Finnegan & Green, 1990; Hetrick, 1997; Tijerina et al., 1997). Table 1 summarizes these findings.

Table 1. Lane Change Duration as Reported by Various Sources

Source	Range	Mean/Median/Mode	Notes
Worrall & Bullen (1970)	2.3 to 4.1 s	Median = 3.2 s	Underestimated due to resolution
Finnegan & Green (1990)	4.9 to 7.6 s	Median = 6.3 s	Including visual search time
Chovan et al. (1994)	2.0 to 16 s	-	Initial range for Collision Avoidance System
Tijerina et al. (1997)	3.5 to 6.5 s	Mean = 5.0 s	City streets
Tijerina et al. (1997)	3.5 to 8.5 s	Mean = 5.8 s	Highway
Hetrick (1997)	3.4 to 13.6 s	Mode = 6.0 s	City and highway segments
Hanowski et al. (2000)	1.1 to 16.5 s (SD = 1.71)	Mean = 4.8 s (6.0 s if head of 1.25 is added)	Local short-haul truck drivers, speeds < 45 mph; does not include head

Range and Range-Rate

Range is defined as the distance from the front bumper of the following vehicle to the rear bumper of the lead vehicle. This is the distance from the SV to another vehicle ahead in the same lane or to the closest forward vehicle in the destination lane. In the case of a vehicle approaching from behind the SV, range is the distance from the front bumper of the adjacent rear vehicle to the rear bumper of the SV, along a longitudinal axis through either of the vehicles. Range-rate is the rate at which the range between two vehicles is changing. It is measured in terms of relative velocity in which the velocity of one vehicle is subtracted from the velocity of the other vehicle. Range-rate is of concern in terms of distance from the SV to a nearby vehicle (i.e., forward or in adjacent lane). Range-rate is reported in either mph or ft/s. For a total of 2,607 manual lane changes, Fancher (1999) reported an average range of 153.3 ft (SD = 103.6 ft) with 27 percent of lane changes occurring within 70 ft of the preceding vehicle. The average range-rate was –4.1 ft/s (SD = 10.0 ft/s).

Time-to-Collision
Time-to-collision is the time required for two vehicles to collide if they continue on their present speeds and paths (Van Winsum & Heino, 1996). The TTC is calculated as the range between the two vehicles divided by their range-rate or relative velocity (ΔV). Take the case of two vehicles 100 ft apart: If the front vehicle is moving at 100 ft/s and the following vehicle is moving at 120 ft/s, the range-rate would be 100 ft/s minus 120 ft/s, or –20 ft/s. To calculate the TTC, 100 ft is divided by –20 ft/s. Therefore, the TTC is 5.0 s. In other words, it would take 5.0 s for the following vehicle to collide with the lead vehicle if velocity were constant. However, the TTC parameter assumes constant speed and does not account for vehicle acceleration (Smith, Najm, & Glassco, 2002).

Vehicle Position
The position of vehicles surrounding the SV is important. A lead vehicle in front of the SV is of concern since headway must be maintained prior to and during the lane change. A vehicle in the adjacent lane, forward of the SV, needs to be monitored for the same reason. A vehicle next to the SV in the adjacent destination lane is also of concern. The driver of the SV must monitor this vehicle until space behind or in front of it is adequate. Finally, a vehicle in the adjacent lane behind the SV is of concern because there must be adequate space for the SV to enter that lane.

Turn Signal Use
Another important factor for lane changing is the use of the turn signal. Hetrick (1997) found that 92 percent of lane changes were indicated by a turn signal in a study in which an experimenter in the passenger seat gave navigation directions to the driver. In a small-scale pilot study, Tijerina et al. (1997) reported that drivers did not use their turn signals for 14.6 percent of lane changes on highways (10.3 percent for city streets). However, in these studies it is likely that experimenter presence influenced turn signal compliance. The distribution of turn-signal onset time ranged from 3.62 s before the lane change began to 2.42 s after it began (Hetrick, 1997). In other words, the manner in which turn signals are used may vary greatly among drivers, with some drivers activating the turn signals after beginning the lane-change maneuver.

Eye Movements
Driving is "guided chiefly by vision" (Gibson & Crooks, 1938, p. 454), where information is continuously monitored and gathered (Hills, 1980; Mourant & Rockwell, 1970; Wierwille, 1984). Since Gibson and Crooks's statement, perhaps the first investigation relevant to eye movement was that of the eye vantage point performed by James Meldrum of Ford Motor Company. Meldrum conducted an eye position survey to identify position contours (Henderson, 1985). Termed an "eyellipse," this allowed automobile designers the ability to assess what and where the driver can see (e.g., view out the windshield, view of instrument panel).

In contrast to *what* drivers can see is research related to *where* drivers are actually looking while driving. Measures of eye movements have been investigated in terms of the number of eye-glances, total glance time, mean glance time to a particular location, total eyes-off-road (EOR) time, and total task time (the time to complete a task). For example, driving research has been conducted on the performance of completing in-vehicle tasks such as adjusting the radio, viewing in-vehicle displays (e.g., speedometer) or interacting with a navigation system (Dingus, Antin, Hulse, & Wierwille, 1988; Gellatly & Kleiss, 2000; Kurokawa & Wierwille, 1990;

Tijerina, Parmer, & Goodman, 1999). Visual glance duration and the number of glances per task were investigated while performing conventional in-vehicle tasks and navigation tasks (Wierwille, Antin, Dingus, & Hulse, 1988). Findings indicated that glance frequency varied depending upon the task, and that glance duration for a single glance ranged from 0.62 to 1.63 s. The mean number of glances across all tasks was between 1.26 and 6.52 glances. Zwahlen, Adams, & DeBald (1988) reported that "out of view" glance times (rear-view mirror, speedometer, etc.) range from 0.5 to 2.0 s during straight driving. Findings from several additional eye movement studies relevant to lane changing are reviewed in the following sections.

Mirror Glances

An early study by Robinson et al. (1972) measured head movements to study the visual search of drivers while changing lanes on a highway. (The relationship of head movement to eye movement was also investigated and was found to be stable.) Visual search patterns were recorded including movements back (blind spot), to the side, and to the mirrors. Results indicated that lane changes to the left had more searches than right-lane changes. This finding was supported by Taoka (1990), who reported that drivers use the rear-view and left-side mirrors much more than the right-side mirror. In a study of the average duration of glances to center and side mirrors, drivers relied more on the center mirror than on the right mirror during lane changes to the right (Mourant & Donohue, 1977). Robinson et al. (1972) reported that both the outside mirror and blind spot were checked during left-lane changes, and that the inside (rear-view) mirror and blind spot were checked for right-lane changes. It appears that head turns to check the blind spot were only observed in conjunction with lane changes. While traveling straight ahead, only glances to the mirrors were made, and drivers did not make head turns to the side or rear of the car (Mourant & Donohue, 1977).

Mirror Glance Duration

Based on available literature discussed in this section, mirror glance times range from 0.8 to 1.6 s (M = 1.1 s). Searches to the rear (blind spot) appeared to require a minimum of 0.8 s. Rockwell (1988) reported that the average glance duration to the left mirror was 1.10 s (SD = 0.33 s). This finding was consistent across participants in three different experiments over a 6-year period using the same data gathering and reduction technique. Taoka (1990) modeled Rockwell's eye-glance distributions and found that they could be well represented by means of a lognormal distribution. Taoka reported that the average time for viewing the left-side mirror was also 1.10 s (SD = 0.3 s). The 5^{th} percentile value was 0.68 s and the 95^{th} percentile was 1.65 s. For right-side mirror glances, Nagata and Kuriyama (1985) reported that average glance duration was 1.38 s (angle difference from the vertical axis of 70 degrees), while Rockwell reported an average glance duration of 1.21 s (10 percent larger than left glances) with a standard deviation of 0.36 s. For the rear-view mirror, Taoka reported that the average glance time was 0.75 s (SD = 0.36 s). The 5^{th} percentile value was 0.32 s and the 95^{th} percentile was 1.43 s.

Mourant and Donohue (1974) examined the total glance time for lane changes. The average time for a novice driver to complete the visual sampling for a left-lane change was 2.4 s, consisting of 1.38 glances to the left-side mirror, 0.76 glances to the inside (rear-view) mirror, and a head turn. Data was also obtained for experienced and mature drivers and similar patterns of glancing were observed.

Search and Scan Patterns
Early research included the investigation of visual search and scan patterns while driving (Mourant, Rockwell, & Rackoff, 1969; Mourant & Rockwell, 1970; 1972). It was found that as drivers became familiar with a route, they spent more time looking ahead, they confined their sampling to a smaller area ahead, and they were better able to detect potential traffic threats (e.g., movement in the periphery). Mourant and Rockwell (1970) found that peripheral vision is used to monitor other vehicles and lane line markers, that novice and experienced drivers differed in their visual acquisition process, and that novice drivers may be considered to drive less safely.

In another study, it was found that specific eye-glance patterns take place before lane-change initiation (Tijerina et al., 1997). Based on data collected during road studies, the researchers used a Markov process to examine the probability of movement from one location to another. Link diagrams were then created showing glance location and the associated probabilities of a glance to that location during the 10.0 s prior to lane-change initiation. For a lane change from right to left, the probability of glancing at the forward view was 0.41, the probability of glancing at the left mirror was 0.22, the probability of glancing in the center mirror was 0.21, and the probability of glancing over the left shoulder (blind spot) was 0.08. The probability of a glance transition between different locations was also provided (e.g., 0.37 between the forward view and the center mirror).

Tijerina (1999) highlighted pertinent findings from the Tijerina et al. (1997) study. The percentage of lane changes in which side- and rear-view (center) mirrors were used differed for left- and right-lane changes. The left-side mirror is used more frequently in maneuvers to the left (between 65 and 85% of the time) than is the right-side mirror for maneuvers to the right (between 36 and 52% of the time). However, the rear-view mirror is used more often for right-lane changes (between 82 and 92% of the time) than for left-lane changes (between 56 and 67% of the time). This supports the earlier finding that drivers depended most heavily on the rear-view mirror for lane changes to the right (Mourant & Donohue, 1977). Tijerina et al. (1997) found that for lane changes to the left, glances to the center and left mirrors had approximately the same likelihood (0.21 and 0.22, respectively). Over the shoulder (blind spot) glances were more frequent for left-lane changes than right-lane changes.

A recent field study investigated the influence of fatigue on critical incidents involving local short-haul truck drivers (Hanowski et al., 2000). Fatigued drivers involved in critical incidents when making lane changes spent more time looking in irrelevant locations than in relevant locations (such as out-the-windshield, out-the-windows, at the mirrors, or at the instrument panel). The mean proportion of time spent looking at irrelevant locations was 0.079. However, during normal lane changes (not a critical event), the mean proportion of time that drivers spent looking at irrelevant locations was 0.028, a significant difference. In terms of eye behavior, it appears that fatigued drivers involved in critical incidents pay less attention to the road ahead, appropriate mirrors, etc.

Effect of Traffic
Traffic is also likely to affect eye-glance and lane-change behavior. Bhise et al. (1981) conducted field studies on public roads to investigate mirror glance times (eye position and head

movements) during lane-change maneuvers. Participants followed a pickup truck and were instructed to make lane changes in various levels of traffic. It was found that glance durations increased by an average of 0.25 s (a 20% increase) with the presence of traffic (when an overtaking vehicle was present) as compared to situations with no traffic. Single-glance durations were between 1.1 to 1.8 s (*M* =1.3 s) when there was no overtaking traffic in the adjacent lane, and 1.0 to 2.3 s (*M* = 1.5 s) when there *was* overtaking traffic in the adjacent lane. Robinson et al. (1972) reported that the mean visual search time for preparing for a lane change varied with and without traffic. Overall, traffic causes a large (50 to 85%) increase in both total and visual input times. Without traffic, visual search times were 3.7 s for left-lane changes and 3.4 s for right-lane changes. With traffic, visual search times were 6.1 s for left-lane changes and 4.5 s for right-lane changes. Also, mirror glance style was characterized for each participant. For example, most participants glanced at the left outside mirror and often at other locations before changing lanes. Most participants tended to retain a glance style throughout the experiment. Such information might be useful in estimating the timing and duration of a warning presented to the driver prior to lane-change initiation.

NATURALISTIC STUDY OF LANE CHANGES

Method

Lee et al. (2004) conducted the first study of lane changes using a naturalistic method (participants drove the instrumented experimental vehicle for long periods of time during their normal driving without an experimenter present). The general objective of this project was to characterize lane-change behavior using naturalistic data. The data was gathered between October 2000 and July 2001. Data was recorded while commuters drove instrumented vehicles to and from work, and the data was later associated with passing maneuvers. Although no lane-change crashes were observed, this data provides both context and comparison for the lane-change crashes and near-crashes observed in the 100-Car Study.

Sixteen commuters who normally drove more than 25 mi (40 km) in each direction participated. All were volunteers and were paid nominally for their participation. Half commuted on an interstate and half commuted on a U.S. highway; all roadways were located in southwestern Virginia. Half of the participants normally drove a sedan and half normally drove an SUV. Participants were 20 to 64 years old (*M* = 40.8, *SD* = 12.2), with equal gender representation.

The two research vehicles were a sedan and an SUV. Each participant drove each vehicle for 10 days. The data acquisition system included video, sensor, and radar equipment. The video system included five channels to record head/eye position and outside views of the front, rear, and rear sides. Sensors recorded velocity, steering, acceleration, and pedal and turn-signal use. Three radar units, one facing forward and two facing rearward, provided information about surrounding vehicles.

As part of the lane-change identification process, the initiation and end points for each lane change were specified by video review. Each lane change was categorized by maneuver type, direction, severity, urgency, and success/magnitude. Lane-change initiation was the point at which the vehicle first moved laterally; the lane change ended when the vehicle was settled in the destination lane.

Eleven categories of maneuver type were identified, with the four most frequent being slow lead vehicle, return, enter, and exit/prep exit. Slow lead vehicle referred to lane changes made because of a slow vehicle ahead. Return referred to a lane change back into the preferred lane. Enter and exit/prep exit were associated with entering, exiting, or preparing to exit the roadway.

Severity was rated on a 7-point scale (1 = unconflicted, 7 = physical contact), indicating the degree to which the vehicle in the destination lane was cut off. Severity was based on vehicle presence within the proximity zone (from 4 ft in front of the SV to 30 ft behind it) and time-to-reach the edge of the proximity zone for those vehicles within the FAZ (30 to 162 ft behind the SV). Urgency was rated on a 4-point scale (with end points of 1 = not urgent, 4 = critical) indicating how soon the lane change was needed based on TTC with the closest vehicle ahead (or behind for accelerating tailgaters).

Lane-change maneuvers were categorized in terms of success/magnitude as follows: single lane changes, passing maneuvers made within 45 s, multiple lane changes (more than one lane change in the same direction), and unsuccessful (aborted/partial/unintentional).

Results for Full Dataset

There were 8,667 lane changes observed with a mean duration of 9.07 s. Of these, 83 percent were single lane changes with a mean duration of 6.28 s. Analysis of the full dataset revealed that 91 percent of lane changes were uneventful; that is, they were neither high in urgency nor high in severity. In fact, the mean ratings were low overall; mean urgency was 1.04 on a 4-point scale and the mean severity was 1.16 on a 7-point scale. The most common severity rating was 1 (low severity) with 95 percent of lane changes falling into this category. An urgency rating of 1 (low urgency) was also the most common category, covering 96 percent of all lane changes. More than 91 percent of all lane changes could be accounted for by the two-way distribution of low severity by low urgency (rated 1 and 1). This is to be expected given that crashes are rare events and lane-change crashes are a relatively rare subset of all crashes. It should also be noted that no crashes of any type were observed during 10 months of data collection.

There were four independent variables in the experimental design: gender, route, driver type, and vehicletType (experimental vehicle), representing a variety of driver types in a balanced manner. Very few differences were found among variables in terms of frequency, duration, urgency, and severity. Participants drove an average commute of 37.4 mi (60.2 km) in each direction and the mean number of lane changes per mile across all independent variables was 0.36/mi (or about 1 lane change every 2.8 mi).

Most lane changes were to the left (55%) with a mean duration of over 11 s, mean severity of 1.18, and mean urgency of 1.06. Left-lane changes had a larger mean duration (11.1 s) than did right-lane changes (6.6 s), probably because many of the left-lane changes were passing maneuvers consisting of two lane changes within 45 s, whereas many of the right-lane changes were single-lane changes.

In terms of the success/magnitude of the lane change, each change in the set of 8,667 lane changes was categorized as single (83%), passing (12%), multiple (3%), or unsuccessful/partial (1%). Of the 11 lane-change maneuver categories, slow-lead-vehicle lane changes accounted for the single largest category (37%), with a mean duration of 13.0 s, a mean urgency rating of 1.1 and a mean severity rating of 1.2. For the higher severity levels ($\geq$ 3), the slow-lead-vehicle category was even more dominant at 56.2 percent.

Of the 3,228 slow-lead-vehicle lane changes, 2,169 (67.2%) were categorized as single, 1,032 (32.0%) as passing, 9 (0.4%) as multiple, and 18 (0.8%) as unsuccessful/partial. Analysis of slow-lead-vehicle lane changes in terms of frequency, duration, severity, and urgency showed patterns similar to those for the entire set of lane changes. A few statistically significant differences were discovered; however, no practical differences were observed. In terms of direction of initial maneuver, 92 percent of slow-lead-vehicle lane changes were to the left.

The contention that many lane-change maneuvers are caused by a slower lead vehicle is supported by the current research since such a high proportion of events were classified as slow-lead-vehicle maneuvers. Drivers often change lanes to pass in this situation in order to maintain current speed. Of all the lane changes rated greater than or equal to 2 in severity, 55 percent were slow-lead-vehicle maneuvers. This may indicate that drivers are willing to change lanes even when a vehicle is approaching from behind in the adjacent lane. Of all maneuvers rated greater than or equal to 2 in urgency, 78 percent were slow-lead-vehicle maneuvers. This may indicate that drivers feel comfortable with a relatively short TTC to the vehicle ahead. Due to the high prevalence of the slow-lead-vehicle lane change, this type of lane change was analyzed in greater depth than were other types of lane changes.

Results for In-Depth Analyses

The next set of analyses was conducted on the sample of 500 lane changes selected from the full population. This sample included all of the higher severity and most of the higher urgency lane changes. A set of additional variables was investigated beyond those of the full dataset, including steering, lateral acceleration, velocity, braking, turn-signal use, eye-glance patterns, and eye-glance probabilities, as well as distance, relative velocity, and TTC to forward and rearward POVs.

These analyses provided additional insight into those behaviors leading to and including lane-change initiation associated with riskier lane changes. Analysis of the steering, lateral acceleration, velocity, and braking measures did not greatly enhance the understanding of lane-change behavior, although there was some evidence that higher speeds at lane-change initiation are associated with lane changes rated higher in severity and urgency. Examination of the braking data showed that the brakes were rarely applied at lane-change initiation and usually only for slow-lead-vehicle and exit/prep-exit lane changes.

Across participants, turn signals were used only 44 percent of the time, with signals used more often for left-lane changes (48%) than for right-lane changes (35%); however, there was also a large between-subjects variance in the percentage of turn-signal use, ranging from 0 to 92 percent. For right-lane changes, it is hypothesized that drivers may not feel it is important to signal their intentions because they have just passed a slow lead vehicle, and they may assume that the other driver knows their intentions.

Eye-glance behavior was analyzed for the 3 s prior to lane-change initiation; this interval was found to be the critical period for lane-change decision making by Mourant and Donohue (1974). One of the primary findings from the eye-glance analysis is that for every lane change analyzed, there was at least one glance to the forward view during the 3 s prior to lane-change initiation. Forward glances also had a relatively high mean single glance time of 0.8 s.

Eye-glance analyses were also conducted separately for left and right-lane changes, anticipating that their patterns would be distinct. For left-lane changes, the most likely glance locations were forward (probability of 1.0), rear-view mirror (0.52), and left mirror (0.52). The highest link probability value (0.34) was between the forward and rear-view-mirror locations. The most likely glance locations for right-lane changes were forward (1.0), rear-view mirror (0.55), and right mirror (0.21). The highest link probability value (0.60) was between the forward view and rear-view mirror. The link value probability between forward and right mirror and between forward and right blind spot was also relatively high at 0.12.

Analyses were conducted for distance, relative velocity, and TTC to the closest vehicle in terms of a "safety envelope" to further the understanding of the driver's management of the forward and rearward areas at lane-change initiation. It appears that 95 percent of drivers preferred a distance of at least 40 ft frontward and rearward at lane-change initiation. Likewise, 95 percent of drivers preferred a relative velocity (closing rate) of less than 20 ft/s (both forward and rearward), and a TTC of between 4 and 6 s for POVs in either the forward or rearward areas.

100-CAR STUDY BACKGROUND

This section provides a basic overview of the 100-Car Study. Detail is given to the analysis of lane change events. The reader is referred to Dingus, Klauer, Neale, et al. (2006) for more detailed information including the instrumentation, subject recruitment, and vehicle selection. Further, the Dingus, Klauer, Neale, et al. (2006) report provides a more comprehensive look at the scope of effort, implementation, and quality control required to build this event database.

The 100-Car Study examined light-vehicle driver behavior and performance for crash and near-crash events by outfitting 109 vehicles with unobtrusive DASs used to observe naturalistic driving over a 12-month period. Seventy-eight of the 100 vehicles were owned by the participants, while 22 drove leased vehicles provided as part of the study. Evidence of extreme driving behavior (e.g., impairment, fatigue, and judgment error) indicated that drivers quickly disregarded the presence of the instrumentation. Approximately 2,000,000 vehicle-miles and 43,000 h of data were collected using 109 primary and 132 secondary drivers. This large-scale study resulted in driving data with an unprecedented level of detail on driver distraction, fatigue, impairment, judgment error, risk taking, and traffic violations.

One of the major outcomes of the 100-Car Study was an event database comprised of the reduced crashes, near-crashes, and incidents that occurred during the study.

Procedure for Data Reduction: 100-Car Event Database
As stated in Dingus, Klauer, Neale, et al. (2006), data were collected continuously on the instrumented vehicles. As project resources did not allow for the review of all the data, a sensitivity analysis was conducted to establish post-hoc "triggers." A post-hoc trigger uses either a single signature (e.g., any lateral acceleration value greater than ±0.6 *g*) or multiple signatures (e.g., forward TTC value > 3 s plus a longitudinal deceleration value > -0.5 *g*) in the driving performance data stream to identify those points in time when it was likely that a driver was involved in an incident, near-crash, or crash.

Raw data from each vehicle were saved on the network attached storage (NAS) unit at the Virginia Tech Transportation Institute (VTTI) until approximately 10 percent of the data were collected. At that time, a sensitivity analysis was performed to establish post-hoc trigger criteria.

The sensitivity analysis was performed by setting the trigger criteria to a very liberal level, ensuring that the chance of a missed valid event was minimal while allowing a high number of invalid events (false alarms) to be identified. Data reductionists then viewed all of the events produced from the liberal trigger criteria and classified each event as valid or invalid. The number of valid events and invalid events that resulted from this baseline setting was recorded.

Based on data from past VTTI studies, it was originally hypothesized that as many as 26 crashes, 520 near-crashes, and over 25,000 incidents (crash-relevant events and proximity events) would be collected; however, many of these early estimates were based on long-haul truck-driving data. It was soon discovered, after the sensitivity analysis process began, that the variability in light-vehicle drivers' braking, acceleration, and steering behavior is much larger than with truck drivers. These differences in variability are primarily due to the differences in vehicle dynamics and the more uniform driving skill of commercial truck drivers. While greater variability was expected, the extent to which this is true was an interesting result.

Given the variability in light-vehicle driving performance, the sensitivity analysis proved to be challenging. VTTI researchers determined that the best option was to accept a very low miss rate while accepting a fairly high false alarm rate to ensure that few valid events were missed. This resulted in viewing over 110,000 triggers in order to validate 10,548 events.

CHAPTER 3: METHODS

All crashes and near-crashes in which a lane change occurred within the temporal and spatial vicinity of the events were selected from the 100-Car Study event database. Specifically, these events involved lane changes as pre-incident maneuvers, precipitating events, or driver reactions. From these, 3 crashes and 132 near-crashes were selected because they met the lane-change operational definition presented in the Glossary of Terms. Many events were omitted from this analysis because they involved a rear-end (RE) event with a lead vehicle after the SV had completed a lane change. These events are better addressed within the discussion of RE events. As such, 135 events comprise the lane-change event database.

One reductionist then analyzed each event in the lane-change event database for specific parameters relevant to the temporal investigation of lane-change events. These additional parameters are described in Table 2, Table 3, and Table 4.

Table 2. SV Lane Change Parameters

Parameter	Operational Definition
When the SV began to signal	The point in time at which the SV began to signal. This data was collected using sensors inside the vehicle.
When the SV stopped signaling	The point in time at which the SV stopped signaling. This data was collected using sensors inside the vehicle.
When the SV began to change lanes	The point in time at which the SV began to change lanes. This was operationally defined using one of three criteria adopted from Lee et al. (2004): 1. The driver initiated a steering input intended to change the direction of the vehicle relative to the lane. This criterion was predominantly used to establish lane-change initiation. 2. The vehicle began to move laterally relative to the lane. This criterion was used when in-vehicle video footage was not available or during night time driving when the in-vehicle image contrast was low. 3. The driver returned his/her gaze to the forward view after looking at mirrors or directly out a window. This criterion was used in conjunction with the second criterion to define the lane-change initiation. It is important to note that some subjectivity was inherent in determining lane-change initiation.
SV's lane-change destination	The lane the SV was heading toward during the lane change.
SV's lane-change type	A description of whether the lane change was planned at the driver's choice of time or an evasive swerve in response to a forward crash threat.
When the SV crossed the lane	The point in time at which the front wheel of the SV first touched the lane markers.
When the SV's lane change ended	The point in time at which the vehicle stabilized in the target lane.

Table 3. POV Lane-Change Parameters

Parameter	Definition
When the POV began to signal	The point in time at which the POV involved in the crash or near-crash began to signal.
When the POV stopped signaling	The point in time at which the POV involved in the crash or near-crash stopped signaling.
When the POV began to change lanes	The point in time at which the POV's trajectory changed from going straight to heading for the other lane.
POV lane-change destination	The lane the POV was heading toward during the lane change.
When the POV crossed lanes	The point in time at which the POV touched the lane markers.
When the POV lane change ended	The point in time at which the POV stabilized in the target lane.

Table 4. Event Parameters

Parameter	Definition
When the event occurred	The point in time at which the crash or near-crash occurred. For crash events, this was the point of contact. For near-crash events, this was the point at which the SV was closest to a crash. Distance cues were obtained from forward and side video footage recorded from cameras mounted on the subject vehicle.
Event type	A description of the event regarding whether a vehicle sideswiped or swerved to avoid another vehicle.
Weather	A description of weather conditions: clear, raining, or snowing.
Time of Day	A description of when the event occurred, whether during daylight, dusk, or nighttime.

An understanding of the lane-change events observed in this study is gained by classifying them by event severity, lane-change direction, precipitating event, and driver response. Here, severity distinguishes between crashes and near-crashes. Lane-change direction indicates the direction of travel from the perspective of the vehicle executing the lane change. For example, a right-lane change refers to an SV moving from the SV lane to the adjacent right lane, a POV moving from the POV lane to the adjacent right lane, or an SV swerving from the SV lane into the adjacent right lane. The precipitating event is the action of a driver that begins the chain of events leading up to a crash or near-crash. The accompanying driver reactions to these lane-change events are then listed.

Driver rear- and side-view mirror use is examined to gain insight on where drivers looked before and during the lane-change event. Eight exterior eye-glance locations were reduced (Figure 1):

- Left forward (LF)
- Forward (F)
- Right forward (RF)
- Right window (RW)
- Right mirror (RM)
- Center mirror, also termed rear-view mirror (CM)
- Left mirror (LM)
- Left window (LW)

Eye-glances to the front- or back-side windows (between the A and C pillars) were coded as a window eye-glance. It should be noted that rear- and side-view mirror angles were not considered nor controlled in this study. The size and location of the driver blind spots were unknown. As such, eye-glances toward the left and right windows may or may not be indicative of blind spot checks. Since the camera was mounted next to the center mirror, reductionists were easily able to distinguish foveal eye-glances to the forward roadway from those to the center mirror.

Figure 1. Lane-change Appropriate Eye-Glance Locations

Additional interior glance locations were also captured:

- Display behind steering wheel
- Object inside vehicle
- Cell phone
- Eyes closed
- Passenger

Eye-glance data was used to examine glance behavior prior to and during the lane-change maneuver. Eye-glance data collected during the time interval spanning from 8 to 3 s prior to the initiation of the lane change were analyzed to explore driver spatial awareness. This time interval was selected because it was long enough to encompass the California Department of Motor Vehicles driver handbook safe driving practice tip to scan one's mirrors every 2 to 5 s in order to be aware of the position of surrounding vehicles (http://www.dmv.ca.gov/pubs/hdbk/pgs33thru41.htm). For brevity, this time interval will be referred to as the "8-second interval."

Eye-glance behavior spanning the 3 s prior to lane-change initiation was also inspected. This interval is of interest since this is when drivers scan the environment one final time prior to making a go/no-go decision to change lanes (Lee et al., 2004). For brevity, this time interval will be referred to as the "3-second interval."

Eye-glance behavior during the lane change (from the lane-change initiation to the event) is also presented. For brevity, this time interval will be referred to as the "lane change" interval.

Figure 2 below diagrammatically shows the intervals in time for which glance data are reported. Only those events for which eye-glance data were available up to 8 s prior to lane-change event are reported in this chapter.

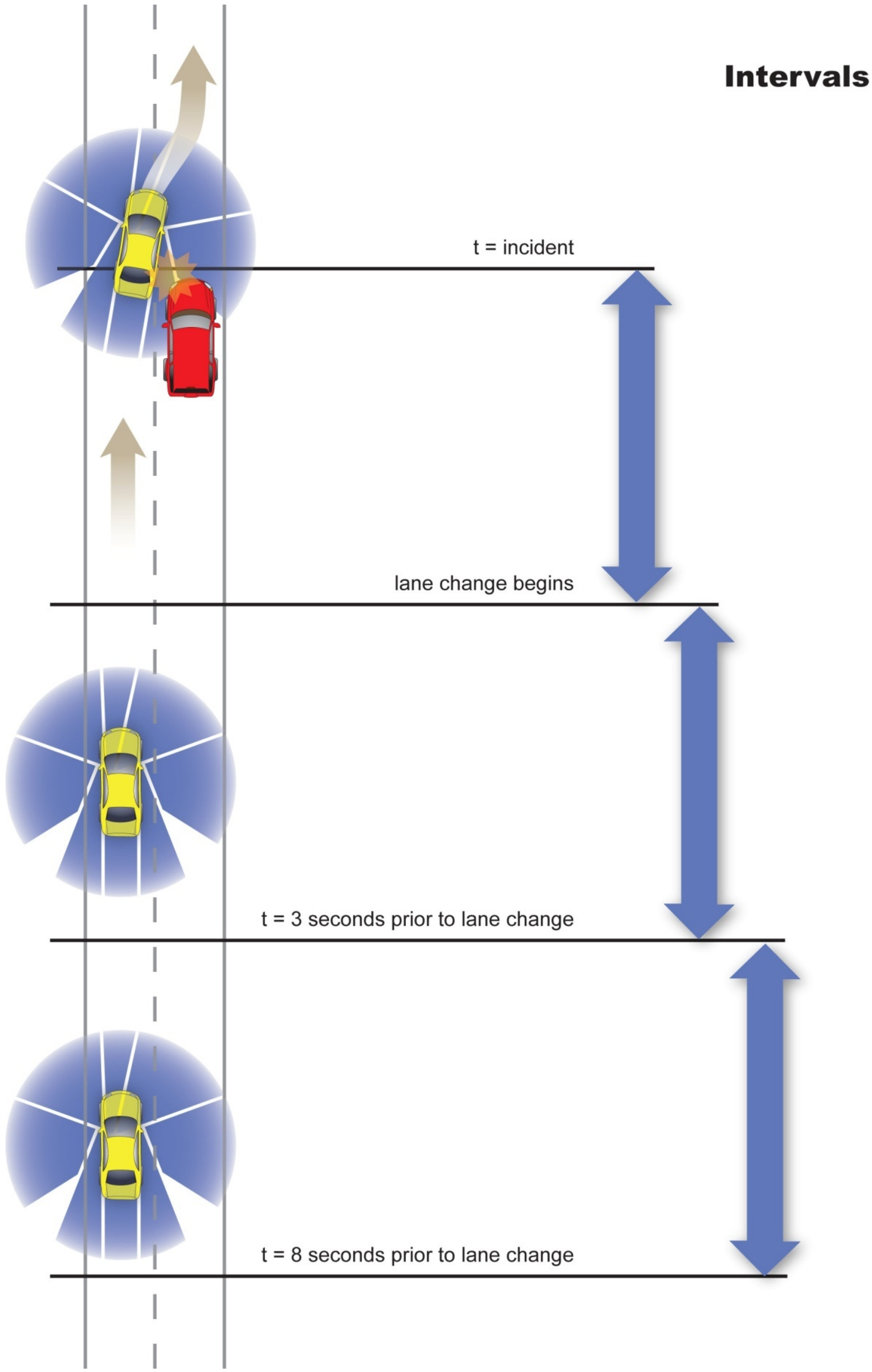

Figure 2. Exterior Eye-Glance Locations Investigated up to 8 s Prior to, as Well as During, Lane-Change Events

The driving conditions at the time of the event are also considered. The traffic density and the number of nearby vehicles prior to the event are reported. Lane-change events are then analyzed from the perspective of SV and POV vehicle control. The SV velocity prior to the lane change, the duration of the lane-change maneuver, the number of vehicles that signaled, and how long the turn signal was used before the lane-change maneuver are reported. Driver reactions are then examined by reporting descriptive statistics on the maximum deceleration observed across each type of avoidance maneuver. Further analyses are conducted on events involving a POV sideswiping the SV. Specifically, the duration of the POV lane-change maneuver, number of POVs that used their turn signals, and how long the turn signal was used prior to the lane-change maneuver are reported. SV driver responses to POV generated lane-change events are then specifically examined inspected by POV turn-signal use.

Distractions that were present during the lane-change events are also reported. However, the reader is referred to Klauer, Dingus, Neale, Sudweeks, and Ramsey (2006) for an in-depth analysis of the events affected by driver distraction.

CHAPTER 4: RESULTS

This chapter analyzes both vehicular parameters and driver behavior data (including eye-glance data) collected during lane-change crashes and near-crashes. The presentation of lane-change crash and near-crash data is organized according to three scenarios.

1. **SV Sideswipe POV:** events that arise from the SV striking, or nearly striking, an adjacent POV while executing a planned lane change. The lane changes performed in this scenario are called "planned" because the SV is in control at the point in time at which the lane change is executed. Examples of planned lane changes include an SV taking a highway's exit ramp, an SV merging onto a highway from an entrance ramp, and an SV selecting a faster or slower traffic flow lane, such as passing a slow lead vehicle. With respect to lane-change near-crashes, either the SV, the POV, or both vehicles perform a rapid evasive maneuver, such as steering away from the conflict, after the SV initiates the planned lane change. If a crash or near-crash occurs with a vehicle in front of or behind the SV prior to the SV stabilizing in the destination lane after a lane change, then it is analyzed in this report. However, events consisting of a rear-end event with a lead vehicle after the SV successfully stabilizes in the destination lane are omitted. This is because the lane change was properly performed and the event arose for reasons unrelated to the lane change; that is, had the SV always been in the destination lane the event would still have occurred.

2. **SV Swerve to Avoid Forward Crash Threat:** events consisting of the SV swerving into an adjacent lane to avoid a rear-end crash with a POV in the SV's original lane. Here, the SV executes an evasive lane change in which the timing is dictated by the actions of the POV. The front of the SV strikes, or nearly strikes, the rear corner of the POV. Two examples are when an SV swerves to avoid either a rapidly decelerating POV or a POV turning into the SV's forward pathway from an intersection. A subset of events in this scenario involves the SV nearly striking an adjacent vehicle when swerving to avoid a lead POV.

3. **POV Sideswipe SV:** events that arise from the SV being struck, or nearly struck, by an adjacent POV executing a lane change. Although the lane change events classified in this scenario primarily involve a POV sideswiping the SV, a subset also involves the SV nearly striking a secondary POV in an adjacent lane upon executing an avoidance maneuver.

Table 5 shows the number of lane-change crashes and near-crashes observed across the three scenarios. Events are also broken down by lane-change direction. A total of 135 lane-change events were observed. The 3 lane-change crashes comprise 4 percent of the 69 crashes observed in the 100-Car Study (Dingus, Klauer, Neale, et al., 2006), while the 132 lane-change near-crashes comprise 17 percent of the 761 near-crashes observed in the 100-Car Study. Of the 132 lane-change near-crashes, 39 percent fell into the *SV Sideswipe POV* scenario, 24 percent fell into the SV Swerving to Avoid Forward Crash Threat scenario, and 37 percent fell into the *POV Sideswipe SV* scenario.

Table 5. Lane-Change Crashes and Near-Crashes by Striking Vehicle Lane-Change Direction

Conflict Scenario		Crashes			Near-Crashes		
		Left	Right	Total	Left	Right	Total
SV Sideswipe POV	Count	0	1	**1**	26	25	**51**
	Row Percent	0%	100%	100%	51%	49%	100%
	Column Percent	0%	33%	33%	40%	37%	39%
SV Swerve to Avoid Forward Crash Threat	Count	0	0	**0**	17	15	**32**
	Row Percent	0%	0%	0%	53%	47%	100%
	Column Percent	0%	0%	0%	26%	22%	24%
POV Sideswipe SV	Count	0	2	**2**	22	27	**49**
	Row Percent	0%	100%	100%	45%	55%	100%
	Column Percent	0%	67%	67%	34%	40%	37%
Total		0	3	**3**	65	67	**132**

In controlling for multiple events occurring per driver, 33 SV drivers fell into the *SV Sideswipe POV* scenario, 23 drivers fell into *SV Swerve to Avoid Forward Crash Threat* scenario, and 34 drivers fell into the *POV Sideswipe SV* scenario. However, some drivers were involved in multiple scenarios. Figure 3 shows the Venn diagram for driver involvement in the three scenarios. It is worth noting that there were an equivalent number of drivers involved in only the *SV Sideswipe POV* scenario (27%) compared to only the *POV Sideswipe SV* scenario (29%).

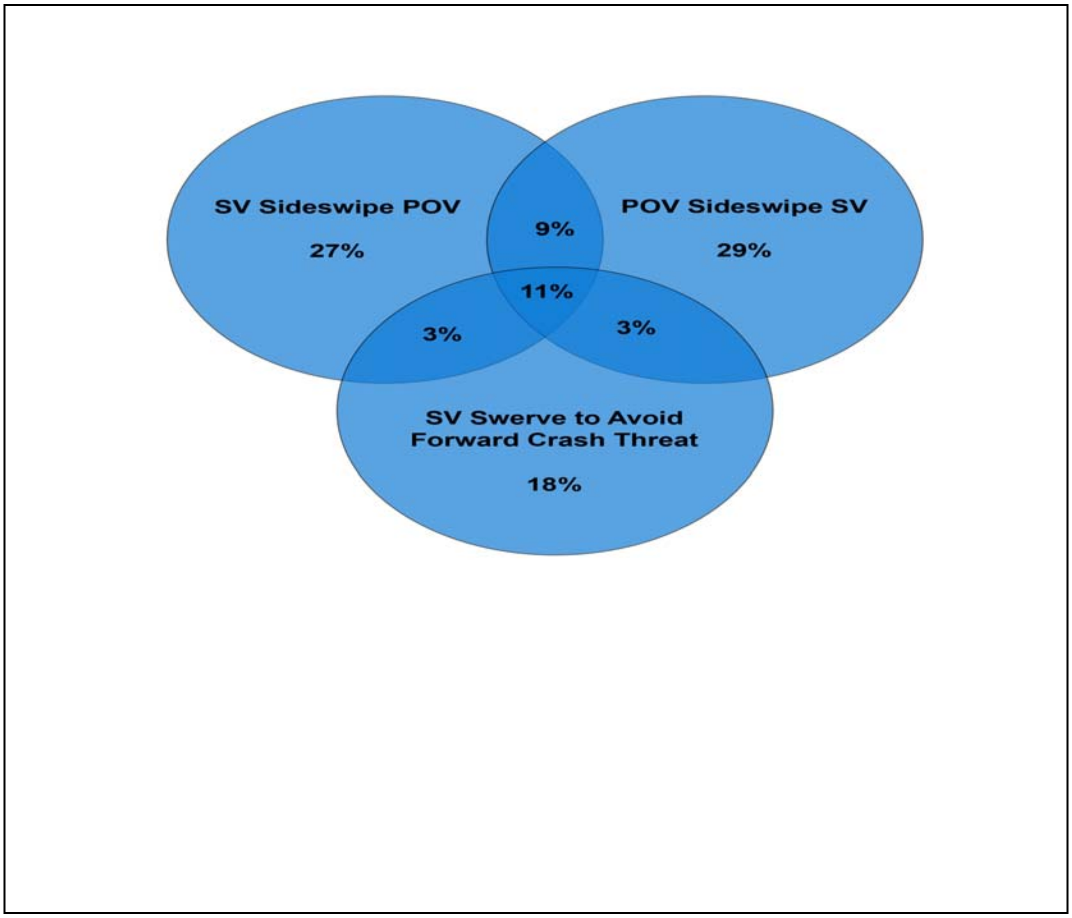

Figure 3. Venn Diagram of Driver Involvement in Lane-Change Near-Crashes

The remaining results are presented according to the three scenarios. Within each scenario, crashes are analyzed first, followed by near-crashes.

EVENTS INVOLVING THE SV SIDESWIPING A POV

Lane-Change Crash #1

One lane-change crash was observed involving the SV sideswiping a POV during a right-lane change. In this lane-change crash, the SV was in stop-and-go traffic. The driver of the SV (an SUV) attempted to steer between a stopped lead vehicle and a parked POV in the right lane by making a right-lane change. The space between these two vehicles was misperceived by the SV driver, resulting in the SV colliding with the parked POV. The SV driver's reaction was to brake.

Driver Eye-Glance Patterns

The SV driver looked forward at the center mirror, right window, and left window during both the 8-second and 3-second intervals. During the lane-change interval, the driver looked forward, at the center mirror, and at the left window. It was only after the back of the SV collided with the parked vehicle on the right that the SV driver looked out the right window to see what had happened. This crash appears to have resulted from a judgment error regarding the space available to pass between two vehicles.

Driving Conditions
For this lane-change crash, the traffic density was classified as unstable flow. There were stoppages caused by a stopped lead vehicle. There was one lead vehicle, one vehicle to the SV's left, one vehicle behind the SV, and one vehicle parked on the right. Clear daytime conditions existed during this event.

SV Lane-Change Behavior
The speed of the SV prior to initiating a right-lane change was 10 mph. The elapsed time from the initiation of the lane change to crossing the lane could not be determined since the SV was straddling the lane marker prior to the lane change. However, the elapsed time from the initiation of the lane change to the event was 0.7 s. The SV did not use the turn signal prior to changing lanes. The SV decelerated at 0.61 *g* in response to the lane-change crash. The SV driver was not involved in a secondary task prior to the event.

Left-Lane-Change Near-Crashes
Of the 51 near-crashes in the *SV Sideswipe POV* scenario, 26 events involved the SVs making left-lane changes. Table 6 categorizes these 26 near-crashes by precipitating event and subsequent driver reaction. It can be seen that the majority of near-crashes consisted of the SV changing lanes in front of the POV and that most SV drivers elected to brake and steer right to avoid a collision, thus returning to their original travel lane. The term "SV Lane Change in Front of POV" encompasses events in which the side or rear of the SV came the closest to the POV as the SV entered the destination lane, while the term "SV Lane Change Behind POV" represents events in which either the front or side of the SV came the closest to the POV during the lane change. The latter events are not to be confused with those excluded from this study involving the SV completing a lane change and then encountering an RE event with a lead POV. Four events involved the SV initiating a planned lane change to pass a slow-moving lead vehicle.

Table 6. Precipitating Event by Driver Reaction for a Near-Crash Involving the SV Sideswiping a POV While Performing a Left-Lane Change

Precipitating Event	Driver Reaction						
	Braked	Braked and Steered Left	Braked and Steered Right	Steered Left	Steered Right	No Reaction	Total
SV Lane Change in Front of POV	4	0	11	0	6	4	25
SV Lane Change Behind POV	0	0	1	0	0	0	1

Driver Eye-Glance Patterns

Figure 4 below shows the percentage of drivers who looked in the observed eye-glance locations during the 8-second, 3-second, and lane-change intervals while executing planned left-lane changes that resulted in sideswipe near-crashes. Two events are not included in this eye-glance analysis because eye-glance data spanning all three intervals were unavailable. It should be noted that the eye-glance data reported is dichotomous; that is, either drivers looked in a given direction or they did not. Multiple glances to a single direction are only counted once in this and subsequent figures of the same sort. For example, since 12 of 24 drivers looked at their left mirrors at least once in the 3-second interval, this is reported as 50 percent on the LW axis in Figure 4.

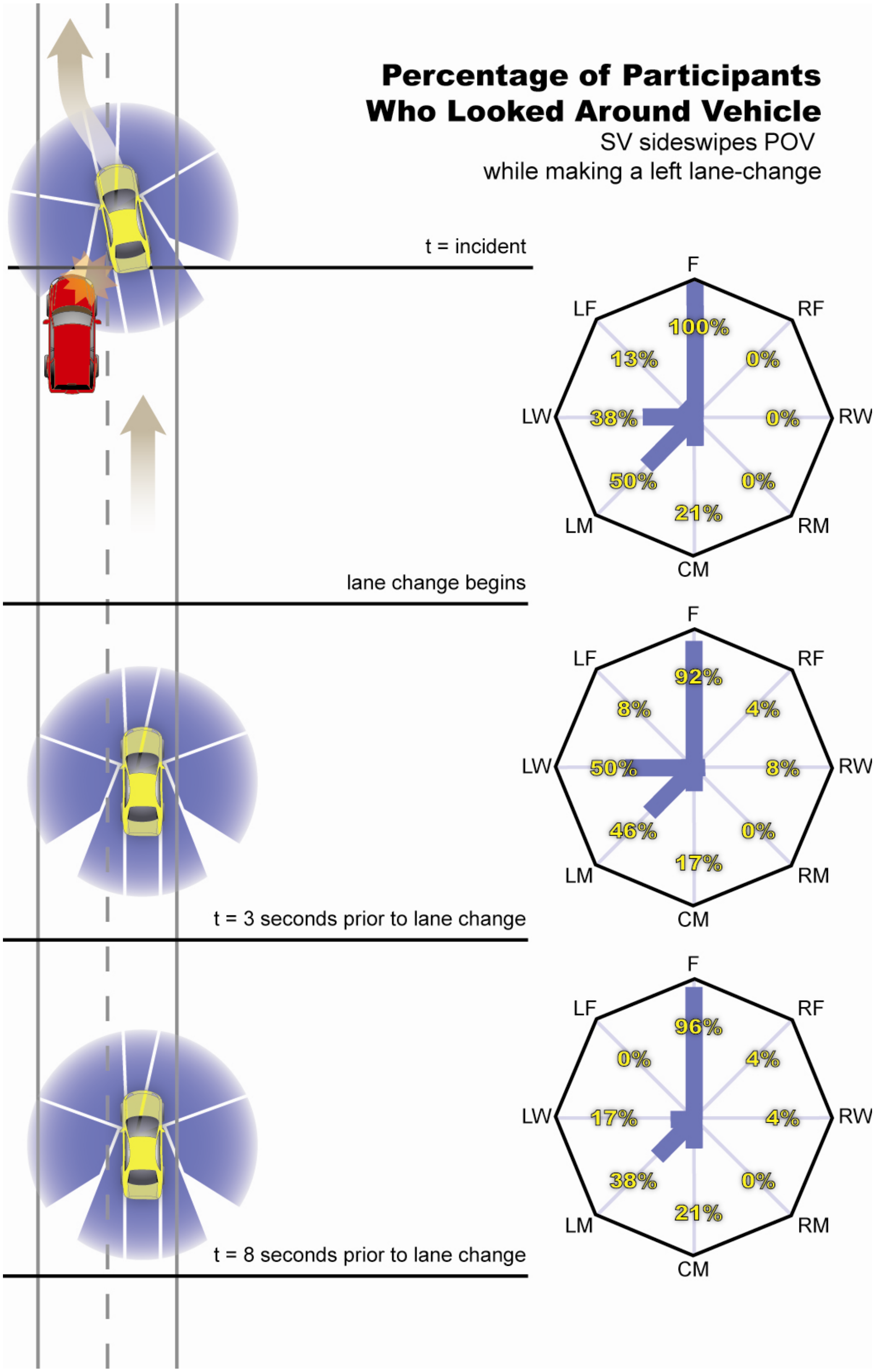

Figure 4. Percentage of Drivers Who Looked Around the Vehicle Prior to and During Left-Lane Changes in Which They Nearly Sideswiped Adjacent Vehicles.

Figure 5 compares the number of drivers who looked in the indicated eye-glance locations during the 8-second, 3-second, and lane-change intervals. Nine of the 24 drivers checked their left mirror, 4 drivers checked their left window, and 5 drivers checked their center mirror during the 8-second interval. During the 3-second interval, 11 of the 24 drivers checked their left mirrors, 12 drivers checked their left windows, and 4 drivers checked their center mirrors. In examining whether these findings were the result of some drivers scanning the periphery during the 8-second interval and others scanning during the 3-second interval, it was discovered that four drivers (17%) did not glance at the left mirrors, left windows, or center mirrors prior to making left-lane changes. Some of these drivers had performed right-lane changes beforehand, and so may have assumed there were no vehicles in their left adjacent lanes when attempting left-lane changes. These findings indicate that some drivers involved in left-lane-change near-crashes inadequately scanned their surroundings prior to changing lanes. During the lane-change interval, 12 of the 24 drivers checked their left mirrors, 9 drivers checked their left windows, and 5 drivers checked their center mirrors.

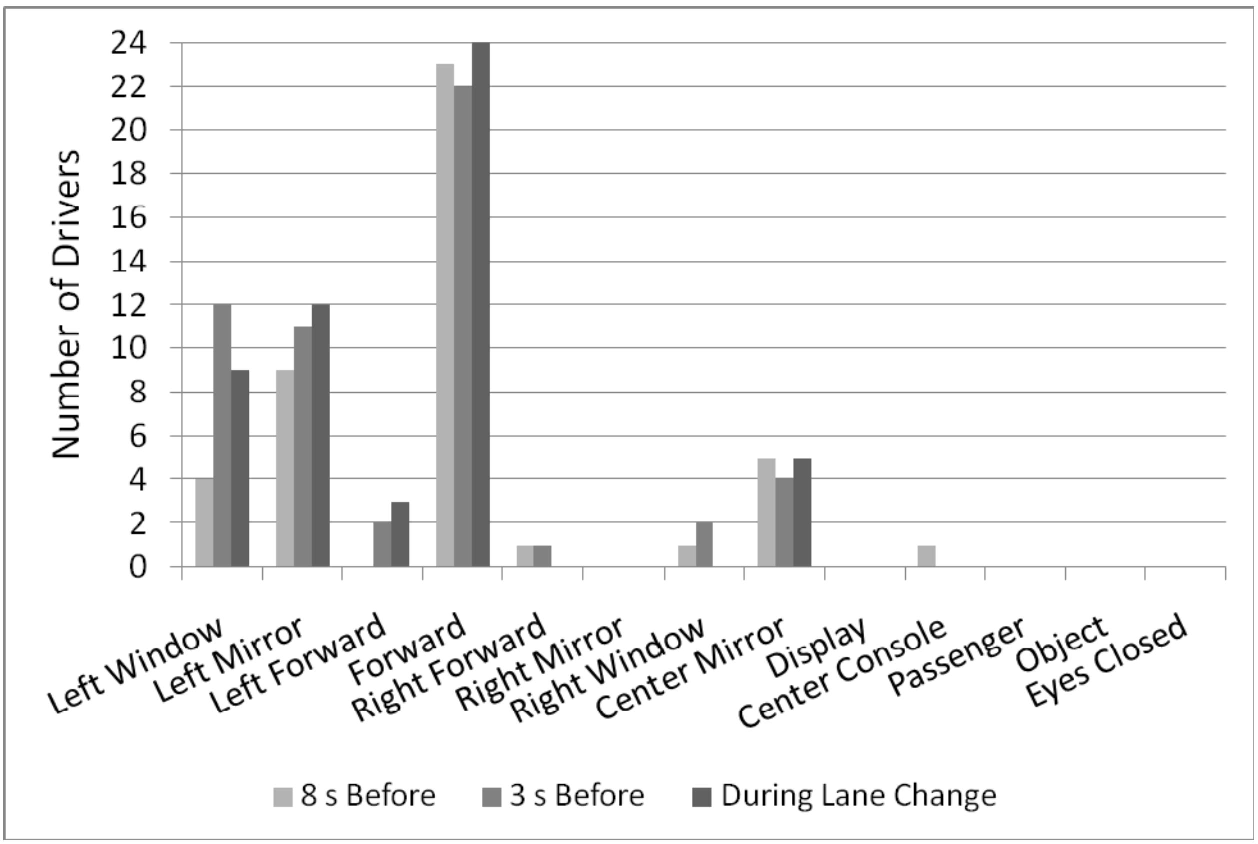

Figure 5. Number of Drivers Who Looked in the Indicated Locations 8 s Prior, 3 s Prior, and During a Lane Change That Nearly Sideswiped Another Vehicle on the Left (N=24)

Driving Conditions

Table 7 shows the traffic density observed during all 26 left-lane-change events involving the SV sideswiping an adjacent vehicle. The majority of events occurred in stable flowing traffic conditions or better.

Table 8 shows the distribution of the number of vehicles that surrounded the SV prior to the event. The majority of sideswipe events arose when just one other vehicle was in the near vicinity. Overall, most sideswipe near-crashes were observed in conditions in which multiple vehicles moved without stoppages. Weather conditions were clear during 96 percent of these events. It was raining during one event. Seventy-three percent of these events took place during the day, 19 percent took place at night, and 8 percent took place at dusk.

Table 7. Traffic Density During the Occurrence of Lane-Change Events Arising From SV Sideswiping a POV During Left-Lane Changes

Density	Frequency	Percent (%)
Free Flow	8	31
Flow with some restrictions	6	23
Stable flow; maneuverability and speed are more restricted	9	35
Unstable flow; temporary restrictions substantially slow driver	2	8
Flow is unstable; vehicles are unable to pass, temporary stoppages, etc.	1	4
Total	**26**	**100**

Table 8. Number of Vehicles in the Vicinity of the SV During the Lane Change

Number of Surrounding Vehicles	Frequency	Percent (%)
1	19	73
2	4	15
3	3	12
Total	**26**	**100**

SV Lane-change Behavior

SVs were travelling at 42 mph on average (standard error [SE] = 3 mph, min = 19 mph, max = 68 mph) prior to initiating the lane change. The average elapsed time from the initiation of the lane change to crossing the lane was 1.5 s (SE = 0.2 s, min = 0.4 s, max = 3.6 s). This finding is of interest since it is at this point that the SV becomes a crash threat to an adjacent vehicle. The elapsed time from the initiation of the lane change to the event was found to average 2.3 s (SE = 0.2 s, min = 0.8 s, max = 5.3 s). It should be noted that one exceptionally long lane change resulting from the SV crossing three lanes and nearly sideswiping a POV in the furthest lane was omitted from the computation of the averages in this paragraph.

It was observed that 22 of the 26 drivers (85%) used their turn signals. Over-the-shoulder video footage was used when turn-signal sensor failure occurred. The turn signal was activated prior to the initiation of the lane change for 14 of the 22 events (8 drivers activated the turn signals after lane change initiation and before the closest part of the near-crashes). The average time from turn signal activation to lane-change initiation for those drivers who signaled before the lane change was 3.4 s (SE = 1.1 s, min = 0.1 s, max = 11.9 s).

Table 9 presents the average peak deceleration levels observed from the initiation of the lane change up to 5 s following the event for each driver reaction. It can be seen that drivers who elected only to brake did so with a deceleration of 0.33 *g*, while drivers who braked and steered right did so with a deceleration of 0.23 *g*.

Table 9. Average Peak Deceleration Performed by SV by Driver Reaction From the Initiation of the Lane Change to 5 s After the Event

Driver Reaction	N	Mean (*g*)	Maximum (*g*)	Minimum (*g*)	Std Error (*g*)	Range (*g*)
Braked	4	0.33	0.68	0.03	0.15	0.65
Braked and Steered Right	12	0.23	0.53	0.03	0.04	0.50
Steered Right	6	0.21	0.68	0.08	0.11	0.76
No Reaction	4	0.04	0.15	0.03	0.04	0.18

Distraction Analysis

Table 10 lists the frequency of left sideswipe events that involved various distractions. It is interesting that the majority (85%) did not involve distraction. Distractions present in the remaining 15 percent involved a passenger occupying the adjacent seat and a cognitive distraction. It should be noted that the SV driver was not necessarily involved in conversation when a passenger was observed to occupy the adjacent seat.

Table 10. Potentially Distracting Behavior Observed Prior to Lane-Change Event

Distraction	Frequency	Percent (%)
Not Distracted	22	85
Passenger in Adjacent Seat	3	12
Cognitive - Other	1	4
Total	**26**	**100**

Right Lane-Change Near-Crashes
Of the 51 near-crashes in the *SV Sideswipe POV* scenario, 25 involved the SV making a right-lane change. Table 11 divides these lane-change near-crashes by precipitating event and subsequent driver reaction. It can be seen that the majority of the near-crashes consisted of the SV changing lanes in front of the POV. Nine events involved the SV initiating a planned lane change to pass a slow moving lead vehicle. SV drivers appear to be split between braking and steering left compared to just steering left to avoid the collision.

Table 11. Precipitating Event by Driver Reaction for Near-Crashes Involving the SV Sideswiping a POV While Performing a Right-Lane Change

	Driver Reaction							
Precipitating Event	Braked	Braked and Steered Left	Braked and Steered Right	Steered Left	Steered Right	Accelerated	No Reaction	Total
SV Lane Change in Front of POV	2	9	0	7	0	0	2	20
SV Lane Change Behind POV	0	3	2	0	0	0	0	5

Two cases occurred in which the SV braked and steered right in response to an event on the right side. This finding may strike the reader as odd. However, since these cases involved the SV nearly striking the rear corner of the POV, the selected collision avoidance maneuver was to steer and brake harder into the destination lane.

Driver Eye-Glance Patterns
Figure 6 shows the percentage of drivers who looked in the observed eye-glance locations during the 8-second, 3-second, and lane-change intervals when performing right-lane changes that nearly sideswiped an adjacent vehicle. Three drivers were excluded from this eye-glance analysis since eye-glance data spanning the three time intervals were unavailable.

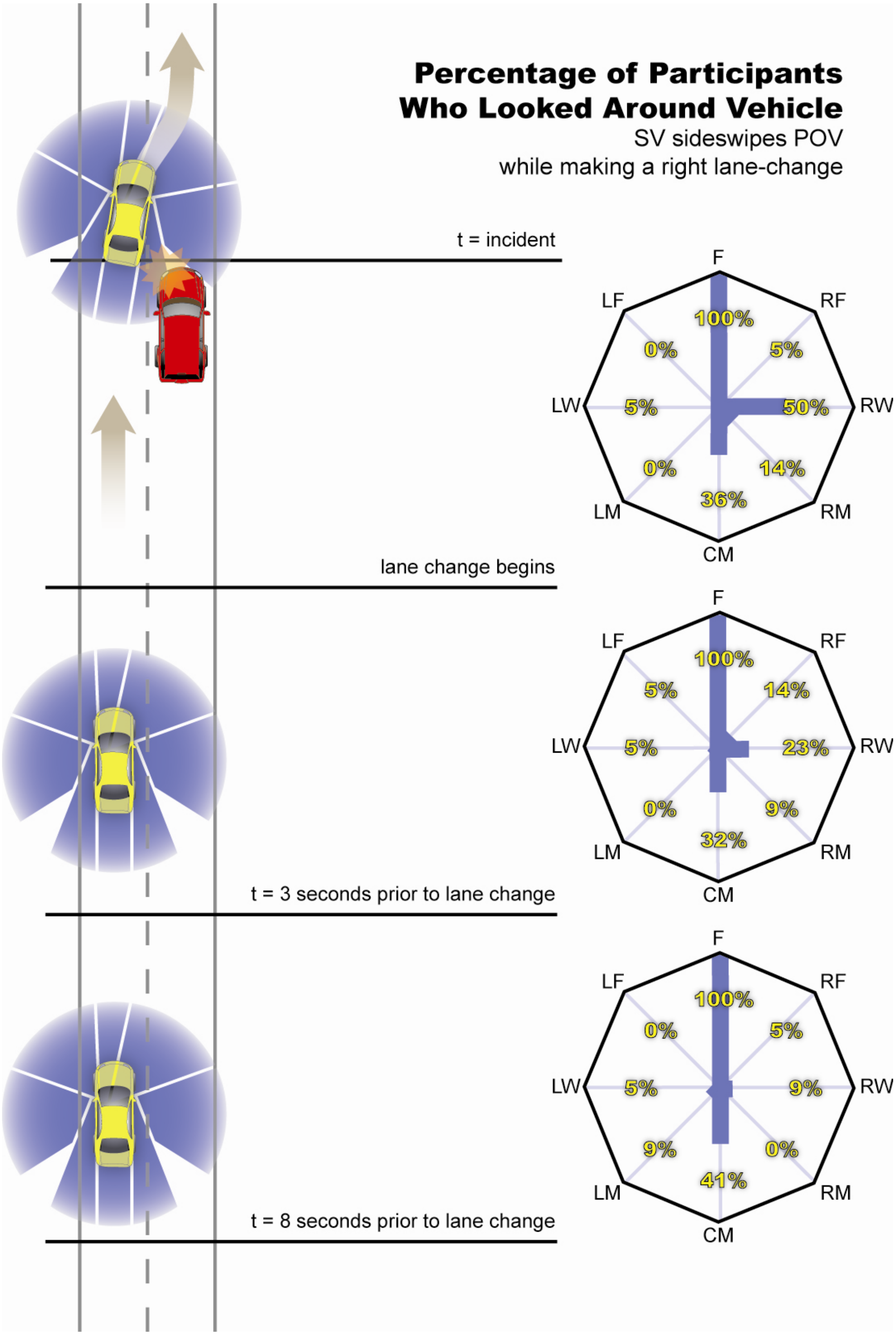

Figure 6. Percentage of Drivers Who Looked Around the Vehicle Prior to and During a Right-lane change in Which They Nearly Sideswiped an Adjacent Vehicle

Figure 7 compares the number of drivers who looked in the indicated glance locations during the 8-second, 3-second, and lane-change intervals. During the 8-second interval, none of the 22 drivers checked their right mirrors, 2 drivers checked their right windows, and 9 drivers checked their center mirrors. Additionally, 2 of the 22 drivers checked their right mirrors, 5 drivers checked their right windows, and 8 drivers checked their center mirrors during the 3-second interval. In examining whether these findings were the result of some drivers scanning the periphery during the 8-second interval and others scanning during the 3-second interval, it was discovered that 8 drivers (36%) did not glance at either the right mirror, right window, or center mirror prior to making a right lane-change. These findings indicate that of the drivers who looked prior to changing lanes, many only relied on their center mirrors. During the lane-change interval, 3 of the 22 drivers checked their right mirrors, 11 drivers checked their right windows and 8 drivers checked their center mirrors.

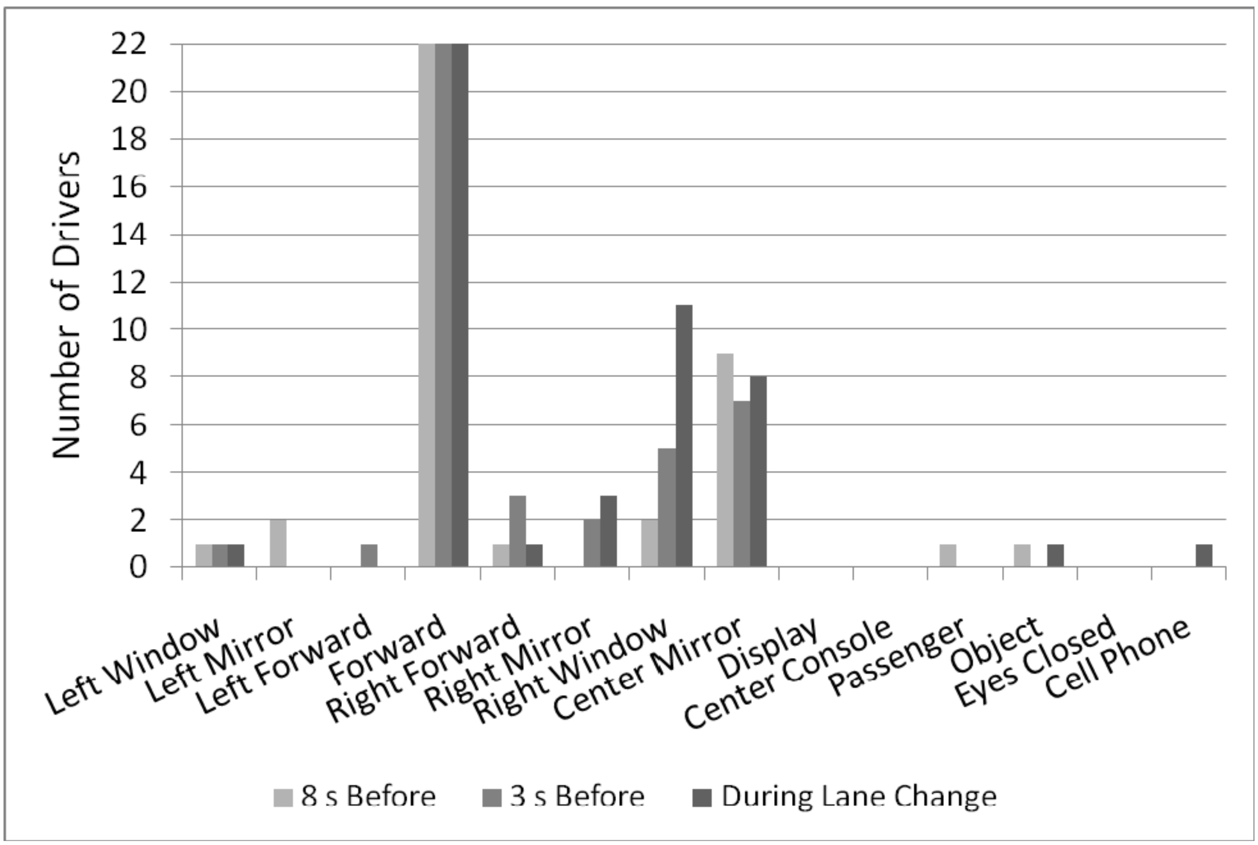

Figure 7. Number of Drivers Who Glanced Toward the Indicated Locations 8 s Prior, 3 s Prior, and During a Right-Lane Change That Nearly Sideswiped Another Vehicle (N=22)

Driving Conditions

The traffic density distribution for these lane-change near-crashes is shown below in Table 12. It can be seen that the majority of events occurred in stable flowing traffic conditions or better. Table 13 presents the distribution of the number of vehicles that surrounded the SV prior to the event. The data indicates that many events occurred with multiple vehicles in the vicinity. The weather conditions were clear during 92 percent of these events. It was raining during 2 events. A total of 60 percent of these events took place during the day, 12 percent took place at night, and 28 percent took place at dusk.

Table 12. Traffic Density During Lane-Change Events Arising From the SV Sideswiping a POV During a Right-Lane Change

Density	Frequency	Percent (%)
Free flow	5	20
Flow with some restrictions	7	28
Stable flow; maneuverability and speed are more restricted	8	32
Unstable flow; temporary restrictions substantially slow driver	3	12
Flow is unstable, vehicles are unable to pass, temporary stoppages, etc.	2	8
Total	**25**	**100**

Table 13. Number of Vehicles Near the SV During the Lane-Change

Number of Surrounding Vehicles	Frequency	Percent (%)
1	13	52
2	11	44
3	1	4
Total	**25**	**100**

SV Lane Change Behavior

SVs were traveling, on average, at 36 mph (SE = 3 mph, min = 15 mph, max = 67 mph) prior to initiating a lane change. The elapsed time from the initiation of the lane change to crossing the lane was 1.3 s on average (SE = 0.1 s, min = 0.3 s, max = 2.5 s), while the elapsed time from the initiation of the lane change to the event was 1.9 s on average (SE = 0.2 s, min = 0.4 s, max = 4.5 s).

Eighteen of the 25 drivers (72%) used their turn signals. The turn signal was activated prior to the initiation of the lane change for 8 of these events. The average time from the turn signal switching on to lane-change initiation for just the drivers who signaled before initiating the lane change was 3.9 s (SE = 1.6 s, min = 0.5 s, max = 3.3 s).

Table 14 presents the average peak deceleration levels observed from the initiation of the lane change up to 5 s following the event for each driver reaction. It can be seen that drivers who elected only to brake did so with a deceleration of 0.38 *g*, while drivers who braked and steered left did so with a deceleration of 0.41 *g*. Drivers who only steered left decelerated at 0.11 *g*.

Table 14. Average Peak Deceleration Observed From SV Lane-Change Start to 5 s After the Event Time Point for Each Driver Reaction

Driver Reaction	N	Mean (g)	Maximum (g)	Minimum (g)	Std Error (g)	Range (g)
Braked	2	0.38	0.48	0.27	0.11	0.21
Braked and Steered Left	12	0.41	0.80	0.10	0.06	0.70
Braked and Steered Right	2	0.43	0.52	0.35	0.09	0.18
Steered Left	7	0.11	0.28	0.03	0.05	0.31
No Reaction	2	0.20	0.27	0.14	0.07	0.13

Distraction Analysis

Table 15 lists the frequency of right sideswipe events that involved distraction. It can be seen that the majority (72%) did not involve distraction. Distractions present in the remaining 28 percent included a passenger occupying the adjacent seat, eating, talking, or operating a cell phone.

Table 15. Potentially Distracting Behavior Observed Prior to Lane-Change Event

Distraction	Frequency	Percent (%)
Not distracted	18	72
Passenger in adjacent seat	2	8
Eating	1	4
Dialing hand-held cell phone	1	4
Taking/singing	1	4
Talking/listening	1	4
No data	1	4
Total	**25**	**100**

EVENTS INVOLVING THE SV SWERVING TO AVOID A FORWARD CRASH THREAT

This scenario consists of an SV swerving into an adjacent lane, thus completing a lane change, at the last possible moment to avoid a leading vehicle or object. Crashes with objects in the forward pathway, or with objects in the adjacent lane, were not observed in this scenario.

Left-Lane-Change Near-crashes

Of the 32 near-crashes involving the SV swerving into an adjacent lane to avoid a forward crash threat, 17 involved the SV swerving into the left lane. Table 16 categorizes these events by precipitating event and subsequent driver reaction. It can be seen that the majority of these near-crashes involved the SV braking and swerving left to avoid a slowing POV. The term "POV Enters from Intersection" refers to events that arose from a POV pulling out in front of the SV from an adjoining road. Four events involved the SV nearly sideswiping an adjacent vehicle on the left when swerving to avoid the POV.

Table 16. Precipitating Event by Driver Reaction for Near-Crashes Involving the SV Swerving Into the Left Lane to Avoid a Forward Crash Threat

	Driver Reaction						
Precipitating Event	**Braked**	**Braked and Steered Left**	**Braked and Steered Right**	**Steered Left**	**Steered Right**	**No Reaction**	**Total**
Slowing POV	0	11	0	1	0	0	12
POV Enters From Intersection	0	4	0	1	0	0	5

Driver Eye-Glance Patterns

Figure 8 shows the percentage of drivers who looked in the various eye-glance locations during the 8-second, 3-second, and lane-change intervals, when swerving left in response to a forward crash threat. Two events are not included in this eye-glance analysis since eye-glance data spanning all three intervals was unavailable.

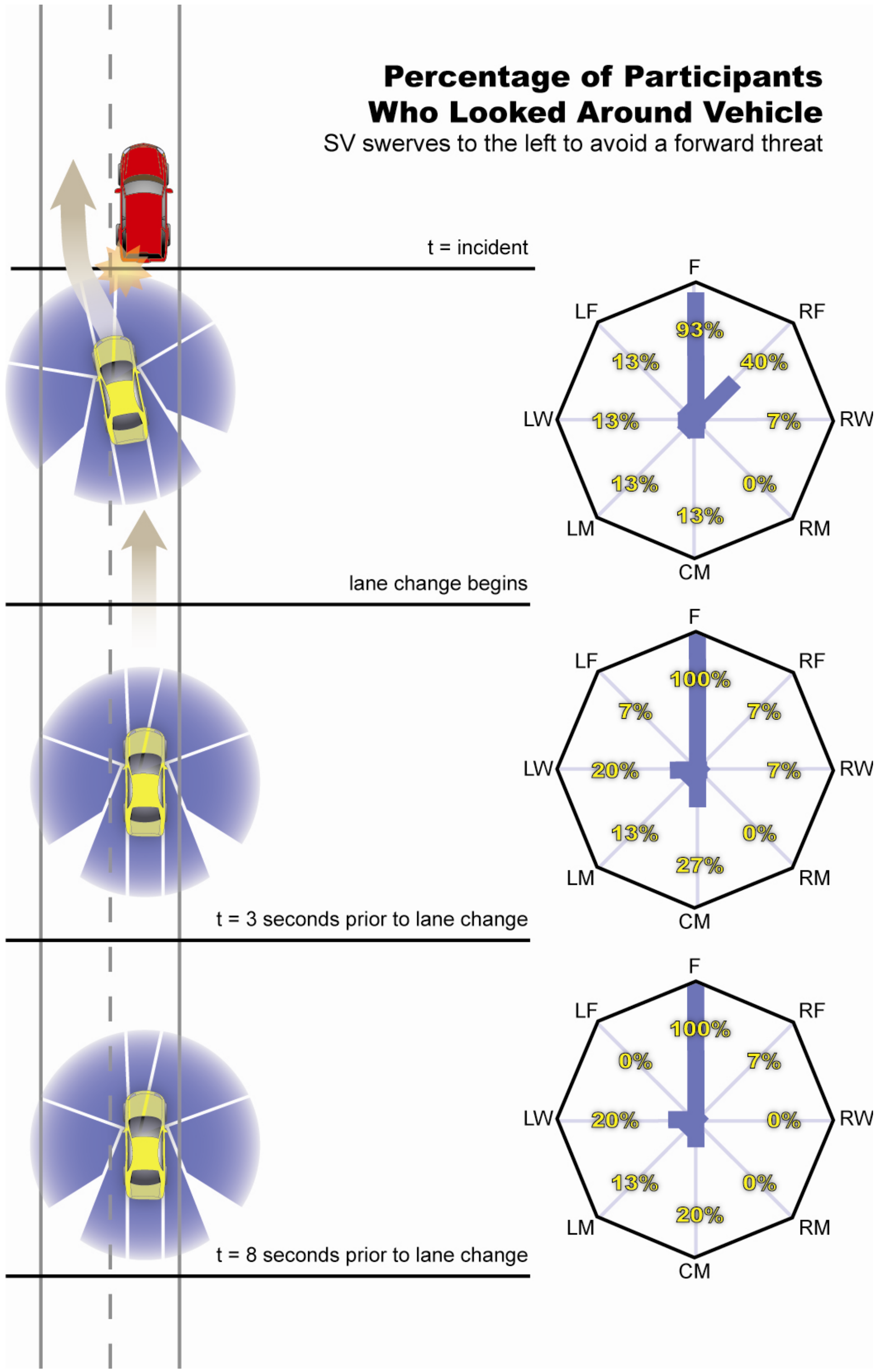

Figure 8. Percentage of Drivers Who Looked Around the Vehicle Prior to, and During, a Left Evasive Lane Change in Response to a Forward Threat

Figure 9 compares the number of drivers who looked in the indicated glance locations during the 8-second, 3-second, and lane-change intervals. Two of the 15 drivers checked their left mirrors, 3 drivers checked their left windows, and 3 drivers checked their center mirrors during the 8-second interval. Additionally, 2 of the 15 drivers checked their left mirrors, 2 drivers checked their left windows, and 2 drivers checked their center mirrors during the 3-second interval. In examining whether these findings were the result of some drivers scanning the periphery during the 8-second interval and others doing the same during the 3-second interval, it was discovered that 5 drivers (33%) did not glance at all to their left mirrors, left windows, or center mirrors prior to swerving into the left lane. These findings indicate that very few drivers scanned their surroundings prior to performing an evasive left-lane change. Two of the 15 drivers checked their left mirrors, 2 checked their left windows, and 2 checked their center mirrors during the lane change. This data suggests that many drivers just looked ahead when executing the evasive lane change.

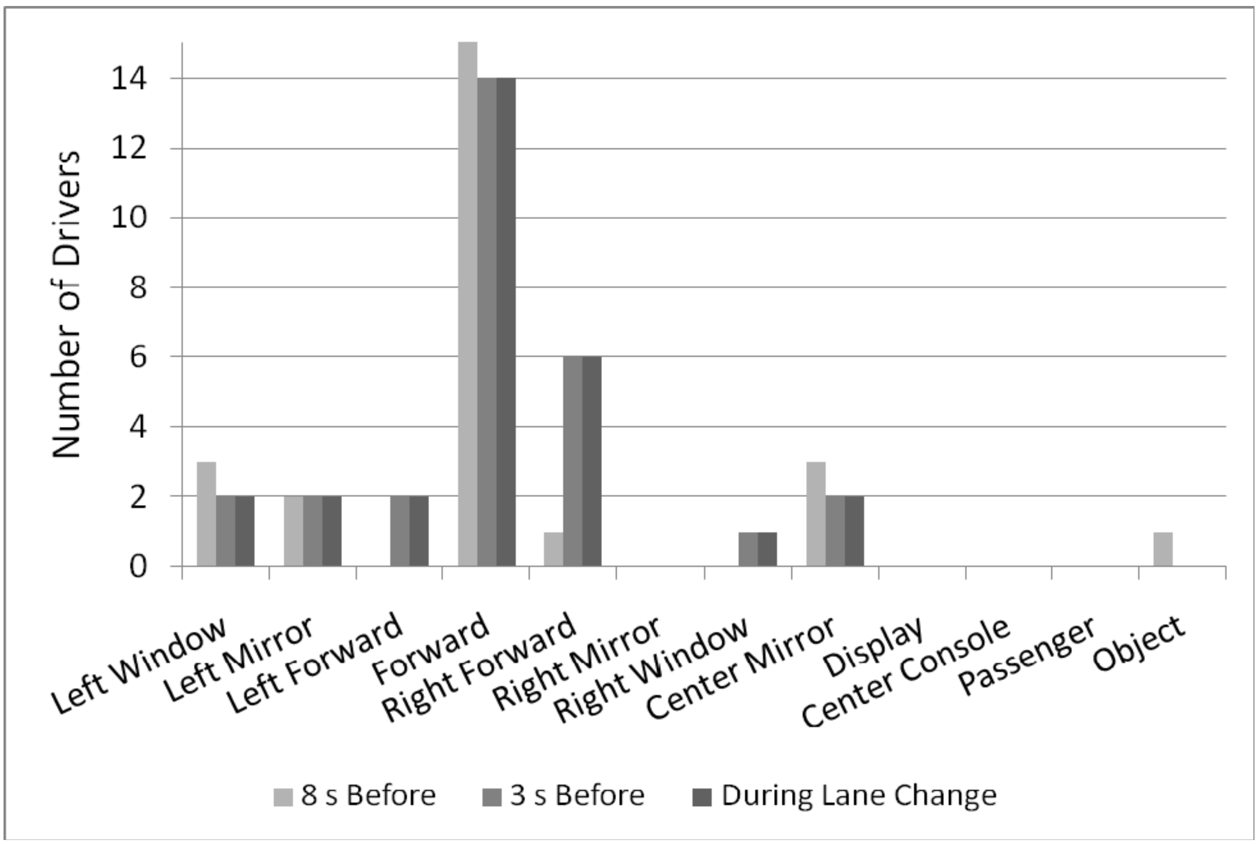

Figure 9. Number of Drivers Who Looked in the Indicated Locations 8 s Prior, 3 s Prior, and During a Left-Lane Change in Response to an Upcoming Obstacle (N=15)

Driving Conditions

Table 17 shows the traffic density distribution that existed during the observed left evasive lane-change events. It can be seen that the majority of events occurred in flowing traffic conditions that did not have stoppages. Table 18 presents the distribution of the number of vehicles that surrounded the SV prior to the event. Many of these events arose with just one other vehicle in front of the SV. However, a striking result is that more than one vehicle was nearby for about one-fourth of the events. The presence of these additional vehicles is of concern since such evasive maneuvers could create additional conflicts with surrounding vehicles. The weather conditions were clear for all of these events; 76 percent took place during the day and 24 percent occurred at night.

Table 17. Traffic Density During the Lane-Change Event

Density	Frequency	Percent (%)
Free flow	6	35
Flow with some restrictions	5	29
Stable flow; maneuverability and speed are more restricted	4	24
Unstable flow; temporary restrictions substantially slow driver	2	12
Total	**17**	**100**

Table 18. Number of Vehicles Near the SV During the Lane-Change

Number of Surrounding Vehicles	Frequency	Percent (%)
1	13	76
2	3	18
3	1	6
Total	**17**	**100**

SV Lane Change Behavior

SVs were traveling at 41 mph on average (SE = 3 mph, min = 14 mph, max = 58 mph) prior to initiating an evasive left-lane change. The elapsed time from the initiation of the lane change to the SV crossing into the POV lane was 1.2 s on average (SE = 0.2 s, min = 0.6 s, max = 3.2 s). The elapsed time from the initiation of the lane change to the event was 1.8 s on average (SE = 0.2 s, min = 0.9 s, max = 3.9 s).

Four of the 17 drivers (24%) used their turn signals when swerving to the left to avoid a forward crash threat. The turn signal was activated prior to the initiation of the lane change for all four events. The average time from the turn signal switching on to lane-change initiation was 1.5 s (SE = 0.7 s, min = 0.4 s, max = 3.3 s).

Table 19 shows the average peak deceleration levels observed from the initiation of the evasive lane change up to 5 s following the event for each driver reaction. Drivers who elected to brake and steer did so with a mean deceleration of 0.48 *g*.

Table 19. Average Peak Deceleration Observed From SV Lane-Change Start to 5 s After the Event Time Point for Each Driver Reaction

Driver Reaction	N	Mean (g)	Maximum (g)	Minimum (g)	Std Error (g)	Range (g)
Braked and Steered Left	15	0.48	0.94	0.11	0.06	0.83
Steered Left	2	0.21	0.28	0.14	0.07	0.14

Distraction Analysis

Table 20 lists the frequency of events that involved distraction. Note that 59 percent of events did not involve distraction. However, just under a quarter of the events involved drivers diverting their gaze from the forward roadway to check their mirrors. This result may be indicative of the difficulty associated with monitoring various crash threats around the vehicle at once.

Table 20. Potentially Distracting Behavior Observed Prior to Lane-Change Event

Distraction	Frequency	Percent (%)
Not Distracted	10	59
Left Window	3	17
Center Mirror	1	6
Cognitive - Other	1	6
Talking/Listening	1	6
No data	1	6
Total	**17**	**100**

Right Lane-Change Near-Crashes

Of the 32 near-crashes, 15 involved the SV swerving into the right lane to avoid a forward crash threat. Table 24 categorizes these events by precipitating event and subsequent driver reaction. It can be seen that reaction for the majority of near-crashes consisted of the SV braking and swerving left to avoid a slowing POV. Four events involved the SV nearly sideswiping an adjacent vehicle on the right when swerving to avoid the POV.

Table 21. Precipitating Event by Driver Reaction for Near-Crashes Involving the SV Swerving Into the Right Lane to Avoid a Forward Crash Threat

	Driver Reaction							
Precipitating Event	Braked	Braked and Steered Left	Braked and Steered Right	Steered Left	Steered Right	Accelerated	No Reaction	Total
Slowing POV	0	0	7	0	2	0	0	9
POV Enters From Intersection	0	0	5	0	1	0	0	6

Figure 10 shows the percentage of drivers who looked in the observed eye-glance locations during the 8-second, 3-second, and lane-change intervals. One event is not included in this eye-glance analysis since eye-glance data spanning all three intervals were unavailable.

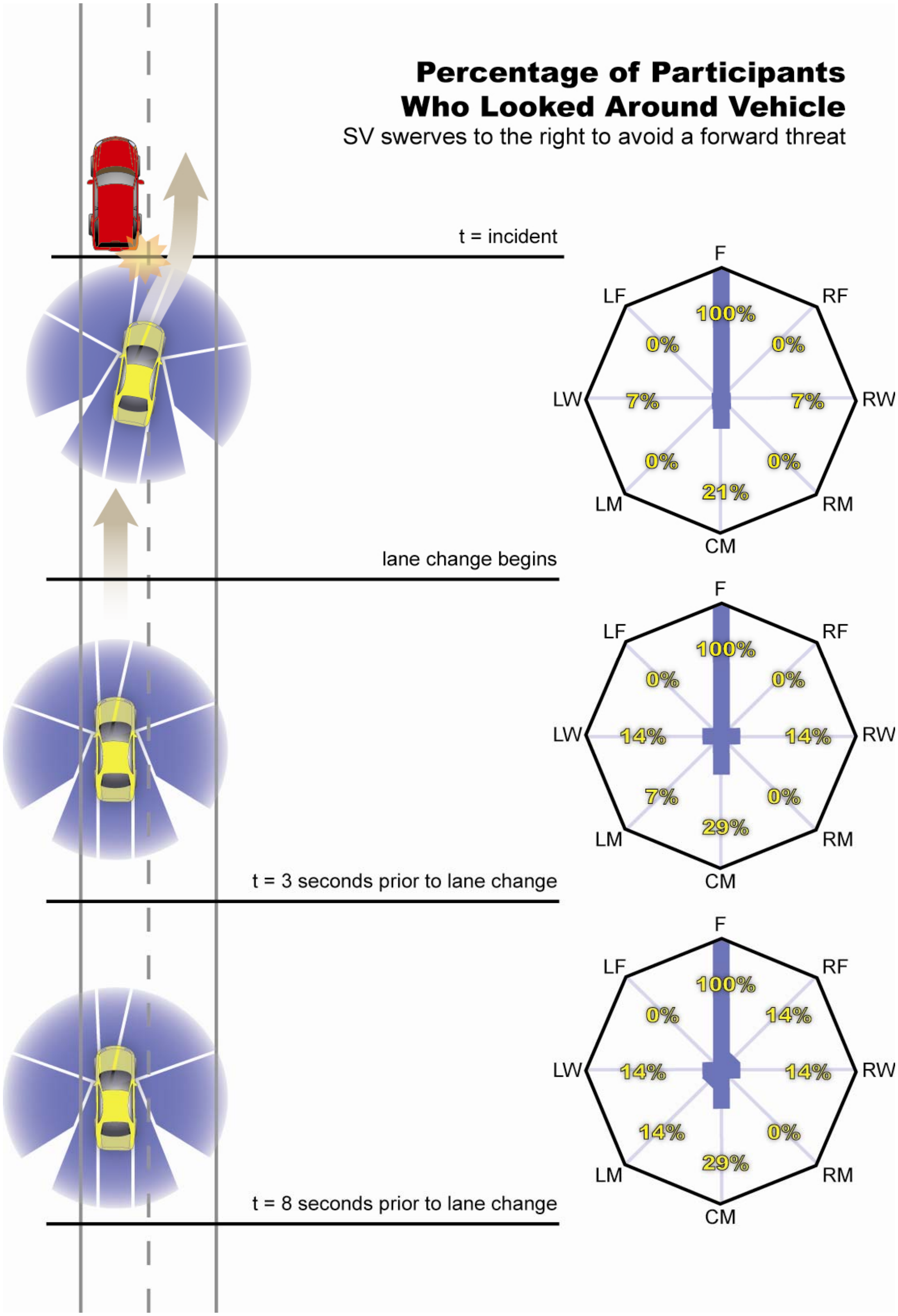

Figure 10. Percentage of Drivers Who Looked Around the Vehicle Prior To and During an Evasive Right-Lane Change

Figure 11 compares the number of drivers who looked in the indicated eye-glance locations during the 8-second, 3-second, and lane-change intervals. None of the 14 drivers checked their right mirror, 2 drivers checked their right window, and 4 drivers checked their center mirror during the 8-second interval. Additionally, none of the 14 drivers checked their right mirrors, 1 driver checked the right window, and 3 drivers checked their center mirrors during the 3-second interval. Six drivers (43%) did not glance at all to their right mirrors, right windows, or center mirrors prior to swerving into the right lane. These data show that drivers inadequately scanned their surroundings prior to performing an evasive lane change. None of the 14 drivers checked their right mirrors, one driver checked the right window, and 3 drivers checked their center mirrors during the evasive lane change.

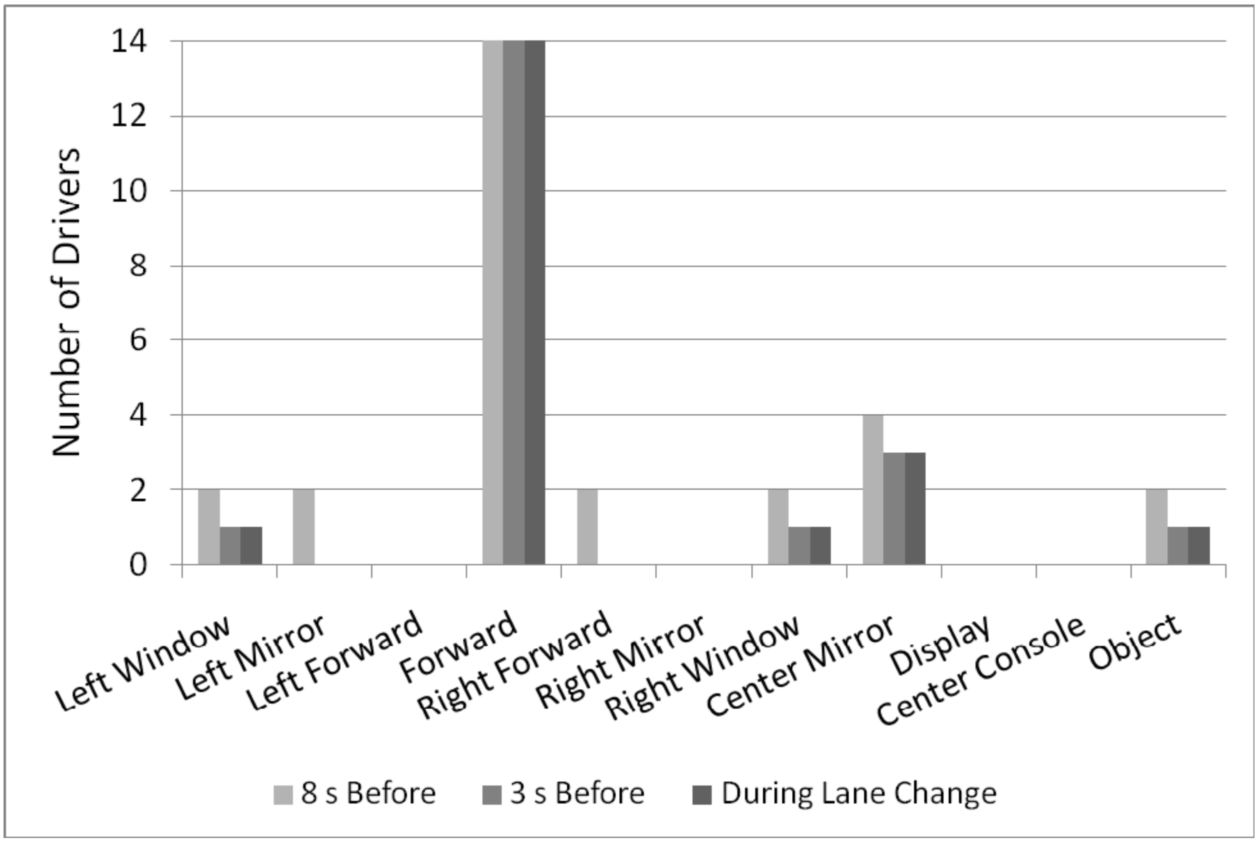

Figure 11. Number of Drivers Who Looked in the Indicated Locations 8 s Prior, 3 s Prior, and During a Right Evasive Lane Change (N=14)

Driving Conditions

The traffic density distribution is shown below in Table 22. It can be seen that the majority of events that arose from the SV swerving to the right to avoid a forward crash threat were divided between free-flow conditions and stable-flow conditions (where maneuverability and speed are more restricted). Table 23 presents the distribution of the number of vehicles that surrounded the SV prior to the event. The majority of the right-swerve events arose when just one other vehicle was in front of the SV. However, two vehicles were present during four events. The weather conditions were clear during 87 percent of these events. It was raining during two events; 67 percent of these events took place during the day and 33 percent at night.

Table 22. Traffic Density During the Lane-Change Event

Density	Frequency	Percent (%)
Free flow	6	40
Flow with some restrictions	3	20
Stable flow; maneuverability and speed are more restricted	6	40
Total	**15**	**100**

Table 23. Number of Vehicles Near the SV During the Lane-Change

Number of Surrounding Vehicles	Frequency	Percent (%)
1	11	73
2	4	27
Total	**15**	**100**

SV Lane Change Behavior
SVs were travelling at 35 mph on average (SE = 4 mph, min = 10 mph, max = 72 mph) prior to changing lanes. The elapsed time from the initiation of the lane change to the SV crossing into the POV's lane was 0.9 s on average (SE = 0.1 s, min = 0.4 s, max = 1.5 s). The elapsed time from the initiation of the lane change to the event was 1.6 s on average (SE = 0.12 s, min = 0.9 s, max = 2.4 s).

Five of the 15 drivers (33%) used their turn signal. The turn signal was activated prior to the initiation of the lane change for four events. The average time from the turn signal switching on to lane-change initiation was 1.3 s (SE = 0.3 s, min = 0.6 s, max = 1.8 s).

Table 28 shows the average peak deceleration levels observed from the initiation of the lane-change up to 5 s following the event for each driver reaction. It can be seen that drivers who elected to brake and steer right did so with a deceleration of 0.38 *g*. Drivers who steered right did so with a deceleration of 0.11 *g*.

Table 24. Average Peak Deceleration Observed From SV Lane-Change Start to 5 s After the Event Time Point for Each Driver Reaction

Driver Reaction	N	Mean (g)	Maximum (g)	Minimum (g)	Std Error (g)	Range (g)
Braked and Steered Right	12	0.38	0.75	0.06	0.06	0.69
Steered Right	3	0.11	0.17	0.03	0.04	0.15

Distraction Analysis
Table 25 lists the frequency of right evasive lane changes that involved distraction. The majority (87%) did not involve distraction. Distractions present in the remaining two events involved a passenger occupying the adjacent seat and the driver preoccupied with something outside the vehicle.

Table 25. Potentially Distracting Behavior Observed Prior to Lane-Change Event

Distraction	Frequency	Percent (%)
Not distracted	13	87
Other external distraction	1	7
Passenger in adjacent seat	1	7
Total	**15**	**100**

EVENTS INVOLVING THE POV SIDESWIPING THE SV

Two lane-change crashes that arose from a POV performing a right-lane change into the SV's path were observed. Each crash is described.

Lane-Change Crash #2

In this event, the SV performed a right-lane change to pass a POV preparing to make a left-hand turn. As the SV passed through the POV's blind spot, the POV aborted the left turn and performed a right-lane change to re-enter the SV's forward path. The POV crashed into the SV's left side as a result. The SV continued driving through the intersection after the crash and stopped the vehicle in a nearby parking lot.

Driver Eye-Glance Patterns
During the 8-second and 3-second intervals before the POV began to change into the SV's lane, the driver looked straight ahead. From the point at which the POV began to change lanes until the event, the driver still only looked straight ahead. Perhaps one of the reasons the SV driver was unable to avoid the lane-change crash was because of a failure to perceive the POV's lateral movement into the SV's lane through peripheral vision.

Driving Conditions
This lane-change crash occurred in stable flow traffic conditions. The POV was positioned in the left-hand turn lane prior to the event. The crash occurred during daylight in clear weather.

POV Lane Change Behavior
The SV was traveling at 18 mph prior to being sideswiped by the POV. Since the POV lane change started as the SV was passing through the POV's blind spot, the POV turn-signal use could not be determined from the video footage.

SV Response Behavior

The SV braked and steered right with a peak deceleration of 0.36 *g* in response to the sideswipe threat occurring on the SV's left side.

Distraction Analysis

This SV driver was not distracted during this lane-change crash.

Lane-Change Crash #3

Prior to this crash, the SV made a right-lane change to pass slow-moving traffic. As the SV passed through the POV's right blind spot, the POV began a right-lane change to exit the highway. The SV swerved to the right in response to the left sideswipe threat and collided with a snow bank that encroached on the right-most lane. The SV then braked and steered left in response to colliding with the snow bank. This lane-change crash did not involve contact between the POV and the SV. Had there not been contact with the snow bank, it would have been classified as a lane-change near-crash.

Driver Eye-Glance Patterns

The SV driver only looked forward from the 8 s prior to the POV lane change to the event.

Driving Conditions

This lane-change crash occurred in stable-flow traffic conditions. Two vehicles were positioned in the left lane prior to the event. The weather comprised clear daytime conditions with snow on the side of the road.

POV Lane-Change Behavior

The time elapsed from the POV initiating a right-lane change until it crossed the lane was 1.2 s. Two seconds elapsed from the lane-change initiation to the event with the snow bank. The POV turn-signal use could not be determined because of glare in the video footage.

SV Response Behavior

The SV was traveling at 30 mph prior to being nearly sideswiped by the POV. The SV steered right (deceleration recorded at 0.11 *g*) in response to the sideswipe threat.

Distraction Analysis

This SV driver was talking on a hand-held cell phone during this lane-change crash. The cell phone was held by the right hand up to the right ear.

Left-Lane-Change Near-Crashes

Of the 49 near-crashes involving a POV almost sideswiping the SV, 22 events involved the POV making a left-lane change. Table 26 categorizes these near-crashes by precipitating event and subsequent driver reaction. It can be seen that the majority of SV drivers braked and steered left to avoid the event. Two events involved the SV nearly sideswiping an adjacent vehicle on the left when avoiding the POV.

Table 26. Precipitating Event by Driver Reaction for Near-Crashes Involving a POV Sideswiping the SV While Performing a Left-Lane Change

Precipitating Event	Driver Reaction							
	Braked	Braked and Steered Left	Braked and Steered Right	Steered Left	Steered Right	Accelerated	No Reaction	Total
POV Enters SV Lane	5	15	0	2	0	0	0	22

Driver Eye-Glance Patterns

Figure 12 shows the percentage of drivers who looked in the observed eye-glance locations 8 s prior, 3 s prior, and during a POV left-lane-change in which they were nearly sideswiped. Eye-glance data was available for all 22 events.

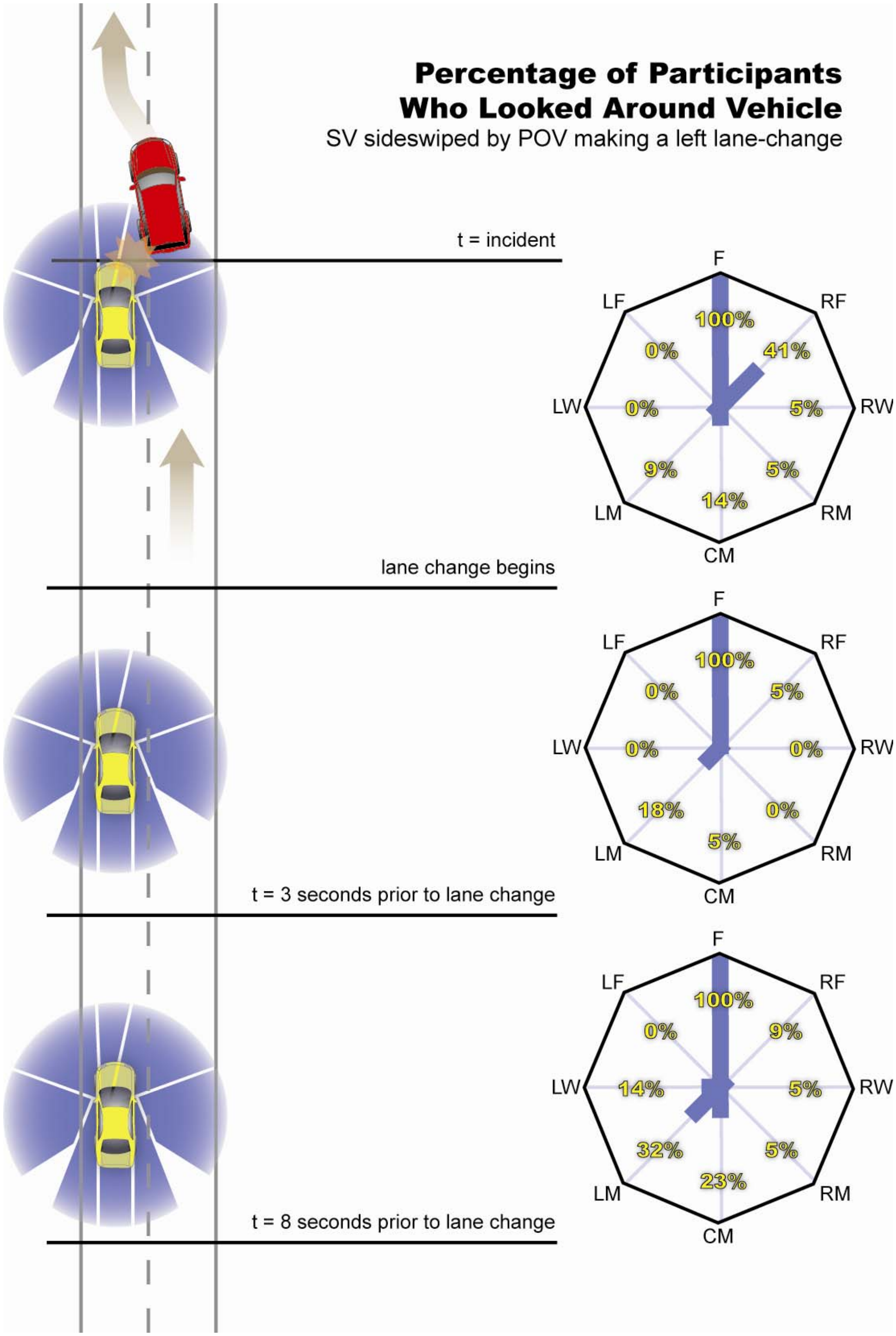

Figure 12. Percentage of Drivers Who Looked Around the Vehicle 8 s Prior, 3 s Prior, and While Nearly Being Sideswiped by Another Vehicle on the Right

Figure 13 compares the number of drivers who looked in the indicated locations 8 s prior, 3 s prior, and during POV lane-change intervals. All drivers looked forward and 9 drivers looked right forward as the POV executed the lane change. Eye-glances to the forward roadway may have assisted SV drivers in perceiving the crash threat and responding to the POV lane-change in a timely manner.

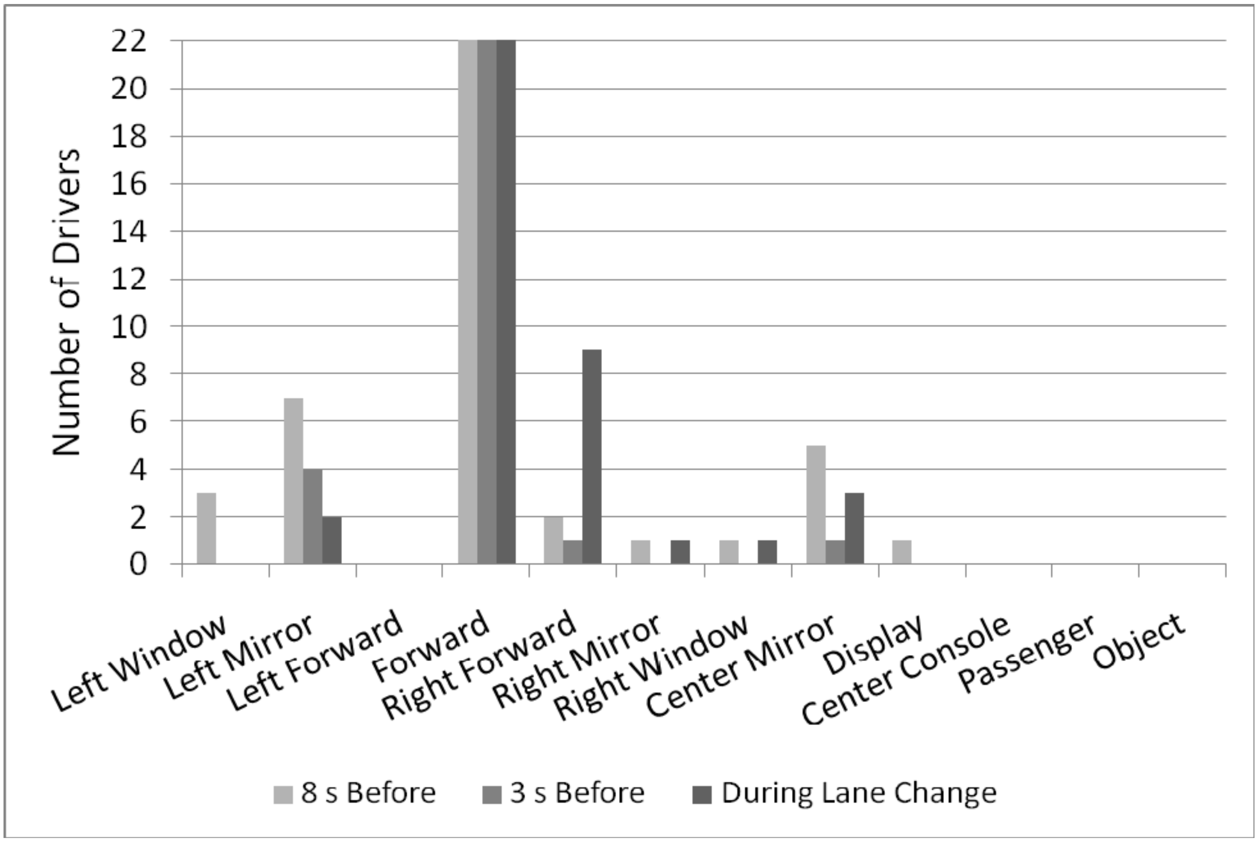

Figure 13. Number of Drivers Who Looked in These Locations 8 s Prior, 3 s Prior, and While a POV Made a Left-Lane Change That Nearly Sideswiped the SV (N=22)

Driving Conditions

The traffic density distribution is shown below in Table 27. The majority of the events that arose from the POV nearly sideswiping the SV during a left-lane change occurred in traffic conditions with few restrictions. Table 28 shows that the POV was the only vehicle in the vicinity for the majority of the events. The weather conditions were clear during 95 percent of these events. It was raining during one event. Altogether, 72 percent of these events took place during the day, 14 percent took place at night, and 14 percent took place at dusk.

Table 27. Traffic Density During Lane-Change Events in Which the SV is Sideswiped by a POV Making a Left-Lane Change

Density	Frequency	Percent (%)
Free flow	8	36
Flow with some restrictions	7	32
Stable flow; maneuverability and speed are more restricted	3	14
Unstable flow; temporary restrictions substantially slow driver	4	18
Total	**22**	**100**

Table 28. Number of Vehicles in the Vicinity of the SV During the Lane Change

Number of Surrounding Vehicles	Frequency	Percent (%)
1	17	77
2	5	23
Total	**22**	**100**

POV Lane-Change Behavior
SVs were traveling at 45 mph on average (SE = 4 mph, min = 16 mph, max = 83 mph) prior to the POV initiating the lane change. The average elapsed time from the POV initiating the lane change to crossing into the SV's lane was 1.4 s (SE = 0.14 s, min = 0.6 s, max = 2.7 s). The elapsed time from the initiation of the POV lane change to the event averaged 2.1 s (SE = 0.13 s, min = 1 s, max = 3.9 s). One outlier was removed during the computation of these averages.

Video reduction determined that 11 of the 22 POV drivers (50%) used their turn signals during these events. The turn signals were activated prior to the initiation of the lane change for five events. The average time from the turn signal switching on to POV lane-change initiation was 1.2 s (SE = 0.2 s, min = 0.3 s, max = 1.6 s).

Table 29 shows the average peak deceleration levels observed for each driver reaction to a POV left-lane-change event. SV drivers braked moderately hard when braking was the only response; they braked less hard when steering was incorporated into their avoidance maneuver.

Table 29. Average Peak Deceleration Levels Observed for Each Driver Reaction to a POV Left-Lane-Change Event

Driver Reaction	N	Mean	Maximum	Minimum	Std Error	Range
Braked	5	0.59	0.72	0.27	0.08	0.45
Braked and Steered Left	15	0.30	0.85	0.03	0.06	0.88
Steered Left	2	0.05	0.10	0.01	0.06	0.11

Turn signals notify others of a driver's intentions to change lanes. Braking behavior to both signaling and non-signaling POVs was inspected to explore whether turn signal feedback allowed SV drivers to anticipate the POVs' movement. Table 30 shows the average peak deceleration levels observed for each driver reaction to a signaling and non-signaling POV lane-change event. It can be seen that driver braking and steering responses to signaling POVs tend to have greater decelerations than driver braking and steering responses to non-signaling POVs. It is interesting that four times as many drivers only braked when there was a turn signal, while there was 1.3 times the braking and steering response when no turn signals were used. This suggests that when turn signals were used, more drivers were able to brake such that they did not also have to perform a steering avoidance maneuver.

Table 30. Average Peak Deceleration Levels Observed for Each Driver Reaction to a Signaling and Non-Signaling POV Left-Lane-Change Event

	Signaling POV			Non-Signaling POV		
Driver Reaction	N	Mean	Std Error	N	Mean	Std Error
Braked	4	0.58	0.1	1	0.62	.
Braked and Steered Left	6	0.37	0.09	9	0.25	0.09
Steered Left	1	0.1	.	1	0.01	.

Drivers' BRT to a POV entering their lane was also inspected. SVs took 1.1 s on average to press the brake pedal in response to a POV initiating a lane change into the SV's forward pathway (SE = 0.6 s, min = 0.1 s, max = 4.4 s). Exploring braking behavior by turn-signal use revealed that SVs took, on average, 1.0 s to brake to a signaling POV (SE = 0.4 s, min = 0.1 s, max = 2.7 s) and 1.2 s to brake to a non-signaling POV (SE = 0.6 s, min = 0.1 s, max = 4.4 s). These longer brake response times may be why drivers had to also steer in many of the events.

Distraction Analysis

Table 31 lists the frequency of left sideswipe events that involved distraction. The majority (95%) did not involve distraction. Distraction was present in one event, and involved a passenger occupying the adjacent seat.

Table 31. Potentially Distracting Behavior Observed Prior to a POV Making a Left-Lane Change That Nearly Sideswiped the SV

Distraction	Frequency	Percent (%)
Not distracted	21	95
Passenger in adjacent seat	1	5
Total	**22**	**100**

Right Lane-Change Near-Crashes

Of the 49 near-crashes involving a POV sideswiping the SV, 27 involved the POV making a right-lane change. Table 32 divides these 27 near-crashes by precipitating event and subsequent driver reaction. It can be seen that the majority of SV drivers braked and steered right to avoid an event with POVs making a right-lane change into the SV's lane. One event involved the SV nearly sideswiping an adjacent vehicle on the right when avoiding the POV.

Table 32. Precipitating Event by Driver Reaction for Near-Crashes Involving a POV Sideswiping the SV While Performing a Right-Lane Change

	Driver Reaction							
Precipitating Event	**Braked**	**Braked and Steered Left**	**Braked and Steered Right**	**Steered Left**	**Steered Right**	**Accelerated**	**No Reaction**	**Total**
POV Enters SV Lane	7	0	18	0	2	0	0	27

SV Driver Eye-Glance Patterns

Figure 14 shows the percentage of drivers who looked in the observed eye-glance locations 8 s before, 3 s before, and during a POV right-lane change in which the SV was nearly sideswiped. Eye-glance data was available for all 27 events.

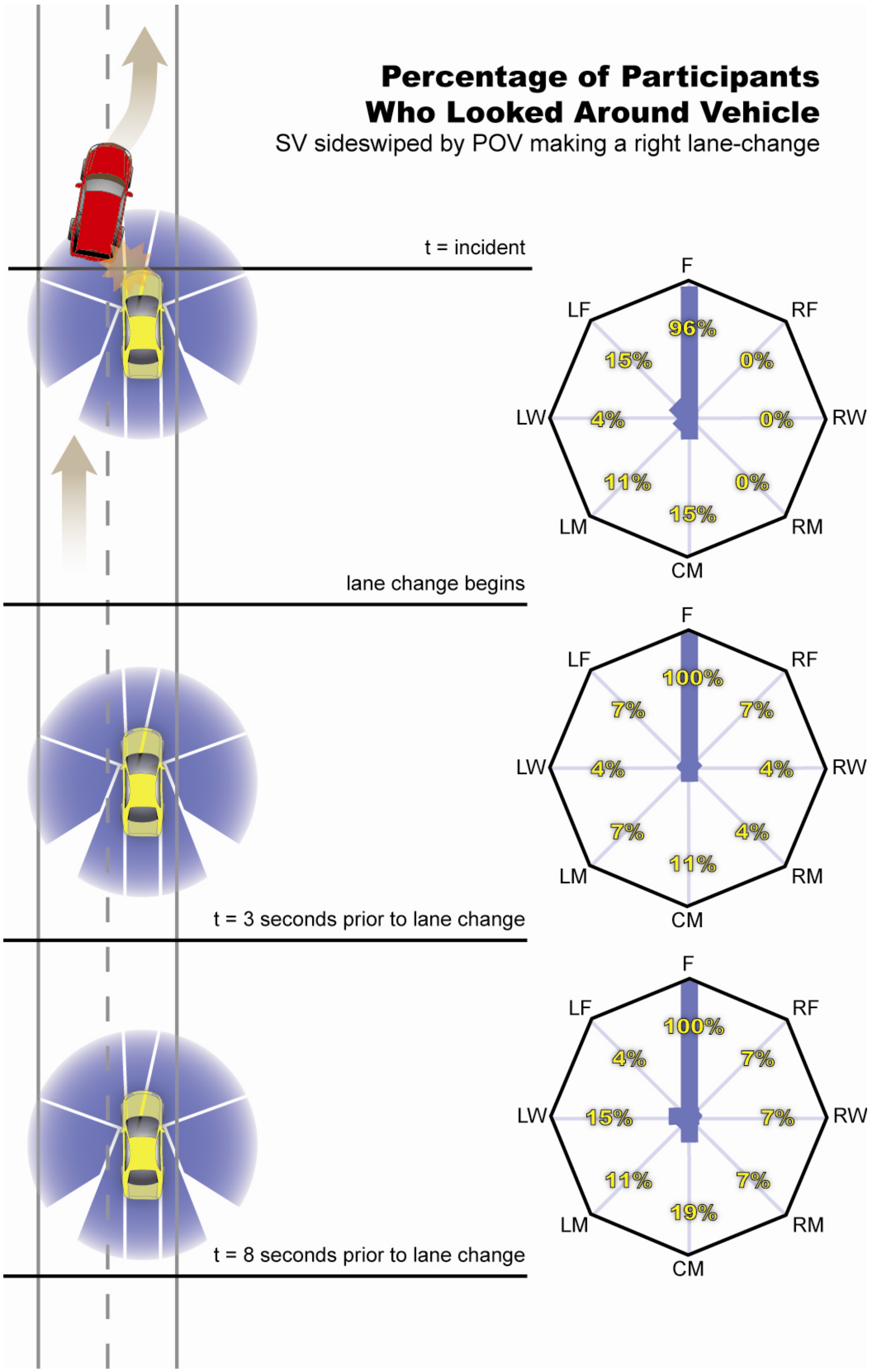

Figure 14. Percentage of Drivers Who Looked Around the Vehicle 8 s Prior, 3 s Prior, And While Nearly Being Sideswiped by Another Vehicle on the Left

Figure 15 compares the number of drivers who looked in the indicated locations during the 8 s prior, 3 s prior, and during POV lane-change intervals. In all, 26 drivers looked forward, and 4 looked left-forward, as the POV made a right-lane change into the SV's lane. Eye-glances to the forward roadway may have assisted SV drivers in perceiving the crash threat and responding to the POV lane change in a timely manner.

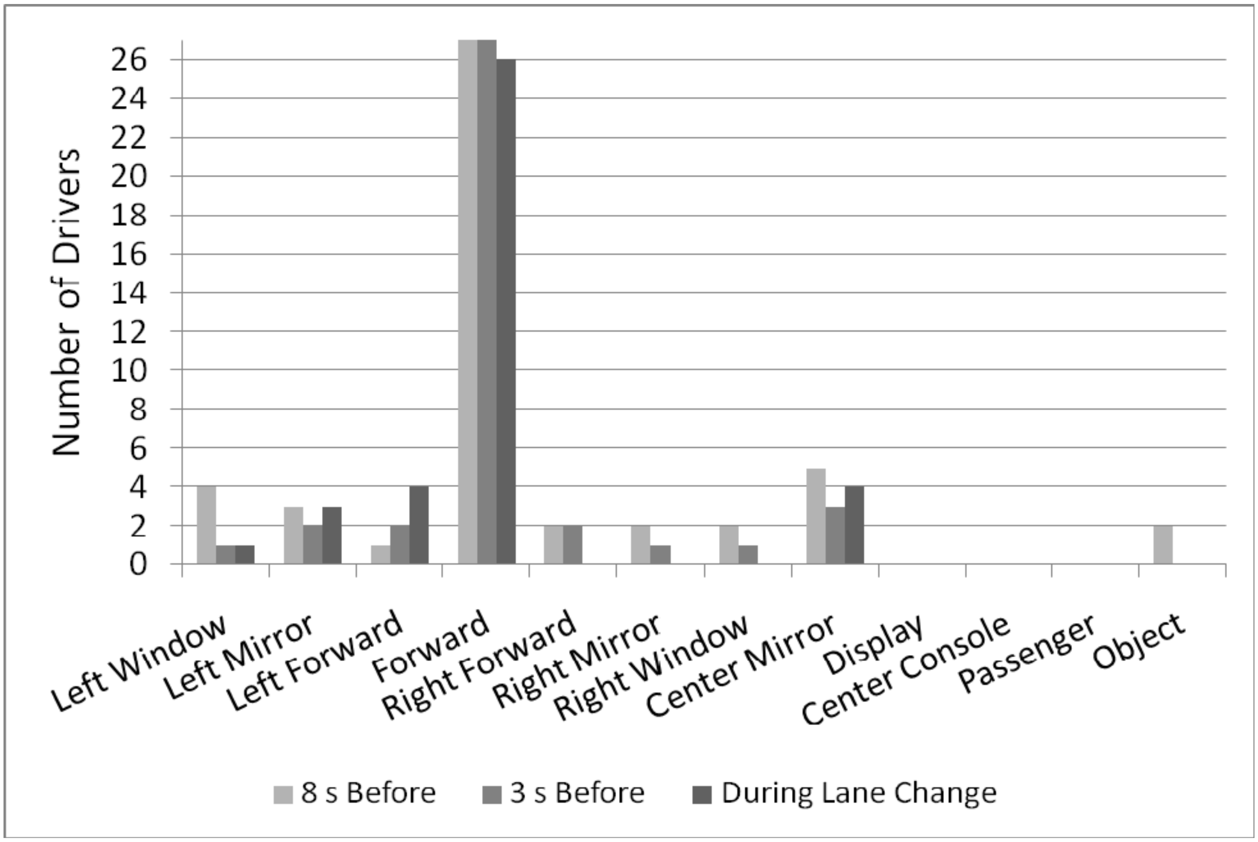

Figure 15. Number of Drivers Who Looked Toward the Indicated Locations 8 s Prior, 3 s Prior, and While a POV Made a Right-Lane Change That Nearly Sideswiped the SV (N=27)

Driving Conditions

The traffic density distribution is shown below in Table 33. It can be seen that the majority of events occurred in stable-flowing traffic conditions where maneuverability and speed were more restricted. Table 34 shows that the POV was the only vehicle in the SV's vicinity for the majority of the events. The weather conditions were clear during 89 percent of these events, and raining during 3 events (11%). Eighty-five percent took place during the day and 15 percent at night.

Table 33. Traffic Density During the Lane-Change Event

Density	Frequency	Percent (%)
Free flow	8	30
Flow with some restrictions	6	22
Stable flow; maneuverability and speed are more restricted	9	33
Unstable flow; temporary restrictions substantially slow driver	2	7
Flow is unstable; vehicles are unable to pass, temporary stoppages, etc.	2	7
Total	**27**	**100**

Table 34. Number of Vehicles Near the SV During the Lane Change

Number of Surrounding Vehicles	Frequency	Percent (%)
1	23	85
2	4	15
Total	**27**	**100**

POV Lane-Change Behavior

SVs were traveling at 34 mph on average (SE = 3 mph, min = 4 mph, max = 80 mph) prior to the POV initiating a right-lane change. The average elapsed time from the POV initiating the lane change to the POV crossing into the SV's lane was 1.3 s (SE = 0.12 s, min = 0.1 s, max = 2.9 s). The elapsed time from the initiation of the POV lane change to the event averaged 2.2 s (SE = 0.3 s, min = 0.2 s, max = 6.5 s).

Nine of 25 POV drivers (36%) used their turn signal when generating a sideswipe event during a right-lane change (turn-signal use for two events could not be determined). Five of these drivers signaled prior to making the lane change. The turn signal was on for 1.0 s (SE = 0.3 s, min = 0.1 s, max = 1.8 s) prior to the initiation of the lane change.

Table 35 shows the average peak deceleration levels observed for each driver reaction to a right POV lane-change event.

Table 36 shows the average peak deceleration levels observed from the initiation of a signaling-POV lane change and a non-signaling POV lane-change. It can be seen that driver response does not seem to differ by POV turn-signal use.

Table 35. Average Peak Deceleration Levels Observed for Each Driver Reaction to a POV Right-Lane Change Event

Driver Reaction	N	Mean (*g*)	Maximum (*g*)	Minimum (*g*)	Std Error (*g*)	Range (*g*)
Braked	7	0.58	0.94	0.44	0.07	0.49
Braked and Steered Right	18	0.56	1.00	0.40	0.03	0.60
Steered Right	2	0.00	0.07	0.07	0.07	0.14

Table 36. Average Peak Deceleration Levels Observed for Each Driver Reaction to a Signaling and Non-Signaling POV Right-Lane Change Event

	Signaling POV			Non-Signaling POV		
Driver Reaction	N	Mean	Std Error	N	Mean	Std Error
Braked	7	0.58	0.07	2	0.76	0.17
Braked and Steered Right	18	0.56	0.03	7	0.57	0.07
Steered Right	2	0	0.07	NA	NA	NA

Drivers' BRTs to a POV entering their lane was also inspected. SVs took 1.7 s on average to press the brake pedal in response to a POV entering the SV's forward pathway from the left (SE = 0.3 s, min = 0.1 s, max = 4.9 s). Exploring braking behavior by turn-signal use revealed that SVs took an average of 1.8 s to brake to a signaling POV (SE = 0.4 s, min = 0.2 s, max = 3.4 s), and 1.5 s to brake to a non-signaling POV (SE = 0.5 s, min = 0.1 s, max = 4.9 s).

Distraction Analysis

Table 37 lists the frequency of POV right sideswipe events that involved distraction. The majority (85%) did not involve distraction. Distractions present in the remaining 15 percent involved the SV driver talking/listening on a cell phone, combing/fixing hair, and a passenger occupying the adjacent seat.

Table 37. Potentially Distracting Behavior Observed Prior to a POV Making a Right-Lane Change That Nearly Sideswiped the SV

Distraction	Frequency	Percent (%)
Not distracted	23	85
Talking/listening	2	7
Combing or fixing hair	1	4
Passenger in adjacent seat	1	4
Total	**27**	**100**

CHAPTER 5. DISCUSSION

This report investigated the lane-change crashes and near-crashes observed in the 100-Car Study. The combined parametric and video data collection of both the driving environment and the driver during these lane-change events provides insight on why they occurred. Specifically, lane-change events were examined with respect to the driving conditions present, SV-driver eye-glance and vehicle-control behavior, as well as the POV-driver vehicle-control behavior. The findings as they relate to the five research objectives are discussed in this chapter. Where possible, lane-change event behavior is compared to the behavior observed during the higher severity, and higher urgency, non-event lane changes reported in Lee et al. (2004).

OBJECTIVE 1. CLASSIFY LANE-CHANGE EVENTS

A total of 135 lane-change events were identified in this study. The 3 lane-change crashes comprise 4 percent of the 69 crashes observed in the 100-Car Study (Dingus, Klauer, Neale, et al., 2006). This percentage is in alignment with the 4 to 10 percent reported in previous studies (Barr & Najm 2001; Eberhard et al., 1994; Wang & Knipling, 1994; Young et al., 1995). The 132 lane-change near-crashes comprise 17 percent of the 761 near-crashes observed in the 100-Car Study. This suggests that the lane-change crash problem could potentially become larger, particularly as more vehicles crowd the nation's roads and impinge on the clearance required to change lanes safely.

Lane-change events were differentiated by the role of the SV. SVs that instigated lane-change events were considered to be striking vehicles, while SVs that were hit, or nearly hit, by a POV making a lane change were considered to be struck vehicles. Events were then classified into one of three scenarios: (1) events involving the SV sideswiping a POV, (2) events involving the SV swerving to avoid a forward crash threat, and (3) events involving the POV sideswiping the SV. Scenarios 1 and 2 pertain to the striking vehicle category, while scenario 3 pertains to the struck vehicle category (scenario 2 was classified as striking to align with the fault designation of "following too closely"). Of the three lane-change crashes observed, one involved the SV sideswiping a POV, while two arose from a POV sideswiping the SV (vehicle-to-vehicle contact was made in one case, while the other case involved contact with a snow bank). In comparison, no lane-change crashes were recorded in Lee et al.'s (2004) comprehensive examination of naturalistic lane changes. Reasons why lane-change crashes were observed in the 100-Car Study may be the larger number of drivers who participated as well as the increased traffic density in the Northern Virginia/Washington, DC, area. There was also much more data collected in the 100-Car Study than in the earlier lane-change study.

Of the 132 lane-change near-crashes, 27 percent of the drivers were involved in only the scenario with an SV sideswiping a POV, 29 percent were involved in only the POV sideswiping the SV scenario, and 18 percent were involved in only the scenario of the SV swerving to avoid a forward crash threat. In disregarding events in which the SV swerved to avoid a forward crash threat for a moment, it is interesting that the drivers studied encountered a nearly equivalent number of sideswipe events from both a striking and struck vehicle perspective. This suggests that a majority of the sampled SV drivers were no different from the POV drivers in terms of their contribution to lane-change event causation. On the other hand, seven of the 66 SV drivers (11%) encountered events in all three scenarios. It is possible that these drivers exhibited improper driving behavior, such as inadequate scanning and fast approach speeds, which made them prone to encountering lane-change events.

All of the lane-change crashes observed in the 100-Car Study occurred during right-lane changes. However, this may be a consequence of a small sample size. Left and right lane-change near-crashes were evenly observed across the three scenarios. This data suggests that drivers are equally likely to encounter events when performing lane changes in either direction. This finding is in alignment with Chovan et al. (1994), who analyzed lane-change crashes using 1991 General Estimates System (GES) data.

The majority of the lane-change events (93%) took place during clear conditions, which is in line with the 89 percent of inattention-related baseline epochs sampled in the 100-Car Study (Dingus, Klauer, Neale, et al., 2006) for the driver inattention analysis. The majority of events also took place during the day (73%), which is comparable to the 66 percent of inattention-related baseline epochs identified in the 100-Car Study. Lane-change event frequency did not appear to be related to adverse weather conditions or to nighttime driving.

SVs were predominantly observed to resolve all three lane-change near-crash scenarios by braking and steering away from the crash threat. This suggests that drivers attempt all they can to avoid a crash threat once it is identified. The next most likely driver reaction for events involving the SV sideswiping a POV and SV swerving to avoid a forward crash threat was for the SV to steer away from the crash threat without braking. In contrast, the second most likely avoidance maneuver to a POV sideswiping the SV was for the SV to brake without a concomitant steering maneuver. These results somewhat contradict Chovan et al.'s (1994) finding that 5 of 8 SV drivers reported that they did not attempt an avoidance maneuver when involved in a lane-change crash. Chovan et al. do advise that their small sample size of driver self-reports merits caution when extrapolating their results.

OBJECTIVE 2. EXPLORE THE DIFFERENCES BETWEEN STRIKING AND STRUCK VEHICLES WITH REGARD TO REAR- AND SIDE-VIEW MIRROR SAMPLING BEHAVIOR

Where SV drivers looked prior to striking a POV was a primary research interest in this study. This is because an examination of driver eye-glances prior to changing lanes can provide insight on whether degradations in visual attention contributed to the event. Table 38 and Table 39 summarize the observed percentage of striking drivers who looked at their side-view mirrors, side windows, and center mirrors prior to and during left and right lane-change near-crashes, respectively. The p values in these tables show the results of Fisher's exact tests (performed at the 0.1 level of significance) to investigate significant differences between the two striking vehicle scenarios in peripheral eye-glance locations.

Table 38. Percentage of Striking Drivers Who Scanned Their Periphery During Left-Lane-Change Events

Eye-Glance Location	Time Interval	SV Sideswipe POV	SV Swerve to Avoid Forward Crash Threat	*p*-value
Left Mirror	8 s Interval	38%	13%	0.150
	3 s Interval	46%	13%	**0.045**
	Lane-Change Interval	50%	13%	**0.038**
Left Window	8 s Interval	17%	20%	1.000
	3 s Interval	50%	20%	**0.093**
	Lane-Change Interval	38%	13%	0.150
Center Mirror	8 s Interval	21%	20%	1.000
	3 s Interval	17%	27%	0.686
	Lane-Change Interval	21%	13%	0.686

Table 39. Percentage of Striking Drivers Who Scanned Their Periphery During Right Lane-Change Events

Eye-Glance Location	Time Interval	SV Sideswipe POV	SV Swerve to Avoid Forward Crash Threat	*p*-value
Right Mirror	8 s Interval	0%	0%	-
	3 s Interval	9%	0%	0.511
	Lane-Change Interval	14%	0%	0.267
Right Window	8 s Interval	9%	14%	0.634
	3 s Interval	23%	14%	0.681
	Lane-Change Interval	50%	7%	**0.011**
Center Mirror	8 s Interval	41%	29%	0.501
	3 s Interval	32%	29%	1.00
	Lane-Change Interval	36%	21%	0.467

A notable finding from this analysis was that a number of drivers (17% during left-lane changes and 36% during right-lane changes) failed to scan their surroundings during the entire 8 s prior to the initiation of a planned lane change (8-second and 3-second intervals combined). Since this is when drivers formulate spatial awareness of surrounding vehicles and make a go/no-go decision to change lanes, it is foreseeable that these events occurred because drivers failed to perceive the adjacent POV prior to changing lanes. This poor scanning behavior may be indicative of drivers assuming that the relative position of nearby vehicles would not change from the last time they observed them in their side-view and rear-view mirrors. With respect to those drivers who did scan their surroundings prior to changing lanes, events may have occurred because drivers failed to recognize that the traffic conditions in the adjacent lanes were hazardous, such as when an adjacent vehicle was closing quickly.

SV drivers who swerved to avoid a forward crash threat were also poor at scanning their surroundings prior to changing lanes. A number of SV drivers (33 percent during left swerves and 43 percent during right swerves) failed to scan their surroundings during the entire 8 s prior to the execution of the evasive lane change. Fisher's exact tests were performed at the 0.1 level of significance to investigate whether there are significant differences in the peripheral eye-glance locations between the two striking vehicle scenarios. The results are reported in Tables 38 and 39. Significantly more SV drivers in the *SV Sideswipe POV* left-lane-change scenario looked at their left mirror during the 3-second and lane-change intervals than SV drivers in the *SV Swerve to Avoid Forward Crash Threat* left-lane-change scenario. This was also true with respect to eye-glances made toward the left window during the 3-second interval. The inadequate amount of mirror sampling observed prior to evasive lane changes may have occurred because drivers did not have enough time to look away from the forward crash threat under the increased time pressure to change lanes. Furthermore, it was found that significantly fewer drivers looked out their right windows during the lane-change interval of right evasive lane changes as compared to right planned lane changes. In fact, at most 21 percent of the drivers scanned their surroundings during this interval of time in the *SV Swerve to Avoid Forward Crash Threat* scenario. These results suggest that drivers preoccupied with a forward crash threat are unlikely to monitor their periphery as they perform an evasive lane change. That is, if drivers have not perceived an adjacent POV prior to performing an evasive lane change, they are unlikely to perceive a POV during the maneuver.

For events in the *SV Sideswipe POV* scenario, 46 percent of the drivers looked at their left side-view mirrors and 17 percent looked at the center mirrors during the last 3 s prior to left-lane changes, The corresponding values for right side-view mirror and center mirror for right-lane changes were 9 percent and 32 percent (significantly more drivers glanced to the left side-view mirrors during left-lane changes than drivers who glanced to the right side-view mirrors during right-lane changes [Fisher's exact test, $p = 0.0083$]). To compare the results to non-event lane changes, Lee et al. (2004) found that, during the last 3 s prior to left non-event lane changes, 52 percent of the drivers looked at the left side-view mirrors and 52 percent looked at the center mirrors one time or more. The corresponding values for right side-view mirror and center mirror for right-lane changes were 21 percent and 55 percent. It should be noted that these lane changes were performed in more-rural areas of Virginia compared to the areas studied in the 100-Car Study. Nevertheless, the results from both studies suggest that drivers inadequately check their rear- and side-view mirrors prior to changing lanes, whether or not the lane change leads to a crash or near-crash as in the cases reported here.

With regard to SVs being struck or nearly struck by POVs, all drivers were observed to look forward (including left- and right-forward) during the interval of time spanning 8 s prior to the POV initiating a lane change. Additionally, 32 percent of the SV drivers did not look to any side-view mirrors, side windows, or center mirrors prior to a POV making left-lane changes (41 percent for when the POV made a right-lane change). The eye-glance data suggest that these events did not occur due to inattention to the forward roadway. Looking forward may have assisted the SV drivers in perceiving the crash threat and responding to the POV lane change before a crash occurred. It is possible that these events may have been more severe had the SV drivers not perceived the crash threat when they did.

In using the eye-glance data to help explain the occurrence of lane-change events, one can see that safe driving requires drivers to concurrently monitor the forward roadway and surrounding traffic. However, drivers are limited in that they can visually attend to only one location at a time. As traffic becomes denser from an increasing amount of vehicles occupying limited roadway real estate, it is foreseeable that the driving task demands of simultaneously monitoring multiple vehicles may exceed this human performance limitation. Systems that assist drivers in acquiring spatial awareness as they monitor the forward roadway as well as recognize when conditions in the adjacent lane are hazardous during imminent lane changes may help remedy this safety problem.

OBJECTIVE 3. EXPLORE THE VEHICLE CONTROL BEHAVIOR OF SV DRIVERS

The majority of the lane-change events involving the SV striking a POV occurred in driving conditions in which traffic flow was restricted, but with no stoppages. SVs were observed to travel at 38 mph on average prior to initiating a lane change in which they nearly sideswiped a POV. Not all SV drivers used their turn signals before or during the lane change (85 percent for left-lane changes and 72 percent for right-lane changes). Even fewer drivers signaled prior to initiating the lane change (64 percent for left-lane changes, 44 percent for right-lane changes). Turn signals were activated for an average of 3.4 s prior for left-lane changes and 3.9 s prior for right lane-changes. To compare, Lee et al. (2004) found that turn signals were only used 48 percent of the time for left-lane changes and 35 percent of the time for right-lane changes. Lee et al. reported, however, that there was a large between-subjects variance in the percentage of turn-signal use, ranging from 0 to 92 percent. Nevertheless, the hypothesis that drivers making right-lane changes after passing slow lead vehicles chose to not signal because of the belief that other drivers know their intentions appears to be supported by the observed trend in the 100-Car Study lane-change data.

It was found that an average of 1.5 s elapsed from the initiation of planned left-lane changes to the SV crossing into the adjacent lane (1.3 s for planned right-lane changes). These time intervals are shorter than reported in Lee et al. (2004) for non-event lane changes, where single lane changes were found to take an average of 6.3 s to be completed and roughly 2 s for the vehicle to cross into the adjacent lane. The shorter intervals observed in the 100-Car Study may be a result of the driving conditions present in the Northern Virginia/Washington, DC, area or more aggressive driving on the part of the participants. An average of 2.3 s elapsed from the initiation of planned left-lane changes to the sideswipe near-crashes (1.9 s for planned right-lane changes). This finding is striking since this is the amount of time available for a lane-change warning system to detect a crash threat, notify the driver of the impending collision, allow the driver to confirm the crash threat, and have the driver make an appropriate avoidance maneuver. This short interval of time identifies a need for drivers to be aware of adjacent POVs prior to initiating lane changes. The majority of the SVs elected to brake and steer away in response to the event (0.23 g when braking and steering away from a left crash threat, and 0.41 g when braking and steering away from a right crash threat).

SVs that swerved to avoid a forward crash threat were observed to travel at 38 mph on average. Turn-signal use was lower for this scenario relative to the *SV Sideswipe POV* scenario. The 24 percent who used their turn signals when swerving to the left was significantly lower than the 85 percent observed when the SV made planned left-lane changes ($p < 0.001$, χ^2 Statistic = 16.045).

Similarly, the 33 percent who used their turn signals when swerving to the right was also significantly lower than the 72 percent compliance observed when SVs made planned right-lane changes ($p = 0.017$, χ^2 Statistic = 5.736). Since turn signals communicate to surrounding traffic a driver's intention to change lanes, it is possible that the lack of turn-signal use may have been a contributing factor for these lane-change events. The relative decrement in turn-signal use shown by SVs swerving to avoid forward crash threats is of particular interest. The data reinforces the notion that these drivers did not have adequate time to signal their lane changes. It is also possible that they did not have sufficient attentional resources available to signal while they focused on the execution of the collision avoidance maneuver. If failing to signal is a contributing factor to lane-change events, then these drivers are at an increased risk of endangering adjacent vehicles as they perform evasive lane changes. Furthermore, the data indicates that a lane-change warning system cannot rely on turn-signal use as a lane change predictor, and that such systems should be designed to operate even when turn signals are not used.

Evasive lane changes were observed to occur very quickly. An average of 1.2 s elapsed from the initiation of left evasive lane changes to the SV crossing into the adjacent lane (0.9 s for right evasive lane changes). Furthermore, an average of 1.8 s elapsed from the initiation of left-lane changes to the near-crashes with the forward crash threat (1.6 s for right evasive lane changes). This data shows how quickly a striking vehicle can become a crash threat and reinforce the need for drivers to be aware of adjacent POVs prior to changing lanes.

The majority of SV drivers braked and steered left with a deceleration of 0.48 g and to the right with a deceleration of 0.38 g when performing evasive lane changes. Taken together with the *SV Sideswipe POV* scenario findings, a trend appears to exist in that striking vehicle drivers brake and steer harder to the left than to the right. This may have occurred because SV drivers cannot see as clearly how close the POV is when it is located to the right-rear. As a result, their lane changes may have progressed further along and required a more severe avoidance maneuver.

OBJECTIVE 4. ANALYZE THE RELEVANT LANE-CHANGE BEHAVIOR OF NEARBY VEHICLES THAT MAY HAVE CONTRIBUTED TO CRASH AND NEAR-CRASH EVENTS

The lane-change behavior of POVs nearly sideswiping SVs was found to resemble the behavior of SVs sideswiping POVs from a vehicle-control perspective. An average of 1.4 s elapsed from the POV initiating a left-lane change to crossing into the SVs' lane (1.3 s when crossing to the right lane). An average of 2.1 s elapsed from the POV initiating a left-lane change to the event (2.2 s when making a right-lane change). The data helps indicate how quickly a vehicle can become a crash threat to surrounding traffic as it performs a lane change.

Fifty percent of the POV drivers used their turn signals when making left-lane changes (36 percent signaled when making right-lane changes). These percentages may be lower than the turn-signal compliance exhibited by SVs because they were determined through video inspection rather than by output from the vehicle's DAS. Turn-signal use could not be determined for a number of events when video footage was not clear. Nevertheless, these findings, in addition to the SV turn-signal use previously reported, support the notion that turn-signal use cannot be relied on as a predictor of lane-changes leading to crashes or near-crashes. Of the POV drivers who signaled, 45 percent did so prior to making left-lane changes (55 percent signaled prior to making right-lane changes). Turn signals were activated on average for 1.2 s prior to POVs making left-lane changes (1.0 s for right-lane changes). This suggests that SV drivers had to rely on perceiving a change in the POV's trajectory to ascertain the POV's lane-change intentions.

Determining the POV behavior that led to the lane-change events is difficult without direct observation of where these drivers looked and what tasks they were involved in. However, from analyzing POV lane-change duration and turn-signal use, the lane-change events they initiated do not appear to be drastically different from the lane-change events initiated by SV drivers. This trend suggests that the sampled POV drivers were no different from the sampled SV drivers in terms of their contribution to lane change events.

OBJECTIVE 5. ANALYZE THE RESPONSE TIME, DECELERATION, AND BRAKING BEHAVIOR FOR FOLLOWING DRIVERS TOWARD VEHICLES WHO ENTER THE FORWARD DRIVING PATH BY SIGNAL USE

SVs were observed to travel on average at 42 mph prior to being nearly sideswiped by a POV. It was determined that the majority of SV drivers braked and steered away in response to these lane-change events. Drivers' BRTs to a POV entering their lane were found to be quite quick. SVs took on average 1.1 s to press the brake pedal in response to a POV making a left-lane change into the SV's lane and 1.7 s to press the brake pedal in response to a POV making a right-lane change. Average peak deceleration levels were observed to be 0.3 *g* when braking and steering left and 0.6 *g* when braking and steering right. Perhaps these drivers would not have had to brake as hard had they started the braking maneuver earlier. Collision avoidance systems that provide automatic braking may allow events to be avoided with less deceleration.

An examination of SV event response behavior by POV turn-signal use may provide insight on the warning cues turn signals are intended to provide. SVs took, on average, 1.0 s to brake to a signaling POV making a left-lane change, and 1.2 s to brake to a non-signaling POV. SVs took, on average, 1.8 s to brake to a signaling POV making a right-lane change, and 1.5 s to brake to a non-signaling POV. Overall, SV BRT did not appear to differ by POV turn-signal use. This suggests that drivers relied on perceiving the POV's trajectory as a predictor of lane-change events. SVs braked and steered away with an average peak deceleration of 0.37 *g* in response to a signaling POV making a left-lane change and 0.25 *g* in response to a non-signaling POV. In contrast, SVs braked and steered away with an average peak deceleration of 0.57 *g* in response to a signaling POV making a right-lane change and 0.55 *g* in response to a non-signaling POV. In this case, there may be a trend that SVs braked harder to signaling POVs making left-lane changes than to non-signaling POVs making left-lane changes.

Driver response does not appear to depend on POV turn-signal use. Very small differences were observed in the performance data. However, the majority of drivers were observed to steer in response to POVs entering their forward pathway. This is worrisome, given that the eye-glance analyses presented earlier show that few of the drivers who swerved to avoid a forward crash threat scanned their surroundings prior to changing lanes.

CHAPTER 6: CONCLUSIONS

The 100-Car Study was the first study to establish a direct relationship between immediate, pre-event driving inattention and crash and near-crash involvement. Glances away from the forward roadway greater than 2 s were shown to increase crash risk by at least two times. This is because drivers looking away from the road stand to miss critical changes in the environment that affect where they can safely travel. Similarly, the current study found that drivers who nearly sideswiped an adjacent vehicle inadequately monitored their side-view mirrors, side windows, and center mirrors prior to changing lanes. It is foreseeable that these drivers also failed to perceive changes in their environment, such as a fast-approaching POV in the adjacent lane, prior to changing lanes. These events may have been avoided had these drivers monitored their surroundings more closely. The notion that monitoring one's surroundings as a protective driving behavior is supported by the 100-Car Study finding that driving-related glances away from the forward roadway of less than 2 s were found to reduce crash risk (odds ratio of .048). Taken as a whole, these findings exemplify a dilemma that drivers face between monitoring the forward roadway and monitoring the areas around them. For example, a driver checking the blind spot in preparing to change lanes to pass a slow-moving lead vehicle may fail to notice when it suddenly decelerates. On the other hand, a driver closely attending to a decelerating lead vehicle may fail to notice a fast-approaching POV in the adjacent lane when attempting to pass. Being aware of surrounding traffic conditions may be a protective driving behavior, but surrounding traffic conditions may make it difficult to safely gather this information.

The lane-change task requires drivers to divide their attention between monitoring the forward roadway, their surroundings, steering the vehicle, regulating the vehicle's speed, and using the turn signal. Drivers who are pressed to change lanes may exhibit degraded performance in one or more of these subtasks. This analysis found that some drivers failed to use their turn signals when changing lanes. This was particularly true when drivers swerved into an adjacent lane to avoid a forward crash threat. This data suggests that turn-signal use degrades as driver time-pressure to change lanes increases. It is also evident from the data that some drivers were simply unwilling to signal prior to changing lanes. In short, turn signals were not a reliable predictor of lane changes leading to crashes or near-crashes.

Few of the drivers who experienced lane-change events were involved in secondary tasks (27%). Although involvement in complex secondary tasks was found to increase crash risk by 7.1 times in the 100-Car Study, it is not believed to be a predominant contributing factor to the observed lane-change events.

The findings from this report enhance the understanding of lane-change events. The lane-change events were observed to occur in less than 2 s. Typically, 1.5 s elapsed from the initiation of the lane change to the vehicle crossing into the adjacent lane. These findings show that drivers had little time to respond to the lane-change events. Perhaps this is why a combination of braking and steering were predominantly observed as a collision avoidance maneuver. One final aspect of the study worth noting is that there were a sufficient number of events to come to an understanding of the parameters surrounding lane-change event scenarios and the direction of lane-change events. It is therefore reasonable to expect a proportionately equivalent number of events to be observed across lane-change scenarios and directions in future naturalistic lane-change studies.

APPLICATION OF RESULTS

Awareness of the relative position of surrounding vehicles is gathered by visually sampling the side-view mirrors, side windows, and center mirror and mentally integrating this information. All of this is interleaved with the primary task of monitoring the forward roadway. Since many of the drivers in this study inadequately scanned their surroundings prior to changing lanes (both during planned and evasive lane changes), it is foreseeable that some of the lane-change events would not have occurred had these drivers been aware of the relative position of surrounding vehicles. For those drivers who did scan their surroundings, it is possible that the lane-change events occurred because they did not properly recognize the behavior of the POV, such as its approach speed. A system that communicates the relative position of surrounding vehicles and supports drivers in recognizing when they become hazards may address this shortcoming. If this information is reliable, a system that allows drivers to concurrently perceive assembled vehicular position presented through a single display may foster enhanced spatial awareness.

Lane-change events were observed to occur in less than 2 s. As such, a collision-avoidance-based lane-change warning system that solely notifies the driver of an impending collision once a lane change has been initiated may be suboptimal. Rather, a system that allows the lane-changing drivers to better judge whether a lane change can be safely completed *prior to* initiation may be more appropriate. However, impending collision warnings may still be appropriate when drivers are inattentive to their surroundings. Furthermore, the data indicate that a lane-change warning system cannot rely on turn-signal use as a lane-change predictor, and should be designed for use in the absence of turn signals.

LIMITATIONS OF THE STUDY

The findings presented in this report are limited in that an insufficient number of lane-change events were observed within the classification scheme to perform inferential statistics for certain parameters. It was originally hoped that there would be enough lane-change crash and near-crash events that baseline data could be used to develop estimates of crash risk for issues such as failure to use turn signals while changing lanes. However, the relatively small number of data points made this infeasible. Nevertheless, the interested reader can compare many of the findings in this study, especially regarding eye-glance patterns and turn-signal use, to the naturalistic lane-change study described earlier (Lee et al., 2004). The nearly 9,000 normal lane changes in that study can be considered as a comparison group to the current study. Together, the two studies provide a valuable database of information for normal lane changes, as well as for lane change crashes and near-crashes.

REFERENCES

Barr, L., & Najm, W. G. (2001). *Crash problem characteristics for the intelligent vehicle initiative.* (Paper No. 01-2471). TRB 80th Annual Meeting, Washington, DC.

Bhise, V. D., Meldrum, J., Jack, D., Troell, G., Hoffmeister, D., & Forbes, L. (1981). *Driver head movements in left outside mirror sampling.* (SAE paper 810761). Warrendale, PA: Society of Automotive Engineers.

Chovan, J. D., Tijerina, L., Alexander, G., & Hendricks, D. L. (1994). *Examination of lane change crashes and potential IVHS countermeasures.* (DOT HS 808 071). Washington, DC: National Highway Traffic Safety Administration. Available at: http://www.itsdocs.fhwa.dot.gov/\JPODOCS\REPTS_TE/61B01!.PDF.

Dingus, T. A., Antin, J. F., Hulse, M. C., & Wierwille, W. W. (1988). Human factors associated with in-car navigation system usage. In *Proceedings of the Human Factors Society 32nd Annual Meeting,* 1448-1452. Santa Monica, CA: Human Factors Society.

Dingus, T. A., et al. (2006). *The 100-Car naturalistic driving study: Phase II – Results of the 100-Car field experiment.* Contract No. DTNH22-00-C-07007 (Task Order 6), Washington, D.C.: National Highway Traffic Safety Administration.

Eberhard, C. D., et al. (1994). *Development of performance specifications for collision avoidance systems for lane change, merging and backing. Task 1 interim report: Crash problem analysis.* (DOT HS 808 431). Washington, DC: National Highway Traffic Safety Administration. Available at http://www.itsdocs.fhwa.dot.gov/\JPODOCS\REPTS_TE/3C01!.PDF

Evans, L. (1991). *Traffic safety and the driver.* New York: Von Nostrand Reinhold.

Fancher, P. (1999). *Report on Tasks: S-1, Analysis of driver response delays and S-2, lane changes: Analysis of data on speed-change and lane-change behavior in manual and ACC driving.* (UMTRI-99-23). Technical report. Washington, DC: National Highway Traffic Safety Administration.

Finnegan, P., & Green, P. (1990). *The time to change lanes: A literature review.* (IVHS Technical Report-90-13). University of Michigan, Transportation Research Institute.

Gellatly, A. W., & Kleiss, J. A. (2000). *Visual attention demand evaluation of conventional and Multifunction in-vehicle information systems.* In Proceedings of the IEA 2000/HFES 2000 Congress, 3, 282-285. Santa Monica, CA: Human Factors and Ergonomics Society.

Gibson, J. J., & Crooks, L. E. (1938). A theoretical field-analysis of automobile driving. *American Journal of Psychology*, 51, 453-471.

Hanowski, R. J., Wierwille, W. W., Garness, S. A., Dingus, T. A., Knipling, R. R., & Carroll, R. J. (2000). A field evaluation of safety issues in local/short haul trucking. In *Proceedings of the XIVth Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Society*. Santa Monica, CA: Human Factors and Ergonomics Society, vol. 3, pp. 365-368.

Henderson, R. L. (1985). Driver Anthropometrics. R. L. Henderson (Ed.) *NHTSA Driver Performance Data Book.* Washington, DC: National Highway Traffic Safety Administration.

Hetrick, S. (1997). *Examination of driver lane change behavior and the potential effectiveness of warning onset rules for lane change or "side" crash avoidance systems.* Unpublished master's thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia. Available at: http://scholar.lib.vt.edu/theses/available/etd-382915749731261/unrestricted/etd.pdf.

Hills, B. L. (1980). Vision, visibility, and perception in driving. *Perception*, 9, 183-216.

Jula, H., Kosmatopoulos, E., & Ioannou, P. (1999). *Collision avoidance analysis for lane changing and merging*. University of Southern California, Los Angeles, USC Center for Advanced Transportation Technologies Department of Electrical Engineering-Systems. Available at: http://www.usc.edu/dept/ee/catt/99papers/jula.pdf.

Klauer, S. G., Dingus, T. A., Neale, V. L., Sudweeks, J.D., & Ramsey, D. J. (2006). *The Impact on driver inattention on near crash/crash risk: An analysis using the 100 Car naturalistic driving study data.* (Report No. DOT HS 810 594). Washington, DC: National Highway Traffic Safety Administration.

Knipling, R. R. (1993). IVHS technologies applied to collision avoidance: Perspectives on six target crash types and countermeasures. In *Proceedings of the 1993 Annual Meeting of IVHS America: Surface Transportation: Mobility, Technology, and Society,* 249-259. Washington, DC.

Kurokawa, K., & Wierwille, W. W. (1990). Validation of a driving simulation facility for instrument panel task performance. *Proceedings of the Human Factors Society 34th Annual Meeting*, 1299-1303.

Lee, S. E., Olsen, E. C. B., & Wierwille, W. W. (2004). *A Comprehensive Examination of Naturalistic Lane Changes*. (Final Report. DOT HS 809 702). Washington, DC: National Highway Traffic Safety Administration.

McLaughlin, S. B. (1998). *Measurement of driver preferences and intervention responses as influenced by adaptive cruise control deceleration characteristics*. Unpublished master's Thesis. Virginia Polytechnic Institute and State University: Blacksburg, VA.

Mourant, R. R., & Donohue, R. J. (1974). *Mirror sampling characteristics of drivers.* (SAE paper 740964). Warrendale, PA: Society of Automotive Engineers.

Mourant, R. R., & Donohue, R. J. (1977). Acquisition of indirect information by novice, experienced, and mature drivers. *Journal of Safety Research*, 9(1), 39-46.

Mourant, R. R., & Rockwell, T. H. (1970). Mapping eye-movement patterns to the visual scene in driving: An exploratory study. *Human Factors*, 12(1), 81-87. Santa Monica, CA: Human Factors Society.

Mourant, R. R., & Rockwell, T. H. (1972). Strategies of visual search by novice and experienced drivers. *Human Factors*, 14(4), 325-335. Santa Monica, CA: Human Factors Society.

Mourant, R. R., Rockwell, T. H., & Rackoff, N. J. (1969). Drivers' eye movements and visual workload. *Highway Research Record*, 292, 1-10. Washington, DC: National Research Council.

Nagata, M. & Kuriyama, H. (1985). *Drivers' visual behavior with door and fender mirror systems (SAE Paper No. 850330).* Warrendale, PA: Society of Automotive Engineers.

Najm, W. G., & Smith, J. D. (2002). *Breakdown of light vehicle crashes by pre-crash scenarios as a basis for countermeasure development*. ASCE's 7th International Conference on Applications of Advanced Technology in Transportation, Cambridge, MA. August 5-7.

National Highway Traffic Safety Administration. (2001). *Traffic safety facts 2000.* Washington, DC: National Highway Traffic Safety Administration. Available at: http://www-fars.nhtsa.dot.gov/pubs/1.pdf or http://www-nrd.nhtsa.dot.gov/pdf/nrd-30/NCSA/TSFAnn/TSF2000.pdf.

Ohta, H. (1993). Individual differences in driving distance headway. In A. G. Gale, I. Brown, C. M. Haslegrave, & S.P. Taylor (Eds.), *Vision in Vehicles IV* (pp. 91-100). Amsterdam: North Holland Press.

Redelmeier, D. A., & Tibshirani, R. J. (2000). *Lane changes while driving occasionally cause collisions. Do we make too many lane changes? Are those other drivers really going faster?* Chance, 13(3), 8-14. Alexandria, VA: American Statistical Association. Available at: http://www.public.iastate.edu/~chance99/133.redelmeier.pdf.

Robinson, G. H., Erickson, D., Thurston, G., & Clark, R. (1972). Visual search by automobile drivers. *Human Factors*, 14 (4), 315-323. Santa Monica, CA: Human Factors Society.

Rockwell, T. H. (1972). Skills, judgment, and information acquisition in driving. In T.W. Forbes (Ed.), *Human Factors in Highway Traffic Safety Research* (133-164). New York: Wiley Interscience.

Rockwell, T. H. (1988). Spare visual capacity in driving – revisited: New empirical results for an old idea. In A. G. Gale, M. H. Freeman, C. M. Haslegrave, P. Smith, & S.P. Taylor (Eds.), *Vision in Vehicles II* (pp. 317-324). Amsterdam: North Holland Press.

Shinar, N. (1978). *Psychology on the road: The human factor in traffic safety*. New York: Wiley.

Smith, D. L., Najm, W. G., & Glassco, R. A. (2002). *The feasibility of driver judgment as a basis for crash avoidance database development.* (Paper No. 02-3695). Transportation Research Board (TRB) Annual Meeting. Washington, D.C. Transportation Research Board.

Talmadge, S., Chu, R., Eberhard, C., Jordan, K., & Moffa, P. (2000). *Development of performance specifications for lane change crash warning systems.* (Draft Final Report). Redondo Beach, CA: TRW Space and Defense.

Taoka, G. T. (1990). Duration of drivers' glances at mirrors and displays. *Institute of Transportation Engineers Journal*, October, 60(10), 35-39.

Tijerina, L. (1999). Operational and behavioral issues in the comprehensive evaluation of lane change crash avoidance systems. *Journal of Transportation Human Factors*, 1(2), 159-176.

Tijerina, L., Garrott, R, W., Glecker, M., Stoltzfus, D., & Parmer, E. (1997). *Van and passenger car driver eye glance behavior during lane change decision phase.* (Revised Draft: Interim Report). Transportation Research Center, Inc. and National Highway Traffic Safety Administration, Vehicle Research and Test Center.

Tijerina, L., Parmer, E.B., & Goodman, M.J. (1999). Individual differences and in-vehicle distraction while driving: a test track study and psychometric evaluation. In *Proceedings of the Human Factors and Ergonomics Society 43rd Annual Meeting*, pp. 982-986. Santa Monica, CA: Human Factors and Ergonomics Society.

Van Winsum, W. & Heino, A. (1996). Choice of time-headway in car-following and the role of time-to-collision information in braking. *Ergonomics*, 39(4), 579-572.

Van Winsum, W., De Waard, D., & Brookhuis, K. A. (1999). *Lane change maneuvers and safety margins.* Transportation Research Part F 2, 139-149. Amsterdam: Elsevier.

Wang, J.-S. & Knipling, R. R. (1994). *Lane change/merge crashes: Problem size assessment and statistical description (Final Report, DOT HS 808075).* Washington, DC: National Highway Traffic Safety Administration. Available at: http://www.itsdocs.fhwa.dot.gov/%5CJPODOCS%5CREPTS_TE/B_01!.PDF.

Wierwille, W. W. (1984). Driver steering performance (Chapter 16). In G. A. Peters & B. J. Peters (Eds.), *Automotive Engineering and Litigation*, 1, 407-434. New York: Garland Law.

Wierwille, W. W., Antin, J. F., Dingus, T. A., & Hulse, M. C. (1988). Visual attentional demand of an in-car navigation display system. In A. G. Gale, M. H. Freeman, C. M. Haslegrave, P. Smith, & S.P. Taylor (Eds.), Vision in Vehicles II (pp. 307-316). Amsterdam: North Holland Press.

Worrall, R. D., & Bullen, A. G. R. (1970). *An empirical analysis of lane changing on multilane highways.* Highway Research Board, 303, 30-43.

Young, S. K., Eberhard, C. A., & Moffa, P. J. (1995). *Development of performance specifications for collision avoidance systems for lane change, merging, and backing. Task 2: Functional goals establishment.* TRW Space and Electronics Group. Washington, DC: National Highway Traffic Safety Administration. Available at: http://www.itsdocs.fhwa.dot.gov/jpodocs/repts_te/2w101!.pdf.

Zwahlen, H. T., Adams, C. C., & DeBald, D. P. (1988). Safety aspects of CRT touch panel controls in automobiles. In A.G. Gale, Freeman, M.H., Haslegrave, C.M. Smith, P., & Taylor, S.P. (eds.). *Vision in Vehicles II* (335-344). Amsterdam: Elsevier.

DOT HS 811 147
June 2009

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

NHTSA
www.nhtsa.gov