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16. Abstract

This research effort provided valuable insight into the nature and severity of lane changes in a naturalistic driving environment. Sixteen commuters who normally drove more than 25 miles (40 km) in each direction participated. The two research vehicles were a sedan and an SUV; each participant drove each vehicle for ten days. Data gathering was automatic, and no experimenter was present in the vehicle. There were 8,667 lane changes observed over 23,949 miles of driving, making this the largest known data collection effort for the study of lane changes. Analysis of the full data set resulted in many interesting findings regarding the frequency, duration, urgency, and severity of lane changes in regard to maneuver type, direction, and other classification variables. A subset of the full data set (500 lane changes) was then analyzed in greater depth using the sensor data collected by the instrumented vehicle. The sampled lane changes were generally of the more severe and urgent types since these are the cases in which a lane change collision avoidance system is likely to be of greatest help. Variables analyzed for the sampled lane changes included turn signal use, braking behavior, steering behavior, eye glance patterns, and forward and rearward area analysis. The concept of a safety envelope for lane changes was then developed using the forward and rearward area analyses. Finally, the data were used to provide recommendations for designers of lane change CAS in terms of display location and activation criteria. Overall, the research described in this report provides insight into the behaviors and parameters associated with lane changes, while the naturalistic data archive has the potential to address other questions related to driving behavior.

17. Key Words

lane change, collision avoidance system, eye glance behavior, driver behavior, turn signal, time-to-collision

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EXECUTIVE SUMMARY

Project Overview

Transportation researchers estimate that lane change crashes account for 4 to 10% of all crashes (Barr & Najm, 2001; Eberhard et al., 1994; Wang & Knipling, 1994; Young, Eberhard & Moffa, 1995). Research has revealed that most drivers in lane change crashes did not attempt an avoidance maneuver; this suggests that the driver did not see or was unaware of the presence of another vehicle or crash hazard (Chovan, Tijerina, Alexander & Hendricks, 1994; Eberhard et al.; Tijerina, 1999). According to Knipling (1993), 75% of lane change/merge crashes involve a recognition failure by the driver. Thus, to reduce lane change crashes, it would seem that drivers must be made aware of impending hazards before lane change initiation (Chovan et al.; Tijerina).

In-vehicle technology seems a logical option to assist drivers in maintaining awareness and reducing crashes and lane change crashes have been targeted as a prime candidate for which technology could help reduce crashes (Wang & Knipling, 1994). Such technology would use in-vehicle alerts to signal the driver when necessary. The use of a crash avoidance system (CAS) has been proposed to inform or warn drivers and thereby reduce lane change crashes (Eberhard et al., 1994; Talmadge, Dixon & Quon, 1997).

The general objective of this project was to characterize lane change behavior using naturalistic data. The data were gathered between October 2000 and July 2001. Data were recorded while commuters drove instrumented vehicles to and from work and were later associated with passing maneuvers.

Experimental Methods

Sixteen commuters who normally drove more than 25 miles (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. The interstate route was I-81 in southwestern Virginia, a heavily traveled divided interstate with hills and many heavy vehicles. The highway route included both U.S. 460 and U.S. 11. These roads require lane changes at somewhat slower travel speeds (45 to 55 mph) and are largely 4-lane (two in each direction). Half of the participants normally drove a sedan and half normally drove an SUV (sport utility vehicle). Participants were aged 20 to 64 ($M = 40.8$, $SD = 12.2$), with equal gender representation.

The two research vehicles were also a sedan and an SUV. Each participant drove each vehicle for ten days. The data collection 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 that the vehicle first moved laterally; the lane change ended when the vehicle was settled in the destination lane.

The mixed-factors experimental design included three between-subjects independent variables, gender, driver type (sedan driver or SUV driver), and route (interstate or highway), and one within-subject independent variable, vehicle type (sedan and SUV). For clarification, driver type refers to the vehicle normally driven by the participant, whereas vehicle type refers to the vehicle driven for the experiment.

Eleven categories of Maneuver Type were identified, including 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 (4 feet in front of the subject vehicle [SV] to 30 feet behind it) and time-to-reach the edge of the proximity zone for those vehicles within the fast-approach zone (30 to 162 feet behind the SV). These zones refer to areas in the adjacent destination lane (beside/behind the SV) that should be monitored before lane change initiation (Talmadge, Chu, & Riney, 2000).

Urgency was rated on a 4-point scale (1 = not urgent, 4 = critical) indicating how soon the lane change was needed based on time to collision (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 seconds, multiple lane changes (more than one lane change in the same direction), and unsuccessful (aborted/partial/unintentional).

Naturalistic Lane Change Task Overview

The Naturalistic Lane Change effort was divided into three primary subtasks:

- Subtask 1, First Data Pass-Through. This subtask included an evaluation of all video data for the purpose of identifying lane-change and passing maneuvers. Severity ratings using the 7-point scale indicated the degree to which the vehicle in the destination lane was cut off based on vehicle presence in the adjacent destination lane. Urgency ratings using the 4-point scale indicated how soon the lane change was needed based on the time-to-collision with the closest vehicle in the same lane as the subject vehicle (either forward or rearward). The maneuver type classification scheme was also used to categorize maneuvers according to lane change motivation (e.g., to pass a slow lead vehicle).

  All lane changes were identified, graded, and classified during the first data pass-though. There were 8,667 lane changes identified and these were categorized into 11 maneuver types.

- Subtask 2, Data Reduction. Subtask 2 required that a sample of 500 lane changes be selected from the total population for in-depth analysis. A sampling plan was developed with input from the COTR and colleagues; the plan emphasized lane changes in the more severe and urgent categories. After the sampling plan was approved, 500 lane changes were selected to fulfill the criteria set out by the plan. Data reduction software was developed to allow the analysts to categorize the 500 selected lane changes in-depth. The program allowed the analysts to integrate radar, video, and sensor data and then display the event in a graphical format. Modifications of the initial software were made based on feedback from the data analysts. A total of 500 events were analyzed in-depth. After the lane change events were reduced using the Lane Change program, the video clip for each lane change was digitized, thus creating an easily accessible archive of lane changes. The Lane Change program also generated an event table in a spreadsheet format containing relevant lane change parameters for all 500 lane changes. The event table was used in Subtask 3.

- <u>Subtask 3, Data Analysis.</u> Analysis included one-way and two-way distributions of lane changes as a function of the severity ratings, urgency ratings, and type classification for the full population of 8,667 lane changes. One-way and two-way distributions of lane changes as a function of gender, vehicle type, driver type, and route were also developed. Other distribution variables included direction and success/magnitude of the lane change. Analysis of variance was also possible for the full set when examining certain dependent measures including duration, urgency, and severity, given the independent variables of gender, vehicle type, driver type, and route. Similar analyses were also conducted for slow lead vehicle lane changes and single lane changes.

  The event table generated in Subtask 2 was used to conduct more in-depth analyses for the sample of 500 lane changes selected from the full population. A much greater level of detail was available for this data set. Additional variables were investigated beyond those of the full data set including steering, lateral acceleration, velocity, braking, turn signal use, three measures of eye glance behavior, and distance, relative velocity, and TTC to forward and rearward POVs (principal other vehicles).

Results for Full Data Set

There were 8,667 lane changes observed with a mean duration of 9.07 s. Of these, 83% were single lane changes with a mean duration of 6.28 s. Analysis of the full data set revealed that 91% 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. This is to be expected given that crashes are rare events and lane changes 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. The lack of a crash over 23,949 miles of driving is not surprising given crash frequency per mile traveled.

There were four independent variables in the experimental design: gender, route, driver type, and vehicle type (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 miles (60.2 km) in each direction and the mean number of lane changes per mile across all independent variables was 0.36/mile (or about 1 lane change every 2.8 miles). This indicates the frequency with which a lane change assist device might be accessed by the driver.

A two-way interaction for gender by route was observed; female interstate drivers performed significantly more lane changes than male interstate drivers, or any of the highway drivers. However, male highway drivers had more lane changes per mile with viewing the data normalized by lane changes/mile. A two-way interaction gender by driver type was also observed, as both male and female sedan drivers made more lane changes than male or female SUV drivers.

In terms of severity (degree to which the vehicle in the destination lane was cut off) and urgency (how soon the lane change was needed based on TTC), the most common severity rating was 1 (low severity) with 95% of lane changes falling into this category. An urgency rating of 1 (low urgency) was also the most common category, covering 96% of all lane changes. More than 91% of all lane changes could be accounted for by the two-way distribution of low severity by low urgency (rated 1 and 1).

Most lane changes were to the left (55%) with a mean duration of over 11 seconds, 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 whereas many of the right lane changes were single lane changes.

In terms of the success/magnitude of the lane change, the set of 8,667 lane changes was categorized as single (83%), passing (12%), multiple (3%), or unsuccessful/partial (1%). Of the eleven 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 (≥ 3), the slow lead vehicle category was even more dominant at 56.2%. The distribution of maneuver types for the 8,667 lane changes is presented in Figure 3.1 of this report.

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% 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 in this situation to maintain their current speed by passing. Of all the lane changes rated greater than or equal to 2 in severity, 55% 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% 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.

Analysis of the complete data set showed that more lane changes were completed by interstate drivers because the interstate drivers drove longer routes. Sedan drivers made significantly more lane changes than SUV drivers, perhaps because sedan drivers spend more time in the right lane and make lane changes to pass while SUV drivers drive faster and prefer to drive in the left lane, resulting in fewer 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. A much greater level of detail was available for this data set. The sample of lane changes was analyzed in-depth and 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 data set 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 the behavior associated with riskier lane changes leading up to and including lane change initiation. 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 (t_0) 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% 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%. 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 the other drivers know their intentions.

Eye glance behavior was analyzed for the three seconds prior to t_0.; 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 three seconds prior to t_0. 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 the patterns would be distinct for lane changes in these two directions. 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 probabilities between forward and right mirror and between forward and right blind spot were also relatively high at 0.12.

A comparison of eye glance patterns for SUV versus sedan lane changes was also conducted. Despite the differences in visibility afforded by the two vehicle types (e.g., window size and field of view), both the mean single glance times and the glance probabilities were nearly the same for each glance location.

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% of drivers feel comfortable when there is a distance of about 40 feet frontward and rearward at lane change initiation. Likewise, 95% of drivers feel comfortable with a relative velocity (closing rate) of less than 20 ft/s (both forward and rearward), and a TTC of between 4 and 6 seconds for POVs in either the forward or rearward areas.

Preliminary recommendations for designers are also included at the end of this report. Highlights include the recommendation that lane change CAS should either be always on, or displayed when requested by the driver (it would not be appropriate to depend on turn signal actuations, since these were used only 44% of the time). As a starting point, it appears that warnings should be issued at approximately 5 seconds TTC, regardless of position of the closest vehicle (forward or rearward). The most logical place for a lane change CAS would be in the forward view since all drivers have at least one glance to the forward view during the three seconds prior to the lane change (assuming designers want to take advantage of drivers' natural scan patterns). The format of the CAS could include simple LED (light emitting diode) displays, head-up displays, or other modes such as auditory or tactile displays. Request buttons could also be implemented to activate the display only when requested (to minimize distraction). Lane change CAS should also be designed and tested to complement other CAS currently under development (e.g., forward-collision warning systems).

Overall Summary

This research effort provided valuable insight into the nature and severity of lane changes in a naturalistic driving environment. There were 8,667 lane changes observed over 23,949 miles of driving, making this the largest known data collection effort for the study of lane changes. Analysis of the full data set resulted in many interesting findings regarding the frequency, duration, urgency, and severity of lane changes in regard to maneuver type, direction, and other classification variables. A subset of the full data set was then analyzed in greater depth using the sensor data collected by the instrumented vehicle. The sampled lane changes were generally of the more severe and urgent types since these are the cases in which a lane change CAS is likely to be of greatest help. Variables analyzed for the sampled lane changes included turn signal use, braking behavior, steering behavior, eye glance patterns, and forward and rearward area analysis. The concept of a safety envelope for lane changes was then developed using the forward and rearward area analyses. Finally, the data were used to provide recommendations for designers of lane change CAS in terms of display location and activation criteria. Overall, the research described in this report provides insight into the behaviors and parameters associated with lane changes, while the naturalistic data archive has the potential to address other questions related to driving behavior.

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The opinions expressed in this report are those of the authors and do not necessarily reflect the official positions of the National Highway Traffic Safety Administration or any other organization.

GLOSSARY AND ACRONYMS

(CAS) Crash Avoidance System: An in-vehicle integrated system of sensors and displays that can issue alerts when a potentially dangerous situation is present. A lane change CAS monitors areas to the rear to provide information to the driver about vehicles approaching in the adjacent lane.

Duration: Refers to the time required to complete lane change. Duration is calculated by subtracting the end synch number from the start synch number. See also *Warning Duration*.

Eye Glance Position: The position to which the driver is looking. Discrete positions include center forward, left forward, right forward, right mirror, left mirror, rear view mirror, right window, left window, right blind spot, left blind spot, instrument cluster, other interior, and indeterminate.

Fast Approach Crash: A case in which there is a longitudinal gap between vehicles prior to the start of the lane change; this gap is closed at a substantial velocity differential between the two vehicles. Typically, this is the case in which a vehicle from behind is approaching a vehicle ahead that attempts a lane change into the path of the approaching vehicle.

(FAZ) Fast Approach Zone: The area in the adjacent lane from 30 to 160 feet behind the rear bumper of the SV.

Frequency: Refers to the number of lane changes completed given a certain length of time or distance. Frequency is likely influenced by lane choice, velocity, and traffic density.

Headway: Refers to the forward area between a lead vehicle and a following vehicle, in time or distance. For this proposal, time headway, 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, is used. Headway = Range/Velocity of the following vehicle. Headway may also refer to the time between the SV and the closest forward vehicle in the destination lane, or the time between a following vehicle in the destination lane and the SV ahead of it.

(POV) Principal Other Vehicle: Surrounding vehicles that are likely influential on the SV, such as a slow lead vehicle.

Proximity Crash: A case in which there is little or no longitudinal gap and the velocity differential between vehicles is small. This is the most frequently occurring lane change crash.

(PZ) Proximity Zone: The area in the adjacent lane from 4 feet in front of the bumper of the SV to 30 feet behind the rear bumper of the SV. This area generally includes the blind spot and the area beside and behind the vehicle in which another vehicle is likely to travel.

NHTSA: National Highway Traffic Safety Administration.

Radian: A unit of angular measurement. There are 2π radians in a circle. Therefore 1 radian = 57.3 degrees.

Range: The distance from the front bumper of the following vehicle to the rear bumper of the lead vehicle. For this report, this is the distance from the SV to the slow lead vehicle in the same lane or to the closest forward vehicle in the destination lane, or the distance from the front bumper of the closest rear vehicle in the adjacent lane to the rear bumper of the SV, along a longitudinal axis through either of the vehicles.

Range-rate: The rate at which the range between two vehicles is changing, measured in terms of relative velocity (ΔV) in which the velocity of one vehicle is subtracted from the velocity of the other vehicle. Range-rate will be of concern in terms of distance to the slow lead vehicle, distance to the vehicle in the forward adjacent lane, and distance to an approaching vehicle in the rearward adjacent lane.

Relative Velocity: The difference between velocities of two vehicles. See also *Range-rate*.

SAIC: Science Applications International Corporation

SUV: Sport Utility Vehicle.

(SV) Subject Vehicle: The vehicle making the lane change. For this proposal, the SV is the instrumented vehicle.

(TTC) Time to Collision: Time required for two vehicles to collide if they continue on at their present speed and path (McLaughlin, 1998). TTC = range/range-rate.

TRW: TRW, Inc.

Vehicle Position: The position of vehicles surrounding the SV, in terms of in front, forward in the adjacent lane, next to the SV in the adjacent lane, and rearward in the adjacent lane.

VTTI: Virginia Tech Transportation Institute.

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CHAPTER 1: INTRODUCTION

The development of countermeasures to reduce crashes 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. This report describes a data gathering effort using two instrumented vehicles on two types of roadways and the subsequent data preparation and analysis. The purpose of the data collection effort was to capture accurate naturalistic data associated with passing maneuvers. Analysis of these data was intended to support development of passing maneuver crash countermeasures and also to improve understanding of measures and thresholds drivers use in making decisions regarding passing.

Lane change crashes occur 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% 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). It is also estimated that 386,000 unreported lane change crashes occur (Chovan et al., 1994; Wang & Knipling). In addition, lane change crashes account for between 0.5 to 1.5% of all motor vehicle fatalities, or 224 to 732 fatalities per year (NHTSA; Wang & Knipling). Crashes associated with lane changing account for almost 10% (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.).

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% 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.; Tijerina).

In-vehicle technology is a logical option to assist drivers in maintaining awareness and reducing crashes. Lane change crashes have been targeted as prime situations for which technology could be beneficial in reducing the occurrence of these crashes (Wang & Knipling, 1994). Such technology would use in-vehicle alerts to signal the driver when necessary. The net result would likely be a reduction in both the occurrence and the severity of crashes. More crashes would be avoided, and impact speeds and resulting injuries would be reduced in crashes that do occur (Knipling, 1993). Figure 1.1 shows conceptually the reduction of both crash incidence and crash severity that could result from implementing crash reduction technology. Recent advances in sensor technologies, computer components, and digital processing have led to the potential development of low-cost collision avoidance systems (CAS) to be used on vehicles (Barickman & Stoltzfus, 1999; Eberhard et al., 1994).

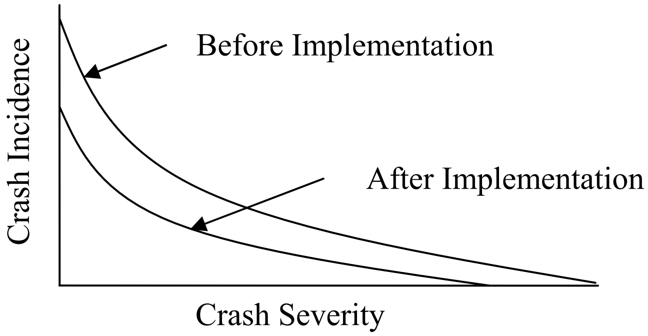


Figure 1.1. Potential Reduction of Crash Incidence and Severity with CAS Implementation (Knipling, 1993).

This report focuses on understanding driving behavior *prior to* the lane change. This understanding must be acquired in order to design usable, safe CAS that will fit well with drivers' behaviors and expectations.

Limitations of Previous Lane Change Efforts

Numerous factors are relevant to changing lanes and passing while driving. Research aimed at identifying and quantifying these factors has been conducted over the past 35 years. However, these data collection efforts have had limitations including: (1) the use of obtrusive equipment, (2) the presence of an experimenter, (3) the collection of data over a short period, and (4) the limitations of controlled settings that prevent generalization of results.

The use of obtrusive equipment, such as eye-markers, helmets, and large visible video cameras (Burger, Mulholland, Smith, Sharkey & Bardales, 1980; Godhelp, 1985; Mourant, Rockwell & Rackoff, 1969; Robinson, Erickson, Thurston & Clark, 1972), may constrict driver behavior by making the driving task unnatural. In most studies an experimenter accompanied the driver and gave driving instructions during data collection (Robinson et al.; Bhise et al., 1981; Hetrick, 1997; Tijerina, Garrott, Glecker, Stoltzfus & Parmer, 1997). It is believed that the presence of an experimenter may influence driver behavior, resulting in a lack of natural driving behavior. In addition, many lane-changing studies have been conducted during a single day over only a short duration (e.g., 1.5 hours) (Hetrick; Tijerina et al.; Van Winsum, De Waard & Brookhuis, 1999).

Findings from these studies have provided insight but may not include a range of behaviors representing normal driver variability. Some studies investigating lane change behavior have included driving over the same route multiple times in a single session; however, data collected over several days would allow a wider range of driving behaviors to be captured. Additionally, collecting driver behavior data over a longer period increases the likelihood that observations represent drivers' normal behavior, after any novelty effects associated with driving an instrumented vehicle have worn off.

Certain studies were conducted in highly controlled, somewhat unrealistic settings. For example, in an investigation of the effects of traffic on lateral head movements for left lane changes, participants followed a pick-up truck and made lane changes when the experimenter in the lead vehicle activated the turn signal (Bhise et al., 1981). While useful timing and head movement information was collected, these data may be limited to controlled, vehicle-following situations. Other driver performance lane change research efforts have been conducted using test tracks or constrained routes. For example, Talmadge, Chu & Riney (2000) investigated the amount of time drivers would prefer to receive a warning when making a lane change by collecting data while driving on a test track and on local freeways. Studying driving in these contexts can provide valuable insight, but again, both the constraint of having an observer present and the need for route control may limit the ability to generalize any findings.

Robinson et al. (1972) concluded that naturalistic experiments should be seriously considered when collecting driving data. This conclusion was echoed by Chovan et al. (1994), who stated that data are needed on normal lane change times and their distribution. Likewise, Staplin, Lococo, Sim & Gish (1998) and Tijerina et al. (1997) recommended that data could be gathered under a wide range of natural driving conditions using unobtrusive observation. More recently, Tijerina (1999) suggested that studies of "plain old driving" are needed to understand lane changing, including on-road studies with instrumented vehicles and non-obtrusive video surveillance. This type of data collection effort, in which a large database of driving maneuvers has been assembled based on a field experiment involving the collection of naturalistic data, is described in this report.

The following literature review describes much of the relevant work that has been conducted on lane changes and lane change behavior. The review identified numerous research needs for this topic area. Although the literature review is comprehensive in identifying these needs, not all research needs were addressed by this research effort.

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 lane. 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.

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.

For this report, no single definition of lane change was selected; however, the start and end points of a lane change were operationally defined in terms of first lateral movement (start) and settling point (end) in the new lane. These definitions are described in detail in Chapter 2.

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, and a change in the number of lanes available. 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). The lane changes described in this report include categories of lane change maneuver types.

Lane Change Crash Scenarios

There are two primary types of lane change crashes in which a principal other vehicle (POV) is approaching from behind the subject vehicle (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 crash case occurs infrequently.

The most frequently occurring lane change crash scenario 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% of lane change collisions involve low closing speeds (i.e., relative speed < 15 mph); however, because of the low relative speeds that prevail, it is likely that there is adequate time to prevent many of these collisions by warning the driver beforehand via in-vehicle alerts (Eberhard et al., 1994).

Najm and Smith (2002) have 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%), or merging (2.5%). However, these pre-crash scenarios are predicated on the eventual outcome of a crash. When studying lane changes where no crash occurred, it is not possible to categorize to this level of detail. Thus, the separation of lane changes into fast approach and proximity cases seems to be the most relevant distinction for this report, with further categorization possible for lane change maneuver types.

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 (Jula, Kosmatopoulos & 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 feet/second at a range of 100 feet (100 feet ÷ 100 feet/second) would have a time headway of 1 second. Time headway can be thought of as a margin of safety. One convention states that headway should be at least two seconds (Evans, 1991), which is referred to as the "two-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).

Four distinct headway zones have been described: the danger zone (within 0.6 s of the vehicle ahead), the critical zone (0.6 s to 1.1 s), the normal driving zone (1.1 s to 1.7 s), and the pursuit zone (> 1.7 s) (Ohta, 1993).

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). The average appears to be 1.2 to 1.6 s, as shown in Table 1.1 and described in the following paragraphs.

Table 1.1. Average Time Headway From Three Relevant Studies.

SOURCE	M	SD	N
Van Winsum & Heino (1996)	1.52 s	0.27	54
Allen, Magdaleno, Serafin, Eckert & Sieja (1997)	1.22 s	0.38	36
Fancher (1999)	1.60 s	0.80	108

Van Winsum & Heino (1996) reported a mean headway of 1.52 s (*SD* = 0.27) for 54 drivers traveling at 70 km/h in a driving simulator in a vehicle following task. Allen, Magdaleno, Serafin, Eckert & Sieja (1997) reported a mean headway of 1.22 s (*SD* = 0.38), with values ranging between 0.58 s and 1.90 s, in a highway experiment involving 36 drivers. Results from a recent field operational test indicate that the most-likely value for headway is 0.8 s for speeds > 55 mph (Fancher et al., 1998). Test vehicles were given to 108 volunteer drivers to use for two or five weeks as their personal vehicles. For slow lead vehicle lane changes, some drivers allow a short headway prior to a lane change, perhaps as short as 0.5 s (50 feet at a speed of 100 ft/s) (Rockwell, 1972; Saad, 1997). Recently, Fancher (1999) reported results from a field operation test of manual and automatic or advanced cruise control (ACC) driving. For a total of 2,607 manual lane changes in which a preceding vehicle was present, the average time headway was reported as 1.6 s (*SD* = 0.8 s). Note that the range of values was very large.

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. However, they did not identify any sources for headway data, as the focus of the paper was to explain how traffic simulation could be used to calculate minimum longitudinal spacing.

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 (PZ) and the fast approach zone (FAZ) (Talmadge et al., 2000). The PZ is the area in the adjacent lane from 4 feet in front of the front bumper of the SV to 30 feet 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.). The FAZ is the area in the adjacent lane from 30 to 162 feet behind the rear bumper of the SV. At 100 ft/s (68.2 mph), a vehicle within this zone would have between 0.3 s to 1.6 s of time headway. Both the PZ and the FAZ refer to areas that should be monitored before lane change initiation; however, there are few data regarding the PZ and FAZ. Figure 1.2 illustrates the PZ and the FAZ.

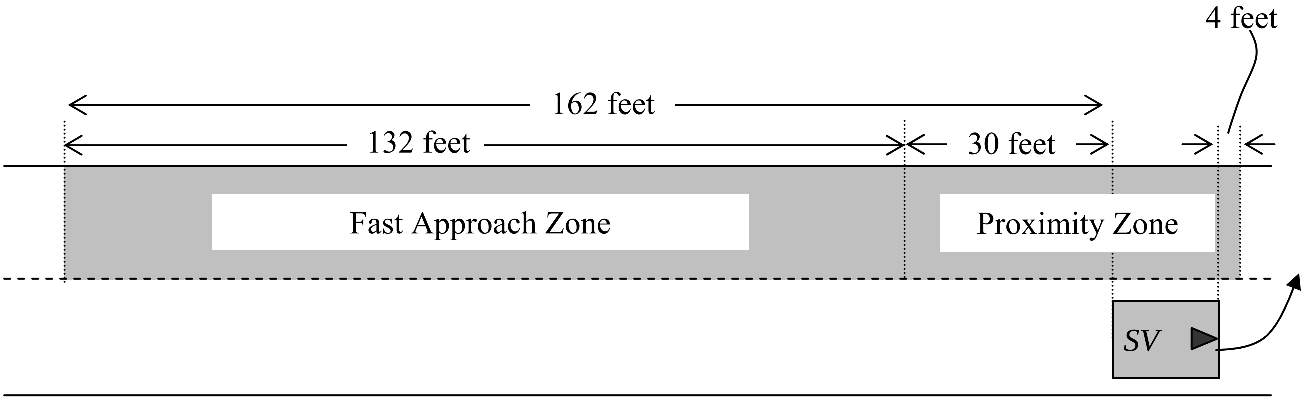


Figure 1.2. Fast Approach Zone and Proximity Zone in Relation to Subject Vehicle.

Crash Avoidance Systems

The use of a crash avoidance system (CAS) has been proposed to reduce lane change crashes by alerting/warning drivers of the presence of a vehicle in the PZ or FAZ (Eberhard et al., 1994; Talmadge, et al., 1997). A CAS is an in-vehicle, integrated system of sensors used to detect hazards (e.g., radar, laser, or optical) and displays (e.g., visual, audio, haptic) to issue alerts or warnings when a potentially dangerous situation is present. A lane change CAS would enhance the ability of the driver to perform safely by monitoring surrounding areas and providing information to the driver about vehicles approaching from the rear adjacent lane. The driver should then respond to the CAS alert and react appropriately when preparing to make a lane change.

A CAS should assist the driver in maintaining awareness of surrounding vehicles. However, an understanding of driver behavior under normal conditions prior to lane change initiation is essential for the design of safe and usable CAS. A CAS should detect what the unaware driver does not detect and provide timely information allowing the driver to drive more safely; however, this information must not be a distraction to the driver (Chovan et al., 1994; Eberhard, Moffa, Young & Allen, 1995). Understanding driver behavior will assist designers in the placement, format, and timing of in-vehicle warnings so that the CAS will fit well with drivers' behaviors and expectations. Lane change CAS can then be successfully designed, implemented, deployed, and smoothly integrated into the driving environment.

Relevant Parameters

Various data are needed for CAS development and operation. This section reviews a variety of relevant parameters including velocity, frequency, duration, time to collision (TTC), range, range-rate, vehicle position, turn signal use, and eye movement.

Velocity

For a CAS to be effective, the underlying warning/advisory algorithm must be sound. This algorithm requires both SV and POV velocity data along with several other parameters. The absolute velocity of the SV (vehicle with the CAS) must be known. Range-rate data can be acquired via radar equipment that monitors vehicles ahead of and behind the SV. The absolute velocity of surrounding vehicles can then be derived using these data. Finally, velocity data can be used in conjunction with appropriate algorithms to calculate details relevant to adjacent vehicles (e.g., velocity, range, position, range-rate, and TTC) to advise or alert the driver when it is unsafe to change lanes (Eberhard et al., 1995; NHTSA, 1996; Young et al., 1995) or when a collision is imminent (Campbell, Carney & Kantowitz, 1998).

Young et al. (1995) have suggested that police accident reports could be examined to derive velocity and kinematic information for lane change collisions. It is unknown if this has been attempted, although Bascuñana (1995) examined the dynamic conditions that set apart safe from unsafe lane changes. Four cases of lane changes were quantified in terms of the relative distances and velocities between vehicles at lane change initiation. The safety of the maneuver was described as a function of braking time, acceleration, separation, and velocity; however, the author concluded that the capabilities of potential countermeasure systems needed to be verified based upon results of test track experimentation.

Distributions of the relative speeds in two-vehicle crashes are not readily available (Eberhard et al., 1994). However, the velocity differential between vehicles is probably between 5 to 15 miles per hour (mph) for the proximity crash case (Chovan et al., 1994; Wang & Knipling, 1994; Young et al., 1995). For the fast approach crash case, in which 94% of crashes have relative velocities less than 30 mph, the velocity differential is typically 15 to 30 mph (Young et al.). Subject vehicle speed distributions and the closing speed distributions are different for lane changes to the right and to the left, according to Eberhard et al. (1995). This is probably due to the tradition of slower vehicles keeping to the right lanes and faster vehicles keeping to the left lanes. The speed of a slow lead vehicle would likely influence the speed (and position) of a vehicle behind it (Eberhard et al., 1994). Hetrick (1997) reported that a vehicle is likely to change lanes to pass a slow lead vehicle and maintain current speed.

Frequency

Vehicle velocity may be correlated with lane change frequency. For example, drivers who maintain a high average velocity relative to traffic may perform more lane changes (i.e., weaving in and out of traffic) than drivers who maintain low velocities. Ferrari, Cascetta, Nuzzolo, Treglia & Olivotto (1984) suggested that differences exist according to a driver's speed and lane choice. A relatively fast driver may choose the left (fast) lane, where there is a low likelihood of being approached by another vehicle from behind or of coming upon a slow lead vehicle. This same driver in the slow (right) lane would need to perform frequent lane changes due to slow vehicles ahead. Likewise, a relatively slow driver may choose to drive in the right lane, given that there is a lower probability of needing to pass slower vehicles (e.g., based on low traffic density). This same driver, if in the left lane, would likely be compelled to change lanes frequently due to faster moving vehicles to the rear. The frequency of lane changes due to a slow vehicle ahead is unknown.

Velocity Differential

Reilly, Pfefer, Michaels, Polus & Schoen (1989) indicated that drivers enter the roadway with a mean 9 mph velocity differential. This conclusion was based on data of vehicles entering the roadway in speed-change lanes in which the SV was pulling in front of another vehicle already on the freeway. However, this study considered only those vehicles merging into relatively small freeway gaps during periods of moderate to high traffic volumes, so this speed differential might be considered extreme for lane changing. Collecting and analyzing velocity differential data may be useful for understanding the effect that an approaching vehicle has on gap acceptance of drivers (i.e., when they choose to change lanes in relation to surrounding vehicles). These data could help identify situations in which the driver could be aided by technology (Knipling, 1993). Having access to the distribution data of lane changes and relative speeds of passing vehicles would be extremely valuable (Chovan et al., 1994; Eberhard et al., 1994).

Duration

Lane change duration for high velocity drivers may be shorter in comparison to low velocity drivers; however, not many on-road duration data exist. Lane change times from 2.0 to 16.0 s are taken as the initial range within which to examine lane change CAS warning requirements (Chovan et al., 1994). Lane change duration was investigated by using an aerial photography technique to make estimates of lane change duration (Worrall & Bullen, 1970). The maneuver was split into head (first lateral movement to lane line intercept) and tail (line intercept to straight-ahead movement) portions. The average head maneuver was 1.25 s ($SD = 0.4$) and the average tail time was 1.95 s ($SD = 0.5$). Therefore, the average lane change duration was approximately 2.3 s to 4.1 s. However, it is believed that the total lane change times were underestimated because of resolution and model-prediction limitations (Chovan et al.).

In a literature review on lane changes, Finnegan & 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 was 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 mode of 6.0 s for 282 lane changes. In this study, 16 participants drove on city and highway segments for 1.5 hours in an instrumented vehicle with an observer present. A recent study investigated the influence of fatigue on local short-haul truck drivers (Hanowski, Wierwille, Garness & Dingus, 2000a). 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 lane changes completed by non-fatigued drivers (*M* = 4.79 s). The average lane change duration was 4.52 s for 260 normative lane change events. The range of duration values was 1.1 to 16.5 s (*SD* = 1.71) for normative events (R. J. Hanowski, personal communication, June 20, 2002). 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; Hetrick; Tijerina et al.). Table 1.2 summarizes these findings.

Table 1.2. 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 CAS
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. (2000a)	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

Additional data are needed on normal lane change times and their distribution (Chovan et al.); no extensive sources of normal lane change time data currently exist. In addition, the effect of acceleration on lane change duration should be investigated. It would be helpful to know if drivers accelerate while changing lanes or if constant longitudinal velocity is maintained (Chovan et al.). Finally, acceleration patterns when changing lanes need to be investigated. Note that although acceleration patterns have been identified by some researchers as a research need, acceleration was not investigated as part of the current effort.

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 in relation to the SV and surrounding vehicles is illustrated in Figure 1.3. The range to the vehicle ahead should be monitored constantly while driving, especially when preparing for a lane change.

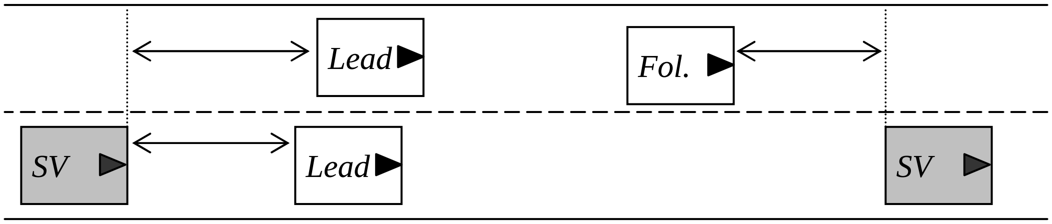


Figure 1.3. Range From SV to Lead Vehicle and From Following Vehicle to SV.

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 miles per hour (mph) or feet per second (ft/s).

Staplin et al. (1998) reported that for speed differentials of 5 mph, younger participants (18-45 years old) estimate that a much smaller distance is required (95 feet) as a minimum safe gap for a vehicle overtaking as opposed to older participants (> 65 years old), who estimated a required distance of 242 feet. For speed differentials of 10 mph, younger participants estimate that a much smaller distance is required (128 feet) as a minimum safe gap as opposed to older participants (261 feet). Overall, to make a lane change with a 10 mph differential speed, only two-thirds of the members of the younger group were willing to make the lane change at a 200-foot vehicle separation, where a lane change remains just feasible under normal operating conditions. Only one-third of this group would make the maneuver with a 25 mph speed differential. For the case in which the speed differential is 25 mph and a vehicle is only 100 feet away, a lane change that is (successfully) made can only be interpreted as a serious driving error. For a total of 2,607 manual lane changes, Fancher (1999) reported an average range of 153.3 feet (*SD* = 103.6 feet) with 27% of lane changes occurring within 70 feet of the preceding vehicle. The average range-rate was –4.1 feet/second (*SD* = 10.0 ft/s). Note that the range of values is quite large.

Time to Collision

Time to collision is the time required for two vehicles to collide if they continue on their present speed and path (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 that are 100 feet apart. If the front vehicle is moving at 100 feet/second and the following vehicle is moving at 120 feet/second, the range-rate would be 100 feet/second minus 120 feet/second, or –20 feet/second. To calculate the TTC, 100 feet is divided by –20 feet/second. 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 was constant. However, the TTC parameter assumes constant speed and does not account for vehicle acceleration (Smith, Najm & Glassco, 2002). Talmadge et al. (1997) concluded that TTC seems a likely candidate for use in CAS to activate warnings for drivers. They used an experimental CAS built by the Vehicle Research and Test Center (VRTC) of East Liberty, Ohio for a NHTSA effort, using a TTC collision algorithm. The

CAS activated the driver warning system based on this algorithm. If activated, results suggest that a conservative amount of warning time would be 3.0 s TTC for most drivers.

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; however, data are limited on turn signal use. Hetrick (1997) found that 92% of lane changes were indicated by a turn signal in a study in which an experimenter in the passenger seat gave 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% of lane changes on highways (10.3% 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 -2.42 to 3.62 s (with 0 indicating lane-change start) (Hetrick). In other words, the manner in which turn signals are used may vary greatly among drivers, with some drivers activating the turn signal after beginning the lane change maneuver.

Turn signal use is an important factor because the two most likely implementations of a lane change CAS are one where the CAS is activated by the turn signal (or some other indication of lane change initiation), and the one which is always on when the vehicle is moving forward (Moffa, Austin, Dow, Ikizyan & Hibben 1996). There is, however, an apparent split in opinion of how turn signal use should relate to CAS warnings. According to Hyland (1995), there is a 50/50 split between drivers who want the warning system activated only with the turn signal and those who want it in monitor mode all the time. According to Eberhard et al. (1995), participants driving a simulator responded in favor of turn signal activation of CAS warnings. The level of warning issued may be tied into turn signal use; according to Mazzae and Garrott (1995), auditory warnings should only be provided when the turn signal is activated (at least for side collision avoidance systems). Evaluating data on turn signal use in relation to lane changing will likely be helpful when addressing these issues.

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; 1993). 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. 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 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, Palmer & 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 0.62s to 1.63s. The mean number of glances across all tasks was between 1.26 and 6.52 glances. Zwalen, 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 next sub-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. reported that both the outside mirror and blind spot were checked during left lane changes and the inside (rearview) mirror and blind spot was 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). These findings may be useful to CAS designers, especially if confirmed based on analyses of the naturalistic data collected from this field experiment. For both right and left lane changes, the center (rear-view) mirror is used often. In the future, CAS might use head turn information to sense when a lane change is about to begin, assuming head turns could be successfully monitored.

Mirror Glance Duration

Based on available literature discussed in this section, mirror glance times range from 0.8 to 1.6 s (*M* = 1.1s). Searches to the rear (blind spot) appeared to require a minimum of 0.8 s. Nagata & Kuriyama (1985) investigated the influence of driver glance behavior in obtaining information through door and fender mirror systems placed on passenger vehicles. For door mirror systems, the average glance duration to the near-side (i.e., right side in this case) mirror was 0.69 s. However, some portion of the duration may be attributable to longer transition time due to angle differences from the vertical axis (42 degrees for near-side). 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 six-year period using the same data gathering and reduction technique. Taoka (1990) modeled eye glance distributions of Rockwell and found 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 5th percentile value was 0.68 s and the 95th percentile was 1.65 s. For right side mirror glances, Nagata & Kuriyama 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% larger than left glances) with a standard deviation of 0.36s. For the rear-view mirror, Taoka reported that the average glance time was 0.75s (*SD* = 0.36 s). The 5th percentile value was 0.32 s and the 95th percentile was 1.43 s.

Mourant and Donohue (1974) examined the total glance time for lane changes. The number of glances and duration of each glance during lane changes was recorded as participants drove on a freeway in which an experimenter monitored the driver from the back seat. Results indicated that 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 (rearview) mirror, and a head turn. Data were also obtained for experienced and mature drivers and similar patterns of glancing were observed. Obtaining data on glance duration and timing of eye movements for a variety of drivers may be useful in understanding driver behavior prior to lane change initiation. For example, knowing the duration of glances and glance location prior to lane change initiation could be useful for the timing of CAS displays and their design. In addition, characterizing the search and scan patterns of drivers prior to lane change initiation may be important for CAS developers.

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 the results collected during road studies, the researchers used a Markovian 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 the lane change start. For a sedan 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 rearview (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% in the study) than is the right side mirror for maneuvers to the right (between 36 and 52%). However, the rearview mirror is used more often for right lane changes (between 82 and 92%) than for left lane changes (between 56 and 67%). This supports the earlier finding that drivers depended most heavily on the rearview mirror for lane changes to the right (Mourant & Donahue, 1977). Tijerina et al. 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). Shoulder glances were more frequent for left lane changes than right lane changes.

Staplin et al. (1998) evaluated mirrors in the context of a lane change task. One rationale for conducting the study was that lane changing and merging were involved in 24% of crashes related to problems of visibility from vehicles. Results from self-reports indicated that all younger participants (aged 18 - 45) and two-thirds of the older participants (> 65 years old) reported using the outside rearview (i.e., left side) mirror, followed by a blind spot check before lane change initiation to the left. One-third of the older participants reported using the outside mirror alone (no blind spot check) before initiation. The conclusion was that sampling of mirrors may be limited to only a single glance in high density lane change situations, where instantaneous "go/no-go" decisions sometimes have to be made. However, these results may not be representative of normal driving, because participants were instructed to maintain a forward view until a cue was given indicating they were to switch attention exclusively to the outside mirror until responding.

A recent field study investigated the influence of fatigue on critical incidents involving local short haul truck drivers (Hanowski et al., 2000a). Fatigued drivers involved in critical incidents when making lane changes spent more time looking in irrelevant locations (i.e., locations other than 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. This finding may be relevant to CAS designers in terms of creating different systems for passenger vehicles vs. commercial vehicles, where issues such as scanning patterns and fatigue may differ.

Recarte & Nunes (2000) recently conducted testing in highway and road traffic to investigate the consequences of performing mental tasks on visual search while driving. In this study, they used an unobtrusive eye tracking system with an infrared video camera installed on the dashboard. Specifically, they tested whether high attentional workload produced attentional focus narrowing. When driving on highways, glances to the rearview mirror were 10 times more frequent than when driving on conventional roads (likely due to overtaking maneuvers on the highway); glances to the left mirror were more than twice as frequent on highways as on conventional roads. During normal driving, the instrument panel was glanced at almost twice as often as the left mirror, and the left mirror was glanced at more than twice as often as the rearview mirror, depending on route. When driving normally, 14/1000 eye fixations were directed at the rearview mirror. This decreased to 4/1000 when performing a verbal task and 2/1000 for a spatial-imagery task. When performing mental tasks, glances toward the rearview mirror declined substantially and frequency of visual inspection using the side (left) mirror decreased. During ordinary driving (no task), the percentage of glances to the mirrors or instrument panel was 3 to 4% of the total number of glances observed; this decreased to 1% or less when a mental task was performed. A reduction of the visual inspection window, an imaginary box representing both the horizontal and vertical gaze of the driver, was also observed. While driving and performing mental tasks, a reduction of the window was observed in the horizontal direction between 25 to 40%; in the vertical direction, the visual inspection window was reduced by between 40 to 60%, as compared to the window observed during ordinary driving.

This research, while not specific to lane changes, has many implications. It appears that differences exist in mirror and instrument panel glances depending on route, mental workload, and driving situation. The authors note some limitations, however. As the visual inspection window narrows, there may be less information available, and driving may therefore become more risky. However, this is only true if all attentional resources are focused only on relevant driving information. When observing a reduction in the inspection of speedometer, mirrors, or the functional visual field, it is not known whether the eliminated glances correspond to relevant or irrelevant information, as far as road safety and strategy are concerned.

Understanding eye glance patterns may be useful in developing and evaluating potential lane change CAS systems. Conclusions from Tijerina et al. (1997) indicate that for potential CAS visual displays to be compatible with normal eye movement patterns, both center rearview and side mirror locations should be considered. A CAS display (e.g., a "go" light) could potentially be placed within a mirror. Such a display might fit well with the hypothesized last glance that drivers normally make prior to lane change initiation – a glance to the rearview or side mirror. Head-up displays (HUD) might be considered as well since drivers spend much of their time looking at the forward view (Mourant et al., 1969; Tijerina et al.). In fact, Honda has developed an experimental blind-spot warning system in which a HUD presents vehicle location, distance, and relative velocity (range-rate) information and issues auditory warnings if necessary (Yoshioka, Nakaue & Uemura, 1999; Yoshioka, Uemura & Nakano 1998).

Eye glance patterns might also indicate driver intention; for example, if a large proportion of glances are directed towards the right mirror and rearview (center) mirror, this may indicate that a right lane change is about to occur. Such information could be useful for a CAS that would monitor driver eye movement to predict lane change direction and initiation. In terms of evaluation of potential CAS, the Recarte & Nunes (2000) approach may be useful for comparing a baseline of normal (straight) driving to lane changing (passing). Also, normal glance patterns and glance durations could be compared among drivers in which a CAS was available.

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 =1.25 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 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.

Lane Change Sequence

The sequence for a lane change made from the right lane into the left lane due to a slow vehicle ahead is presented based loosely on Chovan et al. (1994) and Wierwille (1984), as illustrated by Figure 1.4. It represents a somewhat idealized maneuver; however, it may aid in understanding the processes involved. In the figure, SV refers to the subject vehicle, POV_L refers to lead principal other vehicle and POV_F refers to following POV. POV_{LO} refers to lead POV in the original lane, and POV_{FO} refers to following POV in the original lane; POV_{LD} refers to lead POV in the destination lane, and POV_{FD} refers to following POV in the destination lane. SV-POV_{FD} refers to the gap between vehicles as in "SV to following POV in the destination lane;" SV-POV_{LO} refers to the gap between the SV and the lead POV in the original lane, and so on (Jula et al., 1999).

The driver scans mirrors, noting number, position, and range-rate of surrounding vehicles to collect information required for making a successful lane change. Just before the driver decides to initiate a maneuver, a final visual check, either in the mirror and/or over the shoulder, is made. A go/no-go decision is then made. If a go decision is made, the initial steering wheel input occurs, usually in conjunction with a turn signal. If a no-go decision is made, the driver maintains current position or adjusts position accordingly until a go decision can be reached. When a go decision is made, the lane change is initiated.

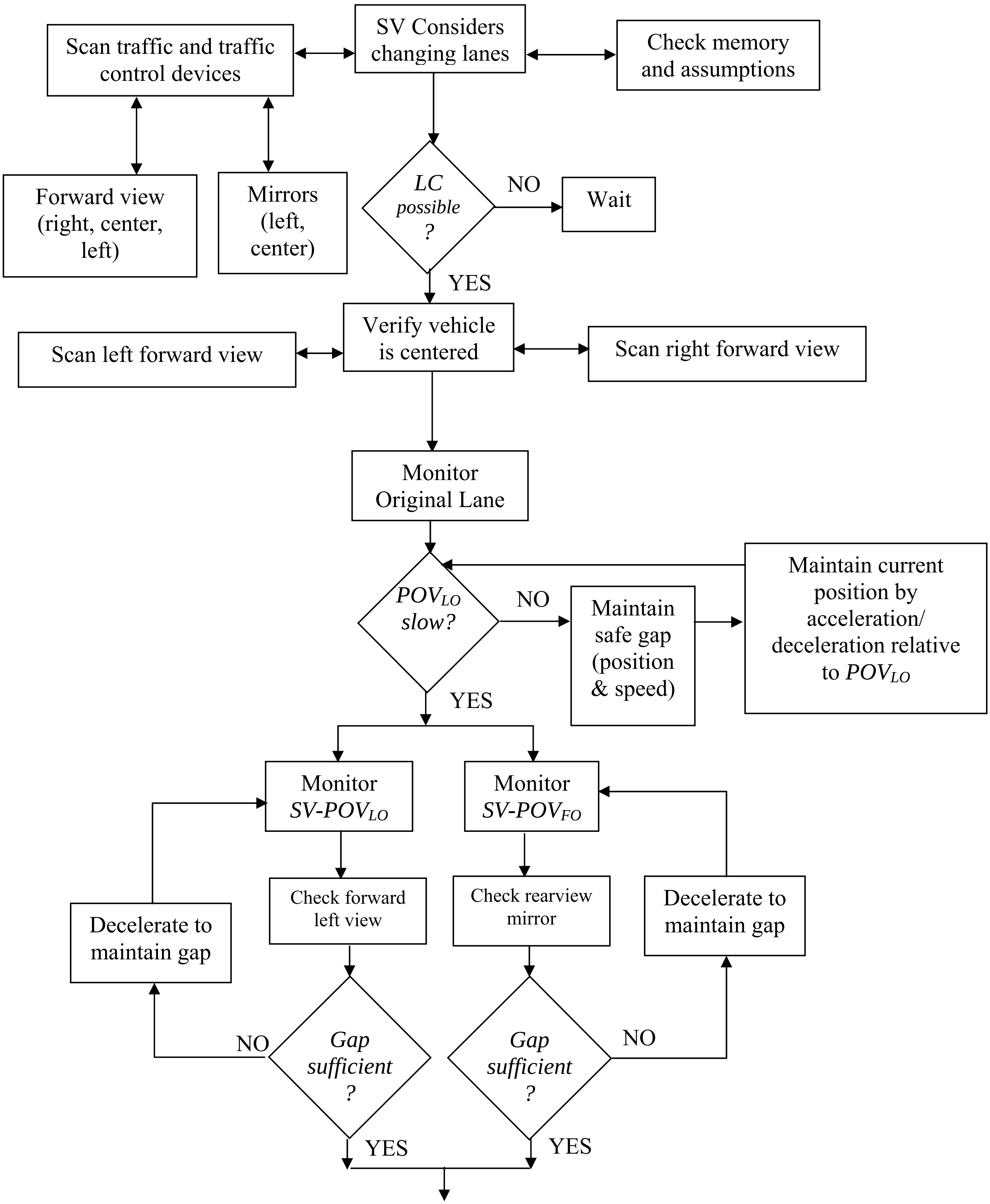


Figure 1.4. Lane Change Event Sequence Diagram.

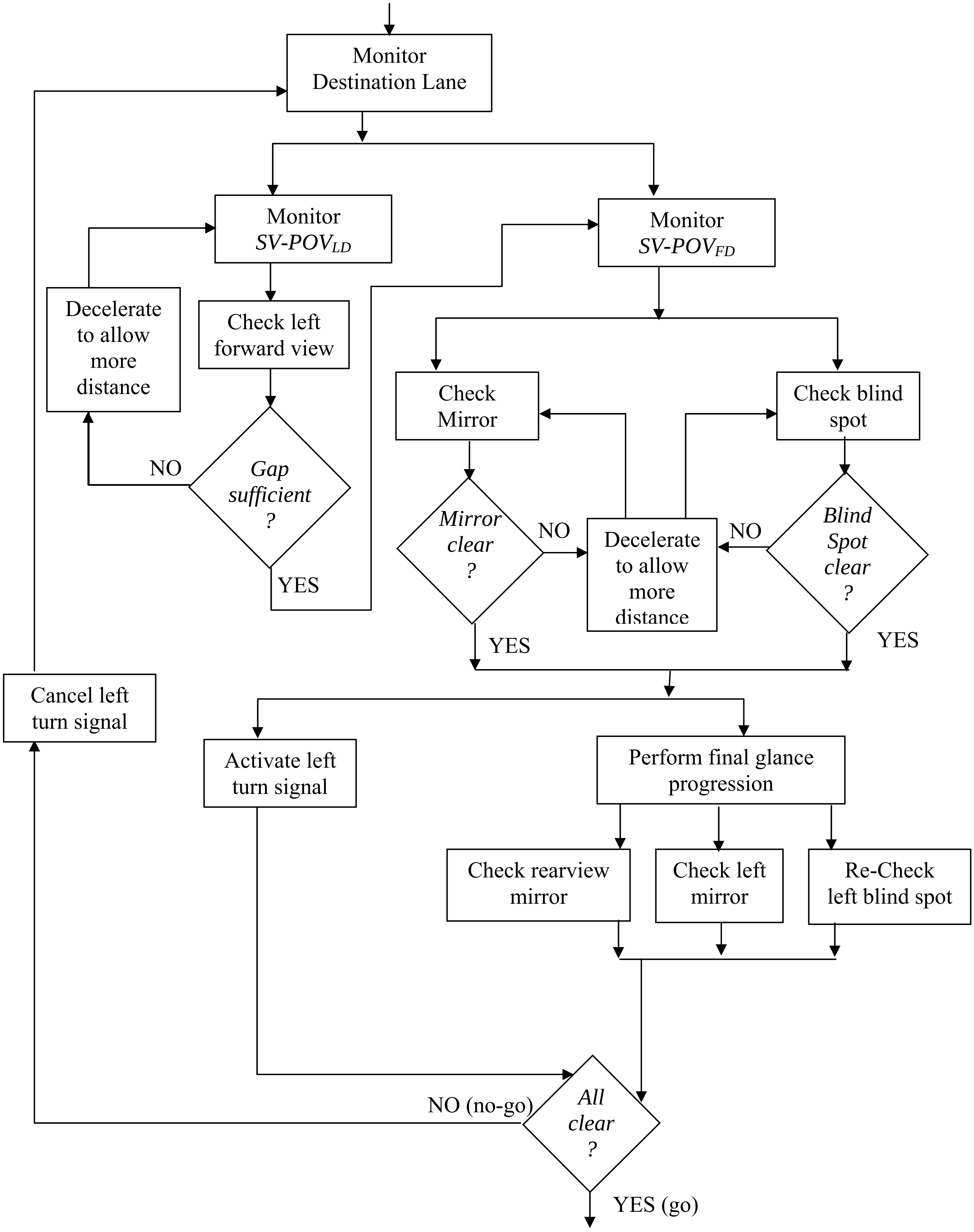


Figure 1.4. Lane Change Event Sequence Diagram (cont.).

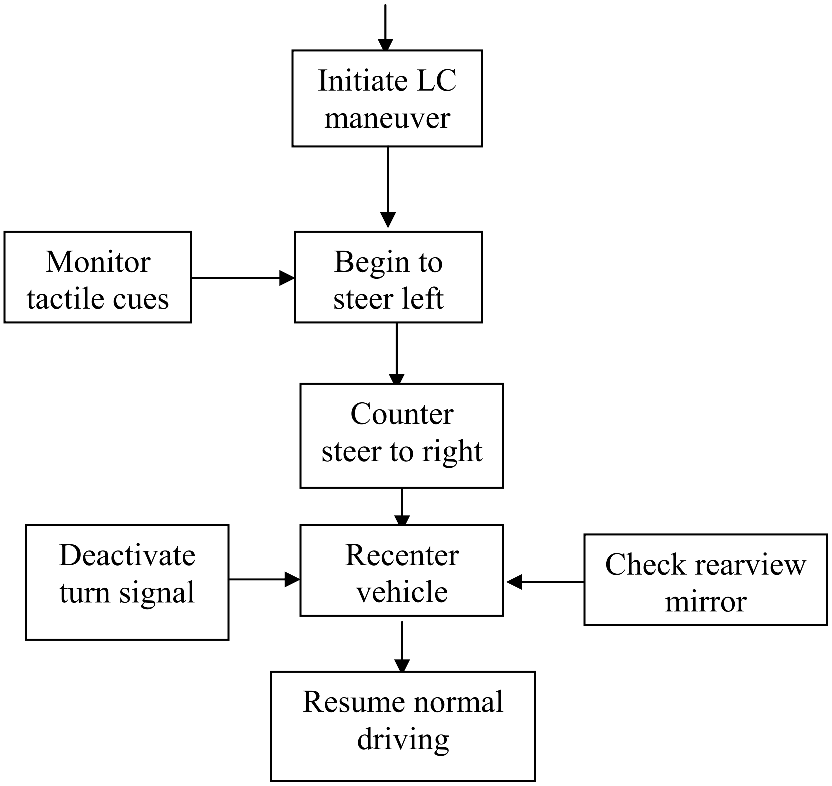


Figure 1.4. Lane Change Event Sequence Diagram (cont.).

Lane Change Research Needs

The literature review provided valuable insight into the types of research that have been conducted into the lane change maneuver. The review also pointed out numerous areas in which the research is lacking, and this provided direction for the remainder of this study. Some of the areas in need of further research include the following:

1. There is a lack of "naturalistic data." Most data were gathered with an experimenter present, under controlled settings, with obtrusive equipment, and for short durations. Subjects were unlikely to drive in a "naturalistic" manner under such conditions, and thus the results of these studies should probably not be generalized as representative driving behaviors.

2. There is a need for better understanding of glance patterns as a function of the criticality of the lane change passing maneuver. Do eye glances follow a specific pattern for certain categories of lane changes, and if so, can this information be used to help determine the location and design of a lane change CAS? Again, it would be better to have naturalistic data for eye glance patterns, especially involving scanning leading up to lane change initiation.

3. There is a general lack of information about types of lane changes and their relative frequencies, especially as they occur in a naturalistic environment (as opposed to being performed as instructed by an experimenter). Such information could provide insight as to when and under what circumstances a lane change CAS might be most useful.

4. There has been a lack of lane change data for certain environments such as:
    - US highway vs. Interstate.
    - Suburban/rural vs. urban roadways.
    - Hilly terrain (most data has been collected on flat roads).

5. There are no data as to any differences that may exist for lane change behavior for various vehicle types, such as between SUVs and sedans.

6. CAS designers lack fundamental information required for effective lane change CAS design, such as:

    - What are the most prevalent glance locations of drivers who are preparing to make lane changes?
    - When and under what circumstances do drivers look at particular mirrors/locations?
    - Do drivers reliably use their turn signals when preparing to make a lane change, and if so, can this be used to trigger a lane change CAS?

The experiment reported herein was designed to fill as many of these data and information gaps as possible so that future researchers and designers would have a more complete picture of lane change behavior and characteristics.

CHAPTER 2: METHOD

The approach for this research was to obtain a large amount of highway data using instrumented vehicles and ordinary commuting drivers. The vehicles gathered data automatically; no on-board experimenter was needed. The instrumentation was unobtrusive and required no attention by the driver. Following data collection, the gathered data were then examined for lane changes.

Data Collection

Participants

Sixteen drivers who normally drove 25 or more miles in each direction to and from work were recruited to obtain a representative sample of drivers and lane-changing behaviors. One group consisted of eight drivers who commuted daily on Interstates 81 and/or 581 in southwestern Virginia. The other group was comprised of eight commuters in southwestern Virginia who traveled on U.S. 460, U.S. 11, or a combination of the two roads. Half of each group of eight ordinarily drove an automobile to and from work, while the other half ordinarily drove an SUV, van, or pickup truck. Participants were between 20 and 64 years of age with equal gender representation in each subgroup. Each driver drove each of two research vehicles for ten business days, for a total of twenty days of driving for each participant, and a grand total of 320 days of lane change data. The order in which the participants drove the research vehicles was counterbalanced in each subgroup of four drivers. Participants received $10/day for each day of driving and were reimbursed for gasoline. Participation was determined after screening and selection criteria were met as described in the Experimental Procedure sub-section.

Experimental Design

The research design used for the naturalistic data collection of driving behavior is shown in Figure 2.1. The study was a mixed factors design. There were four independent variables: route, driver type, gender, and vehicle type. The between-subjects independent variables were route (interstate or highway), driver type (sedan driver or SUV driver), and gender. Vehicle type (experimental sedan or experimental SUV) was a within-subject independent variable. For clarification, driver type refers to the vehicle normally driven by the participant, whereas vehicle type refers to the two VTTI vehicles driven for the experiment.

Table 2.1 shows how counterbalancing was accomplished for vehicle type (i.e., whether the sedan or SUV was driven first). Note that route, driver type, and gender were between-subjects variables and had no effect on counterbalancing. However, participants were introduced into the experiment in the order shown in Figure 2.1 and Table 2.1 to the extent possible. The purpose of introducing participants in this manner was to ensure that no one combination of driver type followed a driver of the same type (i.e., a female/sedan/interstate driver did not follow another female/ sedan/ interstate driver in the experiment). In both Figure 2.1 and Table 2.1, M designates a male driver and F designates a female driver.

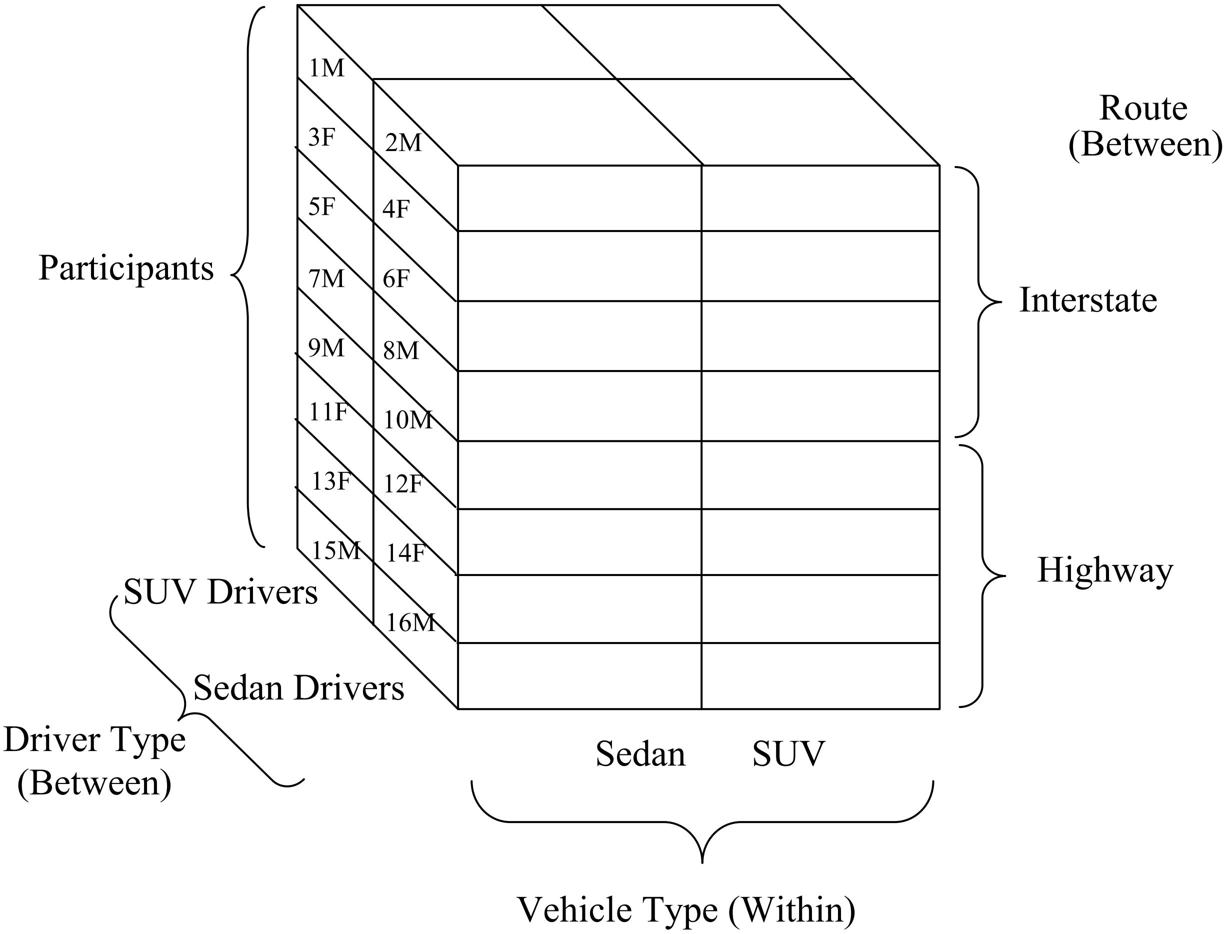


Figure 2.1. Experimental Design.

Table 2.1. Counterbalancing of Participants.

Driver Type	**Vehicle Driven First**	**Route**			
		Interstate		**Highway**	
SUV Drivers	Sedan First	1M	5F	9M	13F
	SUV First	3F	7M	11F	15M
Sedan Drivers	Sedan First	2M	6F	10M	14F
	SUV First	4F	8M	12F	16M

Independent Variables

The four independent variables are listed in Table 2.2.

Table 2.2. Independent Variables.

Independent Variable	**Levels**
Route	Highway or Interstate
Driver Type	Sedan Driver or SUV Driver
Gender	Male or Female
Vehicle Type	Sedan or SUV

The interstate route was I-81 in southwestern Virginia. This is a heavily traveled rural interstate with hills and many heavy vehicles. This road was selected because it represents a situation where lane changes are required and problematic. Interstate drivers also often drove a portion of their route on I-581, a heavily traveled spur route leading into downtown Roanoke, Virginia. The highway route included both U.S. 460 and U.S. 11. These roads require lane changes at somewhat slower travel speeds (45 to 55 mph), are largely 4-lane (2 in each direction), and are generally not access controlled.

As a reminder, driver type refers to the vehicle normally driven by the participant. Participants were separated into two groups: those who ordinarily drove an automobile to and from work; and those who ordinarily drove an SUV, van, or pickup truck. In terms of gender, half of the participants were males and half were females. Information on age, while not used as an independent variable, was also collected.

Apparatus

The two instrumented vehicles (Figure 2.2) were a sedan (Ford Taurus) and an SUV (Ford Explorer). These vehicles were selected because they have substantially different rear and side visibility characteristics. For example, the sedan has relatively "thick" C-pillars resulting from the use of the elliptically shaped rear windows. The back end of the passenger compartment is also a bit high. These factors could lead to small compromises in over-the-shoulder visibility, particularly for shorter drivers. The SUV is a tall vehicle with larger windows. It thus has relatively good visibility to the sides and rear. The SUV also has larger side view mirrors. In addition, because of the drivers' seated height differential, the SUV provided better visibility over lead vehicles on the forward roadway.

Figure 2.2. Research Vehicles.

Each of these research vehicles was equipped with unobtrusive hardware systems to collect data automatically, eliminating the need for a ride-along experimenter. The inconspicuous instrumentation in the vehicle allowed drivers to forget that it was present. It was believed that once drivers adapted to the vehicles, they would exhibit naturalistic, or unmonitored, behavior. Three data collection systems were used to collect data in an integrated, automated, unobtrusive manner: a video system, a sensor system, and a radar system. Resulting data were stored in a locked storage unit located in the rear area of each vehicle.

Video System

A video data collection system was used to capture relevant video data while driving. The video data collection system included five-channel video using miniature cameras, as illustrated by the schematic of camera locations and fields of view in Figure 2.3. Each camera was a monochrome charge coupled device (CCD) weighing about 1 ounce, 10 mm wide, with a fixed focus lens. The forward camera (Figure 2.4) was mounted behind the rear view mirror inside the vehicle to provide a view out the windshield corresponding to the view the driver might see when looking forward. A rearview camera (Figure 2.5) was mounted outside, above the rear window. A driver's face camera was mounted inside the vehicle within the A-pillar (Figure 2.6) to provide a view of the driver's eyes and head. Originally, this camera was placed within the rear view mirror; however, it was discovered that headlights from vehicles behind the SV caused the camera to become saturated so that no image was visible. The camera was thus relocated to the A-pillar. Cameras were also placed outside under each of the two side mirrors (Figure 2.7) to provide views of the area adjacent to and behind the vehicle, including what the driver might see when looking into the mirror. These latter two cameras also included coverage of the lane lines.

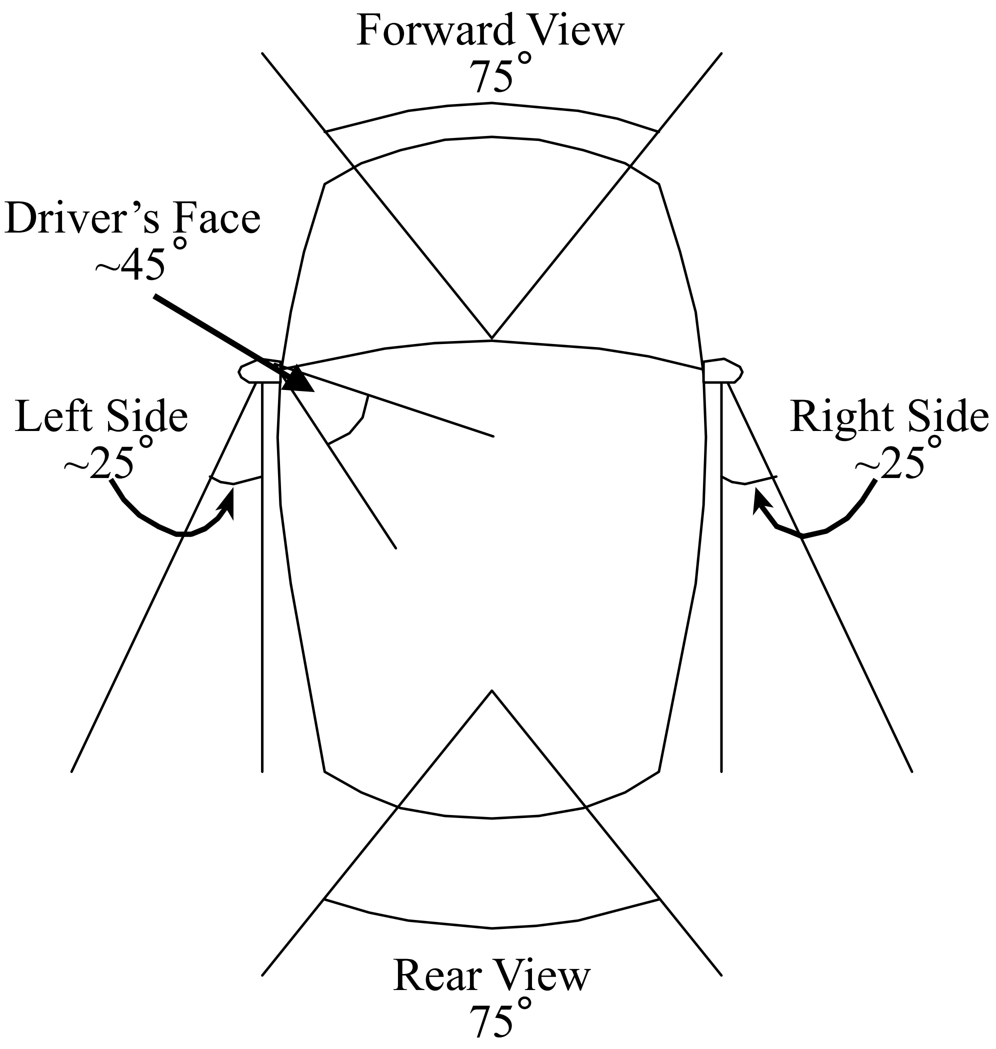


Figure 2.3. Video Camera Locations and Fields of View.

Figure 2.4. Forward View Video Camera Behind the Rearview Mirror.

Figure 2.5. Rearview Video Camera above the Rear Window.

Figure 2.6. Driver's Face Camera Mounted in the A-pillar.

Figure 2.7. Camera Mounted Under the Side Mirror.

The outputs of the five cameras were combined using two quad splitters. The first splitter combined the two side camera images into a single image as depicted in Figure 2.8. The output of this splitter was combined with the other three outputs using a second quad splitter. The resulting composite 5-camera image is shown in Figure 2.9. Note that the lower-right image is based on images from the two outside mirror cameras, divided vertically at the center.

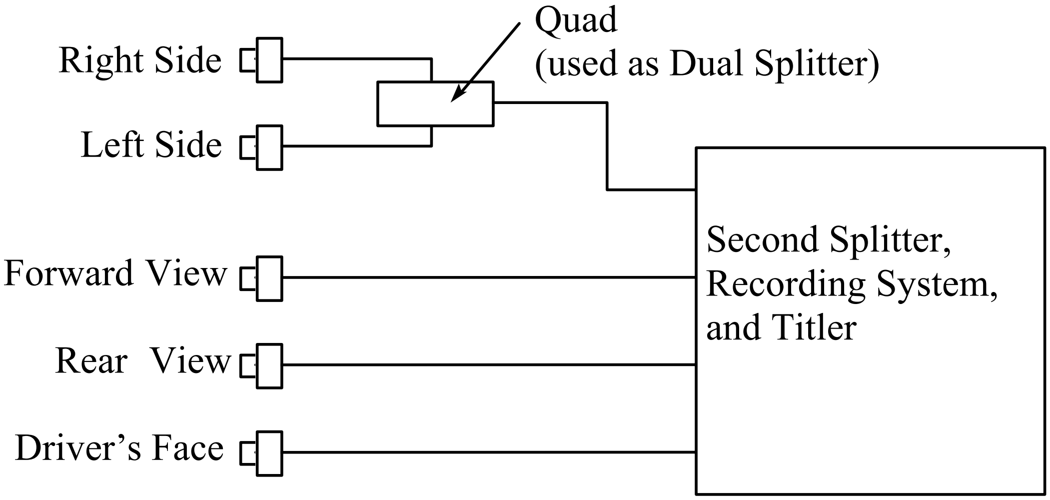


Figure 2.8. Video Diagram Showing Use of Quad Splitters.

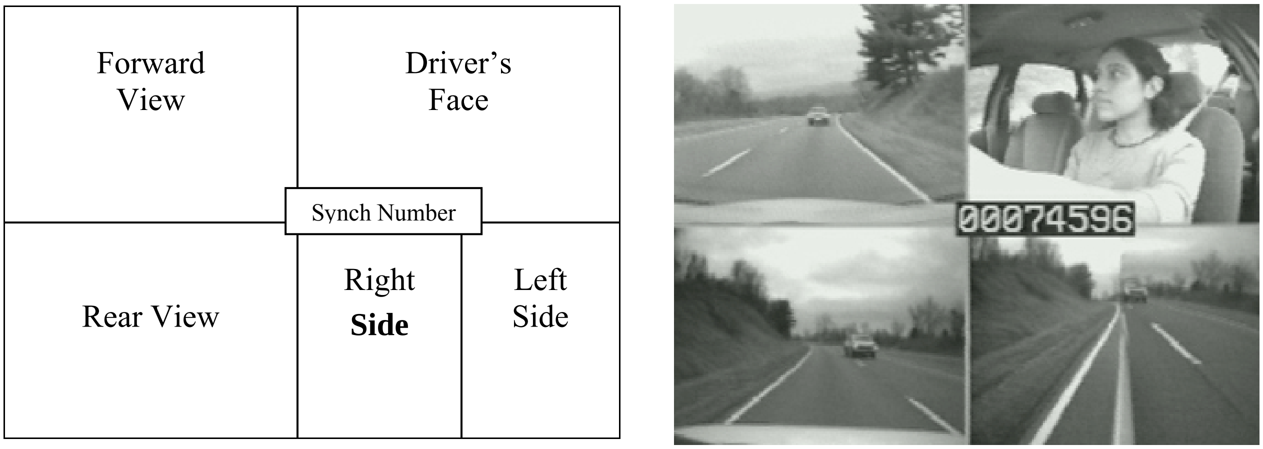


Figure 2.9. Image Arrangement on Quad-Split Screen.

Vehicle Parameter Sensor System

The vehicle parameter sensor system included a series of sensors placed throughout the vehicle, to collect data such as steering wheel position, SV velocity, and turn signal activation. The sensor system was developed by the Hardware Engineering Laboratory at VTTI, based on earlier versions of the system originally developed to investigate safety issues in local and short haul trucking operations (Hanowski et al., 2000). Data collected from this system were synchronized to other data by a time-stamp (or *synch number*, also shown in Figure 2.9) so that files could be compared using time as an anchor. Synch numbers were recorded in tenths of a second.

Radar System

The vehicle parameter sensor system also interfaced with the radar system, consisting of three Eaton Vorad EVT-300 radar units. These units were installed on each research vehicle as illustrated in Figure 2.10. The Eaton radar is a Doppler radar with a 12° angle of coverage and ability to monitor other vehicles up to a range of about 350 feet (Eaton, 2001). This type of radar has been used mostly on semi-tractor trailer trucks as a component of a collision warning system. The radar systems were unobtrusive, so that other drivers were not aware that radar data were being collected. Radar units were installed on the outside of the vehicle (as pointed out to participants during the orientation). However, these units were not visible to the driver while seated in the vehicle. One radar unit was installed in the front bumper facing straight forward (Figure 2.11) and the other two units were installed at the back of the vehicle facing rearward (Figure 2.12) and offset by 6° from the longitudinal axis. The radar units were configured in this manner so that range and range-rate to vehicles interacting with the instrumented vehicle during a lane change or passing maneuver could be determined.

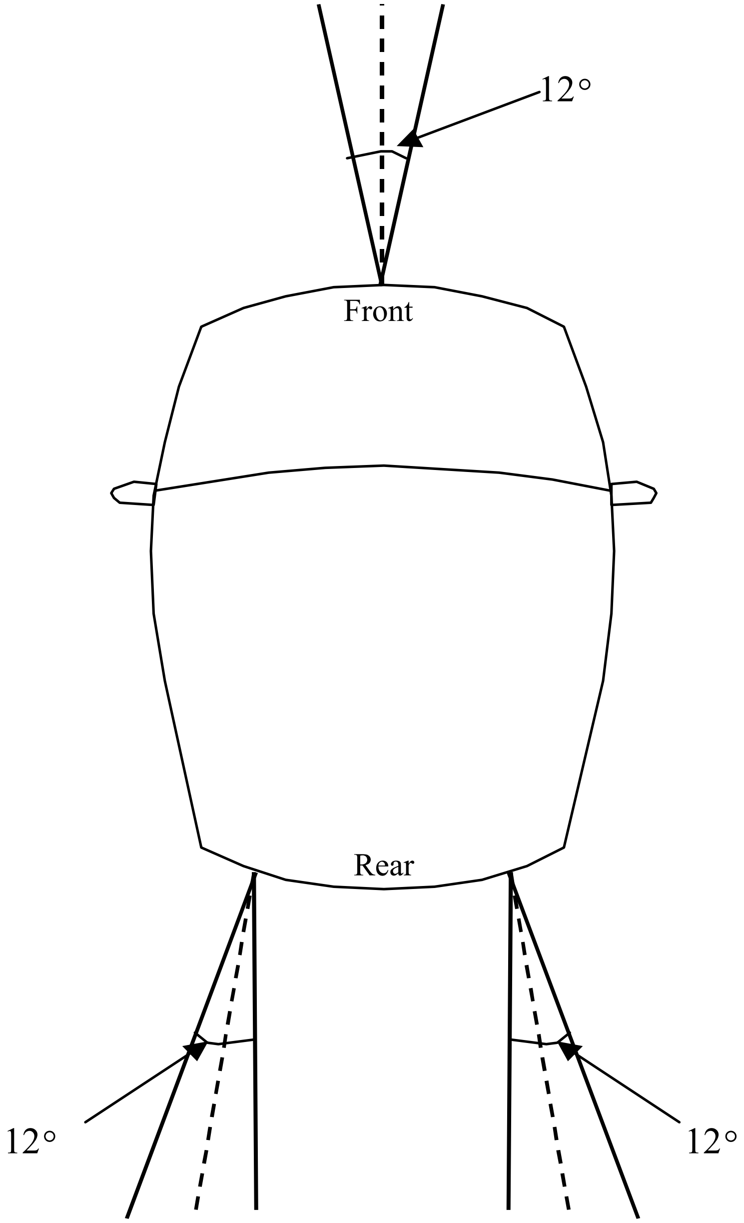


Figure 2.10. Radar Locations and Effective Angles of Coverage.

Figure 2.11. Front Radar Unit.

Figure 2.12. Rear Radar Units Embedded in Black Bumper.

Storage Unit

The system hardware (including two high-8 video cassette recording devices, central processing unit, zip drive, keyboard, quad splitters, titler, and harness bundle) was mounted so as not to be visible to the driver. The video recording devices collected video data using a titler to place a time stamp on each frame of video data collected. The central processing unit combined data from both the vehicle parameter sensor system and the radar system. Data files including data from both of these systems were created for analysis in conjunction with the video data. A storage unit (Figure 2.13) was constructed to house various hardware components of the three data collection systems. The unit was placed in the trunk of the sedan and in the rear area behind the rear seat in the SUV, where it was locked by the experimenter. The unit was very unobtrusive but allowed the experimenter to gain access to the hardware systems to change tapes and download computer data files.

Figure 2.13. Data Collection Systems Storage Unit.

Dependent Variables

The vehicles were instrumented to collect various types of data. Video data included eye behavior for the driver of the SV; the location and duration of eye glances prior to and during lane change or passing maneuvers were later extracted from the video data. Sensor data included driver-vehicle performance variables such as steering wheel position, velocity, and turn signal use. Radar data provided inter-vehicle variables related to lane changing. These data included the range, range-rate, and angle of surrounding POVs in relation to the SV. The position of POVs was categorized relative to the SV (e.g., front, rear left, rear right) and then for each position, by azimuth (angle) from the SV. Table 2.3 lists the dependent variables collected by the sensors within the vehicle or calculated during data analysis.

Table 2.3. Dependent Variables.

Dependent Variable	Unit/level
Eye Glance Position	Discrete position (forward, left mirror, blind spot, etc.)
Steering Wheel Position (Azimuth)	Radians
Success/Magnitude	Single, passing, multiple, unsuccessful
Direction	Left (L) or Right (R)
Severity	7 point scale (1 = unconflicted, 7 = physical contact)
Urgency	4-point scale (1 = not urgent, 4 = critical)
Velocity	MPH or ft/sec (for SV or POV)
Turn Signal Use	0 = off, 1 = right on, 2 = left on
Range to POV	Feet
Range-Rate or Relative Velocity (ΔV)	MPH or ft/sec (difference between vehicle velocities)
Time to Collision (TTC) to POV	Seconds (Range/ΔV)
POV Location	Location (e.g., front, front left, left, rear left, rear, etc.)
POV Position (Azimuth)	Radians
Lane Change Duration	Seconds (End Sync minus Start Sync/10)

Eye Glance Position

Eye glance position is the location to which the driver looked during the three seconds prior to lane change initiation. Particular emphasis was placed on the 3 seconds just prior to t_0 since critical driver decisions must be made during that period. Discrete positions included forward, (center) rear view mirror, left mirror, right mirror, left window, right window, left blind spot, right blind spot, and instrument cluster.

Steering Wheel Position

The position of the steering wheel was recorded at all times during data collection. Position was measured in radians (1 rad = 57.3 degrees).

Maneuver Type

Eleven categories of maneuvers were identified as shown in Table 2.4. Each maneuver type was associated with the motivation for the maneuver. For example, the merging vehicle maneuver indicated that the driver made the maneuver because a vehicle ahead was merging onto the roadway.

Table 2.4. Maneuver Types and Descriptions.

Maneuver Type	Description
Slow lead vehicle	Lane change to pass a slower vehicle so the SV could maintain speed.
Return	Lane change to return to preferred driving lane.
Enter	Lane change to enter road (e.g., from on-ramp).
Exit/prepare to exit	Lane change associated with exiting.
Tailgated	Vehicle tailgating/approaching quickly.
Merging vehicle	Vehicle entering roadway causing SV to change lanes.
Rough/obstacle avoidance	Maneuver to avoid obstacle or rough road surface.
Lane drop	End of driver's lane (e.g., road goes from 3 to 2 lanes).
Added lane	Addition of a lane (e.g., road goes from 2 to 3 lanes).
Unintended	Unintended lane deviation (e.g., distraction in car).
Other	Lane change for any other reason or for no discernible reason.

Success/Magnitude

The success/magnitude dependent measure had four categories: single lane changes; passing maneuvers (a series of 2 single lane changes to pass a vehicle, made within 45 seconds); multiple lane changes (more than 1 lane change completed in the same direction, i.e., crossing multiple lanes of traffic); and unsuccessful lane changes (aborted lane change, unintentional lane change, or partial lane change). Only the initial lane change was analyzed for passing maneuvers. These maneuvers consisted of two lane changes, but the first lane change was the main concern since this usually involved a slow lead vehicle that was being passed and, potentially, a vehicle to the rear in the adjacent lane (i.e., in the blind spot). The return maneuver was of less concern since the SV had just passed the slow lead vehicle, was aware of both its location and presence, and was pulling away from it.

Direction

Lane changes were categorized in terms of the initial direction of the lane change. For example, a lane change in which the SV moved from the right lane into the left lane was categorized as a "left" direction lane change because the movement was to the left. Additionally, a passing maneuver from the right lane into the left lane and back into the right lane was categorized as "left" because the initial movement was to the left.

Severity Rating

After data gathering, all lane change events were rated using the 7-point severity rating scale (1 = unconflicted, 7 = physical contact) indicating the degree to which the vehicle in the destination lane was cut off (Table 2.5). Severity was rated based on vehicle presence within the PZ (4 feet in front of the SV to 30 feet behind it) and time-to-reach the rear edge of the PZ for those vehicles within the FAZ (30 to 162 feet behind the SV). These zones refer to areas in the adjacent destination lane, beside and behind the SV, which should be monitored before lane change initiation (Talmadge, Chu & Riney, 2000). The severity rating scale reflects conflict aspects of vehicle movement, where conflict is associated with vehicles in the adjacent lane when the driver of the SV moves into that lane. A lane change conflict, by definition, requires that there be a vehicle present in the lane into which the driver of the SV wishes to move. In this case, level 6 of this scale pertains to emergency or unplanned maneuvers required to avoid a collision. Levels 1 through 5 of the rating scale are related to other vehicles in the PZ (level 5) or within the FAZ and their relationship to the end of the PZ (levels 1 through 4). The severity scale was created based upon review of work by TRW (Talmadge, Chu, Eberhard, Jordan & Moffa, 2000) in which lane changes were classified into similar categories, and upon input received from discussions held with NHTSA personnel during July of 2001.

Table 2.5. Severity Rating Scale.

Rating	Description
7	Physical contact/collision occurs with a vehicle (or object) in the adjacent lane into which the driver of the SV was attempting to move (no incidents observed).
6	Emergency action/unplanned sudden maneuver required to avoid a collision with a vehicle (or object) in the adjacent lane into which the driver of the SV was attempting to move.
Ratings 5 through 1 are assessed *at initiation (Start Synch)* of the attempted lane change.	
5	POV in the proximity zone.
4	POV in the fast approach zone with time to reach closest end of zone, T_r[†], ≤ 1.0 sec.
3	POV in the fast approach zone with time to reach closest end of zone in the range $1.0 < T_r \leq 3.0$ sec.
2	POV in the fast approach zone with time to reach closest end of zone in the range $3.0 < T_r \leq 5.0$ sec.
1	POV in the fast approach zone with time to reach closest end of zone, T_r, > 5.0 sec, including case where there is no vehicle in the adjacent lane.

[†] T_r is the time required for a POV to reach the front end of the fast approach zone, the point 30 ft behind the SV.

Urgency Rating

Each lane change was also rated in terms of urgency. Urgency was rated on a 4-point scale (1 = not urgent, 4 = critical) that indicated how soon the lane change was needed based on TTC with the closest vehicle ahead (or behind for accelerating vehicles such as tailgaters); this is illustrated in Table 2.5. For example, for a slow lead vehicle maneuver with a TTC to the lead POV of 4.1s, the urgency would be rated as 2 (urgent) because 5.5 s ≥ TTC > 3 s.

Table 2.6. Urgency Rating Scale.

Rating	Description
4	Critical incident/crash: Physical contact/collision occurs with a vehicle (or object) in the same lane as the SV or the opposite adjacent lane, or a sudden maneuver (braking or swerving) is required to avoid such a collision.
3	Forced: The lane change has a high degree of urgency due to a short TTC* (TTC ≤ 3 s) and/or close headway/tailway/distance to vehicle in the same or opposite adjacent lane.
2	Urgent: The lane change is somewhat urgent due to moderate TTC (5.5 s ≥ TTC > 3 s) and/or moderate headway/tailway/distance to vehicle in the same or opposite adjacent lane.
1	Non-urgent: The lane change is not urgent because of a minimal, infinite, or negative TTC (TTC > 5.5 s) with a vehicle in the same or opposite adjacent lane, and/or long headway/tailway/distance, and/or lack of vehicles in the same or opposite adjacent lane.

* Time to collision is the time it would take for vehicles to collide if the rear vehicle did not maneuver. In other words, it is the time from the initiation (Start Synch) of the lane change to the time when the front bumper of the SV is parallel with the rear bumper of the POV (e.g., when the POV is in front of the SV), assuming constant velocity and acceleration.

It is important to note the reason that two separate ratings were developed. The severity rating deals with the situation in the destination lane, while the urgency rating deals with the situation in the driver's current lane, and both aspects are important in understanding driver behavior.

The remaining dependent measures (including velocity, turn signal use, range, headway, range-rate, TTC, POV location, POV position, and lane change duration) were either acquired via sensors or were calculated during data reduction and analysis.

Experimental Procedure

Participant Selection and Screening

One-page recruitment flyers describing the study were posted throughout Blacksburg and Christiansburg, VA to solicit volunteer participants for this study. Respondents contacted the experimenters and were screened over the telephone using a Driver Screening and Demographic Questionnaire (Appendix A). The experimenters used this form to document pertinent information about the potential participant. Only commuters who drove 25 miles or more on either Interstate 81 (or I-581) or select U.S. Routes (460 or 11) were eligible. Other relevant information such as gender, route normally driven, vehicle normally driven, age range, medical and driving history, and use of corrective lenses and sunglasses was also reviewed during the telephone screening. After a series of screenings had been conducted, the process of selecting potential participants began. The experimenters reviewed all screening forms and selected participants who met all required criteria. Those drivers who qualified for the experiment were then contacted, and an appointment was set up for each driver to come to VTTI for orientation.

Participant Orientation

Participants were instructed to meet the experimenter at VTTI. Each participant reviewed the information recorded on the screening and demographic questionnaire for accuracy. The participant was then asked to read and sign the Informed Consent Form (Appendix B) that included an overview of the study. After agreeing to participate, the participant's driver's license was viewed to ensure that it was valid.

The next step was for the participant to review the Driving a Sport Utility Vehicle Form and accompanying video. The video clip was recorded from the evening news and showed a demonstration of what could happen if an abrupt steering maneuver was performed while driving an SUV. The purpose of the form and the video was to raise participants' awareness of the differences between driving a sedan and a SUV. The driver was then shown the vehicle including the location of the cameras and the data storage unit. The Vehicle Orientation and Check Out/In Forms were used as a checklist to familiarize the participant with the vehicle. Finally, the participant conducted a test drive using the Orientation Route Instructions Form.

Driving Instructions

Participants were instructed to drive the vehicle to and from work, as they normally would, in place of their regular commuting vehicle. Participants were reminded that errands on the way to work, during lunch, and on the way home after work was permitted, but that the vehicle was not to be used for personal use in the evenings or on the weekends. Also, participants were reminded not to wear sunglasses or carpool. Having an occasional passenger was permitted, however (e.g., during lunch). As stated in the Informed Consent Form, participants were to drive legally at all times.

Sequence of Data Collection

Each participant drove the sedan and then the SUV (or vice versa) for a total of 20 business days. The experimenter worked with the participant to identify a convenient location and time for data retrieval. The experimenter also coordinated exchange of vehicles with the participant after the first ten days of driving. The participant did not need to be present during data retrieval since the experimenter knew where the vehicle was located. Data retrieval consisted of exchanging videotapes and downloading computer data onto zip disks for later analysis. Once all of the days of driving were completed, the participant was instructed to return to VTTI to drop off the vehicle. While at VTTI, the participant completed the Driver Study Debriefing Form. Payment for the total number of days of participation and reimbursement for gasoline were provided at the end of the second experimental session (i.e., after the last 10 days of driving).

Data Reduction

Data reduction involved a series of steps described in the following sub-sections. As an overview, the entire population of maneuvers was first reviewed so that a representative sample could be obtained for the in-depth analysis. Each lane change maneuver was identified by reviewing the videotapes. The original estimate for the total number of lane changes to be recorded was 4,000 events; however, the data collection effort resulted in 8,667 events, considerably more than had been anticipated. Each of these events was identified, categorized, and rated. A general analysis was performed on all 8,667 events, and an in-depth analysis was performed on the 500 selected events. A data integration program was used to integrate video, radar, and sensor data for each of the in-depth maneuvers. After each event was entered into this program, the event was ready for descriptive and statistical analysis.

Identifying, Categorizing, and Rating All Maneuvers

All lane change instances were identified in terms of specific initiation and end points and then categorized and rated. A training manual was created for analysts to use to assist with this process (Appendix C). The initiation and end points had to be carefully defined.

Initiation Point

An operational definition of the initiation point marking the beginning of a lane change or attempted lane change was required. This point is important because it represents the decision point (go/no-go) at which the driver decided to begin the lane change maneuver. In previous studies (Hanowski, Wierwille, Garness & Dingus, 2000), the point in time representing the beginning of a lane change was defined by a combination of criteria. Experience indicates that drivers ordinarily return fixation direction to the forward view (from the mirrors or direct looks to the rear) when they begin the lane change. Initiation of the lane change itself can ordinarily be detected by a steering input or by movement toward the lane boundary or both. Steering movement is picked up by the steering sensor, and movement toward the lane boundary can be determined visually by the data analyst using the two side-mounted camera images of the recorded video. Thus, when t = 0, the beginning of the lane change or lane change attempt can be determined by monitoring one or more of the following:

1. The vehicle begins to move laterally relative to the lane.
2. Driver initiates a steering input intended to change the direction of the vehicle relative to the lane.
3. Driver returns gaze to the forward view after looking in mirrors or looking directly toward the side or rear.
4. The vehicle leaves the lane at least temporarily.

While four criteria were used to define the beginning point, they were often not all present. Thus, some judgment was necessarily required. In some cases, the driver may not look to the rear, and in other cases the vehicle may naturally drift to the left or right without a steering input. Nevertheless, it was still possible for the reductionist to locate the initiation point in time by looking for the remaining criteria.

An additional cue that was sometimes present was the actuation of the directional signals. This signal alerted the reductionist to a possible lane change, but could not be relied upon for determination of the start point. Signals are not always used, and when they are used, activation varies relative to the actual lane change start point. The activation point varies among drivers (Hetrick, 1997) and for the same driver as a function of conditions, as described in Chapter 1.

End Point

Generally speaking, a lane change or attempted lane change ends when the vehicle "settles" in the new lane (or in the original lane for a passing maneuver). This point is not as critical as the lane-change initiation point in terms of relevance to the decision point. Nevertheless, task completion time and glance direction summaries are affected if the end point is not properly defined. Settling point appears to provide the best concept for the end of a lane change because it allows for lane overshoot, variable lane transition time, and incomplete lane-change attempts. Settling point can be defined in terms of motion relative to the lane boundaries; namely, when the vehicle's lateral velocity relative to the lane is below a threshold for a specified period of time, the lane change is complete. The end point can be determined by having the data reductionist watch the side camera video for the vehicle to "settle" in the lane. This is an informal but accurate method of determining end point.

Categorization and Rating

After each lane change was identified, the event was categorized in terms of maneuver type, success/magnitude, and direction. Each maneuver was also rated in terms of severity and urgency. These categorization variables were described in detail in the Dependent Variables subsection but are briefly repeated here. There were eleven maneuver types (e.g., slow lead vehicle, enter, exit/prep exit), four categories for lane change success/magnitude (single, passing, multiple, unsuccessful), two directions (right, left), seven levels of the severity rating scale (1 = unconflicted, 7 = physical contact) indicating the degree to which the vehicle in the destination lane was cut off, and four levels of the urgency rating scale (1 = not urgent, 4 = critical) indicating how soon the lane change was needed based on TTC with the closest POV in the same lane. During this phase, the information for each maneuver was entered into an Excel spreadsheet and saved, as illustrated in Figure 2.14.

Ss#	Rte	DrvTyp	VehTyp	Gndr	Tape#	Date	Start	End	Type	Succ/Mag	Dir	Sev	Urg
17	I	Sed	Sed	Fem	1701	11-Jun AM	24350	24450	Slow Lead	S	R	4	2

Figure 2.14. Example of a Row from an Excel Spreadsheet Representing a Lane Change for Use with the Data Integration and Analysis Program.

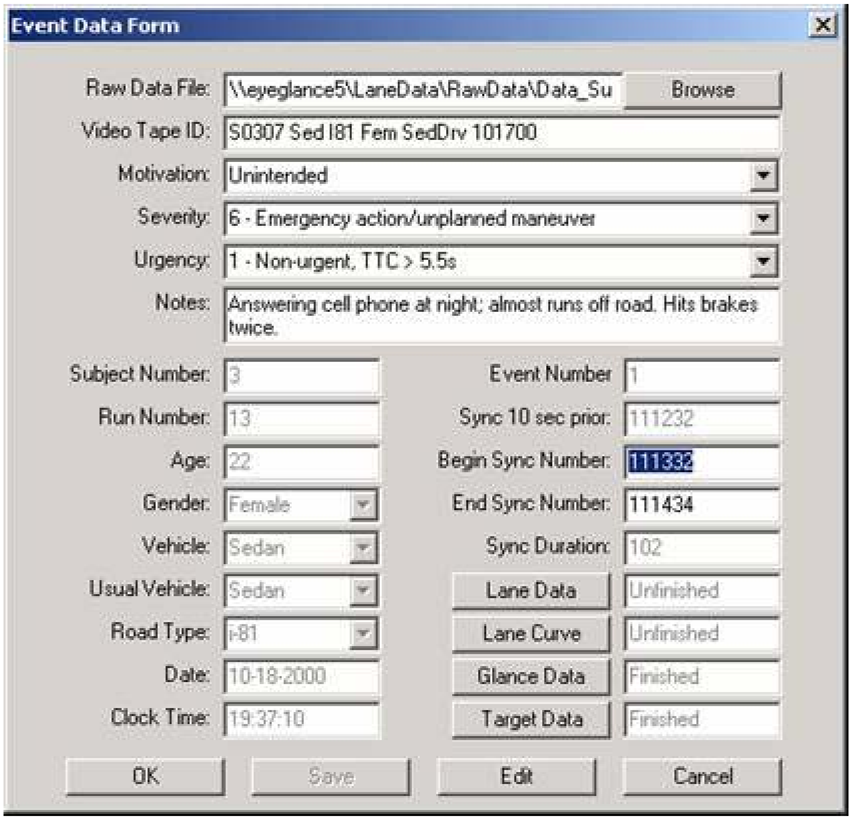
In-Depth Sample Analysis

In-depth analyses were conducted after the final sample of lane changes was selected (sample selection is described later in this chapter). A lane change data integration and analysis program was developed to perform these analyses. The user manual for this program was developed to aid analysts in this effort (Appendix D). This program combined data from the video, radar, and sensor systems as well as data entered into the Excel spreadsheet into a data packet. After events were identified, categorized, rated, and entered into the program, data packets were then available for statistical analyses.

As an overview of the in-depth analysis, the maneuver start point was entered into the event data form and the program automatically identified the point 10-seconds prior to the start point (t minus 10). The end point was also entered. Categorization data (maneuver type, direction, severity, and urgency) for each maneuver were entered using a series of pull-down menus. Lane curve and transition data were also entered. Eye glance behavior was then analyzed starting from 3 seconds before the lane change to the initiation of the lane change. Next, target data for each vehicle were retrieved for radar targets of interest. A complete archive of the event was created. The result was a single integrated data file that could be used for review and statistical analysis. The original video segment was captured in a digitized format to be used in conjunction with the integrated data file. This digitized clip started at t minus 10 seconds and ended with the end point of the lane change (or attempted lane change). Approximately 2 seconds on each side of the above interval were also included.

Identifying Events

For a particular maneuver of interest, the appropriate videotape and data file were located. The video file was originally used to identify maneuvers and was then used later to specify vehicles identified by the radar data as well as to determine eye glance patterns. The radar data file allowed the program to calculate range, range-rate, and time to collision as well as to display a graphical representation of the maneuver. The event data form (Figure 2.15) was the first form to be encountered. Here, the raw file was loaded and identification information was entered, including videotape identification, maneuver type, severity, urgency, and start and end synch values.[*] Participant information (ID number, run, age, gender, vehicle type, usual vehicle [driver type], road type [route], date, time, and event number) was automatically assigned by the program based on the raw data file.



Raw Data File: \\eyeglance5\LaneData\RawData\Data_Su
Video Tape ID: S0307 Sed I81 Fem SedDrv 101700
Motivation: Unintended
Severity: 6 - Emergency action/unplanned maneuver
Urgency: 1 - Non-urgent, TTC > 5.5s
Notes: Answering cell phone at night; almost runs off road. Hits brakes twice.
Subject Number: 3
Run Number: 13
Age: 22
Gender: Female
Vehicle: Sedan
Usual Vehicle: Sedan
Road Type: i-81
Date: 10-18-2000
Clock Time: 19:37:10
Event Number 1
Sync 10 sec prior: 111232
Begin Sync Number: 111332
End Sync Number: 111434
Sync Duration: 102
Lane Data: Unfinished
Lane Curve: Unfinished
Glance Data: Finished
Target Data: Finished

Figure 2.15. Event Data Form.

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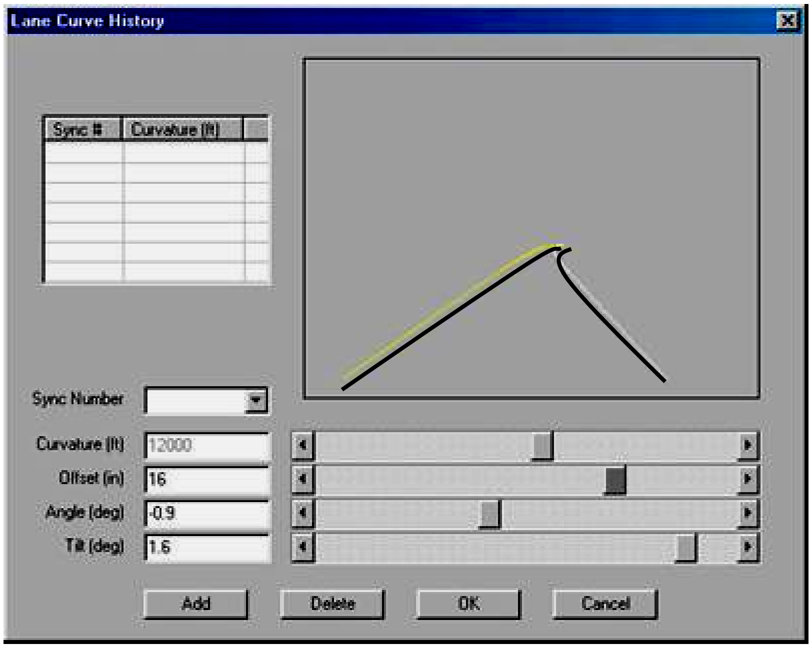
[*] Synch values were in units of tenths of a second. These values were superimposed on the video and were used as the time reference in the spreadsheet data. Thus, videotape segments could be correctly "registered" with sensor data.

The lane curve history form (Figure 2.16) allowed the analyst to enter waypoints to estimate the edge-lines and curvature of the roadway, based on the video image. Parameters included curvature, offset, angle, and tilt. The curvature values are in feet with positive values indicating curvature to the right and negative values indicating curvature to the left; an infinite curvature is a straight road. Offset is a measure in inches with zero indicating the vehicle is centered within the lane and positive values indicating that the vehicle is to the right of center. The angle value represents the angle in degrees (yaw) of the centerline of the camera with respect to the centerline of the road horizontally, with positive values indicating that the vehicle is pointed toward the right, and negative angles indicating that the vehicle is pointed to the left. However, an angle of zero degrees does not necessarily mean that the driver drove straight in the lane; it indicates that the camera is looking straight down the lane. Tilt (pitch) is also in degrees and is the vertical angle of the camera with respect to the road.

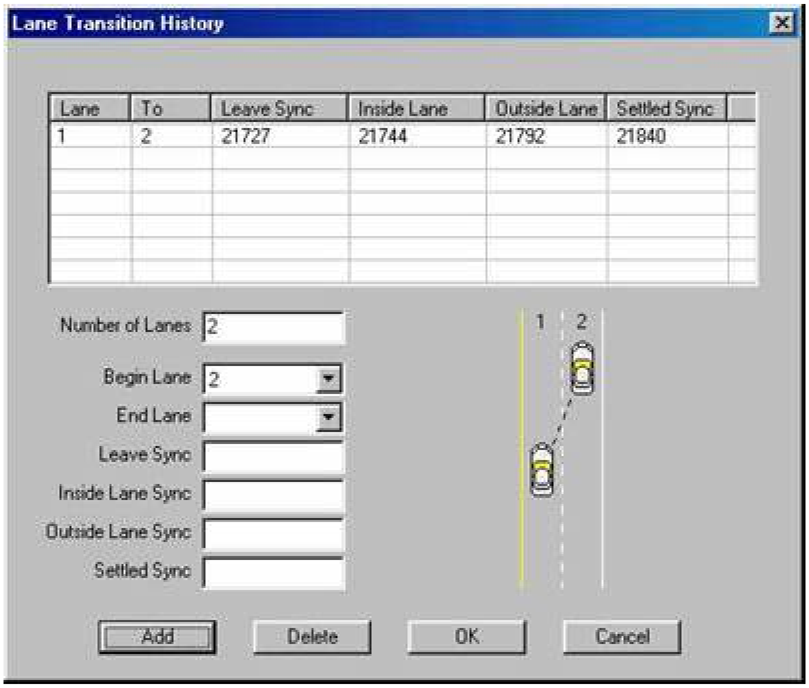


Sync Number
Curvature (ft) 12000
Offset (in) 16
Angle (deg) -0.9
Tilt (deg) 1.6

Figure 2.16. Lane Curve History.

Each parameter could be set using the appropriate scroll bar to approximate the lane edge-lines seen on the videotape. The primary use of this form was to facilitate graphical display of the event and to assist in target identification. In most cases, the parameters offset, angle, and tilt were not manipulated; curvature was the only parameter manipulated to line up the lane curve history window with the video image. Curvature data were not analyzed as part of the data analysis effort.

The lane transition history form (Figure 2.17) allowed the analyst to describe the event over time in terms of lane-changing milestones. Key elements included the number of lanes, original and destination lane, leave (begin) synch number, inside lane synch (point at which the inside of the vehicle crossed the lane line), outside lane synch (point at which the outside of the vehicle crossed the lane line), and settled (end) synch number. This information also helped the program to display the event accurately for event identification.

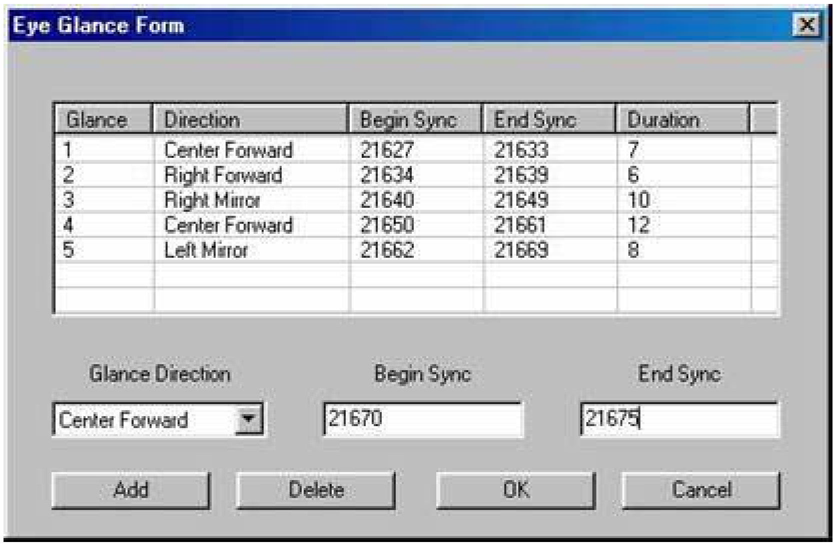


Lane	To	Leave Sync	Inside Lane	Outside Lane	Settled Sync
1	2	21727	21744	21792	21840

Number of Lanes 2
Begin Lane 2
End Lane
Leave Sync
Inside Lane Sync
Outside Lane Sync
Settled Sync

Figure 2.17. Lane Transition History.

The eye glance form (Figure 2.18) allowed the analyst to perform an eye glance analysis in which specific eye behavior data associated with a particular maneuver were entered. The glance direction (location) and beginning and ending synch number were entered and duration was calculated automatically. The glance data form was used in conjunction with the video data to identify where the driver was looking during the maneuver.



Glance	Direction	Begin Sync	End Sync	Duration
1	Center Forward	21627	21633	7
2	Right Forward	21634	21639	6
3	Right Mirror	21640	21649	10
4	Center Forward	21650	21661	12
5	Left Mirror	21662	21669	8

Glance Direction	Begin Sync	End Sync
Center Forward	21670	21675

Figure 2.18. Eye Glance Form.

The radar distance screen (Figure 2.19) displayed radar data in a graphical format. The abscissa was the time synch (1/10 second) value and the ordinate was range (feet). The radar target identification numbers were also displayed (e.g., 128, 127, 119). Each of three views (front radar, rear driver radar, and rear passenger radar) could be displayed via toggle buttons. A vertical line indicated the time location (along the abscissa) as the event progressed.

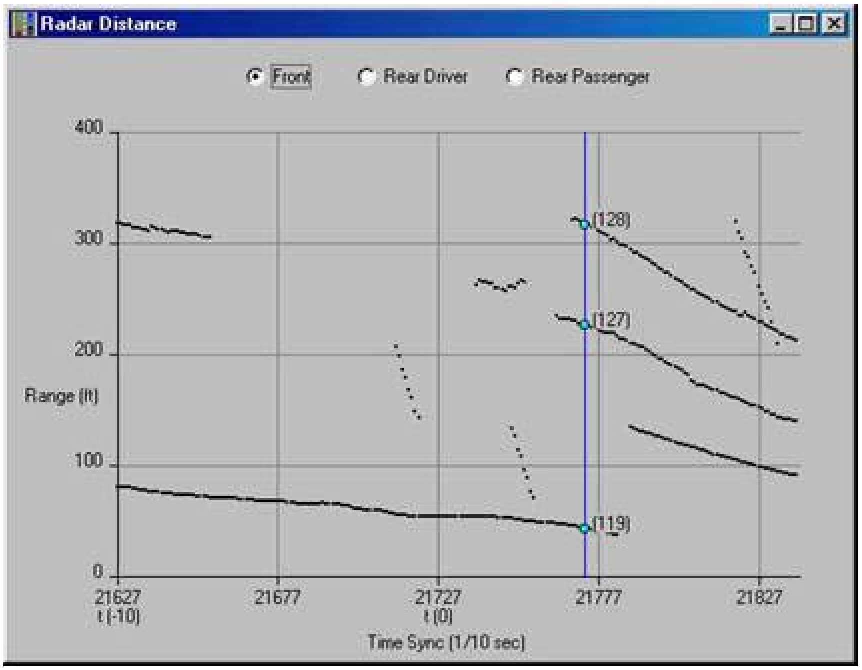
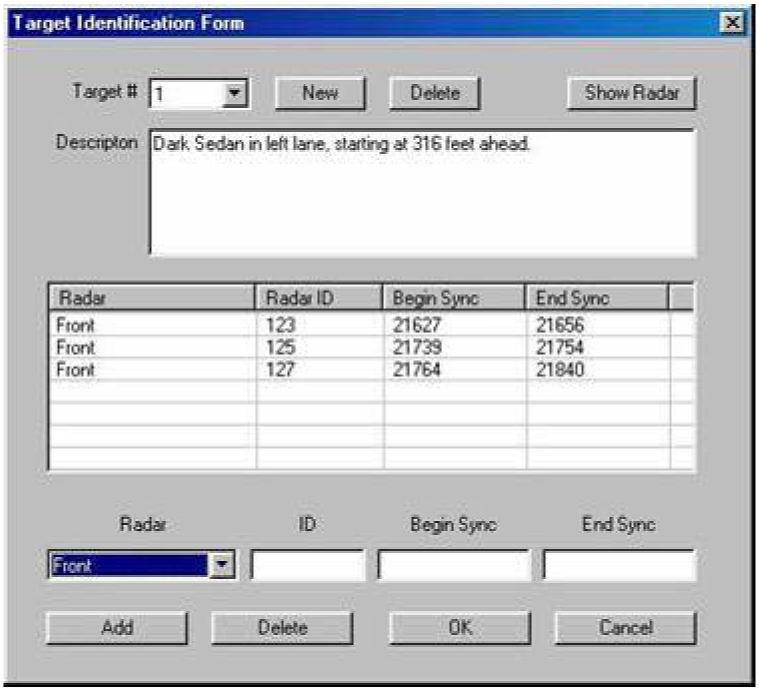


Figure 2.19. **Radar Distance (Front Radar).**

The target identification form (Figure 2.20) allowed the analyst to identify each target with a unique target identification number. This was an important feature for two reasons. First, as targets progressed from front to rear (or vice versa), they were renumbered. For example, when a slow lead vehicle target was detected by the front radar it may have been assigned as "Target #34." Then, as the SV passed the target, it may have been picked up by one of the rear radars and assigned a new identification number such as "Target #22." This re-assignment occurred because each radar system operated independently, that is, as a separate data collection system. Second, the same target may have been reassigned a different target identification number even from within the same radar unit. This type of event occurred if another vehicle blocked the target's path temporarily or if the target went in and then out and then back into range of the radar. After all targets for a particular vehicle were identified, a unique target number was then assigned by the program (Target 1, Target 2, and so on). For the event shown in Figure 2.20, Target 1 was associated with radar targets 123, 125, and 127 from the front radar.



Target # 1

Descripton Dark Sedan in left lane, starting at 316 feet ahead.

Radar	Radar ID	Begin Sync	End Sync
Front	123	21627	21656
Front	125	21739	21754
Front	127	21764	21840

Radar Front

ID

Begin Sync

End Sync

Figure 2.20. Target Identification Form.

Key elements of the target identification form included target number, description, radar, radar identification, and begin and end synch numbers. The target number is the re-assigned number associated with a particular target. In general, Target 1 was the closest POV, Target 2 was the next closest, and so on. The description box included a brief description of the POV including color of the vehicle (dark or light, since the video was black and white), position, and action. Radar (front, rear driver, or rear passenger) referred to the radar unit that detected the target of interest. Radar identification referred to the original ID number (e.g., Target #123) assigned to a particular target by the radar unit. Note that the same radar target could have multiple ID numbers because the radar system would acquire, lose, and then reacquire the same target due to masking by other vehicles, the target going out of range, etc. In addition, if a radar target was acquired by one sensor and then another, each radar system would assign independent target numbers. The begin and end synch numbers represented the beginning and ending of the lane change event. These corresponded to the synch numbers present on the video as well as the sensor data file.

The radar display form was a graphical, bird's eye view of all radar targets as they appeared during an event (Figure 2.21) corresponding to the radar distance window (Figure 2.19). A unique vehicle icon (SUV or Sedan) was displayed with radar coverage regions displayed as appropriate (front, rear driver, rear passenger).

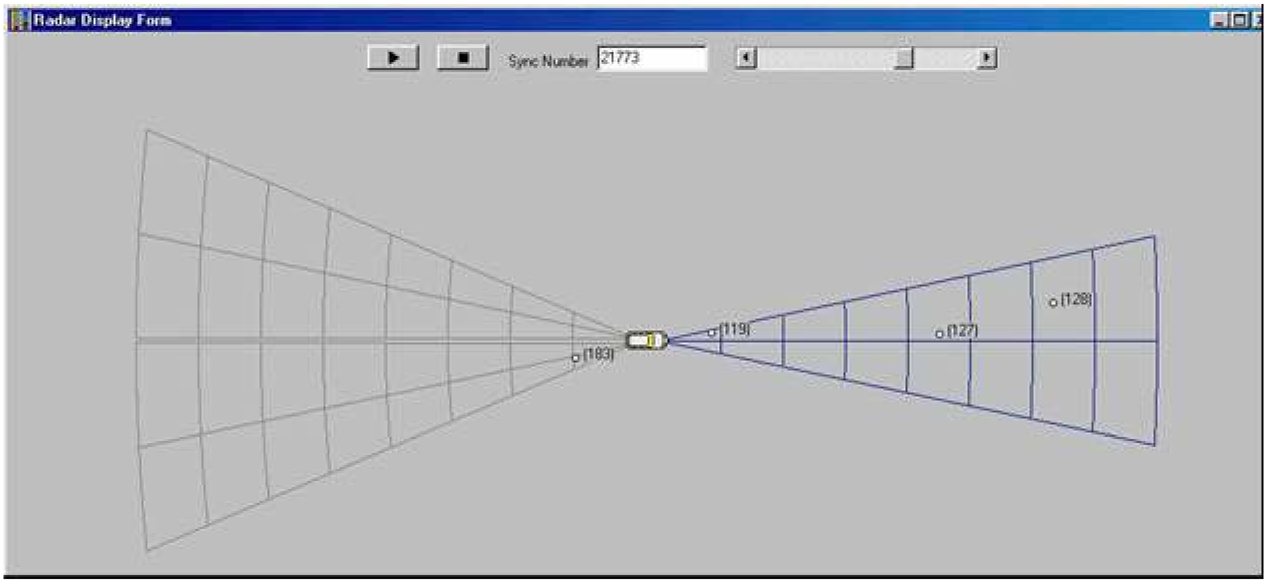


Figure 2.21. Radar Display Form.

Data Analysis

Full Data Set

Analysis included one-way and two-way distributions of lane changes as a function of severity and urgency ratings and type classification for the full population of 8,667 lane changes. One-way and two-way distributions of lane changes as a function of gender, vehicle type, driver type, and route were also developed. Other distribution variables included direction and success/ magnitude of the lane change. Given the experimental design, analysis of variance was also possible for the full set. This was done by looking at certain dependent measures including duration, urgency, and severity, given the independent variables of gender, vehicle type, driver type, and route. Similar analyses were also conducted for certain categories selected from the full population, such as all single lane changes and all single, slow lead vehicle lane changes.

In-Depth Analysis of 500 Sampled Lane Changes

The next set of analyses was conducted on the sample of 500 lane changes selected from the full population, including those representing all levels for each of the independent variables. As described in Chapter 4, the sample was selected to include events that were rated at all levels of severity and urgency. Particular emphasis was given to events with higher ratings (i.e., Severity ≥ 3). A much greater level of detail was available for this data set including steering, lateral acceleration, brake pedal use, velocity, and eye glance behavior. Additional analyses included turn signal use, distance, relative velocity, and TTC to other nearby vehicles.

CHAPTER 3: RESULTS FOR THE FULL DATASET

One-Way and Two-Way Analyses

A total of 8,667 lane changes were collected and identified using the methods described in Chapter 2. In terms of the success/magnitude of the lane changes, there were 7,196 (83.0%) single lane changes, 1,071 (12.4%) passing maneuvers of ≤ 45 seconds, 289 (3.3%) multiple lane changes, and 111 (1.3%) unsuccessful (incomplete/partial) lane changes. Each lane change was categorized according to the 11 maneuver types listed in Table 3.1. The slow lead vehicle, exit/prep exit, return, and enter maneuver types were most prevalent, accounting for 86.3% (7,475) of all lane changes.

Table 3.1. Frequency and Percent of Lane Changes by Maneuver Type.

Maneuver Type	**Frequency**	**Percent**	**Mean Duration**	**Mean Urgency**	**Mean Severity**
Slow lead vehicle	3,228	37.2%	12.98	1.09	1.24
Exit/prep exit	2,018	23.3%	6.25	1.01	1.11
Return	1,549	17.9%	6.72	1.00	1.10
Enter	680	7.9%	6.89	1.00	1.10
Tailgated	353	4.1%	6.08	1.07	1.16
Merging vehicle	226	2.6%	7.39	1.12	1.17
Lane drop	201	2.3%	6.69	1.01	1.07
Other	161	1.9%	10.82	1.00	1.06
Added lane	157	1.8%	5.98	1.03	1.00
Unintended	70	0.8%	13.67	1.01	1.40
Rough/obst avoid	24	0.3%	8.73	1.29	1.21
Grand Total or Mean	**8,667**	**100%**	**9.07**	**1.04**	**1.16**

The results for frequency of occurrence have been plotted in Figure 3.1. The figure shows that the categories of slow lead vehicle, entering, and exiting account for the overwhelming majority of lane changes. The “return” category is associated with a return to the original lane. For the success/magnitude categories, a passing maneuver was categorized as such only if it was ≤45 seconds in duration. In many cases a “return” was the delayed end of a passing maneuver that originated as a slow lead vehicle lane change. Keep in mind that passing maneuvers of more than 45 seconds were counted as two lane changes, while passing maneuvers of ≤45 seconds were counted as a single lane change.

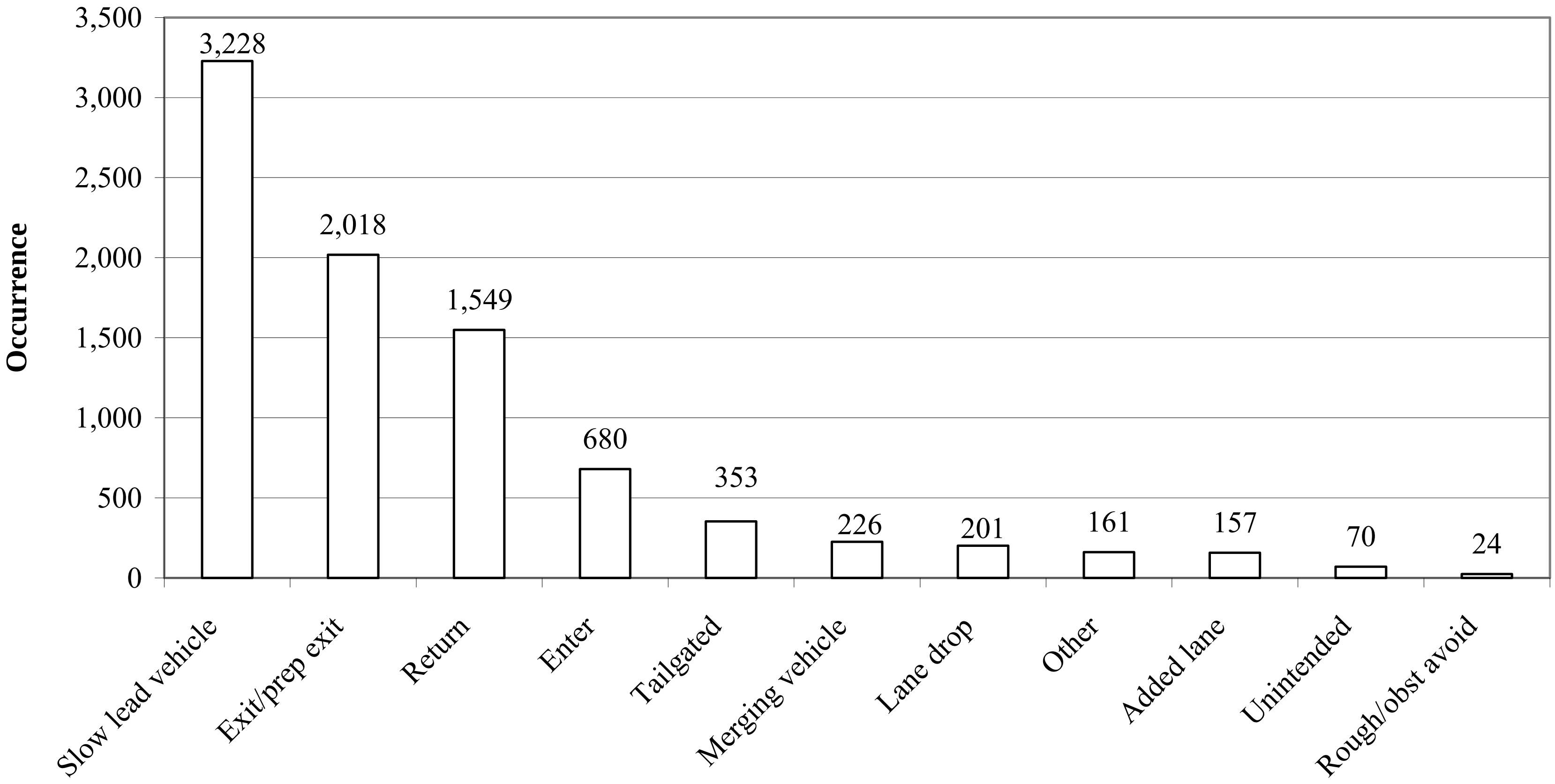


Figure 3.1. Occurrences of Lane Change Maneuver Type in Descending Order.

Route, Driver Type, Vehicle Type, and Gender

There were four independent variables in the experimental design: gender (male or female), route (interstate or U.S. highway), driver type (sedan driver or SUV driver), and vehicle type (experimental vehicle: sedan or SUV). In Table 3.2, the frequency, duration, urgency, and severity are displayed for each of these independent variables. Analyses of variance (ANOVA) were run for the dependent measures of duration, urgency, and severity. Chi-square analyses were performed for the frequency counts to detect differences in the actual and expected values. The significant main effects for both the ANOVA and chi-square analyses are shown using shading in this and subsequent tables.

Table 3.2. One-Way Distributions for Gender, Vehicle Type, Route, and Driver Type.

Independent Variables	**Level**	**Dependent Variables**				
		Frequency (percent of total)	**Normalized Frequency LC/mile**	**Mean Duration seconds (StDev)**	**Mean Urgency 1 to 4 (StDev)**	**Mean Severity 1 to 7 (StDev)**
Route	Interstate	***5,313 (61.3%)***	0.35	***7.88 (6.21)***	1.03 (0.16)	1.19 (0.82)
	Highway	***3,354 (38.7%)***	0.38	***10.96 (10.66)***	1.07 (0.28)	1.11 (0.63)
Driver Type	SUV Driver	***3,834 (44.2%)***	0.32	8.96 (7.56)	1.03 (0.18)	1.11 (0.62)
	Sedan Driver	***4,833 (55.8%)***	0.42	9.16 (8.94)	1.05 (0.24)	1.19 (0.84)
Gender	Male	***4,518 (52.1%)***	0.38	8.94 (8.61)	1.06 (0.25)	1.19 (0.84)
	Female	***4,149 (47.9%)***	0.34	9.21 (8.07)	1.03 (0.18)	1.12 (0.64)
Vehicle Type	SUV	4,271 (49.3%)	0.34	9.07 (8.14)	1.05 (0.22)	1.16 (0.77)
	Sedan	4,396 (50.7%)	0.38	9.07 (8.57)	1.04 (0.22)	1.15 (0.74)
Grand Total or Mean		**8,667**	**0.36**	**9.07 (8.36)**	**1.04 (0.22)**	**1.16 (0.75)**

Gray and Bold Italics = significant main effect of $p \leq 0.001$. Gray = significant main effect $p \leq 0.05$.
Normalized frequency was not statistically analyzed.

Note that a distinction is made between frequency and normalized frequency (lane changes/mile) in Table 3.2. Large differences were noted in examining the frequency counts. For example, there were 5,313 lane changes completed on interstates while only 3,354 were completed on U.S. highways. One possible reason for this discrepancy could be that the interstate drivers drove longer routes. For this reason, an analysis of normalized data was performed for each participant, and the results were used to fill in the cells for normalized data elsewhere in this report. Note that interstate drivers performed 0.35 lane change/mile, while U.S. highway drivers performed 0.38 lane change/mile, showing that most of the difference in frequency was due to the number of miles driven on the two routes. Table 3.3 contains the participant-by-participant analysis for normalized frequency. (Participants are numbered 2 through 17; participant 1 did not complete the experiment.)

Table 3.3. Lane Changes per Mile for Each Participant by Vehicle Type Driven.

Part#	Route	Driver Type	Veh Type	Gender	LCs	Miles	LC/Mile	Miles per LC	Com-mutes	Miles per commute
2	I	SedDrv	Sed	M	409	1,016.3	0.40	2.48	22	46.20
2	I	SedDrv	SUV	M	443	1,190.3	0.37	2.69	20	59.52
3	I	SedDrv	Sed	F	417	920.1	0.45	2.21	20	46.01
3	I	SedDrv	SUV	F	421	1,247.1[*]	0.34	2.96	26	47.97
4	US	SedDrv	Sed	F	139	427.8	0.32	3.08	20	21.39
4	US	SedDrv	SUV	F	124	448.4	0.28	3.62	20	22.42
5	US	SedDrv	Sed	M	334	688.4	0.49	2.06	20	34.42
5	US	SedDrv	SUV	M	319	662.0	0.48	2.08	21	31.52
6	I	SUVDrv	Sed	F	216	950.6	0.23	4.40	23	41.33
6	I	SUVDrv	SUV	F	242	1,258.5[†]	0.19	5.20	25	50.34
7	I	SUVDrv	Sed	M	268	973.4	0.28	3.63	22	44.25
7	I	SUVDrv	SUV	M	233	848.4	0.27	3.64	20	42.42
8	US	SedDrv	Sed	M	239	455.6	0.52	1.91	20	22.78
8	US	SedDrv	SUV	M	212	455.3	0.47	2.15	20	22.77
9	I	SedDrv	Sed	M	201	634.9	0.32	3.16	20	31.75
9	I	SedDrv	SUV	M	237	700.0	0.34	2.95	20	35.00
10	US	SUVDrv	Sed	M	324	607.9	0.53	1.88	20	30.40
10	US	SUVDrv	SUV	M	310	672.7	0.46	2.17	20	33.64
11	US	SUVDrv	Sed	F	156	447.6	0.35	2.87	20	22.38
11	US	SUVDrv	SUV	F	180	509.2	0.35	2.83	18	28.29
12	I	SedDrv	Sed	F	453	927.4	0.49	2.05	20	46.37
12	I	SedDrv	SUV	F	420	897.7	0.47	2.14	20	44.89
13	US	SUVDrv	Sed	F	63	307.1	0.21	4.87	20	15.36
13	US	SUVDrv	SUV	F	37	306.6	0.12	8.29	20	15.33
14	US	SUVDrv	Sed	M	239	772.2	0.31	3.23	20	38.61
14	US	SUVDrv	SUV	M	213	800.8	0.27	3.76	20	40.04
15	I	SUVDrv	Sed	M	263	704.5	0.37	2.68	20	35.23
15	I	SUVDrv	SUV	M	274	703.3	0.39	2.57	20	35.17
16	I	SUVDrv	Sed	F	431	1,019.7	0.42	2.37	20	50.99
16	I	SUVDrv	SUV	F	385	1,105.9	0.35	2.87	20	55.30
17	US	SedDrv	Sed	F	245	629.0	0.39	2.57	20	31.45
17	US	SedDrv	SUV	F	220	660.4	0.33	3.00	21	31.45
Grand Total or Mean					**8,667**	**23,949.1**	**0.36**	**2.76**	**658**	**36.40**

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[*] Participant drove 3 extra days (6 commutes) for testing purposes

[†] Participant drove 2 extra days (4 commutes) for testing purposes

It is interesting to observe that the number of lane changes per mile was quite consistent across all drivers and routes. The most extreme values were 0.12 and 0.53 with a mean of 0.36 per mile. Another way to view these data is by looking at the average number of lane changes per mile for each participant, where route is not specifically considered. As illustrated by Table 3.4, the extreme values are 0.16 and 0.50. In addition, Figure 3.2 is a histogram of lane changes per mile for the set of 16 drivers, showing the relatively tight clustering of this parameter.

A balanced design was used to best represent a large segment of drivers. Participants were selected so that gender, route, vehicle type, and driver type would be equally represented; however, no practical differences in terms of lane change frequency, duration, urgency, and severity level were observed. For this reason, designing separate or specialized systems to account for such factors would not be necessary.

Table 3.4. Lane Changes per Mile for Each Participant.

Part#	Route	Driver Type	Gender	LCs	Miles	LC/Mile	Miles per LC	Com-mutes	Miles per commute
2	I	SedDrv	M	852	2206.6	0.39	2.59	42	52.54
3	I	SedDrv	F	838	2167.2	0.39	2.59	46	47.11
4	US	SedDrv	F	263	876.2	0.30	3.33	40	21.91
5	US	SedDrv	M	653	1350.4	0.48	2.07	41	32.94
6	I	SUVDrv	F	458	2209.1	0.21	4.82	48	46.02
7	I	SUVDrv	M	501	1821.8	0.28	3.64	42	43.38
8	US	SedDrv	M	451	910.9	0.50	2.02	40	22.77
9	I	SedDrv	M	438	1334.9	0.33	3.05	40	33.37
10	US	SUVDrv	M	634	1280.6	0.50	2.02	40	32.02
11	US	SUVDrv	F	336	956.8	0.35	2.85	38	25.18
12	I	SedDrv	F	873	1825.1	0.48	2.09	40	45.63
13	US	SUVDrv	F	100	613.7	0.16	6.14	40	15.34
14	US	SUVDrv	M	452	1573	0.29	3.48	40	39.33
15	I	SUVDrv	M	537	1407.8	0.38	2.62	40	35.20
16	I	SUVDrv	F	816	2125.6	0.38	2.60	40	53.14
17	US	SedDrv	F	465	1289.4	0.36	2.77	41	31.45
Grand Total or Mean				**8,667**	**23,949.1**	**0.36**	**2.76**	**658**	**36.40**

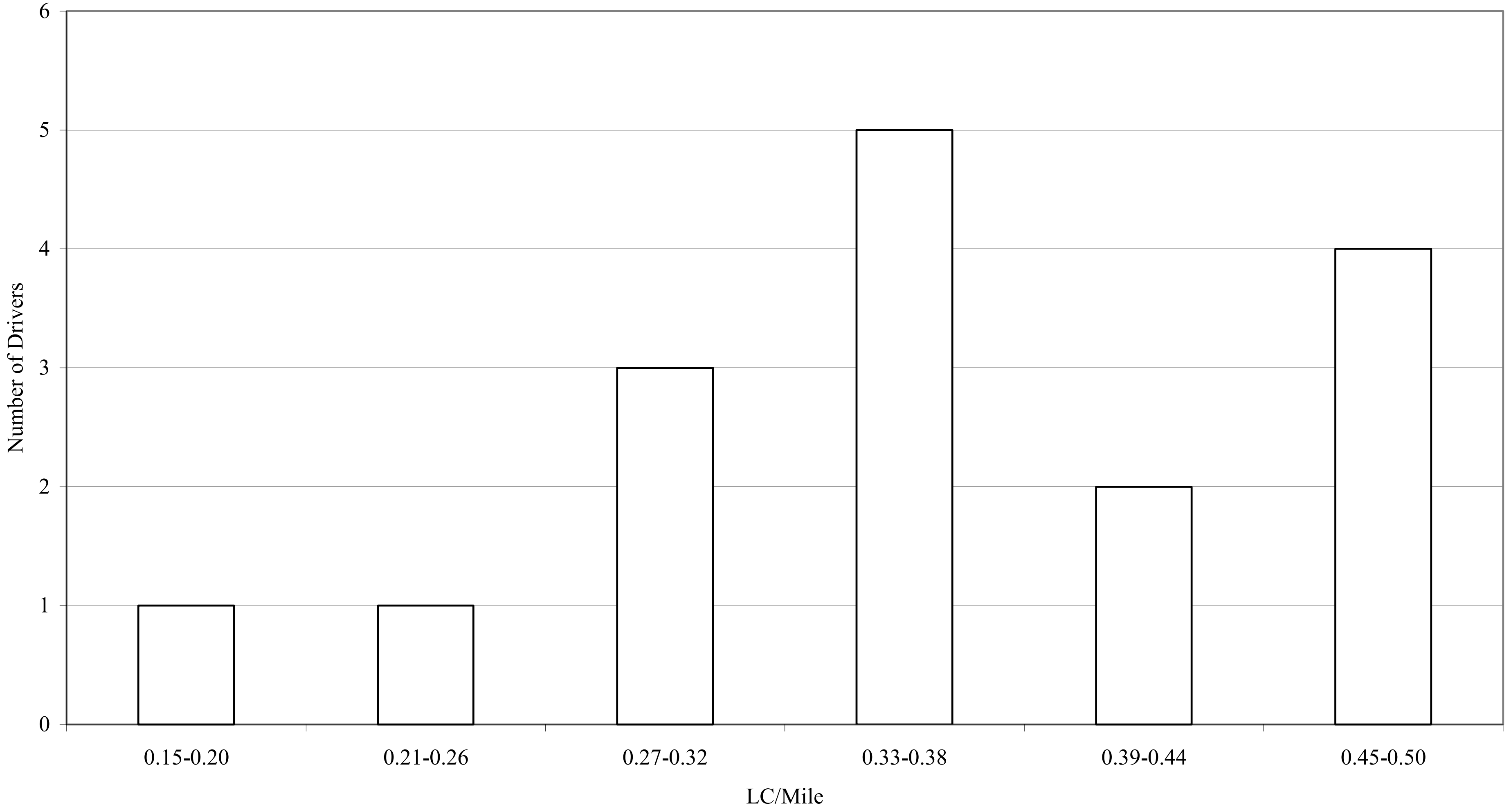

Figure 3.2. Histogram of Average Number of Lane Changes per Mile.
(mean = 0.36 per mile)

The two-way combinations of each independent variable were examined in terms of each dependent measure. These are presented in Tables 3.5 through 3.9, with one table per dependent measure showing all possible two-way combinations. A chi-square analysis was performed for frequency. There were two significant interactions. For the gender by route interactions, female interstate drivers performed significantly more lane changes than did the other three groups (Table 3.5). For the normalized data, male highway drivers had more lane changes per mile (Table 3.6). For the gender by driver type interaction, it appears that both male and female sedan drivers made more lane changes than male or female SUV drivers. This finding was also observed in the normalized frequency analysis. Separate ANOVAs were run for duration, severity, and urgency; however, no significant two-way interactions were found in these analyses.

Table 3.5. Two-Way Distributions of Frequency for Gender, Vehicle Type, Route, and Driver Type.

Frequency		**Driver Type**		**Gender**		**Vehicle Type**	
		SUV Driver	**Sedan Driver**	**Male**	**Female**	**SUV**	**Sedan**
Route	Interstate	2,312	3,001	***2,328***	***2,985***	2,655	2,658
	Highway	1,522	1,832	***2,190***	***1,164***	1,616	1,738
Driver Type	SUV			***2,124***	***1,710***	1,875	1,959
	Sedan			***2,394***	***2,439***	2,396	2,437
Gender	Male					2,241	2,277
	Female					2,030	2,119

Gray and Bold Italics = significant main effect of $p \leq 0.001$.

Table 3.6. Two-Way Distributions of Normalized Frequency for Gender, Vehicle Type, Route, and Driver Type.

Normalized Freq (Lane Changes per Mile)		**Driver Type**		**Gender**		**Vehicle Type**	
		SUV Driver	**Sedan Driver**	**Male**	**Female**	**SUV**	**Sedan**
Route	Interstate	0.31	0.40	0.34	0.36	0.33	0.37
	Highway	0.34	0.41	0.43	0.31	0.36	0.40
Driver Type	SUV			0.35	0.29	0.30	0.34
	Sedan			0.41	0.40	0.38	0.43
Gender	Male					0.37	0.39
	Female					0.32	0.38

Statistical analysis was not possible for this variable since the normalized frequency analysis provided only four data points for each of the values presented in this table. There was only one normalized frequency data point for each driver (e.g., there were four male SUV drivers and four male sedan drivers, and only one data point for each). The low N and large number of variables is the reason that this analysis could not be performed.

Table 3.7. Two-Way Distributions of Mean Duration for Gender, Vehicle Type, Route, and Driver Type.

Mean Duration (seconds)		Driver Type		Gender		Vehicle Type	
		SUV Driver	Sedan Driver	Male	Female	SUV	Sedan
Route	Interstate	7.77	7.96	7.47	8.20	7.81	7.95
	Highway	10.76	11.12	10.50	11.81	11.13	10.79
Driver Type	SUV			8.91	9.02	8.95	8.96
	Sedan			8.97	9.34	9.16	9.16
Gender	Male					8.74	9.14
	Female					9.43	9.00

No significant two-way interactions.

Table 3.8. Two-Way Distributions of Mean Urgency for Gender, Vehicle Type, Route, and Driver Type.

Mean Urgency (scale of 1 to 3)		Driver Type		Gender		Vehicle Type	
		SUV Driver	Sedan Driver	Male	Female	SUV	Sedan
Route	Interstate	1.03	1.03	1.03	1.02	1.03	1.03
	Highway	1.04	1.10	1.09	1.05	1.08	1.07
Driver Type	SUV			1.04	1.03	1.04	1.03
	Sedan			1.08	1.03	1.05	1.05
Gender	Male					1.06	1.05
	Female					1.03	1.03

No significant two-way interactions.

Table 3.9. Two-Way Distributions of Mean Severity for Gender, Vehicle Type, Route, and Driver Type.

Mean Severity (scale of 1 to 5)		Driver Type		Gender		Vehicle Type	
		SUV Driver	Sedan Driver	Male	Female	SUV	Sedan
Route	Interstate	1.14	1.23	1.24	1.15	1.20	1.18
	Highway	1.06	1.14	1.14	1.04	1.11	1.10
Driver Type	SUV			1.14	1.08	1.10	1.12
	Sedan			1.25	1.14	1.21	1.18
Gender	Male					1.21	1.18
	Female					1.11	1.12

No significant two-way interactions.

Urgency and Severity

All lane changes were classified on the basis of urgency and severity as previously defined in Chapter 2. Table 3.10 presents the one-way frequency distributions for severity and urgency followed by the two-way distribution of urgency by severity, along with the mean durations for each category. The most common severity rating was 1 (low severity), with 95% of lane changes falling into this category. For urgency, a rating of 1 (low urgency) was also the most common category, covering 96% of all lane changes. For the two-way distribution of severity by urgency, the low severity, low urgency category (1 and 1) occurred most frequently as it comprised more than 91% of all lane changes.

Table 3.10. Severity and Urgency Distributions.

Severity and Urgency Rating Levels	Frequency	Percentage	Mean Duration
Severity			
1	8,241	95.1%	9.03
2	106	1.2%	8.29
3	14	0.2%	5.83
4	2	<0.1%	17.70
5	299	3.4%	*10.62*
6	5	<0.1%	8.80
Grand Total or Mean	**8,667**	**100%**	**9.07**
Urgency			
1	8,303	95.8%	8.99
2	341	3.9%	11.10
3	23	0.3%	9.67
Grand Total or Mean	**8,667**	**100%**	**9.07**
Severity x Urgency			
S = 1, U = 1	7,933	91.5%	8.95
S = 1, U = 2	290	3.3%	11.12
S = 1, U = 3	18	0.2%	8.94
S = 2, U = 1	100	1.2%	7.91
S = 2, U = 2	6	< 0.1%	14.73
S = 2, U = 3	—	—	—
S = 3, U = 1	13	0.1%	6.00
S = 3, U = 2	1	< 0.1%	3.60
S = 3, U = 3	—	—	—
S = 4, U = 1	2	< 0.1%	17.70
S = 4, U = 2	—	—	—
S = 4, U = 3	—	—	—
S = 5, U = 1	250	2.9%	10.57
S = 5, U = 2	44	0.5%	10.68
S = 5, U = 3	5	< 0.1%	12.30
S = 6, U = 1	5	< 0.1%	8.80
S = 6, U = 2	—	—	—
S = 6, U = 3	—	—	—
Grand Total or Mean	**8,667**	**100%**	**9.07**

Urgency and Severity by Maneuver Type

Distributions were developed showing urgency and severity ratings for each of the 11 maneuver types (e.g., slow lead vehicle, exit/prep exit). These are presented in Tables 3.11 through 3.16 with each table representing a different severity rating. Taken together, these tables represent a three-way distribution with severity as the top-level factor. The most common lane change type using this distribution scheme was the slow lead vehicle, low urgency, low severity category, which represented 32% of all lane changes (2,751/8,667). The next most common category was the low urgency, low severity exit/prep exit (1,941 cases), followed by low urgency, low severity return (1,506 cases). Together, these three categories comprised 71.5% of all lane changes. To save space, only those maneuver type categories with data for at least one urgency category are shown in the tables.

Table 3.11. Distribution of Lane Changes by Urgency and Maneuver Type for Severity Rating = 1.

Frequency (Mean Duration)	**Urgency**			
Type	**1**	**2**	**3**	**Total**
Added lane	152 (6.03)	5 (4.48)	0	**157** **(5.98)**
Enter	647 (6.85)	2 (5.00)	0	**649** **(6.84)**
Exit/prepare to exit	1,941 (6.23)	9 (5.68)	1 (4.90)	**1,951** **(6.23)**
Lane drop	195 (6.69)	1 (5.60)	0	**196** **(6.68)**
Merging vehicle	190 (7.62)	13 (6.28)	5 (8.92)	**208** **(7.57)**
Other	158 (10.88)	0	0	**158** **(10.88)**
Return	1,506 (6.72)	2 (3.85)	0	**1,508** **(6.72)**
Rough/obstacle avoidance	18 (8.92)	3 (5.50)	2 (8.70)	**23** **(8.46)**
Slow lead vehicle	2,751 (13.09)	232 (12.52)	10 (9.41)	**2,993** **(13.03)**
Tailgated	315 (6.12)	22 (5.38)	0	**337** **(6.07)**
Unintended	60 14.76	1 (6.00)	0	**61** **(14.62)**
Grand Total	**7,933** **(8.95)**	**290** **(11.12)**	**18** **(8.94)**	**8,241** **(9.03)**

Table 3.12. Distribution of Lane Changes by Urgency and Maneuver Type for Severity Rating = 2.

Frequency (Mean Duration)	**Urgency**			
Type	**1**	**2**	**3**	**Total**
Enter	15 (7.35)	0	0	**15 (7.35)**
Exit/prepare to exit	13 (6.31)	0	0	**13 (6.31)**
Lane drop	1 (6.40)	1 (11.20)	0	**2 (8.80)**
Merging vehicle	10 (5.92)	0	0	**10 (5.92)**
Other	1 (10.30)	0	0	**1 (10.30)**
Return	4 (6.50)	0	0	**4 (6.50)**
Slow lead vehicle	52 (9.00)	3 (21.73)	0	**55 (9.70)**
Tailgated	1 (5.50)	2 (6.00)	0	**3 (5.83)**
Unintended	3 (7.63)	0	0	**3 (7.63)**
Grand Total	**100 (7.91)**	**6 (14.73)**	**0**	**106 (8.29)**

Table 3.13. Distribution of Lane Changes by Urgency and Maneuver Type for Severity Rating = 3.

Frequency (Mean Duration)	**Urgency**			
Type	**1**	**2**	**3**	**Total**
Enter	5 (7.42)	0	0	**5 (7.42)**
Exit/prep exit	3 (6.00)	0	0	**3 (6.00)**
Merging vehicle	1 (3.60)	1 (3.60)	0	**2 (3.60)**
Slow lead vehicle	3 (5.00)	0	0	**3 (5.00)**
Unintended	1 (4.30)	0	0	**1 (4.30)**
Grand Total	**13 (6.00)**	**1 (3.60)**	**0**	**14 (5.82)**

Table 3.14. Distribution of Lane Changes by Urgency and Maneuver Type for Severity Rating = 4.

Frequency (Mean Duration)	Urgency			
Type	**1**	**2**	**3**	**Total**
Enter	1 (9.10)	0	0	**1 (9.10)**
Slow lead vehicle	1 (26.30)	0	0	**1 (26.30)**
Grand Total	**2 (17.70)**	**0**	**0**	**2 (17.70)**

Table 3.15. Distribution of Lane Changes by Urgency and Maneuver Type for Severity Rating = 5.

Frequency (Mean Duration)	Urgency			
Type	**1**	**2**	**3**	**Total**
Enter	8 (8.41)	1 (21.80)	0	**9 (9.90)**
Exit/prepare to exit	46 (7.24)	4 (6.75)	1 (5.00)	**51 (7.16)**
Lane drop	3 (5.87)	0	0	**3 (5.87)**
Merging vehicle	2 (4.95)	4 (5.10)	0	**6 (5.05)**
Other	2 (6.40)	0	0	**2 (6.40)**
Return	37 (6.66)	0	0	**37 (6.66)**
Slow lead vehicle	138 (13.51)	34 (11.67)	4 (14.13)	**176 (13.17)**
Tailgated	12 (6.62)	1 (4.10)	0	**13 (6.42)**
Unintended	2 (5.80)	0	0	**2 (5.80**
Grand Total	**250 (10.57)**	**44 (10.68)**	**5 (12.30)**	**299 (10.62)**

Table 3.16. Distribution of Lane Changes by Urgency and Maneuver Type for Severity Rating = 6.

Frequency (Mean Duration)	**Urgency**			
Type	**1**	**2**	**3**	**Total**
Enter	1 (2.60)	0	0	1 (2.60)
Rough/obst avoid	1 (15.10)	0	0	1 (15.10)
Unintended	3 (8.77)	0	0	3 (8.77)
Grand Total	**5** **(8.80)**	**0**	**0**	**5** **(8.80)**

Distribution of Lane Change Types for High Severity

An earlier histogram (Figure 3.1) showed the distribution of lane change types for the entire dataset regardless of severity. However, it is also desirable to have data for higher severity lane changes because these may be more closely associated with crashes. Therefore, data for severity levels 3, 4, 5, and 6 were combined and plotted in Table 3.17 and Figure 3.3. The table shows the data by urgency level while the plot sums across urgency levels; the figure shows the frequency of occurrence in descending order.

Figure 3.3 exhibits the same rank ordering of occurrences as that of Figure 3.1, suggesting that low and high severity occurrences are similar in prevalence. However, it should be noted that for high severity lane changes, the slow lead vehicle category is even more dominant than the other categories. Specifically, for all severity levels (Figure 3.1), the slow lead vehicle category accounts for 37.2% of the occurrences, whereas the slow lead vehicle category accounts for 56.2% of occurrences for the higher severity levels.

Table 3.17. Distribution of Lane Changes by Urgency and Maneuver Type for High Severity Ratings (3 through 6).

Frequency (Mean Duration)	**Urgency**			
Type	**1**	**2**	**3**	**Total**
Enter	15 (7.74)	1 (21.80)	0	**16** **(8.62)**
Exit/prepare to exit	49 (7.17)	4 (6.75)	1 (5.00)	**54** **(7.09)**
Lane drop	3 (5.87)	0	0	**3** **(5.87)**
Merging vehicle	3 (4.50)	5 (4.80)	0	**8** **(4.69)**
Other	2 (6.40)	0	0	**2** **(6.40)**
Return	37 (6.66)	0	0	**37** **(6.66)**
Rough/obstacle avoidance	1 (15.10)	0	0	**1** **(15.10)**
Slow lead vehicle	142 (13.42)	34 (11.67)	4 (14.13)	**180** **(13.11)**
Tailgated	12 (6.62)	1 (4.10)	0	**13** **(6.42)**
Unintended	6 (7.04)	0	0	**6** **(7.03)**
Grand Total (Mean Duration)	**270** **(10.37)**	**45** **(10.53)**	**5** **(12.30)**	**320** **(10.42)**

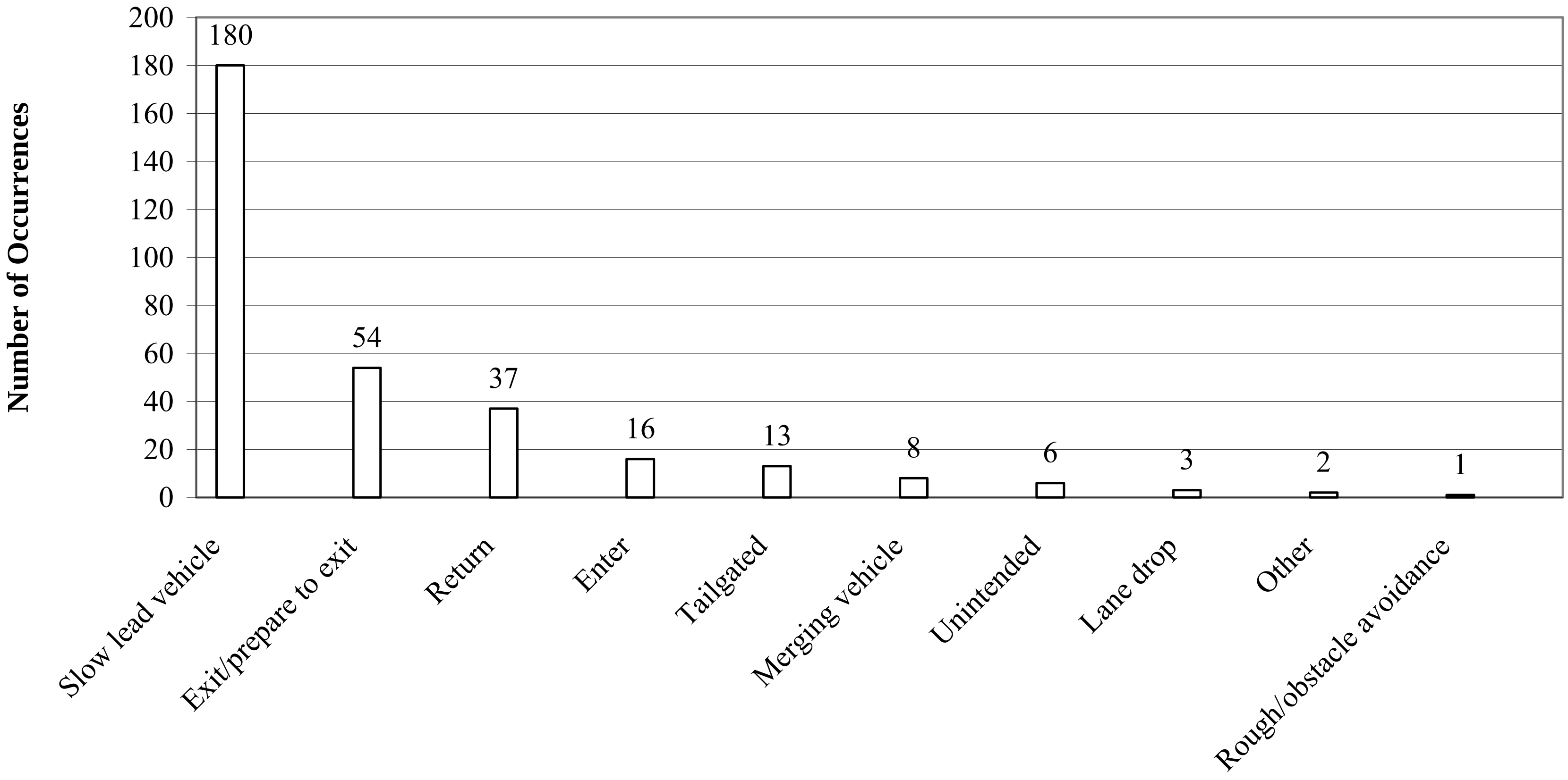

Figure 3.3. Occurrences of Lane Change Maneuver Type for High Severity Events, in Descending Order.

Initial Direction of Maneuver

All lane changes were classified according to the initial direction of maneuver. For example, if the SV was traveling in the right lane and moved to the left lane to pass a slow lead vehicle, the lane change would be classified as left in initial direction of maneuver. Table 3.18 provides the overall distribution of lane changes by direction. Most lane changes were to the left (55%). Lane changes to the left had a mean duration almost twice that of lane changes to the right. This is because most lane changes to the right were single lane changes, while many of the left lane changes were passing maneuvers to pass a slow lead vehicle, and could be up to 45 seconds long.

Table 3.18. Lane Change Direction Distributions.

Lane change direction	**Frequency**	**Mean Duration**	**Mean Severity**	**Mean Urgency**
Left	4,732	11.11	1.18	1.06
Right	3,935	6.62	1.13	1.02
Grand Total or Mean	**8,667**	**9.07**	**1.04**	**1.16**

Table 3.19 presents the two-way distribution of lane change direction by maneuver type. Differences in lane change type characteristics are shown clearly in this table. For example, there were 2,959 lane changes to the left to pass a slow lead vehicle compared to 269 lane changes to the right for the same maneuver type. This is because most drivers spend the majority of their time in the right lane. (As stated in Chapter 2, the highway route [U.S. Route 460] was generally a 4-lane [2 in each direction] roadway. The interstate had occasional segments with more than two lanes in each direction but was generally 2-lane.) It appears that drivers will rarely pass on the right; this seems to fit intuition as well as recommended practice. Thus, it is rare that a slow vehicle is in the left (fast) lane; passing on the right is less likely, and most drivers "settle" into the right lane and stay there the majority of the time. Other notable cases include exit/prep exit (536 to the left and 1,482 to the right), since most exits are to the right, and return (55 to the left and 1,494 to the right), since most of these represent cases of the SV returning to the originating lane after have passed a POV on the left.

Table 3.19. Maneuver Type by Lane Change Direction Distributions.

	Left Lane Changes		**Right Lane Changes**	
Maneuver Type	**Frequency**	**Mean Duration**	**Frequency**	**Mean Duration**
Added lane	57	5.82	100	6.07
Enter	556	6.73	124	7.65
Exit/prepare to exit	536	6.35	1,482	6.21
Lane drop	124	6.85	77	6.43
Merging vehicle	223	7.41	3	6.17
Other	141	11.25	20	7.81
Return	55	6.15	1,494	6.74
Rough/obstacle avoid	21	8.80	3	8.27
Slow lead vehicle	2,959	13.38	269	8.54
Tailgated	5	6.80	348	6.07
Unintended	55	15.29	15	7.73
Grand Total or Mean	**4,732**	**11.11**	**3,935**	**6.62**

Table 3.20 shows the two-way distribution of left and right lane changes by severity. The distribution is fairly even across severity categories. Likewise, Table 3.21 shows the distribution of left and right lane changes across urgency categories.

Table 3.20. Severity by Direction Distributions.

	Left Lane Changes		Right Lane Changes	
Severity Level	**Frequency**	**Mean Duration**	**Frequency**	**Mean Duration**
1	4,446	11.11	3,795	6.58
2	85	8.50	21	7.44
3	12	5.83	2	5.85
4	1	26.30	1	9.10
5	184	12.49	115	7.61
6	4	8.45	1	10.20
Grand Total or Mean	**4,732**	**11.11**	**3,935**	**6.62**

Table 3.21. Urgency by Direction Distributions.

	Left Lane Changes		Right Lane Changes	
Urgency Level	**Frequency**	**Mean Duration**	**Frequency**	**Mean Duration**
1	4,454	11.03	3,849	6.62
2	259	12.62	82	6.32
3	19	9.77	4	9.23
Grand Total or Mean	**4,732**	**11.11**	**3,935**	**6.62**

Success/Magnitude Distributions

All 8,667 lane changes were categorized according to the success and magnitude of the lane change. The four categories were single, passing (within 45 seconds), multiple, and unsuccessful (including partial lane changes). Table 3.22 presents the distributions of these categories. The two-way analysis of success/magnitude by maneuver type is presented in Table 3.23, while the two-way analyses for urgency and severity by success/magnitude are presented in Tables 3.24 and 3.25.

Table 3.22. Success/Magnitude Distributions.

Success/Magnitude	**Frequency**	**Mean Duration** (St Dev)	**Mean Severity** (St Dev)	**Mean Urgency** (St Dev)
Single	7,196	6.28 (2.01)	1.14 (0.69)	1.03 (0.17)
Passing	1,071	26.88 (9.11)	1.25 (0.95)	1.16 (0.40)
Multiple	289	10.97 (4.99)	1.30 (1.05)	1.02 (0.15)
Unsuccessful/partial	111	13.08 (27.22)	1.32 (1.14)	1.06 (0.31)
Grand Total or Mean	**8,667**	**9.07** (8.36)	**1.16** (0.75)	**1.04** (0.22)

Table 3.23. Maneuver Type by Success/Magnitude Distributions.

Maneuver Type	**Single LCs**		**Passing LCs**		**Multiple LCs**		**Unsucc LCs**	
	Freq.	**Mean Dur.**	**Freq.**	**Mean Dur.**	**Freq.**	**Mean Dur.**	**Freq.**	**Mean Dur.**
Added lane	155	5.78	2	21.50	0		0	
Enter	596	6.50	0		83	9.77	1	2.60
Exit/prep exit	1,858	5.87	3	20.60	156	10.49	1	3.40
Lane drop	201	6.69	0		0		0	
Merging vehicle	204	5.89	18	23.47	2	15.65	2	7.85
Other	94	7.50	13	12.86	33	15.36	21	17.27
Return	1,542	6.71	0		2	10.80	5	8.54
Rough/obst avoid	18	7.69	2	8.70	2	17.35	2	9.55
Slow lead vehicle	2,169	6.26	1,032	27.19	9	12.76	18	7.98
Tailgated	353	6.08	0		0		0	
Unintended	6	10.17	1	19.60	2	7.30	61	14.12
Grand Total/Mean	**7,196**	**6.28**	**1,071**	**26.88**	**289**	**10.97**	**111**	**13.08**

Table 3.24. Severity by Success/Magnitude Distributions.

Severity Level	**Single LCs**		**Passing LCs**		**Multiple LCs**		**Unsucc LCs**	
	Freq.	**Mean Dur.**	**Freq.**	**Mean Dur.**	**Freq.**	**Mean Dur.**	**Freq.**	**Mean Dur.**
1	6,877	6.27	997	27.00	266	11.03	101	13.75
2	93	6.23	10	27.54	1	9.20	2	7.45
3	12	5.55	0		1	10.70	1	4.30
4	1	9.10	1	26.30	0		0	
5	212	6.49	63	24.87	21	10.32	3	5.00
6	1	15.10	0		0		4	7.23
Grand Total/Mean	**7,196**	**6.28**	**1,071**	**26.88**	**289**	**10.97**	**111**	**13.08**

Table 3.25. Urgency by Success/Magnitude Distributions.

Urgency Level	Single LCs		Passing LCs		Multiple LCs		Unsucc LCs	
	Freq.	**Mean Dur.**	**Freq.**	**Mean Dur.**	**Freq.**	**Mean Dur.**	**Freq.**	**Mean Dur.**
1	7,000	6.31	915	28.31	282	10.94	106	13.36
2	189	5.04	142	19.19	7	12.40	3	6.93
3	7	6.20	14	11.76	0		2	7.25
Grand Total/Mean	**7,196**	**6.28**	**1,071**	**26.88**	**289**	**10.97**	**111**	**13.08**

One-Way and Two-Way Analyses of Slow Lead Vehicle Lane Changes

Since the maneuver type category of slow lead vehicle was the most common at 37.2% of all lane changes, it was selected for further analysis. This category was analyzed in a similar format as that used for the full data set. The mean duration for slow lead vehicle lane changes was 13.0 s, with a mean urgency rating of 1.1 and mean severity rating of 1.2.

In terms of success/magnitude, there were 2,169 (67.2%) single slow lead vehicle lane changes, 1,032 (32.0%) passes of ≤ 45 seconds, 9 (0.4%) multiple lane changes, and 18 (0.8%) unsuccessful (incomplete) lane changes.

Route, Driver Type, Vehicle Type, and Gender

Table 3.26 displays the frequency, duration, urgency, and severity for each of the independent variables (gender, route, driver type, and vehicle type). ANOVAs were performed for the dependent measures of duration, urgency, and severity, while chi-square analyses were performed to detect differences in actual and expected values for the frequency counts.

When comparing Table 3.26 with Table 3.2, the pattern of results is the same (mean duration of highway lane changes is longer for all the lane changes and for the slow lead vehicle lane changes), although comparisons among independent variables do not have the same levels of significance. Regardless, the practical differences observed appear to be minimal.

Table 3.26. One-Way Distributions for Gender, Vehicle Type, Route, and Driver Type for Slow Lead Vehicle Lane Changes

Independent Variables	Level	Dependent Variables			
		Frequency (Percent of total)	Mean Duration (Seconds) (StDev)	Mean Urgency (1-4) (StDev)	Mean Severity (1-7) (StDev)
Route	Interstate	1,700 (52.67%)	***10.48*** ***(9.82)***	***1.05*** ***(0.21)***	***1.33*** ***(1.07)***
	Highway	1,528 (47.34%)	***15.75*** ***(11.83)***	***1.14*** ***(0.37)***	***1.13*** ***(0.70)***
Driver Type	SUV Driver	***1,330*** ***(41.20%)***	12.67 (10.83)	***1.07*** ***(0.25)***	1.18 (0.78)
	Sedan Driver	***1,898*** ***(58.80%)***	13.19 (11.33)	***1.11*** ***(0.33)***	1.28 (1.00)
Gender	Male	1,700 (52.67%)	***12.59*** ***(10.78)***	***1.12*** ***(0.35)***	***1.28*** ***(0.98)***
	Female	1,528 (47.34%)	***13.41*** ***(11.49)***	***1.06*** ***(0.24)***	***1.19*** ***(0.83)***
Vehicle Type	SUV	1,585 (49.10%)	13.33 (11.58)	1.09 (0.31)	1.25 (0.93)
	Sedan	1,643 (50.90%)	12.64 (10.67)	1.09 (0.30)	1.23 (0.90)
Grand Total or Mean (StDev)		**3,228**	**12.98** **(11.13)**	**1.09** **(0.30)**	**1.24** **(0.92)**

Gray and Bold Italics = significant main effect of $p \leq 0.001$. Gray = significant main effect of $p \leq 0.05$.

All possible two-way combinations of the independent variables were examined in terms of each dependent measure. These are presented in Tables 3.27 through 3.30 with one table per dependent measure. As shown in Table 3.27, chi-square analyses indicated that, in terms of frequency, the interactions between gender and route and between gender and vehicle type were significant. No other interactions were significant. Results from separate ANOVAs performed for duration, severity, and urgency showed no significant two-way interactions (Tables 3.28 – 3.30).

Table 3.27. Two-Way Distributions of Frequency for Gender, Vehicle Type, Route, and Driver Type for Slow Lead Vehicle Lane Changes.

Frequency		**Driver Type**		**Gender**		**Vehicle Type**	
		SUV Driver	**Sedan Driver**	**Male**	**Female**	**SUV**	**Sedan**
Route	Interstate	705	995	***717***	***983***	846	854
	Highway	625	903	***983***	***545***	739	789
Driver Type	SUV			715	615	659	671
	Sedan			985	913	926	972
Gender	Male					866	834
	Female					719	809

Gray and Bold Italics = significant interaction effect of $p \leq 0.001$. Gray = significant interaction effect of $p \leq 0.05$.

Table 3.28. Two-Way Distributions of Mean Duration for Gender, Vehicle Type, Route, and Driver Type for Slow Lead Vehicle Lane Changes.

Mean Duration		**Driver Type**		**Gender**		**Vehicle Type**	
		SUV Driver	**Sedan Driver**	**Male**	**Female**	**SUV**	**Sedan**
Route	Interstate	10.04	10.80	9.56	11.16	10.55	10.42
	Highway	15.64	15.83	14.80	17.48	16.51	15.05
Driver Type	SUV			12.90	12.41	12.76	12.59
	Sedan			12.36	14.09	13.73	12.68
Gender	Male					12.40	12.78
	Female					14.44	12.50

No significant interactions.

Table 3.29. Two-Way Distributions of Mean Urgency for Gender, Vehicle Type, Route, and Driver Type for Slow Lead Vehicle Lane Changes.

Mean Urgency		**Driver Type**		**Gender**		**Vehicle Type**	
		SUV Driver	**Sedan Driver**	**Male**	**Female**	**SUV**	**Sedan**
Route	Interstate	1.05	1.05	1.06	1.04	1.05	1.05
	Highway	1.08	1.18	1.17	1.08	1.15	1.13
Driver Type	SUV			1.08	1.05	1.07	1.06
	Sedan			1.15	1.06	1.11	1.10
Gender	Male					1.13	1.12
	Female					1.05	1.06

No significant interactions.

Table 3.30. Two-Way Distributions of Mean Severity for Gender, Vehicle Type, Route, and Driver Type for Slow Lead Vehicle Lane Changes.

Mean Severity		**Driver Type**		**Gender**		**Vehicle Type**	
		SUV Driver	**Sedan Driver**	**Male**	**Female**	**SUV**	**Sedan**
Route	Interstate	1.25	1.39	1.41	1.28	1.34	1.33
	Highway	1.09	1.16	1.19	1.04	1.14	1.13
Driver Type	SUV			1.23	1.12	1.17	1.18
	Sedan			1.31	1.24	1.30	1.26
Gender	Male					1.30	1.25
	Female					1.18	1.21

No significant effects.

Severity and Urgency

Table 3.31 lists the frequency and mean duration of slow lead vehicle lane changes for severity, urgency, and severity and urgency combinations. For severity, 92.7% of slow lead vehicle lane changes were rated with a severity of 1, and events rated with a severity of 5 were the next most common type (5.45%). As a reminder, events rated as 5 included lane changes in which another vehicle was present in the proximity zone (from 4 feet in front of the SV to within 30 feet of the rear of the SV) in the adjacent lane at the start of the lane change. In terms of urgency, 91.2% of lane changes were rated as urgency of 1. Urgency was an indicator of how soon the lane change was required; only a small percentage (8.76%) of lane changes took place relatively quickly (i.e., TTC < 5.5 s). Events rated low in both severity and urgency (1 and 1) accounted for 85.2% of the total, which is yet another indication that most lane changes observed were relatively safe.

Table 3.31. Severity and Urgency Distributions for Slow Lead Vehicle Lane Changes.

Severity and Urgency Rating Levels	**Frequency**	**Percentage**	**Mean Duration**
Severity			
1	2,993	92.7%	11.17
2	55	1.70%	9.02
3	3	<0.1%	1.04
4	1	<0.1%	—
5	176	5.45%	10.91
6	—	—	—
Grand Total or Mean	**3,228**	**100%**	**12.98**
Urgency			
1	2,945	91.23%	11.32
2	269	8.33%	9.05
3	14	0.43%	4.22
Grand Total or Mean	**3,228**	**100%**	**12.98**
Severity x Urgency			
S = 1, U = 1	2,751	85.22%	11.35
S = 1, U = 2	232	7.19%	9.09
S = 1, U = 3	10	0.31%	3.45
S = 2, U = 1	52	1.61%	8.04
S = 2, U = 2	3	<0.1%	17.82
S = 2, U = 3	—	—	—
S = 3, U = 1	3	<0.1%	*1.04*
S = 3, U = 2	—	—	—
S = 3, U = 3	—	—	—
S = 4, U = 1	1	<0.1%	—
S = 4, U = 2	—	—	—
S = 4, U = 3	—	—	—
S = 5, U = 1	138	4.28%	*11.70*
S = 5, U = 2	34	1.05%	*7.63*
S = 5, U = 3	4	0.12%	*4.52*
S = 6, U = 1	—	—	—
S = 6, U = 2	—	—	—
S = 6, U = 3	—	—	—
Grand Total or Mean	**3,228**	**100%**	**12.98**

Initial Direction of Maneuver

All of the slow lead vehicle lane changes were classified according to the initial direction of the maneuver. Table 3.32 provides the overall distribution of lane changes by direction. The large majority of lane changes were to the left (91.7%). Lane changes to the left had a mean duration that was substantially longer than lane changes to the right. As with lane changes of all types, this is because most lane changes to the right were single lane changes, while many of the left lane changes were passing maneuvers which in some cases were 45 seconds in duration. As previously mentioned, most drivers spend their time in the right lane and pass slower vehicles on the left; passing on the right was relatively rare (less then 9% of the total set of slow lead vehicle lane changes).

Table 3.32. Direction Distributions for Slow Lead Vehicle Lane Changes.

Lane change direction	Frequency	Mean Duration	Mean Severity	Mean Urgency
Left	2,959	13.38	1.23	1.09
Right	269	8.54	1.34	1.16
Grand Total or Mean	**3,228**	**12.98**	**1.24**	**1.04**

Table 3.33 shows the distribution of left and right slow lead vehicle lane changes by severity. A familiar pattern can be observed: regardless of direction, most lane changes (92.9% to the left and 90.3% to the right) were rated low in severity (i.e., severity = 1).

Table 3.33. Severity by Direction Distributions for Slow Lead Vehicle Lane Changes.

	Left Lane Changes		Right Lane Changes	
Severity Level	Frequency	Mean Duration	Frequency	Mean Duration
1	2,750	13.45	243	8.32
2	51	9.74	4	9.10
3	3	5.00	0	
4	1	26.30	0	
5	154	13.49	22	10.87
6	0		0	
Grand Total or Mean	**2,959**	**13.38**	**269**	**8.54**

Table 3.34 shows the distribution across urgency categories. Most lane changes (91.9% to the left and 84.4% to the right) were rated low in urgency.

Table 3.34. Urgency by Direction Distributions for Slow Lead Vehicle Lane Changes.

	Left Lane Changes		Right Lane Changes	
Urgency Level	Frequency	Mean Duration	Frequency	Mean Duration
1	2,718	*13.39*	227	8.77
2	228	13.49	41	7.10
3	13	10.47	1	14.50
Grand Total or Mean	**2,959**	**13.38**	**269**	**8.54**

Success/Magnitude Distributions

Slow lead vehicle lane changes were also categorized according to their success and magnitude in four categories (single, passing, multiple, and unsuccessful). Table 3.35 presents the distributions of these categories. The two-way analyses for urgency and severity by success/magnitude are presented in Tables 3.36 and 3.37.

Table 3.35. Success/Magnitude Distributions for Slow Lead Vehicle Lane Changes.

Success/Magnitude	Frequency	Mean Duration	Mean Severity	Mean Urgency
Single	2,169	6.26	1.23	1.06
Passing	1,032	27.19	1.26	1.16
Multiple	9	12.76	2.00	1.11
Unsuccessful/partial	18	7.98	1.00	1.28
Grand Total or Mean	**3,228**	**12.98**	**1.24**	**1.09**

Table 3.36. Severity by Success/Magnitude Distributions for Slow Lead Vehicle Lane Changes.

Severity Level	Single LCs		Passing LCs		Multiple LCs		Unsucc LCs	
	Freq.	Mean Dur.	Freq.	Mean Dur.	Freq.	Mean Dur.	Freq.	Mean Dur.
1	2,011	6.23	958	27.34	6	13.83	18	7.98
2	44	5.65	10	27.54	1	9.20	0	
3	3	5.00	0		0		0	
4	0		1	26.30	0		0	
5	0		63	24.87	2	11.30	0	
6	0		0	0	0		0	
Grand Total/Mean	**2,169**	**6.26**	**1,032**	**27.19**	**9**	**12.76**	**18**	**7.98**

Table 3.37. Urgency by Success/Magnitude Distributions for Slow Lead Vehicle Lane Changes.

Urgency Level	Single LCs		Passing LCs		Multiple LCs		Unsucc LCs	
	Freq.	Mean Dur.	Freq.	Mean Dur.	Freq.	Mean Dur.	Freq.	Mean Dur.
1	2,041	6.34	881	28.64	8	11.38	15	8.13
2	126	4.98	141	19.20	1	23.80	1	7.30
3	2	8.70	10	11.87	0		2	7.25
Grand Total/Mean	**2,169**	**6.26**	**1,032**	**27.19**	**9**	**12.76**	**18**	**7.98**

One-Way and Two-Way Analyses of Single Lane Changes

As mentioned throughout this report, lane changes were categorized according to their success and magnitude in four categories, the majority of which were *single lane changes* at 83%. Significant one-way effects and two-way interactions are reported here for the 7,196 single lane changes across all levels of maneuver type, severity, and urgency. The two dependent variables of duration and frequency were analyzed by the independent variables of gender, route, driver type, and vehicle type. The mean duration of single lane changes was 6.28 s (*SD* = 2.0) with a median of 6.0 s. There were no significant main effects or interactions for duration (analyzed using an ANOVA), while there were several significant main effects or interactions for frequency (chi-square analysis). Descriptive one-way statistics for frequency and duration are presented in Table 3.38.

Table 3.38. Gender, Vehicle Type, Driver Type, and Route Classifications for Single Lane Changes.

		Freq.	**Duration**	**SD**
Gender	Male	*3,679*	6.15	2.10
	Female	*3,517*	6.42	1.89
Vehicle Type	SUV	3,552	6.21	2.09
	Sedan	3,644	6.35	1.92
Driver Type	SUV Driver	***3,237***	6.46	2.10
	Sedan Driver	***3,959***	6.14	1.91
Route	Interstate	***4,728***	6.25	1.63
	Highway	***2,468***	6.34	2.58

Gray and Bold Italics = significant main effect of $p \leq 0.001$.
(The main effect for gender had $p = 0.056$).

Gender, Driver Type, Vehicle Type, and Route for Single Lane Changes

For frequency, there were two significant main effects for single lane changes. Sedan drivers made significantly more single lane changes (N = 3,959) than did SUV drivers (N = 3,237) ($X_1^2 = 32.37$; $p < 0.001$). Significantly more single lane changes were completed on the interstate (N = 4,728) than on the U.S. highway (N = 2,468) ($X_1^2 = 709.78$; $p < 0.001$). Males (N = 3,679) made more lane changes than females (N = 3,517); this difference was not significant ($X_1^2 = 3.65$; $p = 0.056$); however, given a larger sample size, significant differences might have been observed.

There were also three significant interactions for frequency for single lane changes, as shown in Table 3.39. Female interstate drivers completed significantly more single lane changes than males, while male highway drivers completed more single lane changes than females ($X_1^2 = 307.92$; p < 0.001). Both male and female sedan drivers completed significantly more single lane changes than male and female SUV drivers ($X_1^2 = 40.98$; p < 0.001). On the interstate, both SUV and sedan drivers made significantly more single lane changes than highway drivers ($X_1^2 = 6.43$; p = 0.011).

There were also three significant interactions for frequency for single lane changes, as shown in Table 3.39. Both male and female interstate drivers completed significantly more single lane changes than did male and female highway drivers ($X_1^2 = 307.92$; p < 0.001); however, females made more single lane changes than males on the interstate while males made more lane changes than females on the highway. Both male and female sedan drivers completed significantly more single lane changes than male and female SUV drivers ($X_1^2 = 40.98$; p < 0.001). On the interstate, both SUV and sedan drivers made significantly more single lane changes than highway drivers ($X_1^2 = 6.43$; p = 0.011).

Table 3.39. Significant Frequency Interactions for Single Lane Changes.

		Route		**Driver Type**	
		Interstate	Highway	SUVDrv	SedDrv
Gender	Male	***2,064***	***1,615***	***1,790***	***1,889***
	Female	***2,664***	***853***	***1,447***	***2,070***
Driver Type	SUV Driver	2,076	1,161		
	Sedan Driver	2,652	1,307		

Gray and Bold Italics = significant main effect of $p \leq 0.001$. Gray = significant main effect of $p \leq 0.05$.

CHAPTER 4: SAMPLE DATASET OF 500 LANE CHANGES

The previous chapter described the entire dataset based on data available for all lane change events; the current chapter describes a sample of 500 lane changes in-depth. The sampling plan for selection of the 500 events is presented in this chapter, as well as descriptions of lane change performance in terms of braking, steering, velocity, and turn signal use. Detailed analyses of eye glance patterns and glance probabilities are presented. In addition, the results from a forward distance analysis and an adjacent/rear distance analysis are presented, and the concept of a "safety envelope" is discussed in terms of applicable parameters.

Sampling Plan

As discussed previously, 8,667 lane changes were classified by type, severity, and urgency. A sample of 500 lane changes was selected from this total, including lane changes representing all levels for each of the independent variables. The sampling plan had the following priorities:

1. Higher severity ratings were given first priority.
2. Higher urgency ratings were also considered important.
3. Emphasis was placed on specific maneuver types:
    - Slow lead vehicle.
    - Lane drop.
    - Enter and exit.
4. The balance was filled in to provide a representative sample of the full data set.

The sampling plan includes all 320 events with severity ratings of 3 or greater and all 106 events with a severity rating of 2. The remaining 74 events were selected from those having severity ratings of 1. The final sampling plan, which was derived from the classification of all lane changes, is shown in Figure 4.1.

It is important to note that this sample is purposely biased toward critical and urgent events. Only 26 of the events in the sample (5.2%) had a severity of 1 and an urgency of 1. This biased sampling was used to emphasize analysis for situations when problems with lane changes would be most likely to occur. Also, design of a CAS must be such that it works as well as possible for all lane changes. However, thresholds and timing would probably be based on the more critical situations. Thus, a sample that is purposely biased toward critical situations appears to be appropriate.

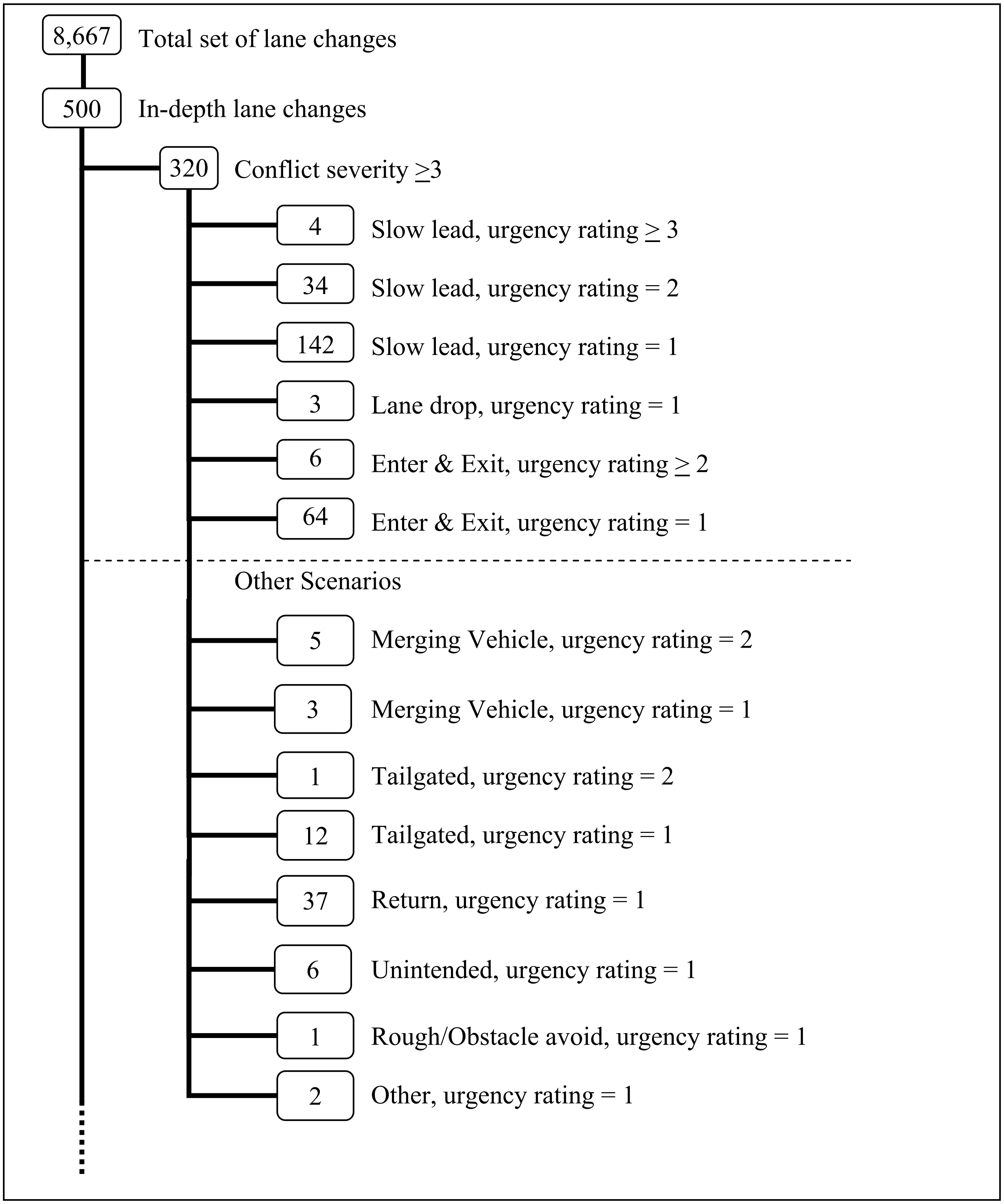

Figure 4.1. Sampling Plan.

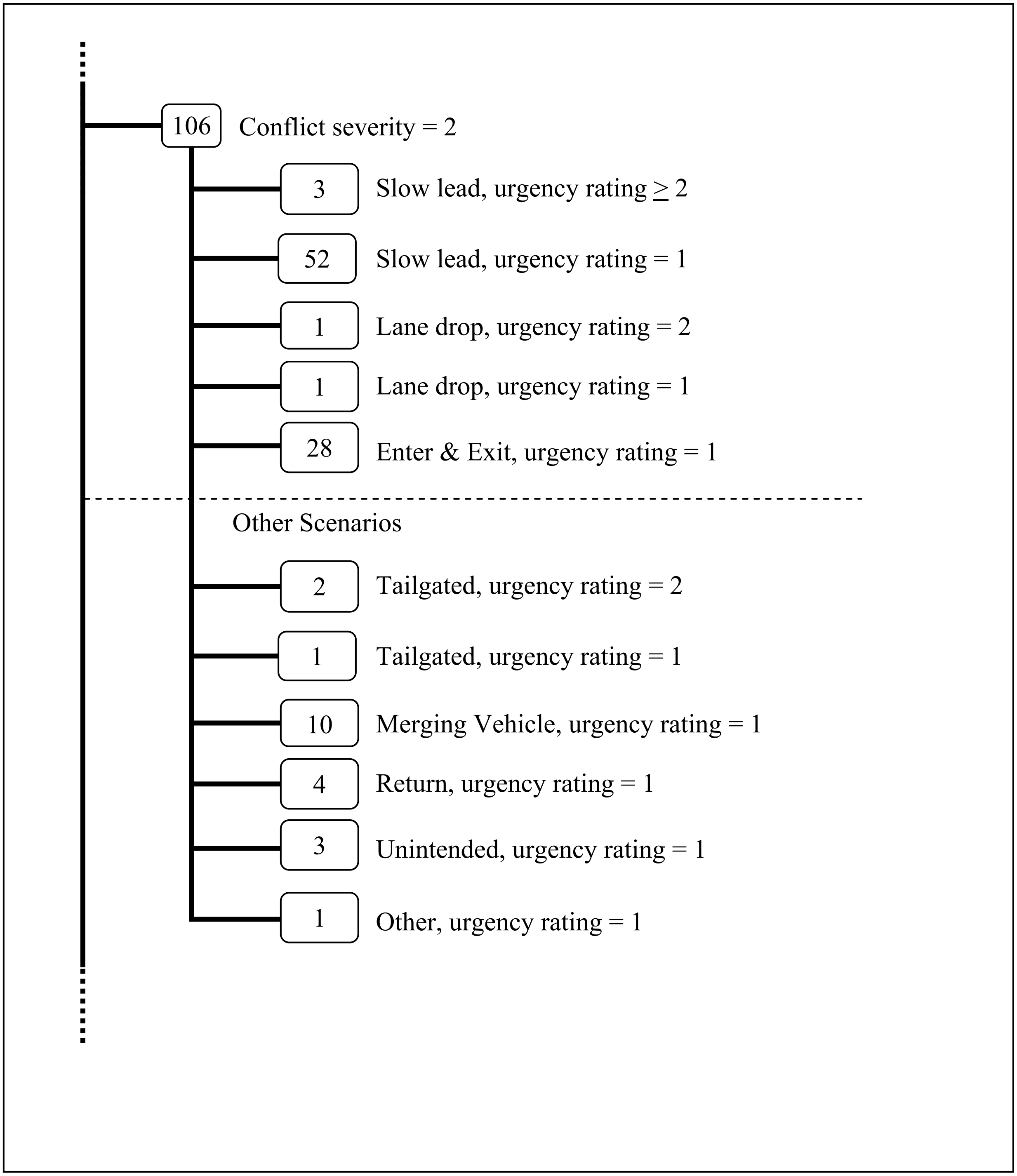

Figure 4.1. Sampling Plan (cont.)

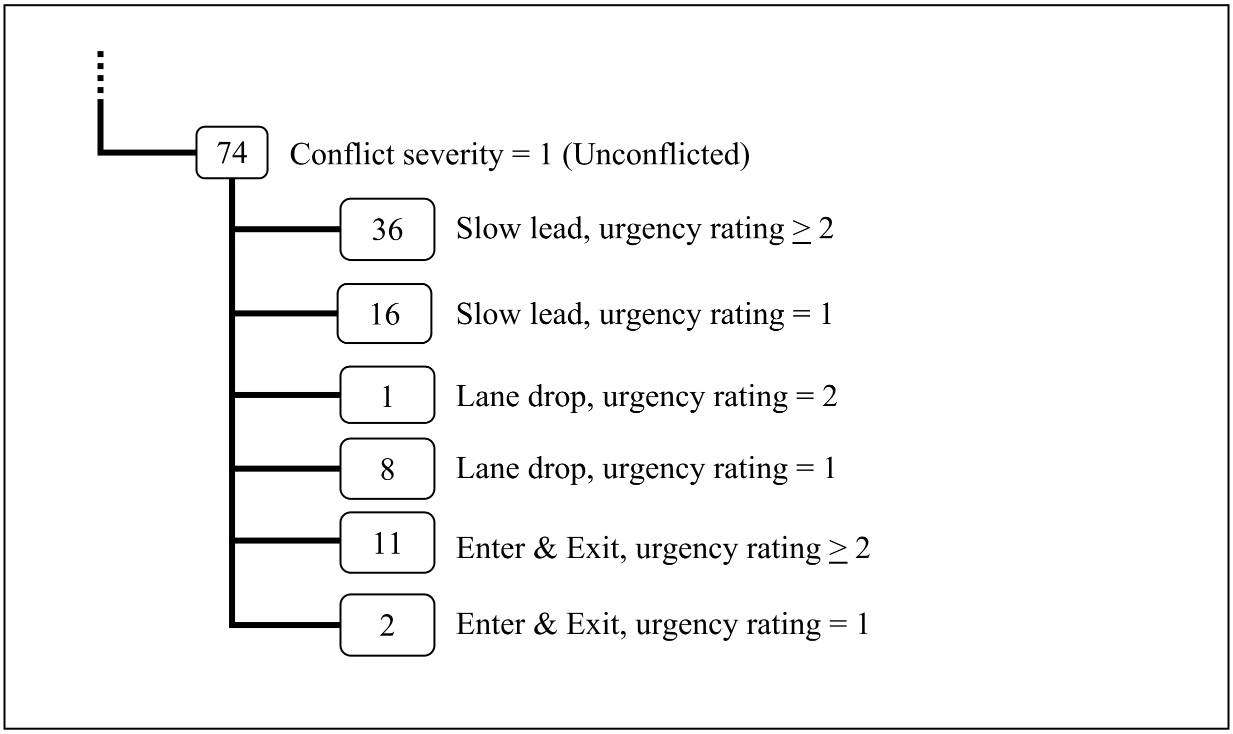

Figure 4.1. Sampling Plan (cont.).

One-Way and Two-Way Analyses of the Sample Data Set

Five hundred lane changes were sampled from the 8,677 lane changes available. In terms of the success/magnitude of this sample, there were 378 (75.6%) single lane changes, 89 (17.8%) passing maneuvers of ≤ 45 seconds, 21 (4.2%) multiple lane changes, and 12 (2.4%) unsuccessful (incomplete/partial) lane changes. Each lane change was categorized according to 10 maneuver types indicated by Table 4.1. (Note that none of the sampled lane changes was in the Added Lane category.)

The slow lead vehicle, exit/prep exit, return, and enter maneuver types were most prevalent, accounting for 87.4% (437) of the sample of lane changes. In general, the pattern of success/magnitude and maneuver type percentages followed the same pattern as was observed for the entire sample (i.e., Table 3.1). Another way to view these data is by observing the lane change frequencies for each participant (Table 4.2). More than 60% of all sampled lane changes were performed by only five participants, perhaps indicative of aggressive driving styles.

Table 4.1. Frequency and Percent of Lane Changes by Maneuver Type.

Maneuver Type	N	Percent	Mean Duration	Mean Urgency	Mean Severity
Slow lead vehicle	295	59.00%	11.49	1.28	3.55
Exit/prep exit	74	14.80%	6.87	1.16	3.92
Return	39	7.80%	6.86	1.00	4.69
Enter	29	5.80%	7.82	1.03	2.93
Merging vehicle	17	3.40%	5.48	1.29	3.12
Tailgated	17	3.40%	6.23	1.18	4.24
Lane drop	15	3.00%	6.79	1.13	1.93
Unintended	9	1.80%	7.23	1.00	4.11
Other	4	0.80%	7.03	1.00	3.25
Rough/obst avoid	1	0.20%	15.10	1.00	6.00
Grand Total or Mean	**500**	**100.00%**	**9.61**	**1.21**	**3.63**

Table 4.2. Number and Percentage of Lane Change Events by Participant.

Participant	# Observations	%	Cumulative %
12	78	15.6%	15.6%
2	62	12.4%	28.0%
9	57	11.4%	39.4%
15	54	10.8%	50.2%
5	51	10.2%	60.4%
3	33	6.6%	67.0%
8	32	6.4%	73.4%
16	30	6.0%	79.4%
7	22	4.4%	83.8%
6	19	3.8%	87.6%
10	16	3.2%	90.8%
17	12	2.4%	93.2%
14	11	2.2%	95.4%
11	10	2.0%	97.4%
13	7	1.4%	98.8%
4	6	1.2%	100.0%
TOTAL	**500**	**100.0%**	**100.0%**

The sample was also classified according to the initial direction of maneuver. Table 4.3 provides the overall distribution of lane changes by direction. Most lane changes were to the left (70%). Lane changes to the left had a mean duration that was substantially larger than those to the right. As with the entire set of maneuvers, this is because most lane changes to the right were single lane changes, while many of the left lane changes were passing maneuvers to pass a slow lead vehicle, and could be up to 45 seconds long (by previous definition).

Table 4.3. Lane Change Direction Distributions.

Lane change direction	**N**	**Mean Duration**	**Mean Urgency**	**Mean Severity**
Left	351	10.52 (9.11)	1.23 (0.49)	3.40 (1.76)
Right	149	7.47 (4.04)	1.17 (0.41)	4.17 (1.49)
Grand Total or Mean	**500**	**961 (8.06)**	**1.21 (0.47)**	**3.63 (1.72)**

Route, Driver Type, Vehicle Type, and Gender

Within the sample there were four independent variables from the original experimental design (gender, route, driver type, and vehicle type). The frequency, duration, urgency, and severity are displayed for each of these independent variables in Table 4.4. For frequency, the percentage of the total is noted (e.g., lane changes made while driving the SUV accounted for 51% of the total). Chi-square analysis was performed for the frequency counts while ANOVAs were run for the dependent measures of duration, urgency, and severity. The significant main effects for both the ANOVA and chi-square analyses are shown using shading in this and subsequent tables.

Table 4.4. One-Way Distributions for Gender, Vehicle Type, Route, and Driver Type.

Independent Variables	**Level**	**Dependent Variables**			
		Frequency (percent of total)	**Mean Duration seconds (StDev)**	**Mean Urgency 1 to 4 (StDev)**	**Mean Severity 1 to 7 (StDev)**
Route	Interstate	***355 (71.0%)***	9.79 (8.56)	1.14 (0.35)	3.75 (1.63)
	Highway	***145 (29.0%)***	9.17 (6.69)	1.41 (0.65)	3.30 (1.87)
Driver Type	SUV Driver	***169 (33.8%)***	8.25 (6.11)	1.17 (0.39)	3.28 (1.72)
	Sedan Driver	***331 (66.2%)***	10.31 (8.82)	1.24 (0.51)	3.79 (1.69)
Gender	Male	***305 (61.0%)***	9.30 (7.33)	1.26 (0.52)	3.74 (1.69)
	Female	***195 (39.0%)***	10.10 (9.08)	1.15 (0.38)	3.43 (1.75)
Vehicle Type	SUV	256 (51.2%)	9.35 (8.03)	1.22 (0.48)	3.60 (1.74)
	Sedan	244 (48.8%)	9.88 (8.10)	1.21 (0.47)	3.64 (1.70)
Grand Total or Mean		**500**	**9.61 (8.06)**	**1.21 (0.47)**	**3.63 (1.72)**

Gray and Bold Italics = significant main effect of $p \leq 0.001$. Gray = significant main effect of $p \leq 0.05$.

Table 4.5. Two-Way Distributions of Frequency for Gender, Vehicle Type, Route, and Driver Type.

Frequency		Driver Type		Gender		Vehicle Type	
		SUV Driver	Sedan Driver	Male	Female	SUV	Sedan
Route	Interstate	125	230	195	160	184	171
	Highway	44	101	110	35	72	73
Driver Type	SUV			103	66	79	90
	Sedan			202	129	177	154
Gender	Male					164	141
	Female					92	103

No significant two-way interactions.

Table 4.6. Two-Way Distributions of Mean Duration for Gender, Vehicle Type, Route, and Driver Type.

Mean Duration (seconds)		Driver Type		Gender		Vehicle Type	
		SUV Driver	Sedan Driver	Male	Female	SUV	Sedan
Route	Interstate	8.47	10.51	9.39	10.28	9.68	9.92
	Highway	7.64	9.84	9.13	9.28	8.52	9.81
Driver Type	SUV			8.59	7.73	7.98	8.49
	Sedan			9.66	11.31	9.97	10.69
Gender	Male					9.53	9.03
	Female					9.03	11.05

No significant two-way interactions.

Table 4.7. Two-Way Distributions of Mean Urgency for Gender, Vehicle Type, Route, and Driver Type.

Mean Urgency (scale of 1 to 4)		Driver Type		Gender		Vehicle Type	
		SUV Driver	Sedan Driver	Male	Female	SUV	Sedan
Route	Interstate	1.15	1.13	1.15	1.12	1.14	1.13
	Highway	1.23	1.49	1.45	1.29	1.43	1.38
Driver Type	SUV			1.19	1.14	1.20	1.14
	Sedan			1.29	1.15	1.23	1.25
Gender	Male					1.27	1.23
	Female					1.12	1.17

No significant two-way interactions.

Table 4.8. Two-Way Distributions of Mean Severity for Gender, Vehicle Type, Route, and Driver Type.

Mean Severity (scale of 1 to 7)		Driver Type		Gender		Vehicle Type	
		SUV Driver	Sedan Driver	Male	Female	SUV	Sedan
Route	Interstate	3.42	3.93	3.78	3.71	3.74	3.76
	Highway	2.89	3.48	3.66	2.14	3.22	3.37
Driver Type	SUV			3.49	2.97	3.20	3.36
	Sedan			3.87	3.67	3.77	3.81
Gender	Male					3.71	3.78
	Female					3.40	3.46

No significant two-way interactions.

Steering, Lateral Acceleration, Velocity, and Brake Pedal Use

Steering

The mean steering angle in degrees (converted from radians) for each maneuver type is listed in Table 4.9 based on the sample of 500 lane changes. This corresponds with the angle of the steering wheel at t_0 when the lane change started. Positive values indicate steering to the right and negative values indicate steering to the left. It appears that the steering angle is not a sensitive measure at t_0. Taking static measurements at t_0 may not provide insight into a dynamic process such as steering behavior prior to performing a lane change. Due to curvature in the road, absolute values of steering wheel angle do not appear to accurately indicate the direction of turn, as illustrated by Table 4.10 (i.e., the overall mean position values are essentially equivalent regardless of direction of turn). It appears that what was measured at t_0 was actually representative of steering behavior before the lane change actually started; however, the fact that the mean steering angle was positive in all cases indicates a bias in the positive direction. This could be due to one of three factors: (1) a bias in the vehicles (i.e., a lack of calibration); (2) the crown in the road; and (3) a general tendency for lane changes to occur on slight curves of road in one direction.

Table 4.9. Mean Steering Angle by Maneuver Type for Lane Change Sample.

Maneuver Type	Frequency	Mean Steering Angle (deg)	Steering Standard Deviation
Slow lead vehicle	295	7.81	10.65
Exit/prep exit	74	7.86	7.86
Return	39	7.98	6.44
Enter	29	11.26	16.84
Merging vehicle	17	8.43	11.33
Tailgated	17	9.81	4.04
Lane drop	15	4.39	8.29
Unintended	9	8.72	13.42
Other	4	15.61	1.51
Rough/obst avoid	1	14.90	1.51
Grand Total or Mean	**500**	**8.11**	**10.31**

Table 4.10. Steering Angle in Degrees by Lane Change Type and Direction (left and right) for Lane Change Sample

	Left Lane Changes		**Right Lane Changes**	
LC Type	**Mean Angle (degrees)**	**SD**	**Mean Angle (degrees)**	**SD**
Enter	12.22	17.81	6.65	11.36
Exit Prep/Exit	7.87	11.27	7.86	5.97
Lane Drop	3.63	10.25	5.54	4.65
Merging	8.43	11.33	n/a	n/a
Other	15.61	1.51	n/a	n/a
Return	7.83	15.10	7.99	5.66
Rough	14.90	n/a	n/a	n/a
Slow Lead	7.74	11.11	8.40	4.73
Tailgate	n/a	n/a	9.81	4.04
Unintended	7.16	19.22	9.97	8.88
OVERALL	**8.09**	**11.73**	**8.16**	**5.73**
	N = 351		**N = 149**	

The steering data only provide information as to SV behavior at t_0. However, steering is a dynamic parameter, and insight into this behavior can only truly be gained by looking at the data over time. As a result, the steering graph time traces generated by the lane change program were examined. An analysis of numerous cases revealed that generally there is no obvious pattern for lane changes in the steering data. These data are quite noisy, possibly due to road crown, road curvature, road irregularities, wind, or driver failure to maintain center lane position. In a few cases, exemplified by Figure 4.2, the steering exhibits the expected pattern and the 10 seconds preceding the lane change show a lack of steering input. In most of the cases, such as that shown in Figure 4.3, the entire time trace is very noisy with no discernible pattern. Figure 4.4 shows a pattern that appears to be a lane change in the 10 seconds preceding t_0, while the true lane change is much less obvious. Using steering traces as indicators for lane changes could be very misleading and result in unacceptably high numbers of false alarms for a lane change CAS.

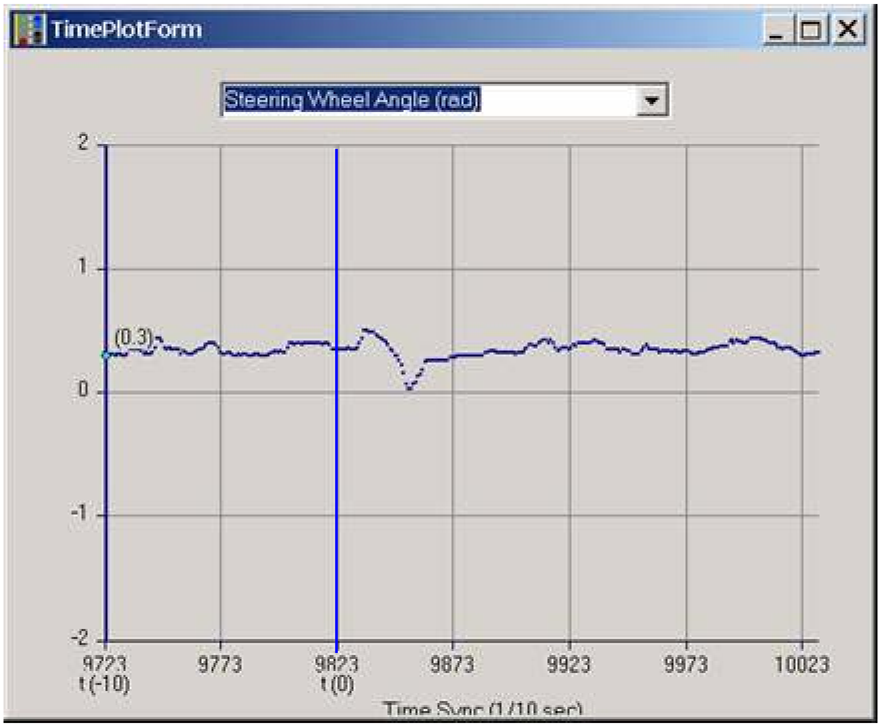

Figure 4.2. Time Trace of Steering Wheel Angle in Radians for the Case in which the Data Follow the Expected Pattern.

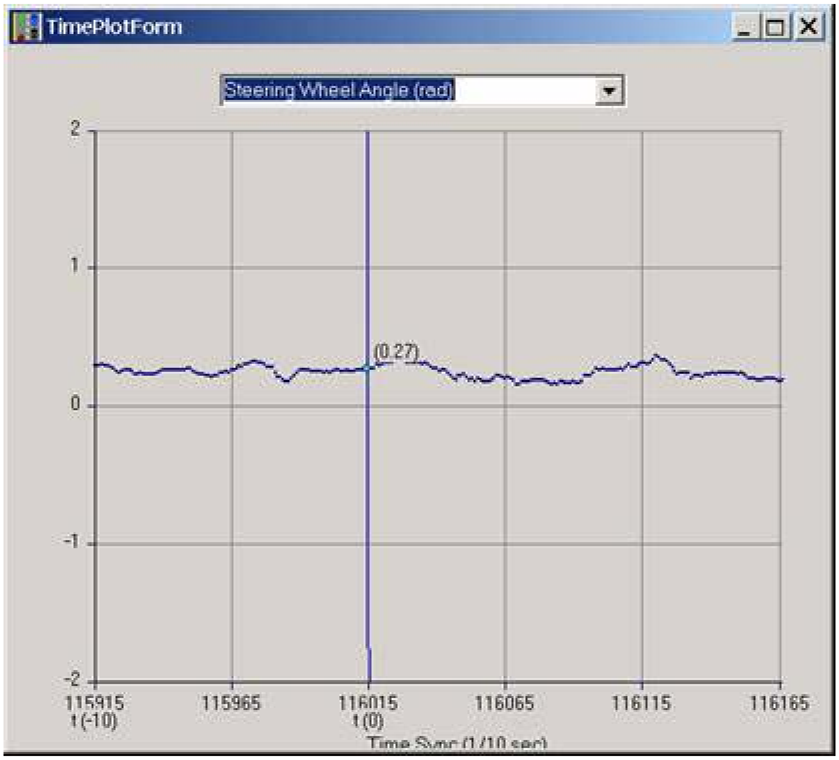

Figure 4.3. Time Trace of Steering Wheel Angle in Radians for the Case in which No Clear Pattern can be Discerned.

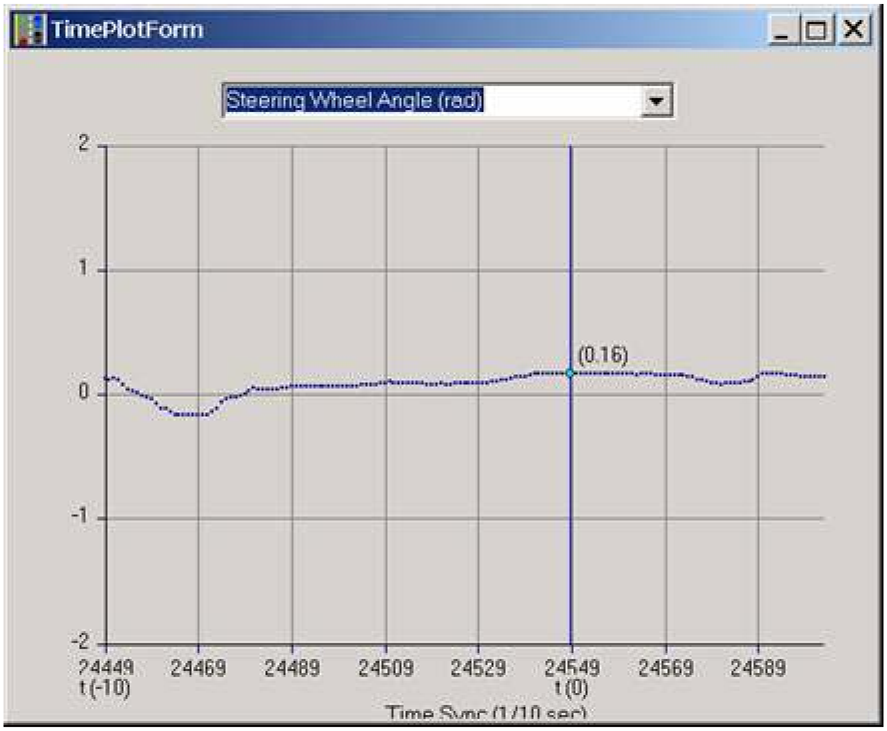

Figure 4.4. Time Trace of Steering for the Case in which the Lane Change Appears to Occur Prior to t_0.

Lateral Acceleration

Lateral acceleration also does not appear to be a sensitive measure around t_0. Table 4.11 illustrates the mean lateral acceleration by maneuver type. For lateral acceleration, negative values (or smaller positive values) are associated with moving to the right (the inverse of the direction of the steering angle) and positive values (or larger positive values) are associated with moving to the left, as evidenced by inspection of Table 4.12.

Table 4.11. Mean Lateral Acceleration by Maneuver Type for Lane Change Sample.

Maneuver Type	**Frequency**	**Mean Lateral Acceleration (gs)**	**Lateral Acceleration Standard Deviation**
Slow lead vehicle	295	0.023	0.05
Exit/prep exit	74	-0.018	0.05
Return	39	-0.026	0.05
Enter	29	-0.040	0.10
Merging vehicle	17	0.022	0.03
Tailgated	17	-0.031	0.03
Lane drop	15	0.005	0.05
Unintended	9	0.011	0.10
Other	4	0.008	0.05
Rough/obst avoid	1	0.020	n/a
Grand Total or Mean	**500**	**0.007**	**0.06**

Table 4.12. Mean Lateral Acceleration in Gs by Lane Change Type and Direction (Left and Right).

	Left Lane Changes		Right Lane Changes	
LC Type	**Mean Angle**	**SD**	**Mean Angle**	**SD**
Enter	-0.05	0.11	0.01	0.05
Exit/Prep Exit	0.02	0.06	-0.03	0.04
Lane Drop	0.04	0.02	-0.04	0.05
Merging Vehicle	0.02	0.03	0	0
Other	0.01	0.05	0	0
Return	0.04	0.09	-0.03	0.04
Rough	0.02	n/a	-0.03	0.04
Slow Lead Vehicle	0.03	0.05	-0.03	0.03
Unintended	0.08	0.10	-0.04	0.06
Enter	-0.05	0.11	0.01	0.05

The data provide a snapshot of SV behavior at t_0. A case can be made that lateral acceleration is a dynamic parameter and that insight can only be gained by looking at the data over time. An attempt was made to do this by examining the lateral acceleration graphs generated by the lane change program. As was true for the steering data, analysis of numerous cases revealed that most of the time there is no "telltale" pattern for lane changes in the lateral acceleration data. Although the data are less noisy than the steering data, these data are still quite noisy. Possible reasons for the high level of noise in the data include road crown, road curvature, road irregularities, wind, or driver failure to maintain center lane position. In a few cases, exemplified by Figure 4.5, the lateral acceleration exhibits the expected pattern and the 10 seconds preceding the lane change show a lack of lateral acceleration. In most cases, as shown in Figure 4.6, the entire time trace is very noisy and no clear pattern can be discerned. (Note the high g-values that were a function of this particular maneuver. This was an aggressive pass to the left of a slow lead vehicle on a curvy, mountainous road. The SV quickly approached the forward POV and then cut off the adjacent vehicle [Event #8]). Figure 4.7, however, shows a pattern that appears to be a lane change in the 10 seconds preceding t_0, while the true lane change is much less obvious. Using lateral acceleration time history as a trigger for such cases could be very misleading and result in unacceptably high numbers of false alarms.

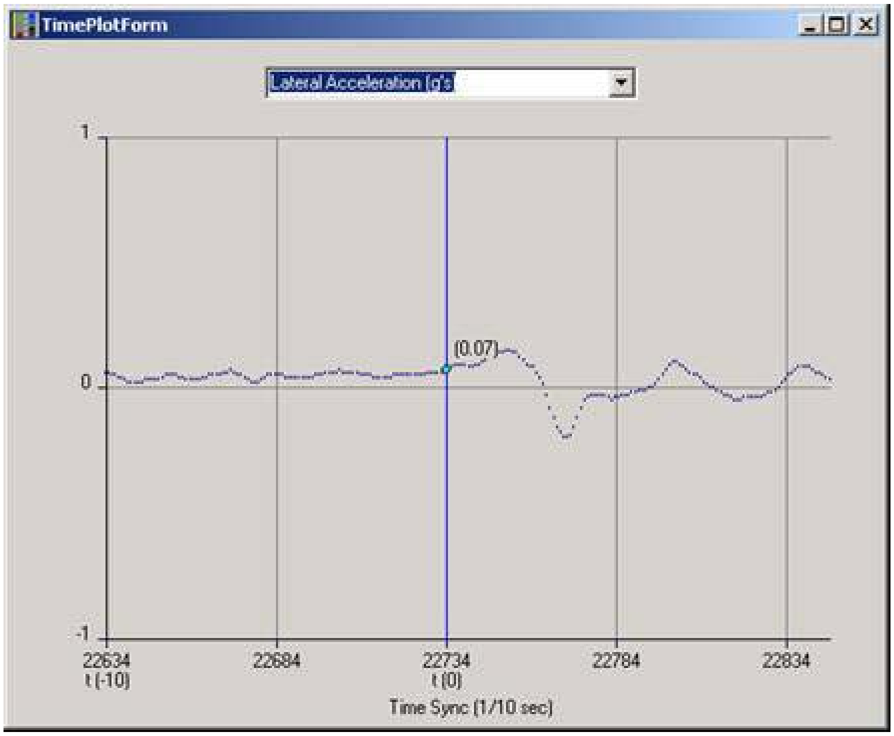

Figure 4.5. Time Trace of Lateral Acceleration for the Case in which the Data Follow the Expected Pattern.

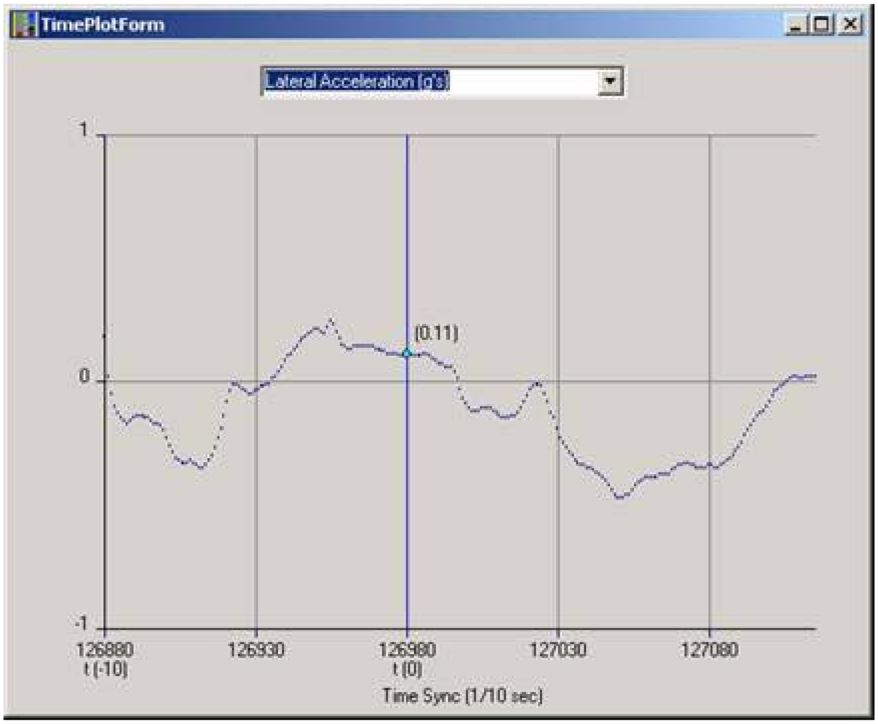

Figure 4.6. Time Trace of Lateral Acceleration for the Case in which No Clear Pattern can be Discerned.

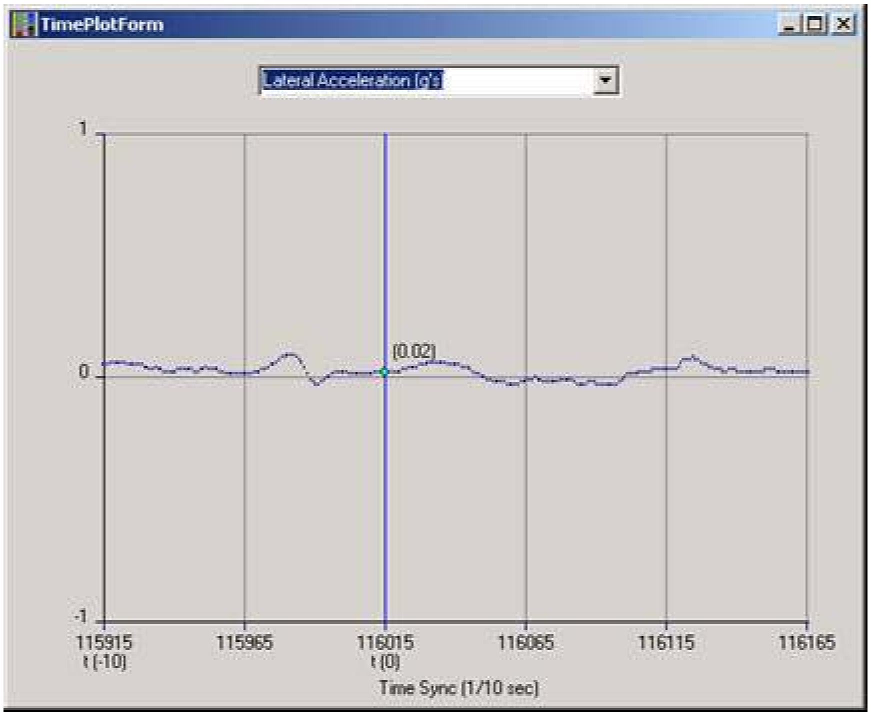

Figure 4.7. Time Trace of Lateral Acceleration for the Case in which the Lane Change Appears to Occur prior to t_0.

Velocity

Table 4.13 illustrates the average velocity of the instrumented vehicle for each maneuver type. For the most common maneuver (slow lead vehicle at 59.2%), the mean velocity of 60.1 was just above the overall average of 59.0. Another way to view these data is in terms of lane change types ranked from fastest to slowest. After inspecting Table 4.13, it is apparent that lane changes such as tailgate and return have the highest mean velocities. This appears reasonable as these events typically are right lane changes in which the driver changes lanes from the left (fast) lane into the right lane. At the extreme is the entering lane change (47.4 mph), in which the driver is entering the roadway and would likely not have reached the mean traffic speed until after entering the road. Yet another way to view these data is in terms of mean vehicle velocity by participant as shown by Table 4.14. In this table the route driven (interstate or U.S. highway) is included, illustrating that most of the faster driving occurred on the interstate.

Table 4.13. Mean Vehicle Velocity Ranked in Descending Order by Lane Change Type.

Type	**N**	**Mean**	**SD**
Tailgate	17	67.65	6.34
Return	39	63.83	9.78
Other	4	62.31	5.47
SlowLead	295	60.11	8.90
Rough	1	58.85	n/a
Unintended	9	57.95	12.47
Merging	17	57.25	8.03
LaneDrop	15	56.01	12.35
ExitPrep	74	55.55	10.48
Enter	29	47.41	9.51
Overall	**500**	**59.01**	**10.02**

Table 4.14. Mean Vehicle Velocity Ranked in Descending Order by Participant.

Participant	**N**	**Miles Driven**	**Route**	**Mean**
9	57	1,334.9	Interstate	65.08
8	32	910.9	US Highway	60.70
12	78	1,825.1	Interstate	60.07
2	62	2,206.6	Interstate	59.90
7	22	1,821.8	Interstate	59.80
5	51	1,350.4	US Highway	58.96
3	33	2,167.2	Interstate	58.84
16	30	2,125.6	Interstate	58.64
15	54	1,407.8	Interstate	58.10
10	16	1,280.6	US Highway	57.61
11	10	956.8	US Highway	54.64
4	6	876.2	US Highway	54.40
6	19	2,209.1	Interstate	53.17
17	12	1,289.4	US Highway	51.19
14	11	1,573.0	US Highway	49.14
13	7	613.7	US Highway	47.63
All Interstate	***355***	***15,098.1***	***Interstate***	***59.92***
All US Highway	***145***	***8,851.0***	***US Highway***	***56.78***
Overall	**500**	***23,949.1***	**n/a**	**59.01**

Comparison of Number of Lane Changes in Sample of 500 with Mean Speed of the Driver

It can be hypothesized that higher mean driving speeds will result in a greater number of lane changes and that such lane changes will have higher severities and urgencies. Higher speeds are usually associated with aggressive driving. Since the sample of 500 is dominated by high severity and high urgency maneuvers, it can be used to test whether there is a correlation between driver average speed and number of more critical lane changes. Thus, correlations were performed using number of lane changes (divided by miles driven) and mean vehicle velocity (Table 4.14) by participant.

For data pooled over interstate and U.S. routes, the correlation values were $r_{16} = 0.672$ ($p = 0.004$) and $r_{s16} = 0.803$ ($p = 0.0002$) for the Pearson and Spearman rank correlations respectively. For the interstate data, the correlation values were $r_8 = 0.588$ ($p = 0.125$) and $r_{s8} = 0.619$ ($p = 0.102$), and for the U.S. route data, they were $r_8 = 0.743$ ($p = 0.035$) and $r_{s8} = 0.667$ ($p = 0.071$). These results suggest that higher speeds are associated with more critical passing maneuvers. When the interstate data and the U.S. highway data are analyzed separately, the failure to achieve significance in some of these situations ($\alpha = 0.05$) is probably a result of the small sample size.

Brake Pedal Use

The total number of cases in which the brake pedal was used at t_0 is shown in Table 4.15. The maneuver type most often associated with brake pedal use was the slow lead vehicle lane change, followed by the exit/prep exit lane change. Although brake use is a relatively rare event, it seems reasonable that the brake pedal might be activated within these two categories of lane change. In the case of the slow lead vehicle, the vehicle ahead is slow and the SV is likely to activate the brake, while the driver is slowing in preparation for exiting the roadway in the exit/prep exit case.

Table 4.15. Brake Pedal Use by Maneuver Type.

Maneuver Type	Total Cases	Percent
Slow lead vehicle	14	2.8%
Exit/prep exit	6	1.2%
Enter	2	0.4%
Return	1	0.2%
Merging vehicle	1	0.2%
Lane drop	1	0.2%
Tailgated	0	0
Unintended	0	0
Other	0	0
Rough/obst avoid	0	0
Grand Total	**25**	**5.0%**

Turn Signal Use

In terms of turn signal use, analysis showed that turn signals were activated at t_0 only 44.2% of the time. The left turn signal was used 76.5% of the time and the right turn signal was used 23.5% of the time (Table 4.16). Turn signal use in terms of lane change direction is illustrated by Table 4.17. For left lane changes the turn signal was activated correctly 47.9% of the time at t_0. A turn signal indicator was correctly used at t_0 33.6% of the time for right lane changes. Another way to view these data is by looking at turn signal use by participant as illustrated by Table 4.18. Participants 14, 8, 10, 2, 6, and 11 used turn signals for fewer than 30% of their analyzed lane changes, while participants 4, 7, 12, 13, and 17 used turn signals in more than 65% of their cases.

Table 4.16. Turn Signal Use by Maneuver Type.

Maneuver Type	**None**	**Left Signal**	**Right Signal**
Slow lead vehicle	165	121	10
Exit/prep exit	34	15	24
Return	34	1	4
Enter	11	14	4
Merging vehicle	1	16	0
Tailgated	10	0	7
Lane drop	11	1	3
Unintended	9	0	0
Other	3	1	0
Rough/obst avoid	1	0	0
Grand Total	**279**	**169**	**52**
Percent (out of 500)	**55.8%**	**33.8%**	**10.4%**
Percent Overall	**55.8%**	**44.2%**	

Table 4.17. Turn Signal Use by Lane Change Direction.

Direction	**Turn Signal Use**			
	None	**Left**	**Right**	**TOTAL**
Left	51.85%	47.86%	0.28%	**351**
Right	65.10%	0.67%	34.23%	**149**
Left + Right	55.80%	33.80%	10.4%	**500**

Table 4.18. Participant Turn Signal Use.

	Turn Signal								
Part. #	**None**	**%**	**Left**	**%**	**Right**	**%**	**Left and Right**	**%**	**Total**
14	11	100.0%	0	0.0%	0	0.0%	0	0.0%	**11**
8	30	93.8%	0	0.0%	2	6.3%	2	6.3%	**32**
10	15	93.8%	0	0.0%	1	6.3%	1	6.3%	**16**
2	48	77.4%	4	6.5%	10	16.1%	14	22.6%	**62**
6	14	73.7%	1	5.3%	4	21.1%	5	26.3%	**19**
11	7	70.0%	3	30.0%	0	0.0%	3	30.0%	**10**
9	39	68.4%	13	22.8%	5	8.8%	18	31.6%	**57**
5	34	66.7%	8	15.7%	9	17.7%	17	33.3%	**51**
16	13	43.3%	13	43.3%	4	13.3%	17	56.7%	**30**
3	13	39.4%	17	51.5%	3	9.1%	20	60.6%	**33**
15	21	38.9%	27	50.0%	6	11.1%	33	61.1%	**54**
4	2	33.3%	4	66.7%	0	0.0%	4	66.7%	**6**
7	7	31.8%	13	59.1%	2	9.1%	15	68.2%	**22**
12	23	29.5%	50	64.1%	5	6.4%	55	70.5%	**78**
13	1	14.3%	6	85.7%	0	0.0%	6	85.7%	**7**
17	1	8.3%	10	83.3%	1	8.3%	11	91.7%	**12**
Total	**279**	**55.8%**	**169**	**33.8%**	**52**	**10.4%**	**221**	**44.2%**	**500**

Turn Signal Use in Comparison with Severity and Urgency

To expose the relationship between turn signal use and maneuver criticality, Table 4.19 illustrates the relationship between turn signal use and severity rating. Out of a total of 5 lane changes rated as severity 6, turn signals were used in 20% of the cases, a reasonable result given that these lane changes were unplanned maneuvers. The same pattern can be seen for each level of severity in terms of percentage of turn signal use, presented in descending order (in terms of "0" – no signal used). The results indicate that drivers used turn signals more often when there was a vehicle in the PZ or FAZ (severities of 2, 3, 4, and 5) than when no such vehicle was present (severity of 1).

Table 4.19. Turn Signal Use by Severity Rating.

Turn Signal Count					
Severity	**None**	**Left**	**Right**	**Left & Right**	**Total**
1	61.5%	29.7%	8.8%	38.5%	**91**
2	45.0%	45.0%	10.0%	55.0%	**100**
3	41.7%	50.0%	8.3%	58.3%	**12**
4	50.0%	50.0%	0.0%	50.0%	**2**
5	57.9%	30.7%	11.4%	42.1%	**290**
6	80.0%	20.0%	0.0%	20.0%	**5**
Total	**55.8%**	**33.8%**	**10.4%**	**44.2%**	**500**

Table 4.20 illustrates the relationship between turn signal use and urgency. Here, one can observe that of 14 total cases rated urgency 3, turn signals were used in only 29% of cases. Similarly, for the most common lane change urgency (i.e., those rated urgency 1), 57% did not have a turn signal indicator on at t_0. Since the urgency ratings refer to the SV's relationship to a lead vehicle in most cases, the lack of turn signal use for urgencies of 3 is not surprising, unless there was also a vehicle in the PZ or FAZ. This possibility is addressed in the next section.

Table 4.20. Turn Signal Use by Urgency Rating.

Turn Signal Percentage					
Urgency	**None**	**Left**	**Right**	**Left & Right**	**Total**
1	57.0%	34.2%	8.8%	43.0%	**409**
2	46.8%	33.8%	19.5%	53.3%	**77**
3	71.4%	21.4%	7.1%	28.6%	**14**
Total	**55.8%**	**33.8%**	**10.4%**	**44.2%**	**500**

Perhaps one of the most complex relationships is that between turn signal use and the combination of severity and urgency ratings. Tables 4.21 through 4.23 illustrate this relationship. For lane changes rated urgency 1 and severity 5, only 40% had either the left or right turn signal activated at t_0. Similarly, for lane changes rated urgency 2 and severity 5, 52% had the turn signal activated at t_0. In the previously discussed case, where the lane change had an urgency of 3, drivers used the turn signals more often when a vehicle was present in the PZ or FAZ (40%) than when no such vehicle was present (22%).

Table 4.21. Turn Signal Use by Severity where Urgency = 1.

Urgency	**Severity**	**None**	**Left**	**Right**	**Left & Right**	**Total**
1	**1**	62.5%	32.1%	5.4%	37.5%	**56**
	2	46.8%	45.7%	7.5%	53.2%	**94**
	3	45.5%	45.5%	9.1%	54.6%	**11**
	4	50.0%	50.0%		50.0%	**2**
	5	59.8%	29.9%	10.4%	40.3%	**241**
	6	80.0%	20.0%		20.0%	**5**
	Total	**56.97%**	**34.23%**	**8.80%**	**43.03%**	**409**

Table 4.22. Turn Signal Use by Severity where Urgency = 2.

Urgency	**Severity**	**None**	**Left**	**Right**	**Left & Right**	**Total**
2	**1**	53.9%	26.9%	19.2%	46.2%	**26**
	2	16.7%	33.3%	50.0%	83.3%	**6**
	3		100.0%		100.0%	**1**
	4					**0**
	5	47.7%	36.4%	15.9%	52.3%	**44**
	6					**0**
	Total	**46.8%**	**33.8%**	**19.5%**	**53.3%**	**77**

Table 4.23. Turn Signal Use by Severity where Urgency = 3.

Urgency	Severity	None	Left	Right	Left & Right	Total
3	**1**	77.8%	22.2%	0.0%	22.2%	**9**
	2					**0**
	3					**0**
	4					**0**
	5	60.0%	20.0%	20.0%	40.0%	**5**
	6					**0**
	Total	**71.4%**	**21.4%**	**7.1%**	**28.6%**	**14**

Eye Glance Patterns

Eye glance patterns were identified and analyzed to obtain a better understanding of driver visual behavior leading up to lane change initiation. It is likely that drivers exhibit set patterns of glance behavior prior to changing lanes. Identifying these patterns may lead to insights as to when drivers are preparing to change lanes based on the timing of glances. This information will be important in the development of CAS displays in terms of display location, the timing of warning/alert information, and overall system design. Additionally, studying glance patterns may assist CAS developers in determining the "last second" that a warning/alert must be issued to assist the driver in making a decision.

Eye glance data for all 500 lane change events are presented in Table 4.24. Eye glance location was analyzed for the 3 seconds prior to lane change initiation. Three seconds was selected for analysis since critical driver decisions must be made during that time period. The review of the full data set of 8,667 lane changes showed that 3 seconds was adequate to capture most pre-lane change scanning behavior. Glance positions of interest included center forward, rear view mirror, left mirror, right mirror, left window, right window, instrument cluster, left blind spot, and right blind spot. As discussed in Chapter 1, Tijerina et al. (1997) examined eye glance behavior using ride-along observers and participants while driving on public roads. It was found that specific eye glance patterns take place before lane change initiation. For example, prior to making a lane change to the left, the likelihood is highest of glancing at the forward view, followed by a glance to the left mirror or the rear view mirror.

Glance data from the current naturalistic lane change field study were analyzed in a similar manner. To understand what drivers do prior to performing lane changes, glance location was evaluated in terms of the proportion of glances to a particular location during the 3 seconds prior to lane change initiation (proportion of times that at least one glance occurred to a particular location was recorded). The highest proportion was associated with glancing forward (last column of Table 4.23) with at least one glance to the forward view for every event during the 3 seconds prior to t_0.

Data were also available for eye glance duration for various locations of interest. Eye glance durations include the transition time to the location of interest. These glances occurred during the 3 seconds prior to the beginning of the lane change; however, if there was a glance in progress at $t_{\text{minus 3}}$ or at t_0, the analysis was extended to cover those complete glances (i.e., the glances were not arbitrarily cut off at $t_{minus\ 3}$ or t_0). The mean analyzed time was 3.4 seconds per event due to this inclusion policy, rather than an even 3.0 seconds.

Glances to the forward view had the highest mean single glance time of 0.90 seconds, as well as the highest overall glance time per event (2.05 s out of 3.38 s analyzed). During the 3 seconds prior to t_0, there was an average of 2.3 glances to the forward view. This finding is not surprising given that driving is primarily a visual forward tracking task even when lateral movement is being planned. Note that the "other interior" category also had a high mean single glance time at 1.09 seconds, but this was limited to 12 glances out of 2,171 glances analyzed. These glances tended to be used for attending to the music system or the cell phone. Right blind spot and left mirror had the next highest durations at 0.72 and 0.68 s, followed by rear view mirror at 0.65 s. All other mean single glance times fell into the range of 0.58 to 0.64 s, except for instrument cluster at 0.51 s.

Table 4.24. Eye Glance Statistics for All Lane Changes, All Glance Locations for the 3 Seconds Prior to t_0 (500 events).

Glance location	**Glances /event (mean)**	**Overall glance time/event (mean)**	**Events w/ at least 1 glance**	**Total glances**	**Mean single glance time (s)**	**Glance probability during 3 s prior to t_0**
Forward - any direction	2.27	2.05	500	1,135	0.90	1.00
Center forward	1.88	1.80	491	922	0.96	0.98
Left forward	1.30	0.84	112	146	0.65	0.22
Right forward	1.22	0.79	55	67	0.65	0.11
RV mirror	1.37	0.89	262	359	0.65	0.52
Left mirror	1.26	0.86	197	248	0.68	0.39
Left window	1.29	0.78	115	148	0.61	0.23
Left blind spot	1.02	0.65	105	107	0.64	0.21
Instrument cluster	1.10	0.56	71	78	0.51	0.14
Right mirror	1.02	0.62	41	42	0.60	0.08
Right window	1.12	0.65	17	19	0.58	0.03
Right blind spot	1.11	0.79	19	21	0.72	0.04
Other interior	1.17	1.28	12	14	1.09	0.02
All events	**4.34**	**3.38**	**500**	**2,171**	**0.78**	**1.00**

The 295 slow lead vehicle lane changes were analyzed in greater depth. It is clear that surrounding vehicles were present. This was also the predominant maneuver type; it could be argued that different maneuver types could exhibit different glance patterns. For example, in a return maneuver, the driver has often just passed a slower vehicle and is aware of the POV's location and relative velocity. The SV driver was observed to make fewer and briefer glances prior to a return lane change than was the case for a slow lead vehicle lane change.

Out of 295 slow lead vehicle lane changes, each lane change had at least one glance to the forward view (i.e., 295 instances/295 lane changes = 1.0) in the 3 seconds prior to t_0. Regardless of the lane change direction, large proportions of glances were allocated for glances to the rear view mirror. Proportions for other glance locations are shown in Table 4.25, along with mean single glance times and overall glance times per event.

Table 4.25. Eye Glance Statistics for Slow Lead Vehicle Lane Changes, All Glance Locations for the 3 Seconds Prior to t_0 (295 events).

Glance location	Glances /event (mean)	Overall glance time/event (mean)	Events w/ at least 1 glance	Total glances	Mean single glance time (s)	Glance probability during 3 s prior to t_0
Forward - any direction	2.31	2.02	295	681	0.88	1.00
Center forward	1.94	1.78	289	560	0.92	0.98
Left forward	1.26	0.84	77	97	0.67	0.26
Right forward	1.20	0.89	20	24	0.74	0.07
RV mirror	1.38	0.80	157	217	0.58	0.53
Left mirror	1.25	0.83	138	172	0.66	0.47
Left window	1.25	0.77	89	111	0.62	0.30
Left blind spot	1.01	0.64	81	82	0.63	0.27
Instrument cluster	1.08	0.56	53	57	0.52	0.18
Right mirror	1.00	0.53	13	13	0.53	0.04
Right blind spot	1.25	0.80	4	5	0.64	0.01
Other interior	1.00	1.50	4	4	1.50	0.01
Right window	1.33	0.80	3	4	0.60	0.01
All events	**4.56**	**3.41**	**295**	**1346**	**0.75**	**1.00**

Glance link analysis was used to analyze eye glance patterns prior to lane change initiation in the manner described by Wierwille (1981). This analysis involves calculating link value probabilities, or the probability of a glance transition between two specific glance locations in the 3 seconds prior to lane change initiation. These probabilities do not indicate the order in which glances occurred but do indicate the likelihood of glancing from one glance location to another or vice versa as presented in Table 4.26.

The glance proportions from Table 4.25 can be combined with the link value probabilities from Table 4.26 as illustrated by Figure 4.8. This figure illustrates the glance proportions (using circles) and glance link probabilities (using arrows) between glance locations for all 295 slow lead vehicle lane changes. Proportions in the circles represent the probability of at least one glance to that location while link probabilities represent the probability of a glance transition between two specific glance locations. In both cases, values are for the 3 seconds prior to lane change initiation.

The two most likely glance locations were forward (1.0) and rear view mirror (0.53) with a link probability between these two locations of 0.35, a pattern similar to that reported by Tijerina et al. (1997). These findings provide valuable input for CAS designers when deciding where to place warning/alert indicators.

Table 4.26. Link Probabilities between Eye Glance Locations for Slow Lead Vehicle Lane Changes (N = 295).[*]

	LW	LM	F	RVM	RM	RW	RBS	IC
LBS	0.04	0.04	0.04					
LW		0.03	0.11	0.01				
LM			0.23	0.01				
F				0.35	0.02	0.01	0.01	0.09
RVM								
RM								
RW								
RBS								

Note: The following key is used for this and subsequent tables and figures:

OI	Other interior	RVM	Rear view mirror
CF	Center forward	IC	Instrument cluster
LF	Left forward	RF	Right forward
LW	Left window	RW	Right window
LM	Left mirror	RBS	Right blind spot
LBS	Left blind spot	RM	Right mirror
Ind	Other/indeterminate		

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[*] In this table and the following tables, link probabilities that do not round to 0.01 or larger are not shown. Due to rounding, in some cases the total of the probabilities is slightly greater than or less than 1.0.

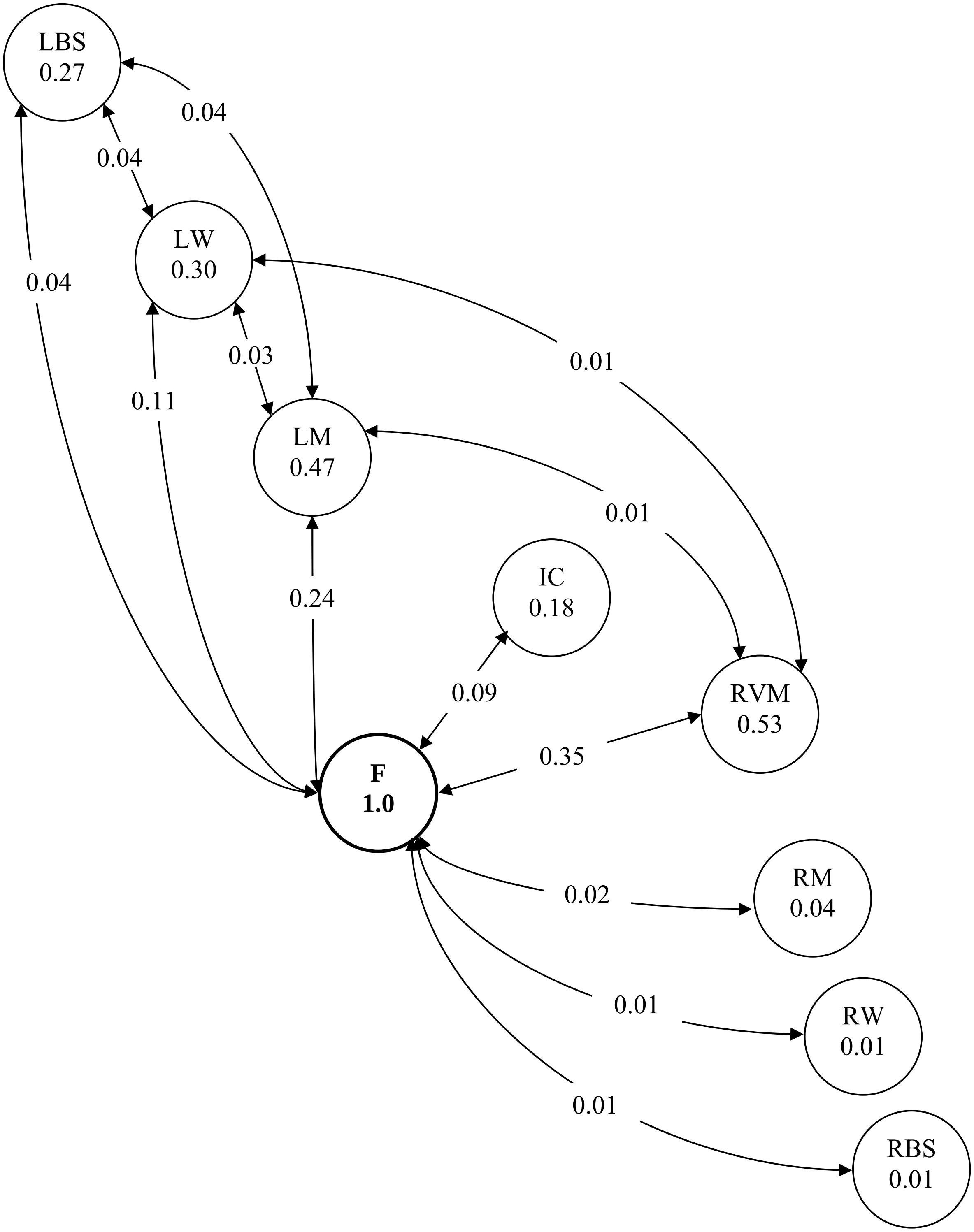

Figure 4.8. Glance Proportions (circles) and Link Probabilities (arrows) for Slow Lead Vehicle Lane Changes (N = 295 lane changes).

Following the same pattern as for all of the slow lead vehicle lane changes, Tables 4.27 and 4.28 present eye glance statistics for lane changes to the left and right. Out of 295 slow lead vehicle lane changes, 90% (266) were to the left and 10% (29) were to the right. Differences in glance proportions can be discovered by inspecting these two tables. For lane changes to the left, a larger proportion of glances were made to the left mirror and left blind spot, whereas more glances were to the right mirror and right blind spot for the right lane changes. The glance link value probabilities for both left and right slow vehicle lane changes are presented in Tables 4.29 and 4.30.

Table 4.27. Eye Glance Statistics for Slow Lead Vehicle Lane Changes to the Left, All Glance Locations, for the 3 Seconds Prior to t_0 (266 events).

Glance location	**Glances /event (mean)**	**Overall glance time/event (mean)**	**Events w/ at least 1 glance**	**Total glances**	**Mean single glance time (s)**	**Glance probability during 3 s prior to t_0**
Forward - any direction	2.34	1.98	266	622	0.85	1.00
Center forward	1.95	1.74	261	510	0.89	0.98
Left forward	1.26	0.84	77	97	0.67	0.29
Right forward	1.07	0.61	14	15	0.57	0.05
Rear view mirror	1.36	0.78	141	192	0.57	0.53
Left mirror	1.25	0.83	137	171	0.66	0.52
Left window	1.25	0.77	89	111	0.62	0.33
Left blind spot	1.01	0.64	81	82	0.63	0.30
Instrument cluster	1.08	0.56	52	56	0.52	0.20
Right mirror	1.00	0.41	7	7	0.41	0.03
Other interior	1.00	1.50	4	4	1.50	0.02
Right window	1.00	0.60	1	1	0.60	0.00
Right blind spot			0			0.00
All events	**4.68**	**3.42**	**266**	**1246**	**0.73**	**1.00**

Table 4.28. Eye Glance Statistics for Slow Lead Vehicle Lane Changes to the Right, All Glance Locations, for the 3 Seconds Prior to t_0 (29 events).

Glance location	Glances /event (mean)	Overall glance time/event (mean)	Events w/ at least 1 glance	Total glances	Mean single glance time (s)	Glance probability during 3 s prior to t_0
Forward - any direction	2.03	2.44	29	59	1.20	1.00
Center forward	1.79	2.20	28	50	1.23	0.97
Left forward			0			0.00
Right forward	1.50	1.53	6	9	1.02	0.21
Rear view mirror	1.56	0.94	16	25	0.60	0.55
Right mirror	1.00	0.67	6	6	0.67	0.21
Right blind spot	1.25	0.80	4	5	0.64	0.14
Right window	1.50	0.90	2	3	0.60	0.07
Left mirror	1.00	0.70	1	1	0.70	0.03
Instrument cluster	1.00	0.50	1	1	0.50	0.03
Left window			0			0.00
Left blind spot			0			0.00
Other interior			0			0.00
All events	**3.45**	**3.31**	**29**	**100**	**0.96**	**1.00**

Table 4.29. Link Probabilities between Eye Glance Locations for Left Slow Lead Vehicle Lane Changes (N = 266).

	LW	LM	F	RVM	RM	RW	RBS	IC
LBS	0.04	0.04	0.04					
LW		0.03	0.12	0.01				
LM			0.25	0.01				
F				0.34	0.01			0.09
RVM								0.01
RM								
RW								
RBS								

Table 4.30. Link Probabilities between Eye Glance Locations for Right Slow Lead Vehicle Lane Changes (N = 29).

	LW	LM	F	RVM	RM	RW	RBS	IC
LBS								
LW								
LM			0.02					
F				0.60	0.12	0.07	0.12	0.03
RVM					0.03	0.02		
RM								
RW							0.02	
RBS								

The glance proportions from Tables 4.27 and 4.28 were combined with the link value probabilities from Tables 4.29 and 4.30 as illustrated by Figures 4.9 and 4.10. These figures show the glance proportions and glance link probabilities between glance locations for the 266 left slow lead vehicle lane changes and the 29 right slow lead vehicle lane changes.

For left lane changes, the most likely glance locations were forward (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 and rear view mirror locations. The link value probabilities between forward and right mirror and between forward and right blind spot were also relatively high at 0.12.

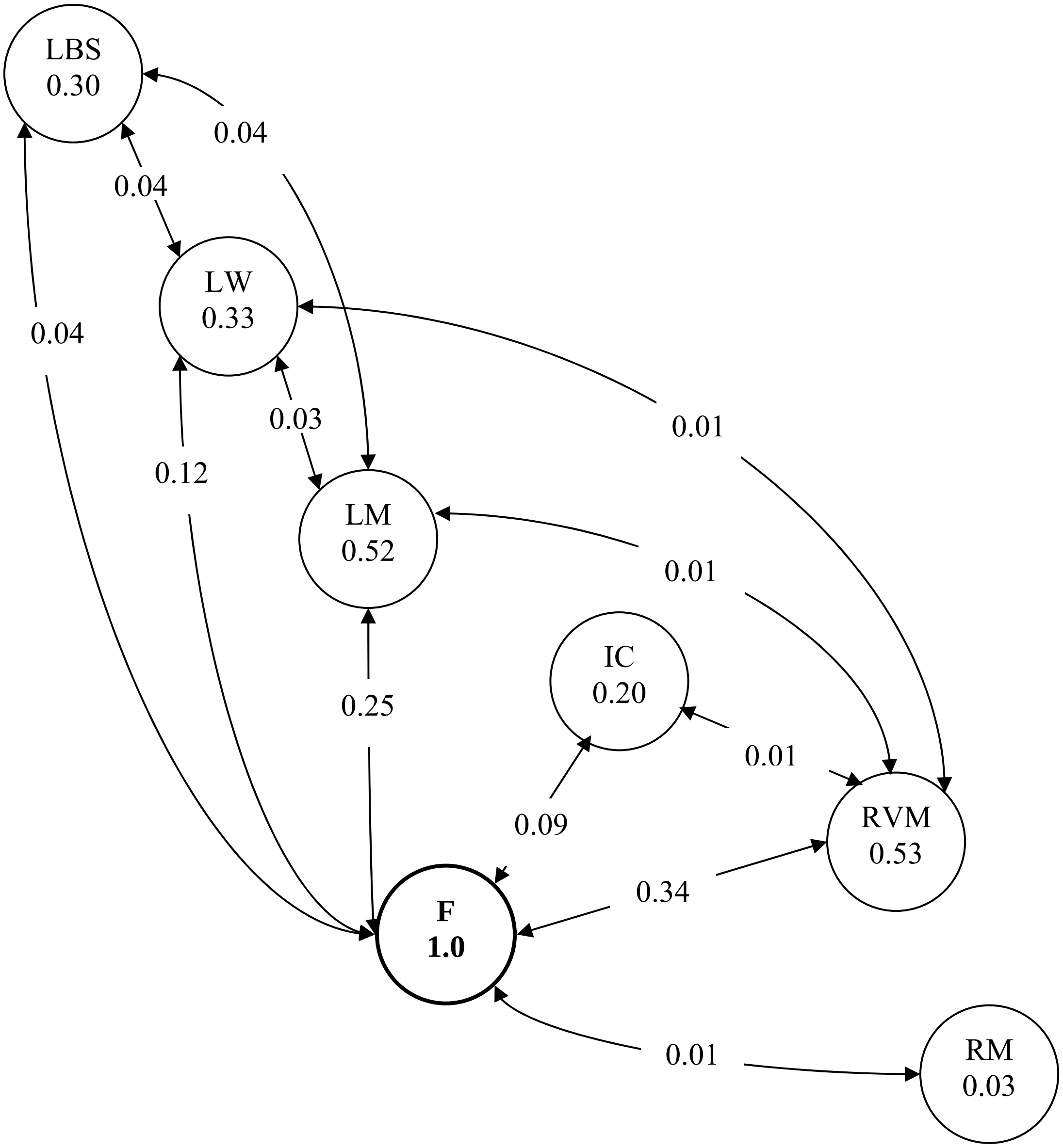

Figure 4.9. Glance Proportions (circles) and Link Probabilities (arrows) for Slow Lead Vehicle Lane Changes to the Left (N = 266 lane changes).

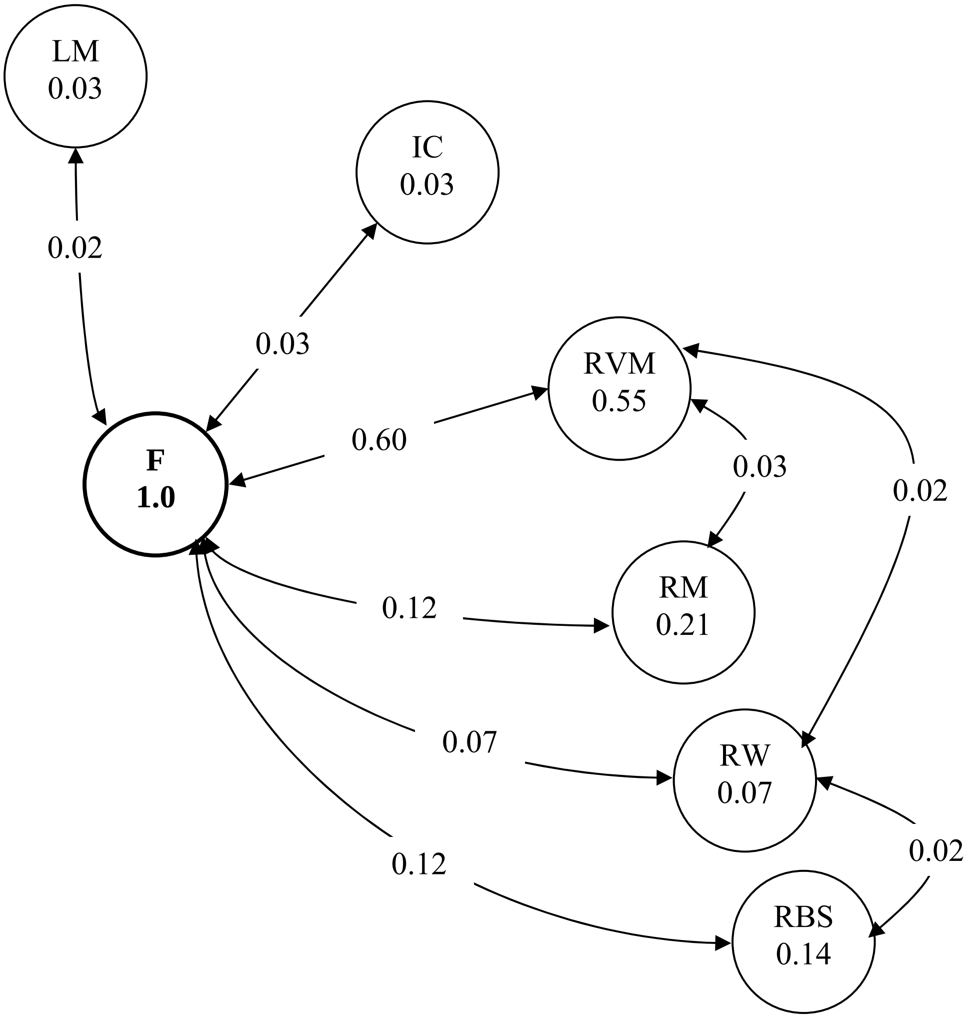

Figure 4.10. Glance Proportions (circles) and Link Probabilities (arrows) for Slow Lead Vehicle Lane Changes to the Right (N = 29 lane changes).

The results presented throughout this section on eye glance probability, link value analysis, and eye glance duration will provide input for a later discussion of lane change CAS location and modality (e.g., visual vs. auditory; always on vs. triggered).

Comparisons of Eye Glance Patterns Between SUVs and Sedans

One rationale for selecting the two experimental vehicle types (sedan and SUV) was that there might be differences in driver field of view between these vehicle types. It was noted that the Ford Explorer had larger windows that went down further that those of the Ford Taurus. The Taurus had relatively large C-pillars that could impede the driver's view of surrounding traffic. These differences led to speculation that the driver's scan patterns might change when using the different vehicle types. For this reason, an analysis of eye glance patterns was conducted comparing the SUV and sedan events. There were nearly equal number of events analyzed for the sedan and SUV. As can be seen in Table 4.31, both the mean single glance times and the glance probabilities (probability of a glance to that location within the three seconds prior to t_0) were nearly equal for every glance location studied. Thus, despite the differences in window size and field of view between the vehicle types, drivers looked at the same locations with similar probabilities and for the same lengths of time.

Table 4.31. Comparison of SUV and Sedan Glance Patterns (there were 244 sedan events and 256 SUV events).

	Mean Single Glance Time		**Glance Probability**	
Location	**SUV**	**Sedan**	**SUV**	**Sedan**
Forward - any direction	0.88	0.93	1.00	1.00
Center forward	0.94	0.99	1.00	0.98
Left forward	0.64	0.66	0.22	0.23
Right forward	0.64	0.66	0.13	0.09
RV mirror	0.63	0.67	0.56	0.48
Left mirror	0.68	0.68	0.40	0.39
Left window	0.59	0.63	0.24	0.22
Left blind spot	0.65	0.63	0.20	0.22
Instrument cluster	0.53	0.49	0.15	0.14
Right mirror	0.60	0.61	0.10	0.06
Right window	0.51	0.67	0.04	0.03
Right blind spot	0.73	0.71	0.04	0.03
Other interior	0.93	1.38	0.03	0.02
All events	**0.76**	**0.80**	**---**	**---**

Forward Analysis

When preparing to perform a lane change, the driver must continually maintain a safe distance from vehicles ahead. This forward area is monitored by the driver. The forward area can be considered a margin of safety that can be quantified as an indication as to how drivers interact with other vehicles.

An analysis was performed to develop insight into the typical range of values for the forward area. This analysis was performed in terms of the closest forward vehicle relative to the SV (in the same lane as the SV). Forward area is reported in terms of distance, relative velocity, and TTC. Results are reported relative to all the sampled events (i.e., including all lane change types from the sample of 500). In addition, urgency and severity are discussed. For some of the graphs in this chapter, all data have been graphed including instances in which very few values were observed (e.g., n = 1).

Distance to Closest Forward Vehicle for the Sample of Events

The distance that drivers allow to the closest forward vehicle relative to the SV was derived from input received from the front radar. The radar detected the closest point on the rear of forward vehicles. Distance represents the forward longitudinal distance between the front bumper of the SV and the rear bumper of the POV and is reported in units of feet.

In some cases, the data indicated that no vehicles were present in front of the SV. This could be because there was no target ahead or because the target was ahead but at an angle the radar could not detect. Out of the 500 events, there were 434 events in which at least one vehicle was present and detected in front of the SV at t_0. These cases were reviewed by an analyst to determine which of the detected targets was the closest vehicle in the same lane as the SV. Target angle data, and in some cases video data, were reviewed to make this determination.

Descriptive statistics for these lane changes are shown in Table 4.32. Figure 4.11 illustrates the percentiles, the mean, and ±1 standard deviation from the mean relative to the SV. Figure 4.12 is a histogram of occurrences for closest lead vehicle, and Figure 4.13 shows cumulative occurrences as a function of distance. Figure 4.13 is best interpreted by example: there were 222 vehicles within a distance of 100 feet for the data set.

Table 4.32. Descriptive Statistics for Distance in Feet to Closest Forward Vehicle for the Sample of Lane Changes.

All Lane Changes	
N	434
Mean	121.39
SD	77.23
Min	23.50
Max (radar limit)	400.00
5th %-ile	39.64
25th %-ile	65.23
50th %-ile	96.40
75th %-ile	155.38
95th %-ile	299.90

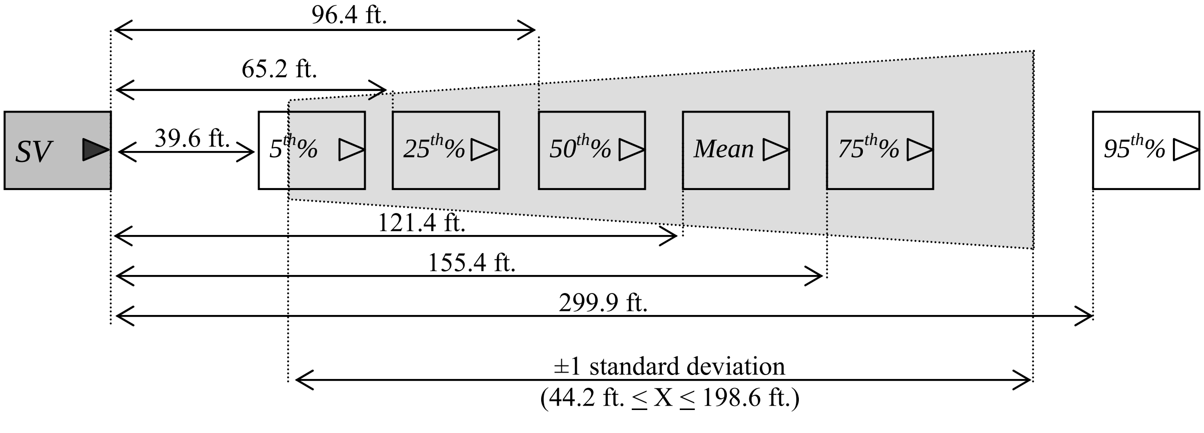

Figure 4.11. Percentile Distances to Closest Forward Vehicle Relative to SV at t_0.

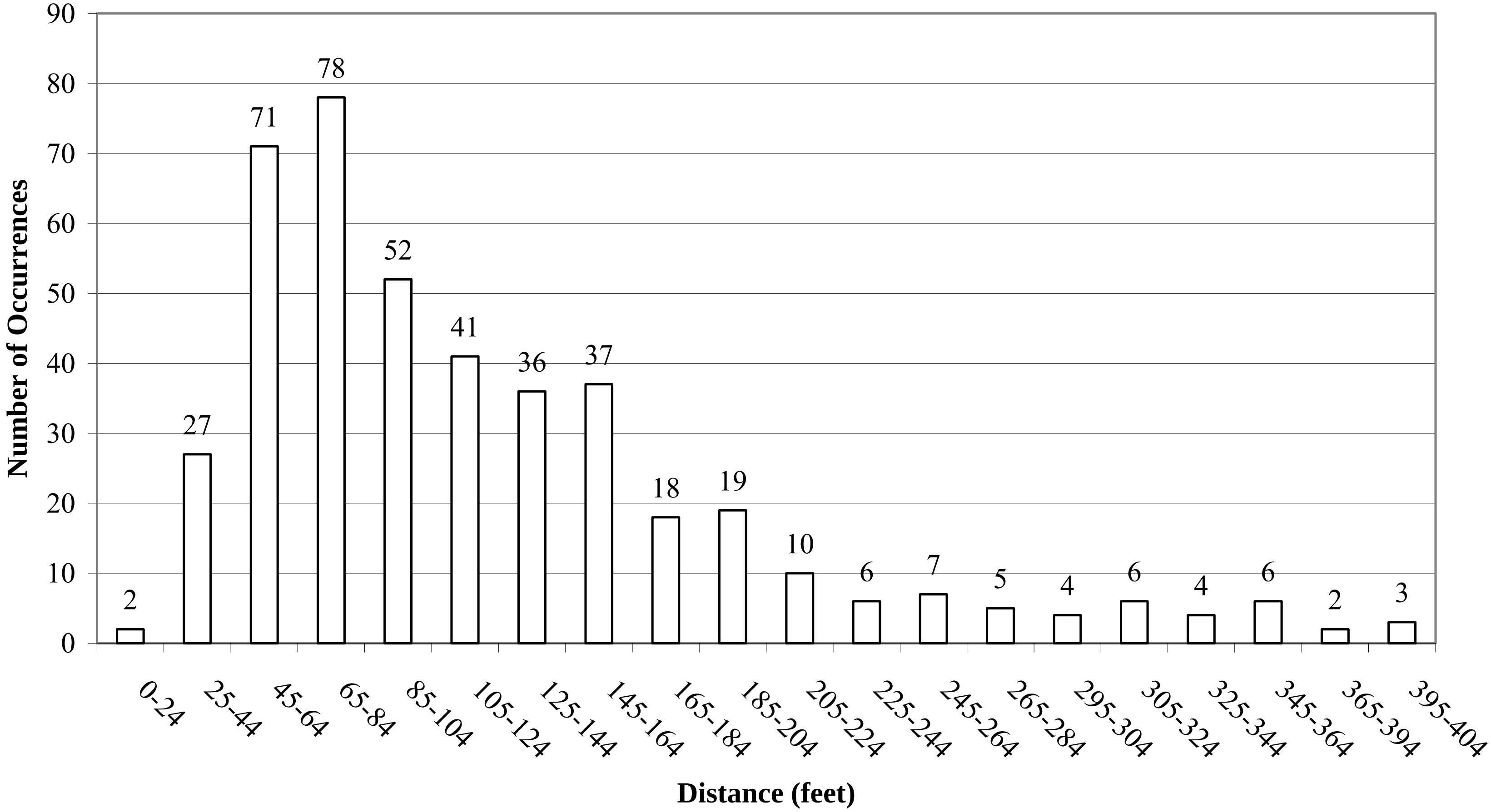

Figure 4.12. Frequency Distribution of Distance to Closest Forward Vehicle at t_0 (N = 434).

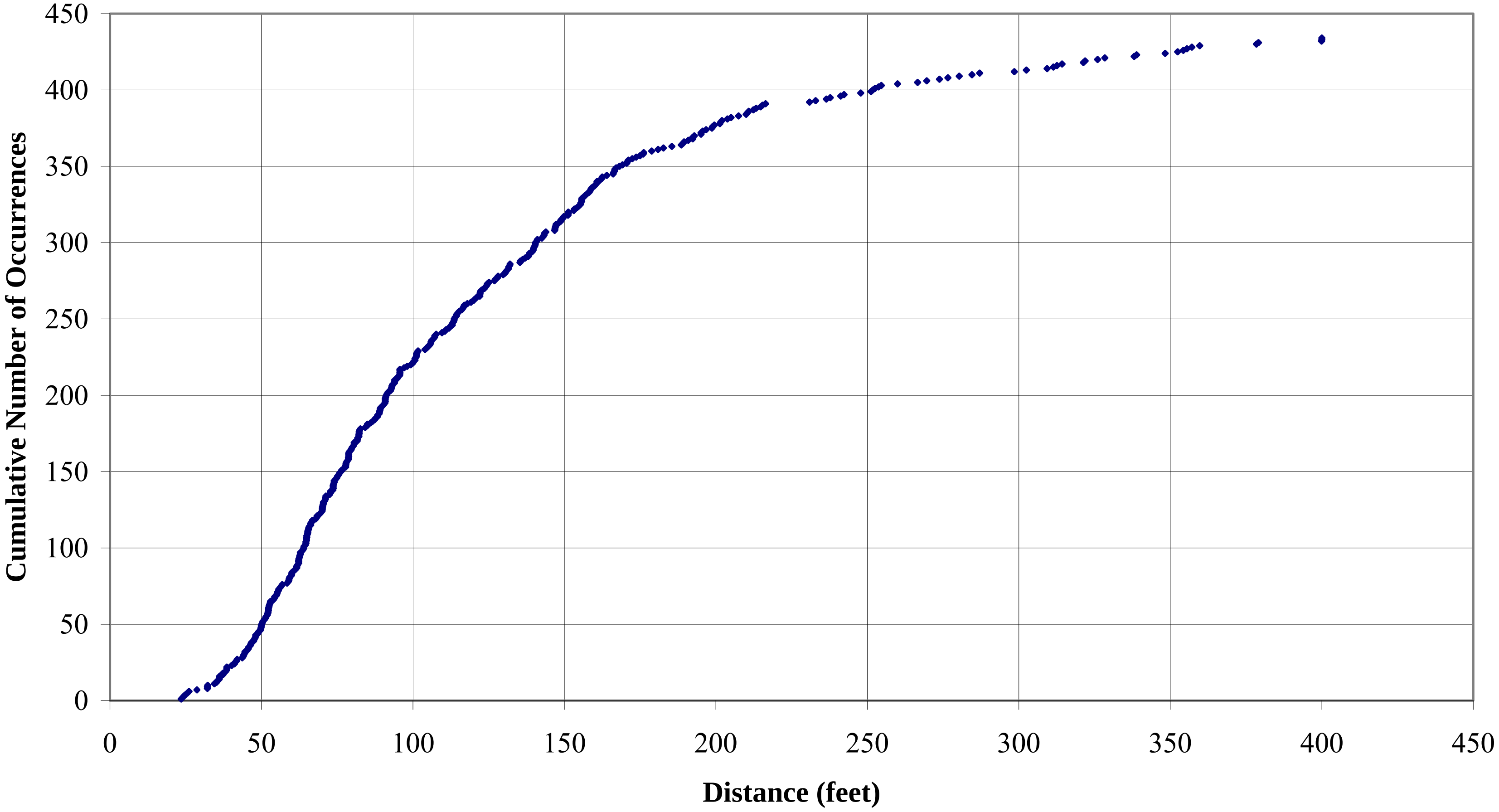

Figure 4.13. Distance to Closest Forward Vehicle for Events in which a Lead Vehicle was Present at t_0 (N = 434).

Distance by Urgency

The number of events and additional descriptive statistics for each urgency level are listed in Table 4.33. Figure 4.14 illustrates distance for all events and at each urgency level. Figure 4.15 shows the cumulative number of occurrences for distance to the closest vehicle for all 434 events, as well as for each urgency level. Results for the 75th percentile show that as the urgency of the lane change increases, the distance from the SV to the closest forward vehicle decreases.

Since urgency ratings are based in part on TTC, and TTC is distance divided by closing speed, it is not surprising that distance is related to urgency. In Figure 4.14 one can observe the decrease in distance between events rated with an urgency of 1 and 2. This makes sense, since events rated higher in urgency are associated with a lower TTC and usually a lower distance at t_0. In most cases (except for tailgating) urgency refers to the lead vehicle and how quickly the SV is closing upon the POV, thus distance and TTC are related. The data in Table 4.33 and Figures 4.14 and 4.15 serve primarily to confirm this relationship and validate to some degree that the urgency ratings were correctly applied by the analysts.

Table 4.33. Descriptive Statistics of Distance in Feet to Closest Forward Vehicle for the Sampled Events and for Each Urgency Level.

	Urgency			**All**
	1	**2**	**3**	
N	347	73	14	434
Mean	127.69	95.55	100.09	121.39
SD	80.39	56.44	61.29	77.23
Min	24.00	23.50	25.00	23.50
Max	400.00	312.60	232.90	400.00
5th	45.95	32.26	33.58	39.64
25th	69.85	48.90	60.93	65.23
50th	101.40	79.50	91.05	96.40
75th	160.55	131.60	122.63	155.38
95th	313.43	180.68	212.82	299.90

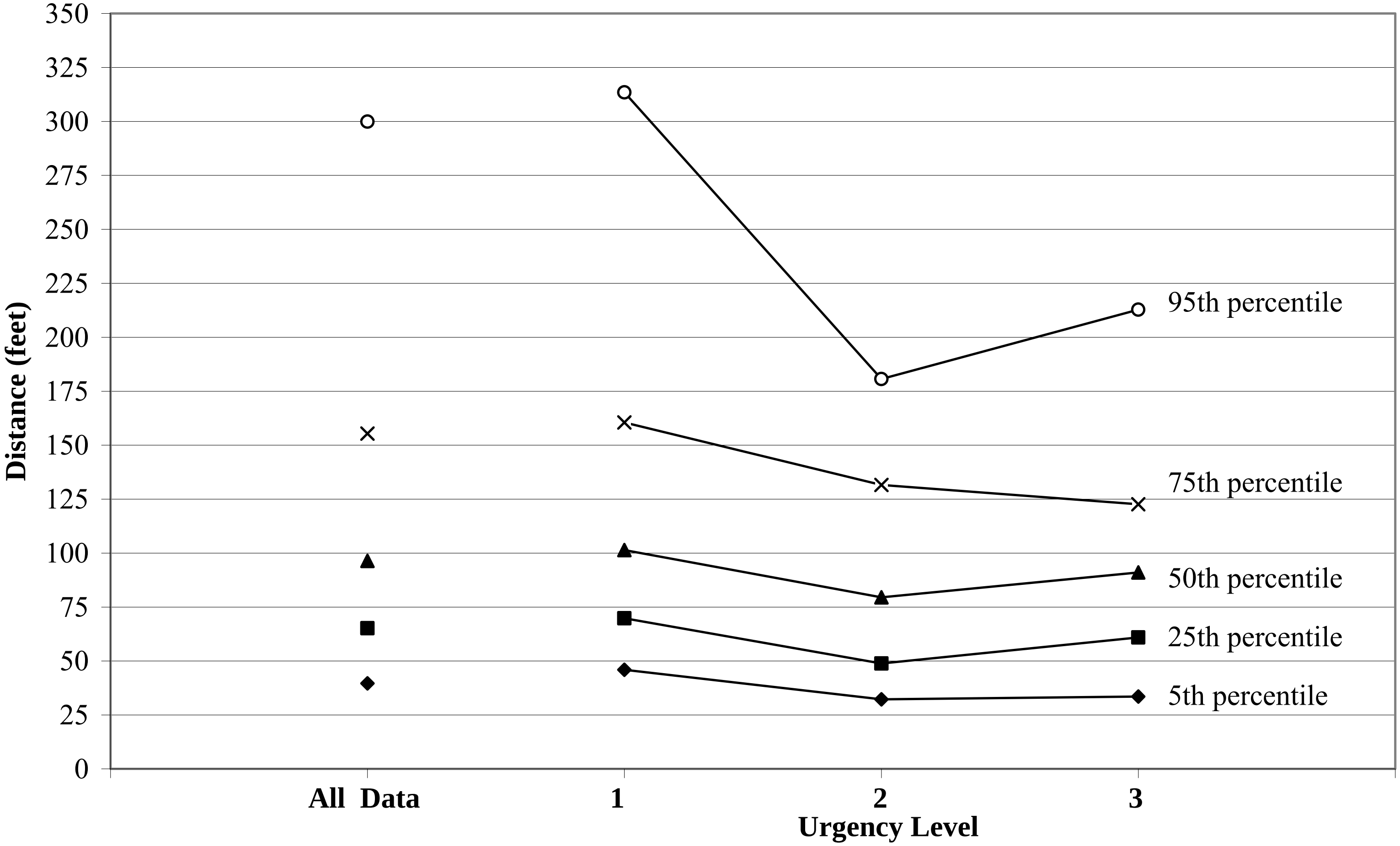

Figure 4.14. Distance Percentiles for the Sampled Events and for Each Urgency Level.

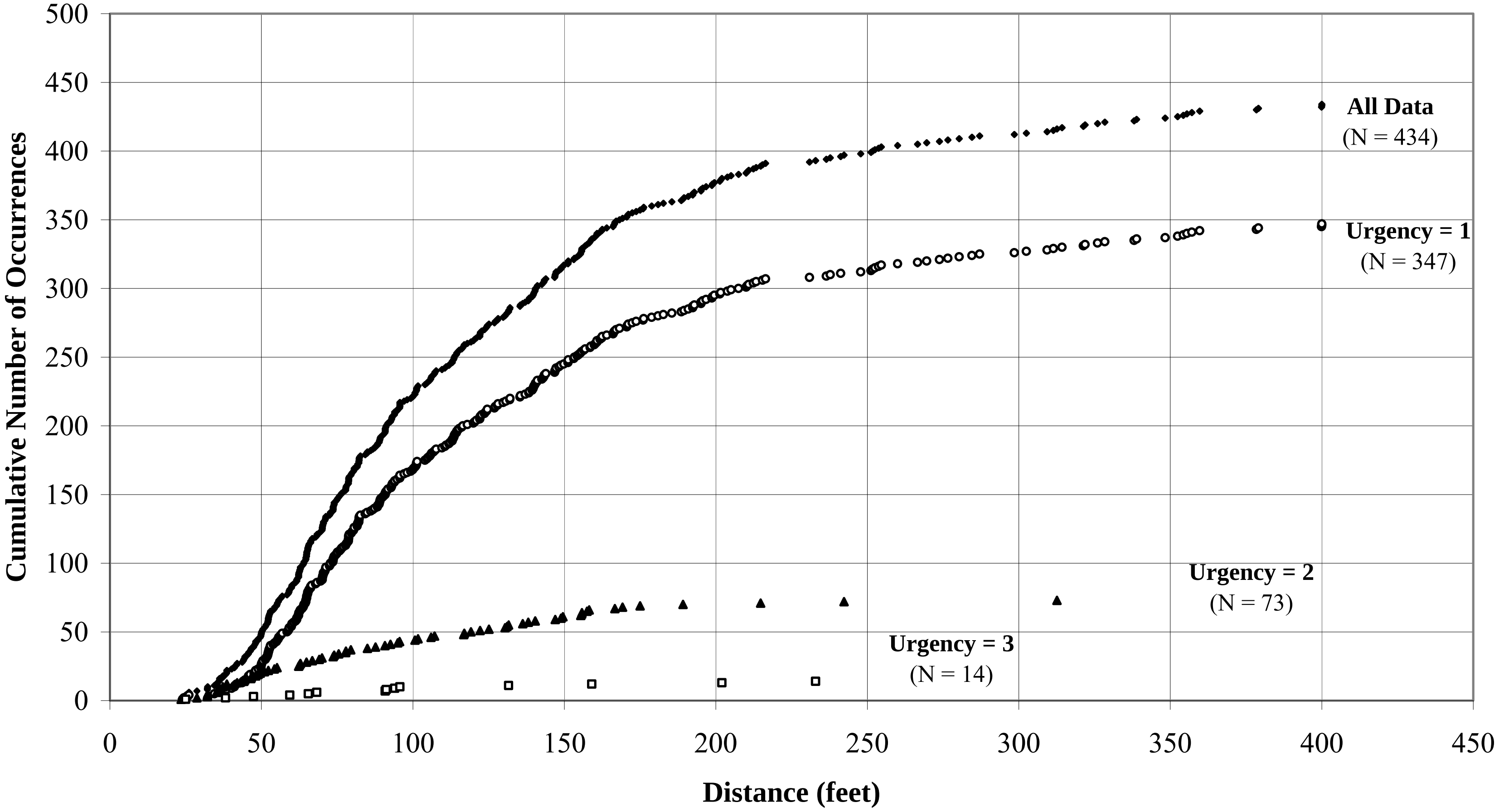

Figure 4.15. Distance to Closest Forward Vehicle for the Sampled Events and for Events at Each Urgency Level in which a Lead Vehicle was Present at t_0.

Distance by Severity

The forward distances of all 434 events for each severity level are presented in Table 4.34. Figure 4.16 illustrates distance for all events and at each severity level. A downward trend is present as severity level increases for events rated 1 through 4 (as the severity of the lane change increases, the distance from the SV to the closest forward vehicle decreases). However, the mean distance and standard deviation increases for events rated 5 or 6. Events rated at these higher severity levels have special circumstances that may aid in understanding this phenomenon.

Table 4.34. Descriptive Statistics of Distance in Feet to Closest Forward Vehicle for Sampled Events and for Each Severity Level.

	Severity						
	1	**2**	**3**	**4**	**5**	**6**	**All**
N	82	87	11	2	250	2	434
Mean	132.94	119.57	102.58	80.95	118.25	263.20	121.39
SD	81.68	65.17	65.42	15.34	78.80	163.91	77.23
Min	24.40	37.30	47.60	70.10	23.50	147.30	23.50
Max	400.00	348.30	276.60	91.80	400.00	379.10	400.00
5th	35.25	46.42	53.40	71.19	39.32	158.89	39.64
25th	78.98	66.05	66.00	75.53	63.58	205.25	65.23
50th	105.60	107.30	78.70	80.95	93.50	263.20	96.40
75th	167.83	152.75	116.35	86.38	152.05	321.15	155.38
95th	300.86	248.20	213.05	90.72	310.46	367.51	299.90

Severity ratings were used to indicate the degree to which the vehicle in the *destination lane* was cut off. The emphasis of this rating scale is on vehicles behind and adjacent to the SV. Severity is not based on the distance to vehicles in front of the SV. For events rated 1 through 4, the vehicle of concern is in the FAZ (30 to 162 feet behind the SV). A 1 would be a relatively safe maneuver in which the time to reach (Tr) the end of the FAZ is >5.0s, whereas a 4 would be indicative of a very aggressive maneuver in which Tr < 1.0 s. For events rated 5, a different situation is present in regard to vehicles in the adjacent rear area. This rating indicates that a vehicle is present in the PZ (4 feet in front of the SV to 30 feet behind it) and does not indicate time to reach the zone (or the rear of the SV itself). It may be the case that when a vehicle is detected in the PZ, the SV often slows to let that vehicle pass before making the lane change. In this case, the distance to the vehicle ahead would increase, as compared to the cases in which the SV does not slow down prior to making the lane change.

Events rated as a 6 pertain to emergency or unplanned maneuvers required to avoid a collision and are quite rare. For those that did occur (N = 2), the mean distance to the vehicle ahead was relatively large.

Figure 4.17 illustrates the cumulative number of occurrences for distance to the closest vehicle for all 434 events, as well as the distance to the closest vehicle for events at each severity level.

Of the remaining 66 events in which no lead vehicle was present at t_0, the majority were Exit/Prepare to Exit events (58%) and Return events (32%). The other remaining events consisted of lane changes in the following categories:

- Enter (14%)
- Tailgate (9%)
- Unintended (6%)
- Slow Lead Vehicle (4.5%)
- Lane Drop (4.5%)
- Rough (1.5%)
- Other (1.5%)
- Merging (1.5%)

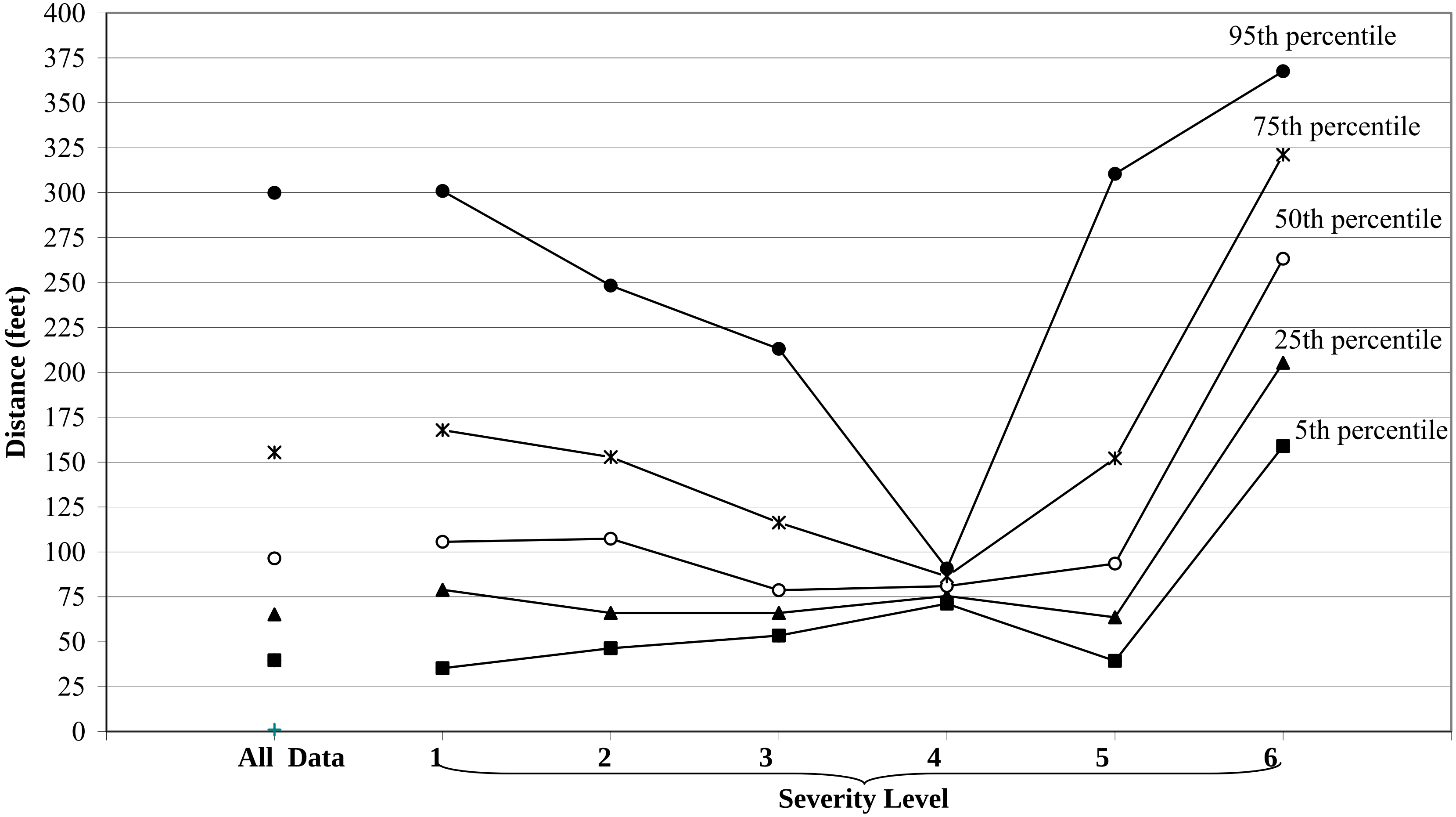

Figure 4.16. Distance Percentiles for the Sampled Events and for Each Severity Level. (Sample sizes for ratings 4 and 6 are small.)

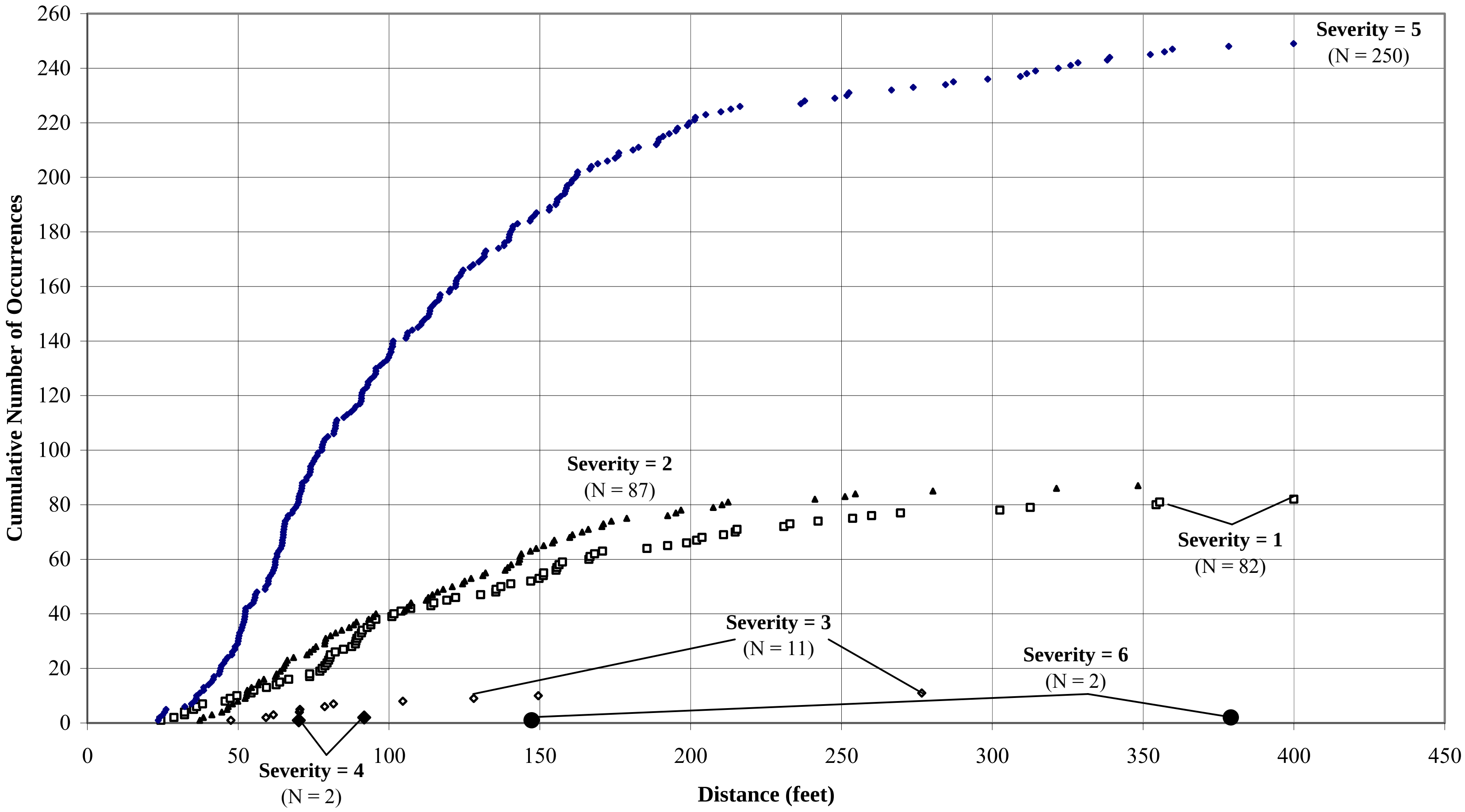

Figure 4.17. Distance to Closest Forward Vehicle for the Sampled Events and for Events at Each Severity Level in which a Lead Vehicle was Present at t_0. (Sample sizes for ratings 4 and 6 are small.)

Relative Velocity in Reference to Closest Forward Vehicle for the Sample of Events

Relative velocity is another important factor that is measured by subtracting the velocity of the POV from the velocity of the SV. Attaining an understanding of the range of values for relative velocity would be valuable for CAS designers. For example, knowing the relative velocity between vehicles prior to t_0 may influence the timing and urgency of issuing a CAS warning/alert. The timing of warning/alert issuance may be different (i.e., presented later) for a relative velocity between vehicles of 7 ft/s versus a relative velocity of 25 ft/s. Relative velocity was derived from input received from the front radar sensor and the speed sensor of the SV.

Out of the 500 events, there were 434 in which a vehicle was present in front of the SV at t_0. Descriptive statistics for the remaining lane changes are shown in Table 4.35. Negative values indicate that the velocity of the SV was higher than the velocity of the slow lead vehicle. If the SV is moving at 100.0 ft/s and the lead POV is moving at 95.0 ft/s, the relative velocity would be –5.0 ft/s. Positive values indicate that the lead vehicle was moving faster relative to the SV.

Figure 4.18 illustrates the percentiles, the mean, and ±1 standard deviation from the mean relative to the SV. Although distance is implied, velocity and distance are not necessarily related. In the figure, the lead POV in the 5th percentile position appears to be close to the SV; however, these vehicles may actually be far apart regardless of the relative velocity. The mean relative velocity is lower than the 50th percentile, unlike in previous figures. Figure 4.19 is a histogram of occurrences for relative velocity to the closest lead vehicle, and Figure 4.20 shows cumulative occurrences as a function of relative velocity. As discussed previously, there were 66 events in which no vehicle was present at t_0, so relative velocity data were not available.

Table 4.35. Descriptive Statistics for Relative Velocity in Feet/Second Between SV and Closest Forward Vehicle for Sampled Lane Changes in Which a Lead Vehicle was Present.

Sampled Lane Changes	
N	434
Mean	–5.90
SD	12.55
Min	–69.10
Max	43.40
5th %-ile	–29.80
25th %-ile	–9.30
50th %-ile	–3.00
75th %-ile	0.60
95th %-ile	9.00

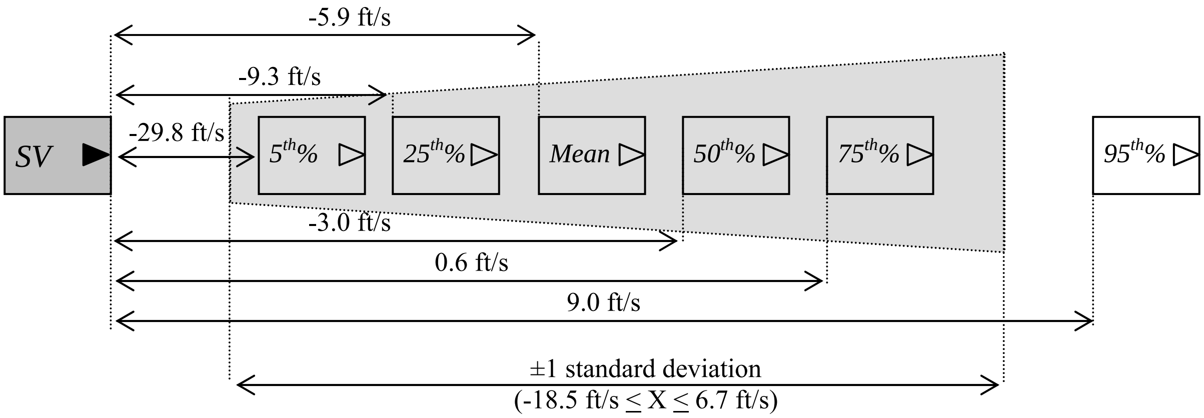

Figure 4.18. Percentile Relative Velocity to Closest Forward Vehicle Relative to SV at t_0. (Note that the diagram is a depiction of relative velocity and not a geometrically accurate representation.)

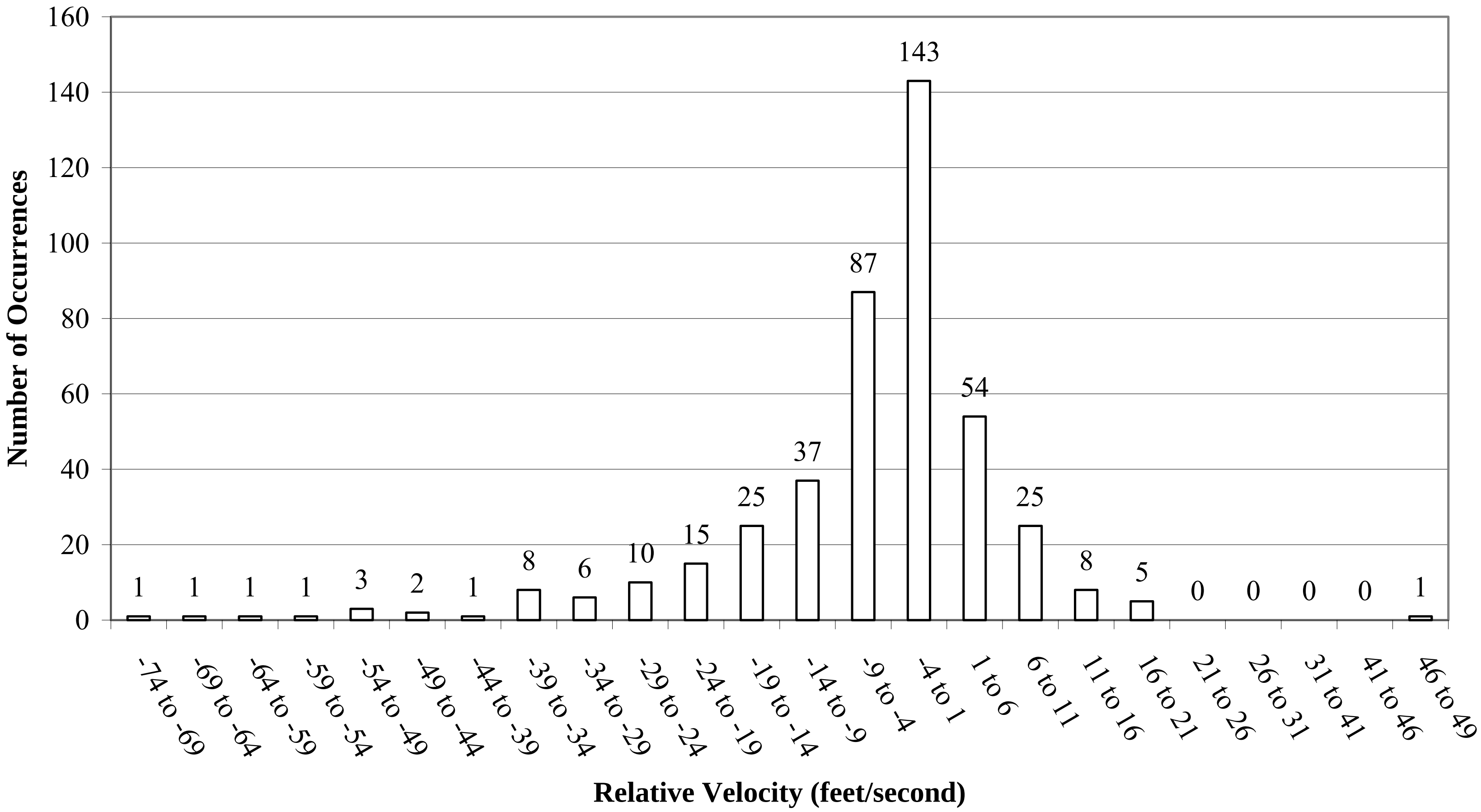

Figure 4.19. Frequency Distribution for the Sampled Events in Which a Lead Vehicle was Present at t_0 Showing Relative Velocity in Relation to Closest Forward Vehicle (N = 434).

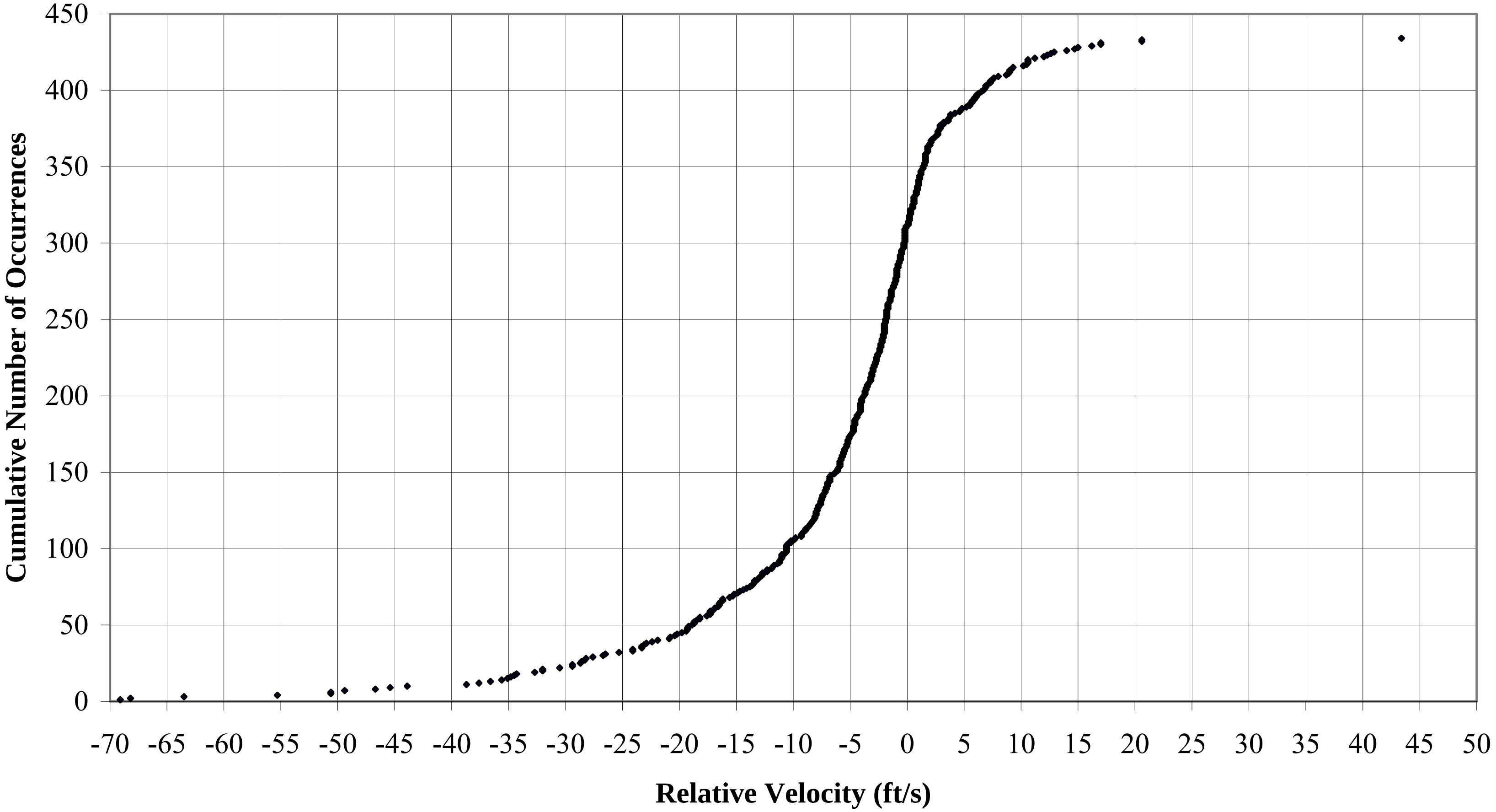

Figure 4.20. Relative Velocity Between SV and Closest Forward Vehicle for the Sampled Events in Which a Lead Vehicle was Present at t_0 (N = 434).

Relative Velocity by Urgency

The relative velocity and descriptive statistics for each urgency level are listed in Table 4.36. Figure 4.21 illustrates TTC for all events at each urgency level. Figure 4.22 illustrates the relative velocity between the SV and the closest vehicle for all 434 events, as well as the relative velocity for events at each urgency level. As the urgency of the lane change increases, the relative velocity to the lead vehicle decreases. That is, the lead POV was moving slower than the SV, which then precipitated the lane change in the slow lead vehicle case.

Table 4.36. Descriptive Statistics of Relative Velocity in ft/s between the Closest Forward Vehicle for the Sampled Lane Changes and for Each Urgency Level.

	Urgency			
	1	**2**	**3**	**All**
N	347	73	14	434
Mean	-3.72	-12.05	-27.86	-5.90
SD	10.25	15.13	18.00	12.55
Min	-63.50	-69.10	-68.20	-69.10
Max	43.40	10.20	-1.50	43.40
5th %-ile	-20.34	-40.78	-56.76	-29.79
25th %-ile	-7.55	-18.20	-34.10	-9.28
50th %-ile	-2.00	-6.30	-25.30	-3.00
75th %-ile	1.05	-2.20	-18.48	0.58
95th %-ile	10.14	4.02	-5.14	9.00

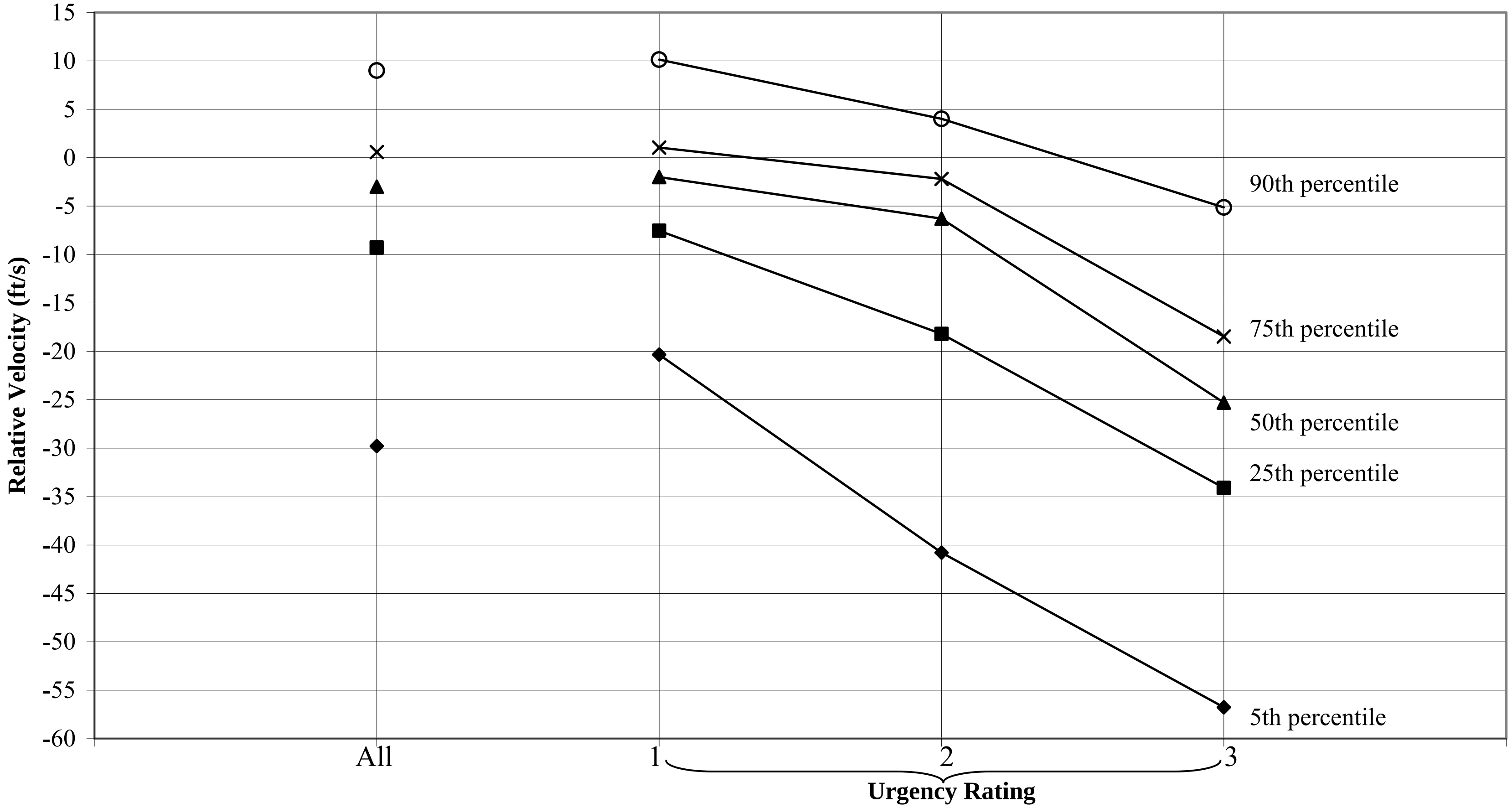

Figure 4.21. Relative Velocity Percentiles for Sampled Events and for Each Urgency Level.

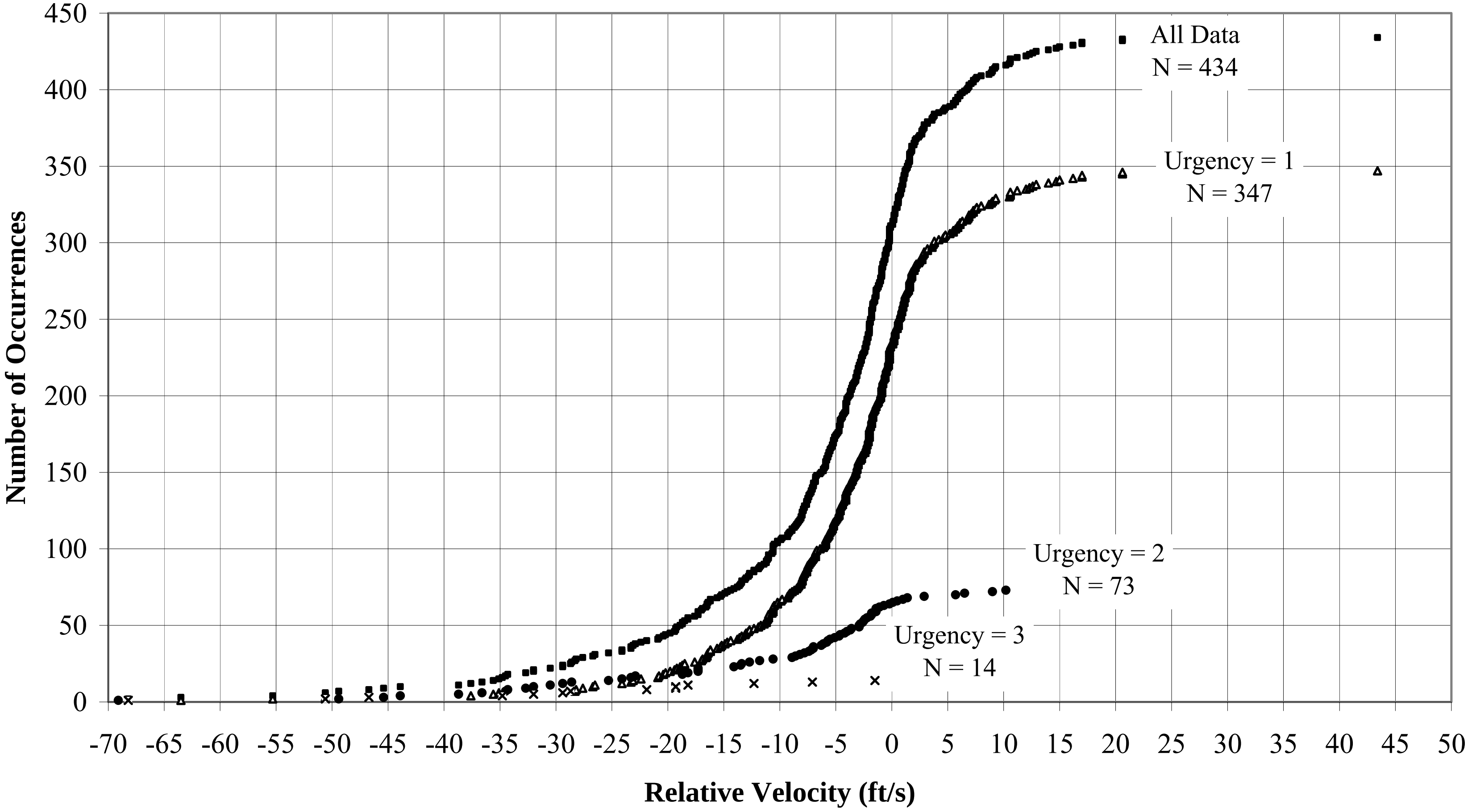

Figure 4.22. Relative Velocity Between SV and Closest Forward Vehicle for Sampled Events and for Events at Each Urgency Level in Which a Lead Vehicle was Present at t_0.

Relative Velocity by Severity

Table 4.37 lists the relative velocity for each severity level. Figure 4.23 illustrates relative velocity percentiles for all events at each severity level, and Figure 4.24 illustrates the relative velocity for events at each severity level. There does not appear to be a clear-cut relationship between relative velocity and severity; the trend appears to be opposite of the one between relative velocity and urgency. As the SV approaches the lead POV in the high severity case (POV in the PZ or FAZ), the SV often slows (thus matching the lead vehicle speed) until the adjacent lane is clear for the lane change.

Table 4.37. Descriptive Statistics of Relative Velocity in Feet per Second to Closest Forward Vehicle for the Sampled Lane Changes and for Each Severity Level.

	Severity						
	1	**2**	**3**	**4**	**5**	**6**	**All**
N	82	87	11	2	250	2	434
Mean	-12.45	-3.67	4.68	-4.00	-5.15	11.25	-5.90
SD	15.39	9.12	15.22	2.26	11.62	1.06	12.55
Min	-69.10	-50.60	-10.20	-5.60	-63.50	10.50	-69.10
Max	17.00	20.60	43.40	-2.40	17.00	12.00	43.40
5th %-ile	-34.79	-16.57	-7.90	-5.44	-28.26	10.58	-29.79
25th %-ile	-19.15	-7.35	-4.50	-4.80	-8.00	10.88	-9.28
50th %-ile	-8.30	-2.70	1.40	-4.00	-2.00	11.25	-3.00
75th %-ile	-2.53	0.55	5.65	-3.20	0.80	11.63	0.58
95th %-ile	2.69	8.63	32.00	-2.56	8.86	11.93	9.00

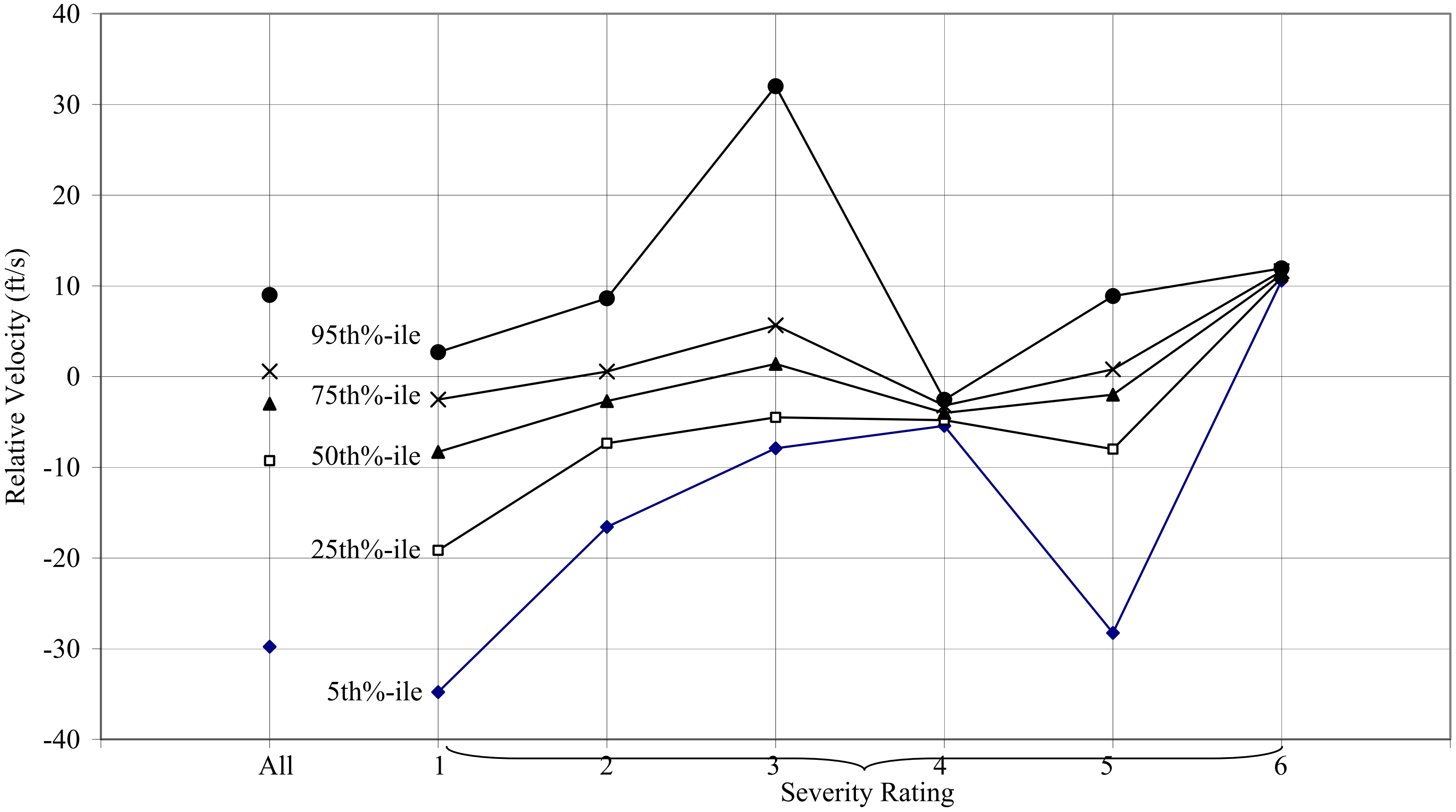

Figure 4.23. Relative Velocity Percentiles for the Sampled Events and for Each Severity Level. (Sample sizes for ratings 4 and 6 are small.)

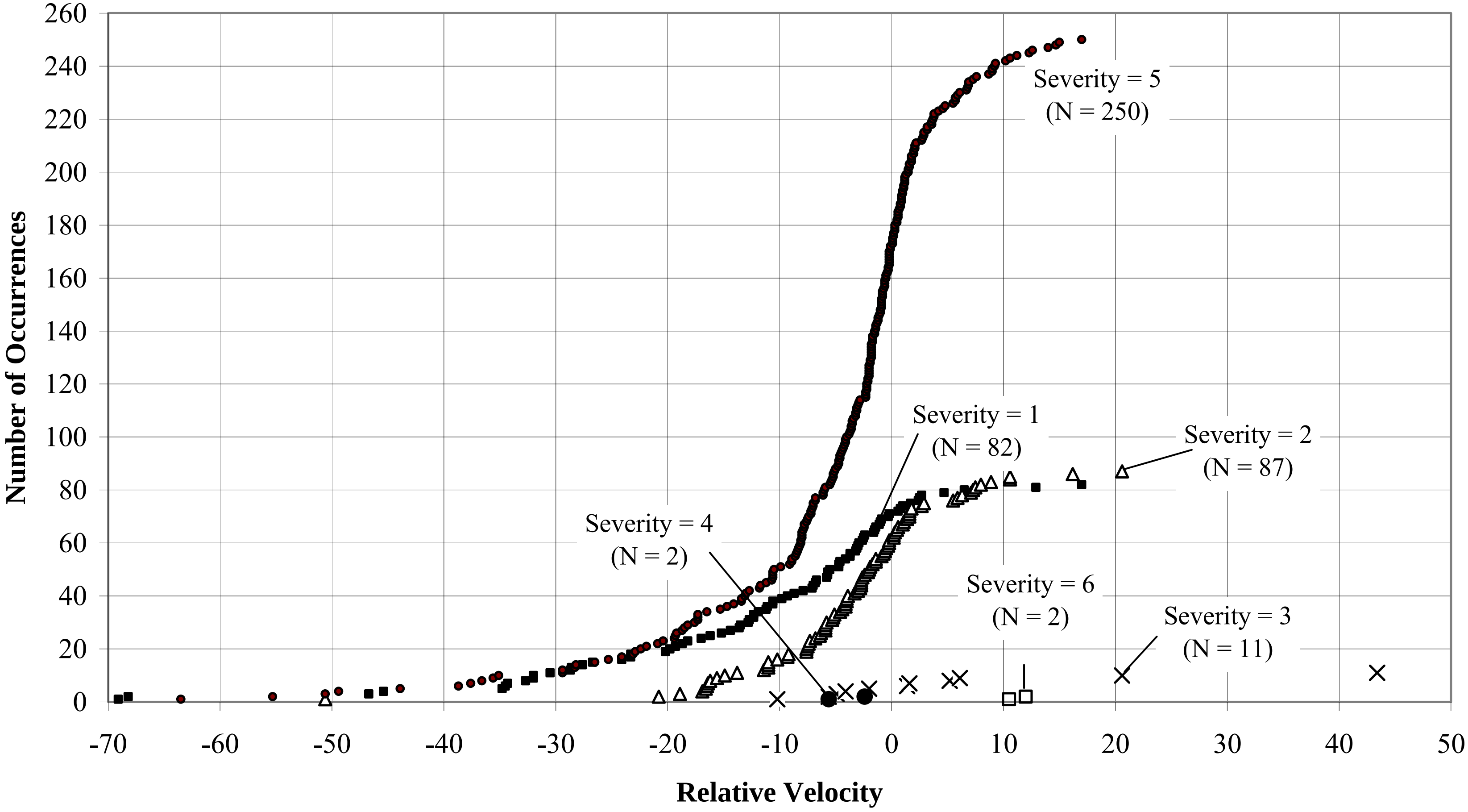

Figure 4.24. Relative Velocity Between SV and Closest Forward Vehicle for the Sampled Events and for Events at Each Severity Level in Which a Lead Vehicle was Present at t_0.
(Sample sizes for ratings 4 and 6 are small.)

Time to Collision to Closest Forward Vehicle for All Events

Time to collision is a measure of how long it takes for the SV to collide with the lead vehicle if velocity is constant and a lane change maneuver is not initiated. Such information is valuable because TTC is likely to be used to issue warnings/alerts to drivers in CAS (Talmadge et al., 1997). Time to collision is the range between two vehicles divided by the relative velocity, reported in seconds.

As with distance, TTC was derived from input received from the front radar. Out of the 500 events, there were 434 events in which a vehicle was present and detected in front of the SV at t_0. Of these, there were 123 events in which a vehicle was present in front of the SV but a TTC was not available because the lead vehicle was moving at either the same or a faster velocity than the SV at t_0.

Descriptive statistics for the remaining lane changes are shown in Table 4.38. Figure 4.25 illustrates the percentiles, the mean, and ±1 standard deviation from the mean relative to the SV. Figure 4.26 provides a histogram of occurrences for TTC to the closest lead vehicle, and Figure 4.27 shows cumulative occurrences as a function of TTC. Several lane changes have a TTC of 60 s as illustrated by both Figure 4.26 and Figure 4.27. For these events, the vehicles likely had a very small relative velocity differential (i.e., -0.1 ft/s) that resulted in a very large TTC (e.g., 220 s). In these cases, the maximum was set at "60." As discussed previously, there were 66 events in which no POV was present at t_0.

Table 4.38. Descriptive Statistics for TTC in Seconds to Closest Forward Vehicle for the Sampled Lane Changes.

Sampled Lane Changes	
N	311
Mean	23.22
SD	19.36
Min	2.60
Max (set limit)	60.00
5th%-ile	4.30
25th%-ile	8.60
50th%-ile	15.30
75th%-ile	32.30
95th%-ile	60.00

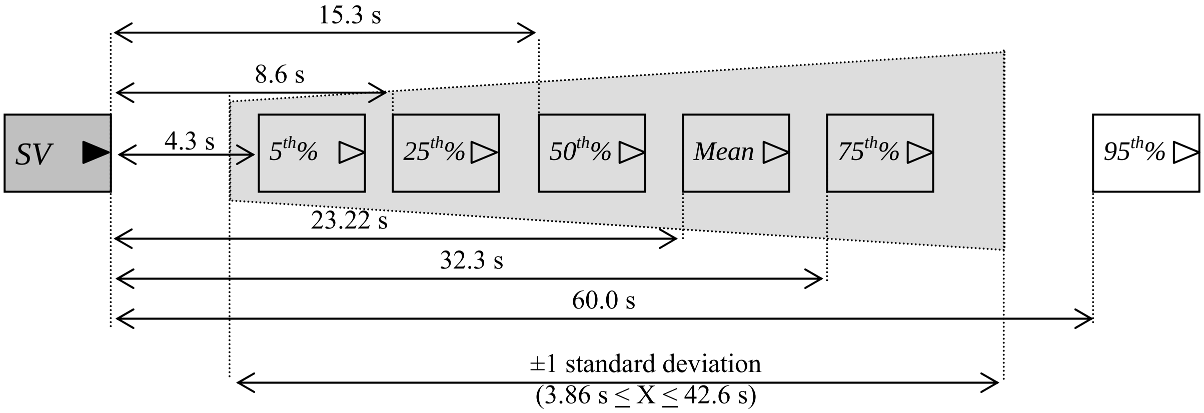

Figure 4.25. Percentile TTC to Closest Forward Vehicle Relative to SV at t_0. (This diagram is a depiction of data and is not geometrically accurate.)

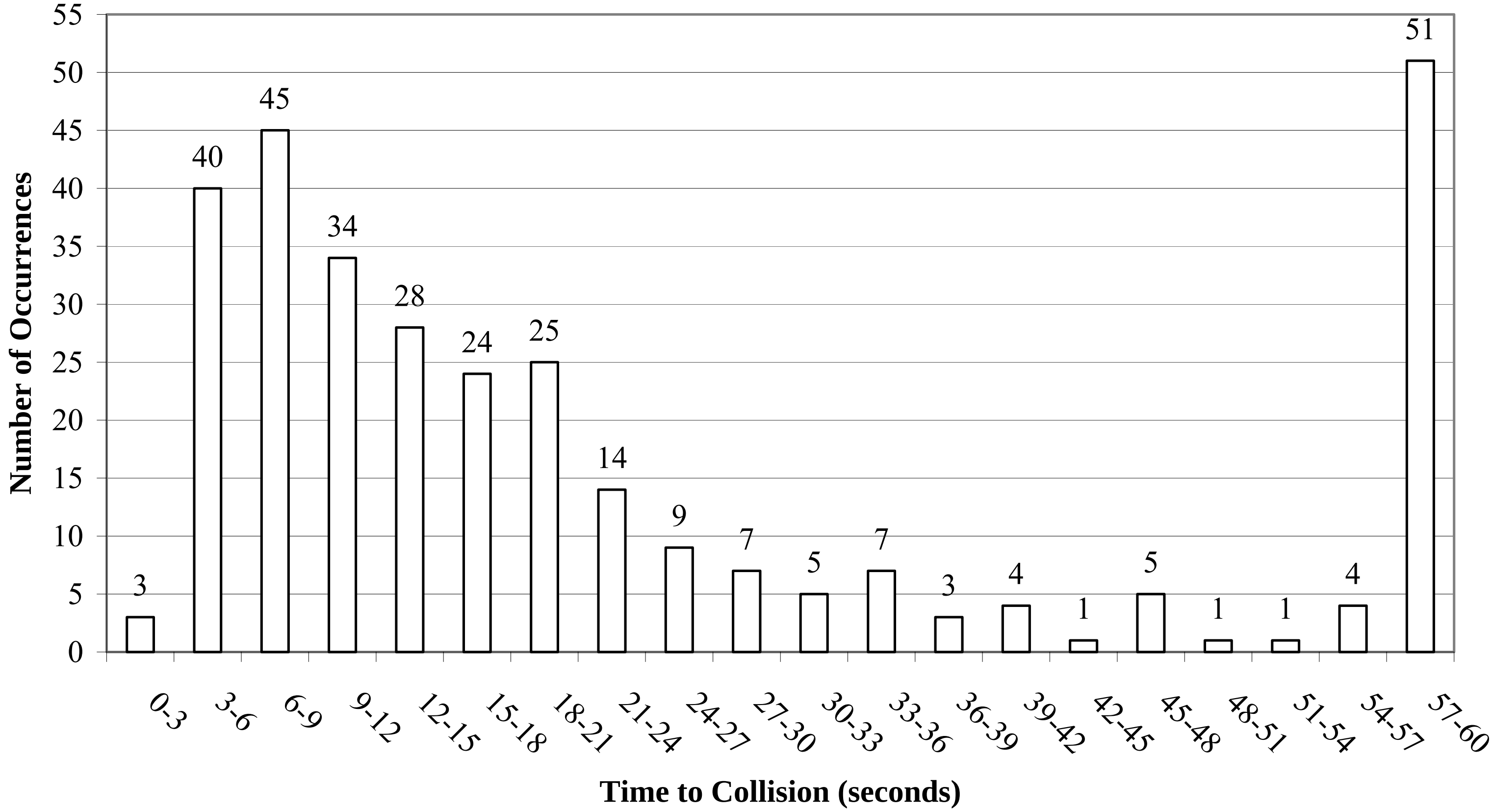

Figure 4.26. Frequency Distribution for the Sampled Events Showing TTC from Closest Forward Vehicle (N = 311).

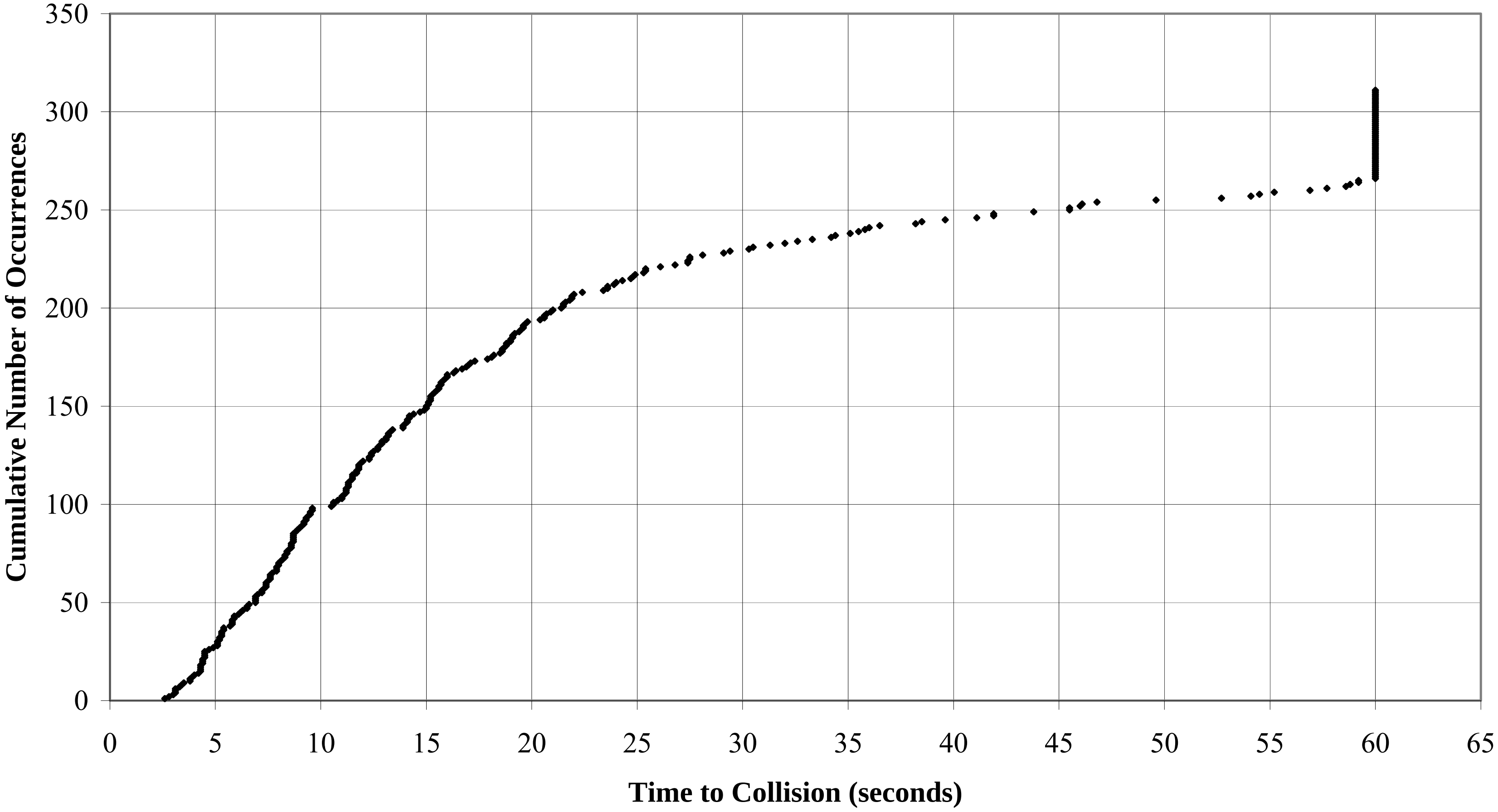

Figure 4.27. Time to Collision to Closest Forward Vehicle for the Sampled Events in Which a Lead Vehicle was Present at t_0 and a TTC could be Calculated (N = 311).

Time to Collision by Urgency

The TTCs for each urgency level are listed in Table 4.39. Figure 4.28 illustrates TTC for all events at each urgency level. Figure 4.29 illustrates the TTC to the closest vehicle for all 311 events, as well as the TTC to the closest vehicle for events at each urgency level. As the urgency of the lane change increases, the TTC from the SV to the closest forward vehicle decreases dramatically. This result is not surprising since the urgency rating scale was based directly on TTC.

Table 4.39. Descriptive Statistics of TTC in Seconds to Closest Forward Vehicle for the Sample of Lane Changes and for Each Urgency Level.

	Urgency			
	1	**2**	**3**	**All**
N	233	64	14	311
Mean	27.03	13.43	4.63	23.22
SD	19.84	12.85	3.58	19.36
Min	4.50	3.10	2.60	2.60
Max	60.00	60.00	16.70	60.00
5th%-ile	6.78	4.03	2.73	4.30
25th%-ile	11.50	5.10	3.10	8.60
50th%-ile	18.80	8.65	3.45	15.30
75th%-ile	43.80	13.50	4.45	32.30
95th%-ile	60.00	44.18	9.36	60.00

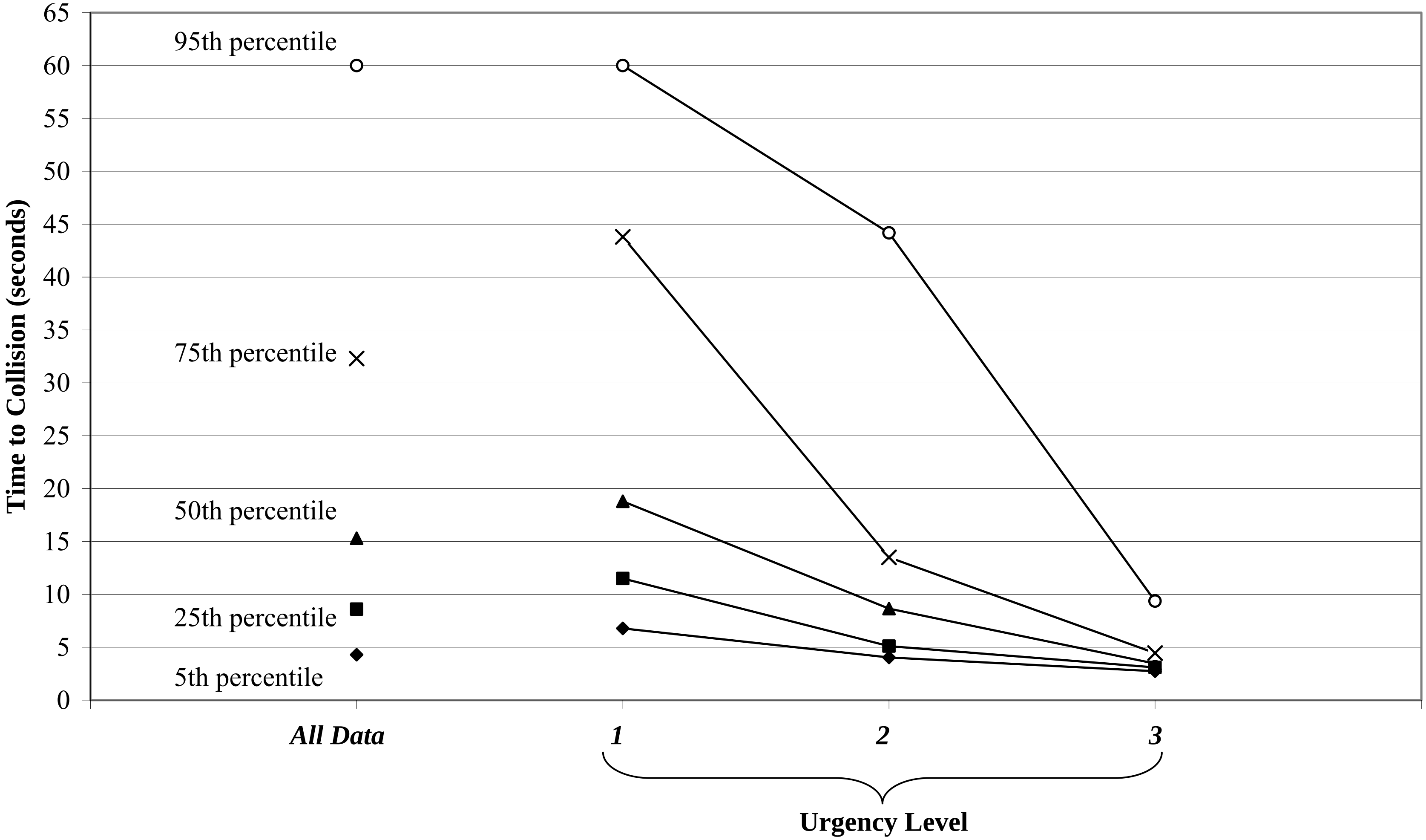

Figure 4.28. TTC Percentiles for the Sampled Events and for Each Urgency Level.

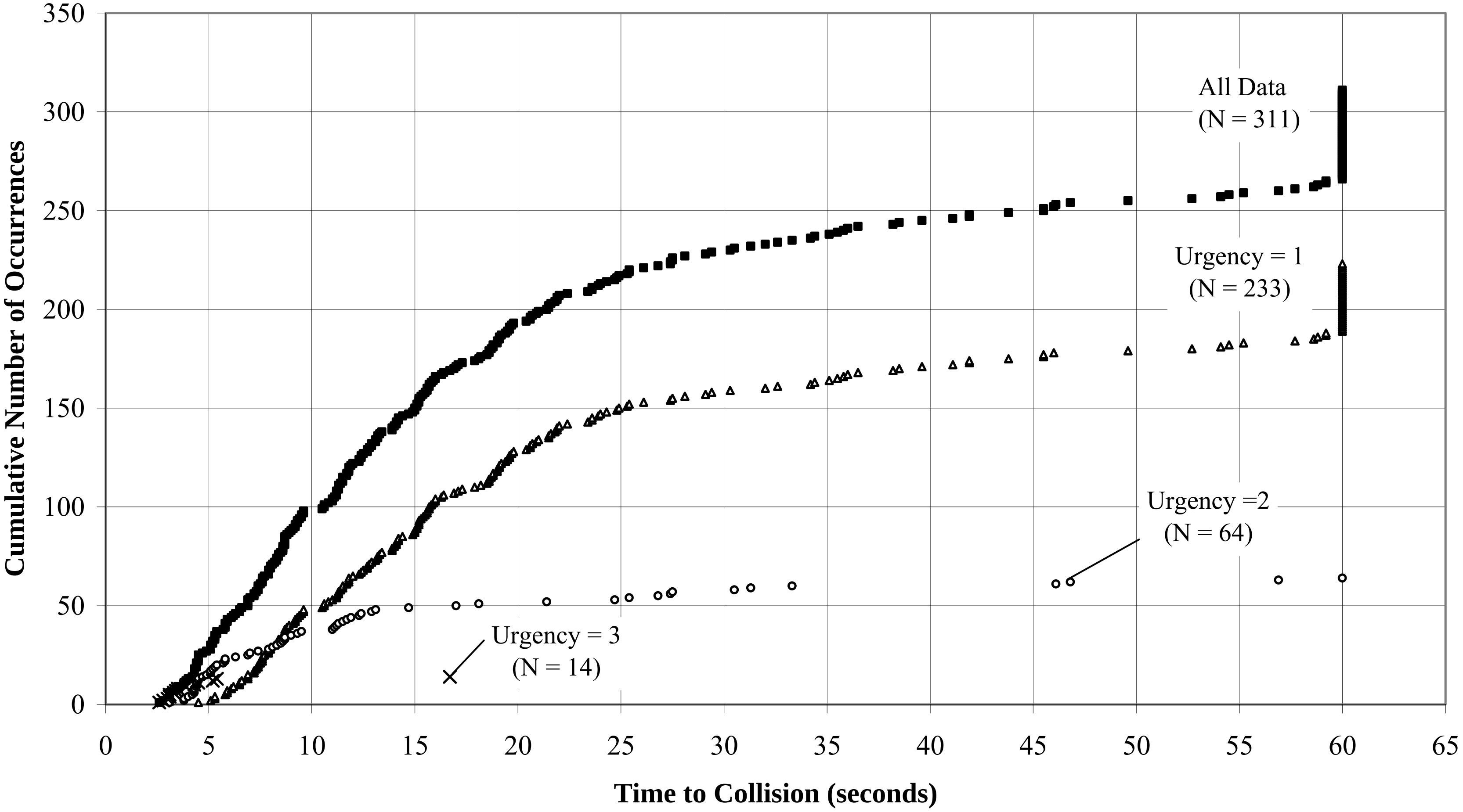

Figure 4.29. TTC to Closest Forward Vehicle for the Sampled Events and for Events at Each Urgency Level in Which a Lead Vehicle was Present at t_0.

Time to Collision by Severity

The TTCs and descriptive statistics for each severity level are listed in Table 4.40. Figure 4.30 illustrates TTC for all events for each severity level, and Figure 4.31 illustrates the TTC to the closest vehicle for all 311 events, as well as for events at each severity level. Results show no easily discernable pattern between TTC to the closest forward vehicle and the severity rating. Given that the severity rating is based on vehicle adjacent to and to the rear of the SV, the lack of such a relationship is not surprising.

Table 4.40. Descriptive Statistics of TTC in Seconds to Closest Forward Vehicle for Sampled Lane Changes and for Each Severity Level.

	Severity						
	1	**2**	**3**	**4**	**5**	**6**	**All**
N	71	61	5	2	172	n/a	311
Mean	17.22	25.48	18.18	25.35	25.02	n/a	23.22
SD	17.50	17.78	10.26	18.17	20.45	n/a	19.36
Min	2.60	5.90	7.70	12.50	3.00	n/a	2.60
Max	60.00	60.00	35.10	38.20	60.00	n/a	60.00
5th %-ile	3.20	7.90	9.04	13.79	4.50	n/a	4.30
25th %-ile	6.15	11.70	14.40	18.93	8.58	n/a	8.60
50th %-ile	11.30	19.10	15.00	25.35	16.35	n/a	15.30
75th %-ile	18.50	36.00	18.70	31.78	42.38	n/a	32.30
95th %-ile	60.00	60.00	31.82	36.92	60.00	n/a	60.00

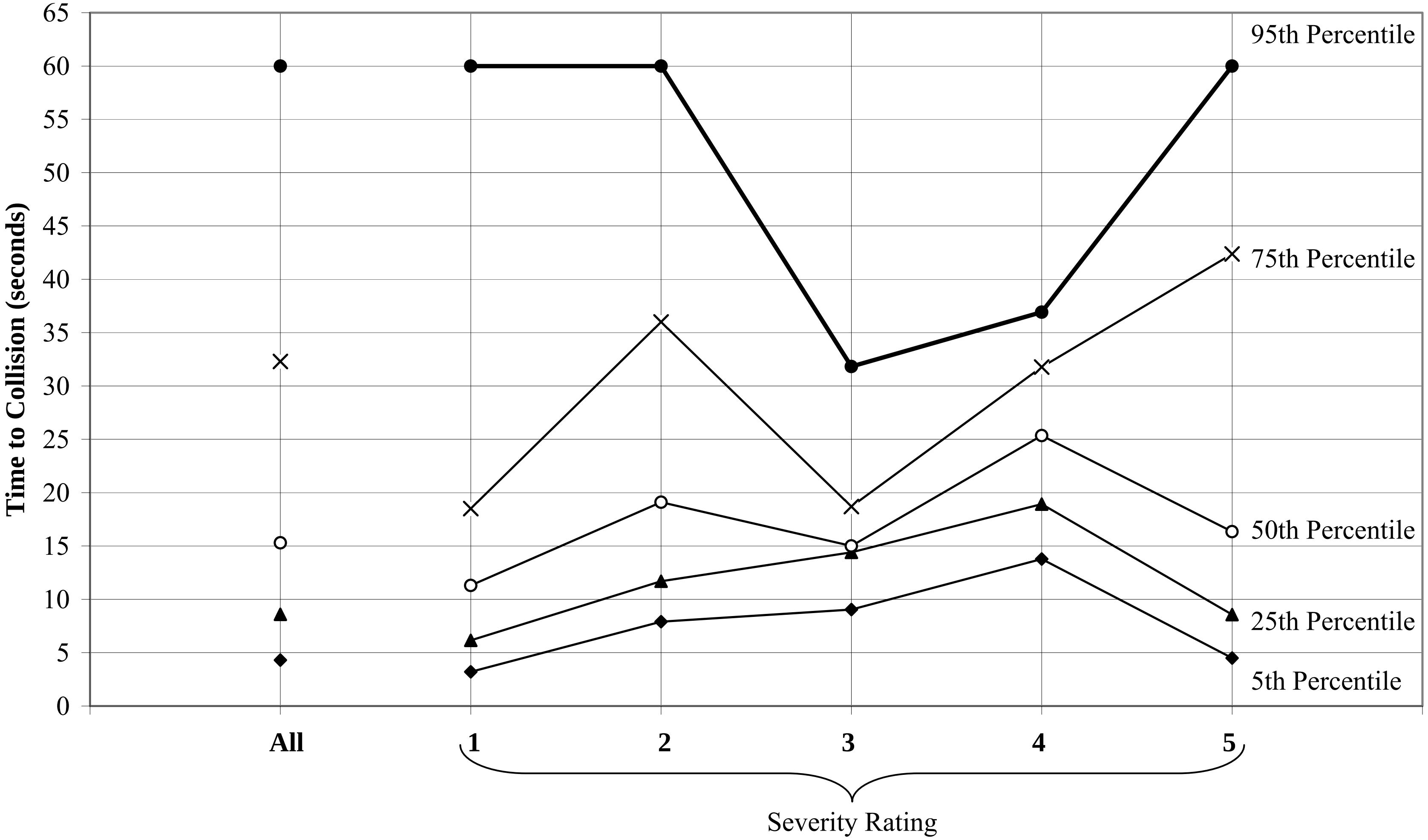

Figure 4.30. TTC Percentiles for Sampled Events and for Each Severity Level. (Note that sample sizes for ratings 3 and 4 are small.)

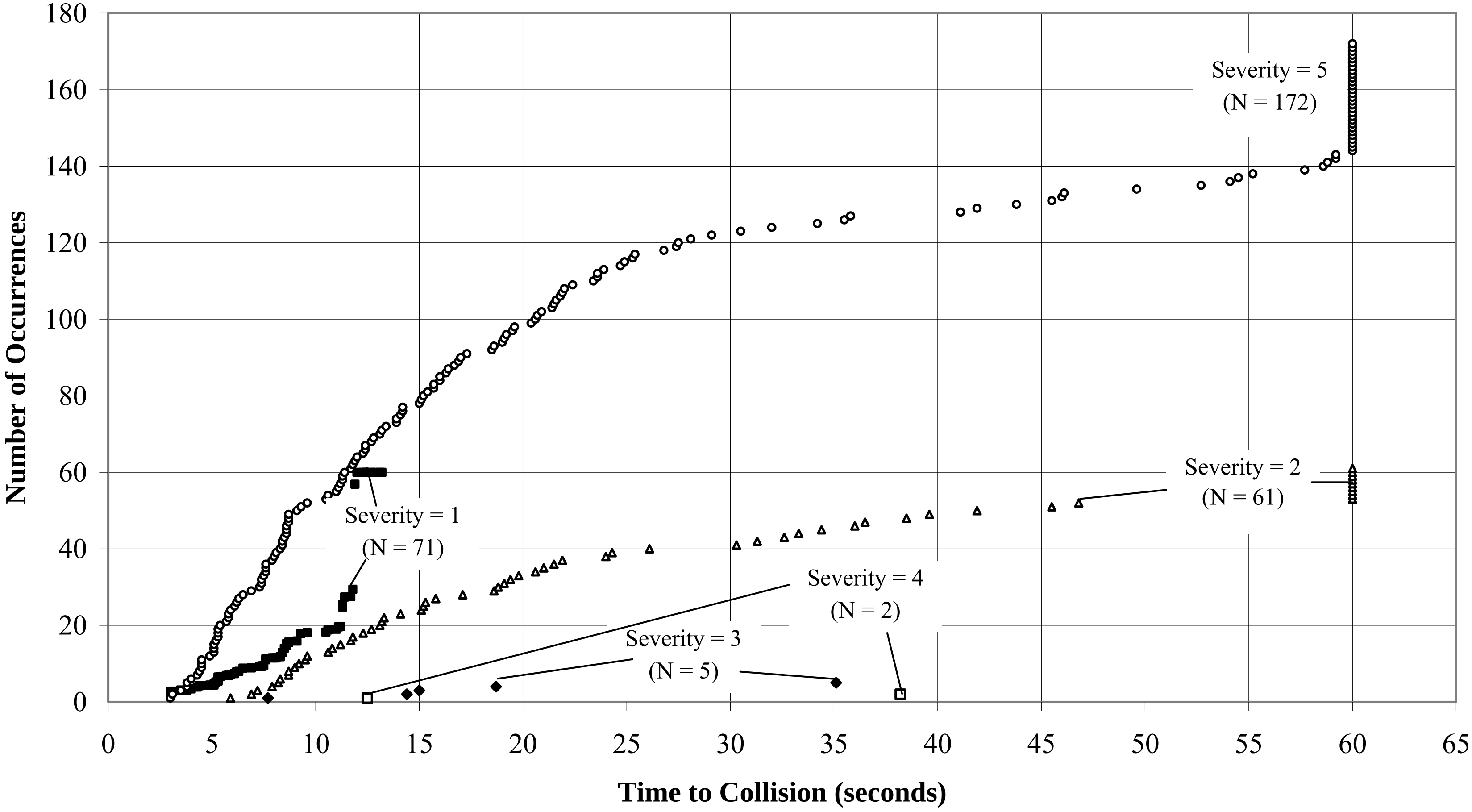

Figure 4.31. TTC to Closest Forward Vehicle for the Sampled Events and for Events at Each Severity Level in Which a Lead Vehicle was Present at t_0. (Note that sample sizes for ratings 3 and 4 are small.)

Rearward Analysis

The rearward analysis identified how close drivers would allow following vehicles to be when making a lane change. Since most lane changes were to the left, only data from the rear left radar were analyzed. Rearward area is the closest detected target at t_0 and is reported in terms of distance, relative velocity, and TTC. Results for slow lead vehicle lane changes and the effects of urgency and severity are also addressed.

Note that reported targets were only those detected in the radar. There are some limitations to this approach. These events were not included for instances with no targets detected at t_0. For cases with only one target detected at t_0, it is assumed that this target was the closest vehicle and the vehicle detected was the POV of concern. In some instances, another POV was closer than the POV detected; however, the vehicle was out of range (too close to the SV) and was not detected by the radar.

A different approach was taken for cases in which more than one vehicle was detected at t_0. Each event was reviewed to verify which vehicle was the POV. In some cases, video data were reviewed to make this determination. For cases in which the POV was *not detected* by the radar, the distance, TTC, and relative velocity were reported at the earliest point at which the vehicle was detected. This was common for events in which the POV was in the PZ. The radar system had a minimum range of approximately 20 to 30 feet (depending on the angle), so vehicles very close to the SV may not have been detected. For example, if a vehicle was passing the SV on the left within the PZ (i.e., next to the SV), it is possible that the POV was out of range of both the left and the front radar. In this case, values were reported when this POV was detected after t_0. Values representing targets detected in the front and left rear radar were reported, providing a glimpse at the safety envelope that drivers allow just after at t_0.

Distance to Closest Rearward Vehicle for All Events

The distance that drivers allow to the closest rearward vehicle relative to the SV was derived from input received from the left rear radar. Distance represents the rearward longitudinal distance between the rear bumper of the SV and the front bumper of the POV and is reported in units of feet.

In some cases, the data indicated that no vehicles were present behind the SV. This could be either because there was no target behind the SV or because the target was very close or beside the SV at t_0 and the radar could not detect the vehicle. Out of the 351 left lane change events, at least one vehicle was present to the rear of the SV at t_0 in 213 events. In these 213 cases, a vehicle was present behind the SV but was not necessarily the POV. Out of the 213 events that had at least one target present, 109 had targets (i.e., categorized as the POV) that were detected by the left rearward radar, 83 events had targets present but *not detected* by the radar at t_0, and 21 events had no targets (i.e., no POV) detected. In the 21 cases with no POV detected, values reflect the closest vehicle detected by the rear radar; however, because it was determined the closest vehicle was not the POV (i.e., not an influence on the driver) these cases were not analyzed further.

Of the 213 events, 70.9% were slow lead vehicle lane changes, followed by enter (8.9%), merging (7.5%), exit/prepare to exit (7%), other (1.9%), return (1.4%), lane drop (1.4%), and unintended (0.9%).

Table 4.41 presents the descriptive statistics for these lane changes. Figure 4.32 illustrates the percentiles, the mean, and ±1 standard deviation from the mean relative to the SV for the 213 events. Figure 4.33 is a histogram of occurrences for closest following vehicle, and Figure 4.34 shows cumulative occurrences as a function of distance.

Table 4.41. Descriptive Statistics for Distance in Feet to Closest Rearward Vehicle for Lane Changes at t_0.

	ALL Instances w/POV	Instances w/POV at t0	Instances w/no POV detected at t0	Instances w/no POV at all
N	213	109	83	21
Mean	137.62	100.73	162.33	231.47
SD	81.85	47.57	86.00	96.31
Min	31.90	31.90	32.10	50.10
Max (radar limit)	400.00	260.20	400.00	396.00
5th %-ile	47.06	42.40	51.21	91.30
25th %-ile	75.00	66.40	95.40	125.90
50th %-ile	116.00	91.90	145.70	270.40
75th %-ile	177.60	127.20	203.75	295.70
95th %-ile	300.04	195.24	326.40	345.90

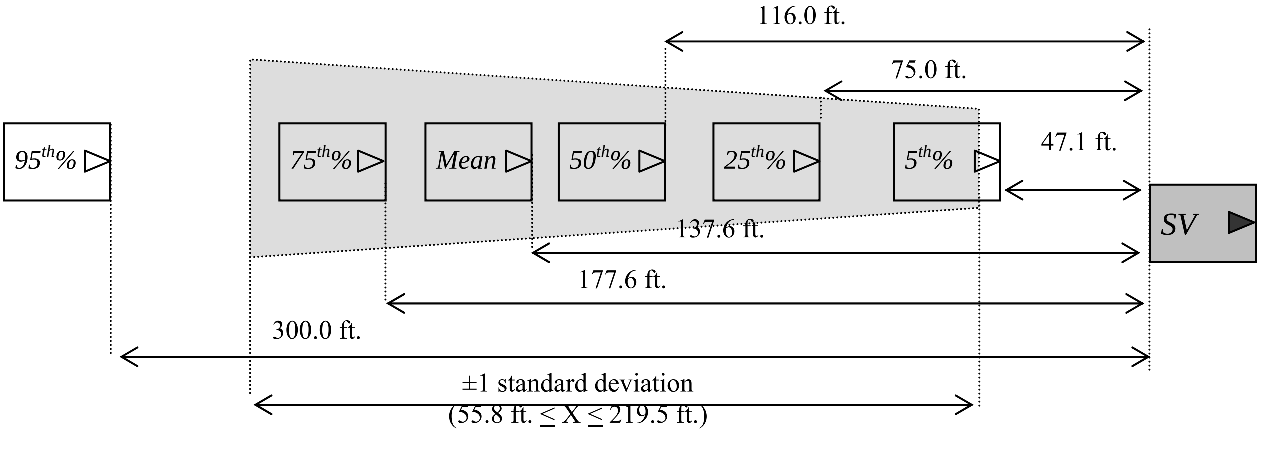

Figure 4.32. Percentile Distances to Closest Rearward Vehicle Relative to SV at t_0 for All Events with a POV Present.

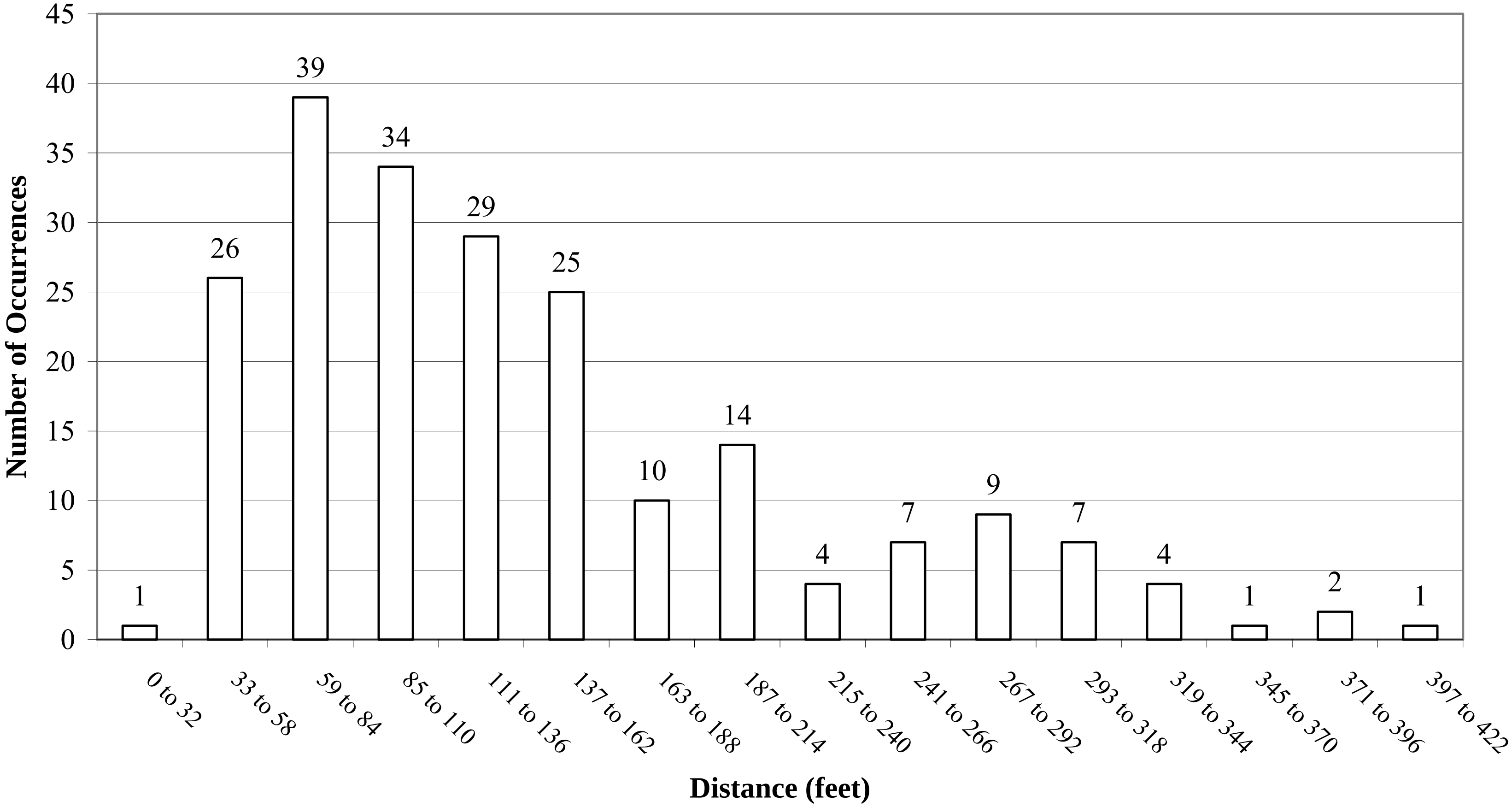

Figure 4.33. Frequency Distribution of Distance to Closest Rearward Vehicle at t_0 (N = 213).

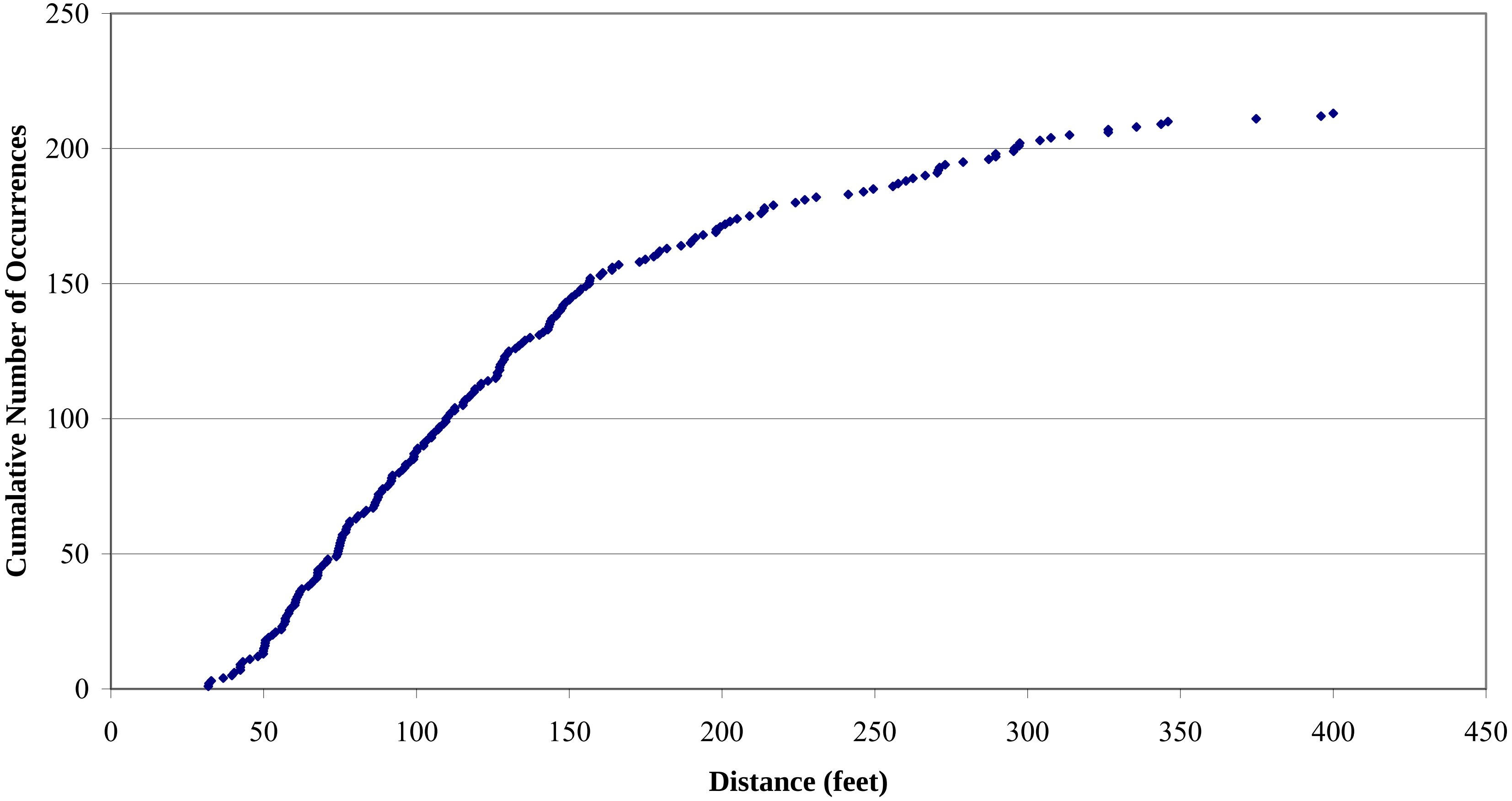

Figure 4.34. Distance to Closest Rearward Vehicle for the Sampled Events in Which a Rear Vehicle was Present at t_0 (N =213).

Figure 4.35 illustrates the percentiles, the mean, and ±1 standard deviation from the mean relative to the SV for the 109 events in which a rearward target was present and detected at t_0 (reported previously in Table 4.41). The 83 cases in which a target was present but not detected at t_0 will be revisited within the discussion on the safety envelope. Notice that values are smaller, reflecting a higher degree of accuracy since *only instances in which a POV was detected* at t_0 are included.

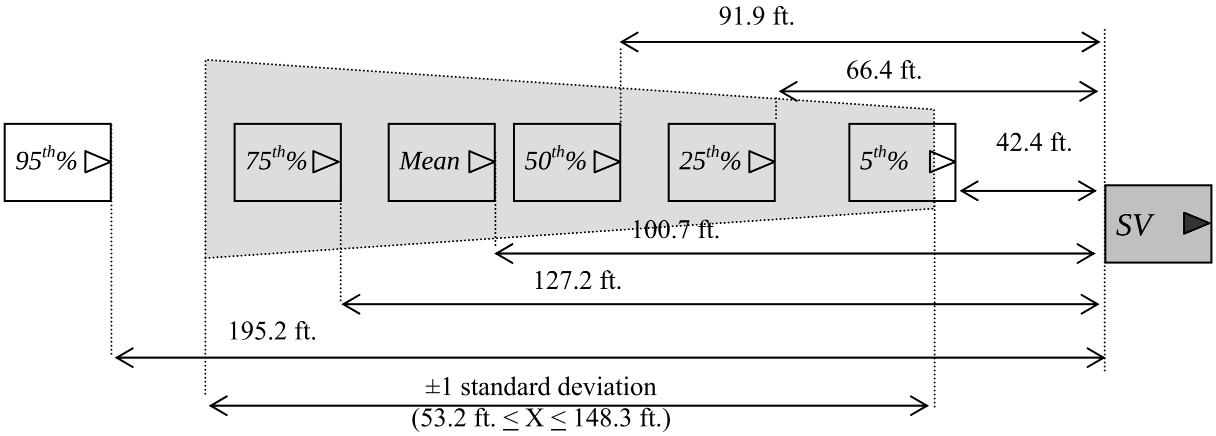

Figure 4.35. Percentile Distances to Closest Rearward Vehicle Relative to SV at t_0 For Cases in which a POV was Detected.

Distance by Urgency

The number of events and additional descriptive statistics for each urgency level are listed in Table 4.42. Figure 4.36 illustrates distance for all 213 events and at each urgency level, and Figure 4.37 illustrates the cumulative number of occurrences for distance to the closest rearward vehicle for each urgency level. Results for the 25th, 50th, and 75th percentiles show that as the urgency of the lane change increases, the distance from the SV to the closest rearward vehicle also increases.

It is important to point out that urgency ratings are predominantly based on the movement of forward vehicles. However, in the case of tailgating, urgency may refer to a rearward vehicle if the urgency with which the lane change was made was not also influenced by a slow lead vehicle.

Table 4.42. Descriptive Statistics of Distance in Feet to Closest Rearward Vehicle for All Events and for Each Urgency Level.

	Urgency			All
	1	2	3	
N	183	28	2	213
Mean	133.69	155.95	241.15	137.62
SD	79.66	91.46	77.15	81.85
Min	31.90	32.90	186.60	31.90
Max	400.00	396.00	295.70	400.00
5th	48.28	43.21	192.06	47.06
25th	74.50	91.05	213.88	75.00
50th	112.60	133.70	241.15	116.00
75th	162.50	204.18	268.43	177.60
95th	303.34	289.60	290.25	300.04

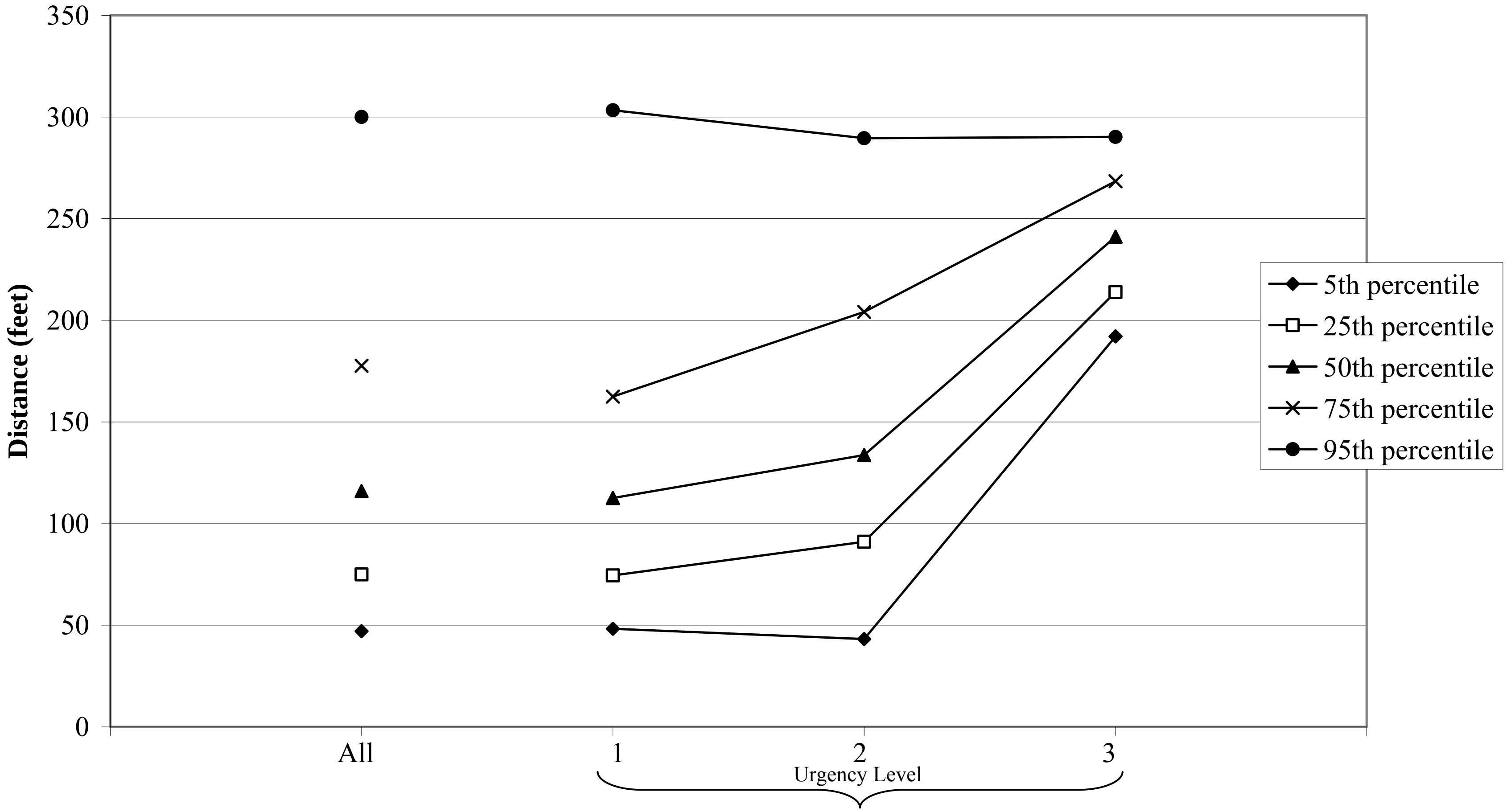

Figure 4.36. Rearward Distance Percentiles for the Sampled Events and for Each Urgency Level. (Note that sample size at urgency level 3 is small.)

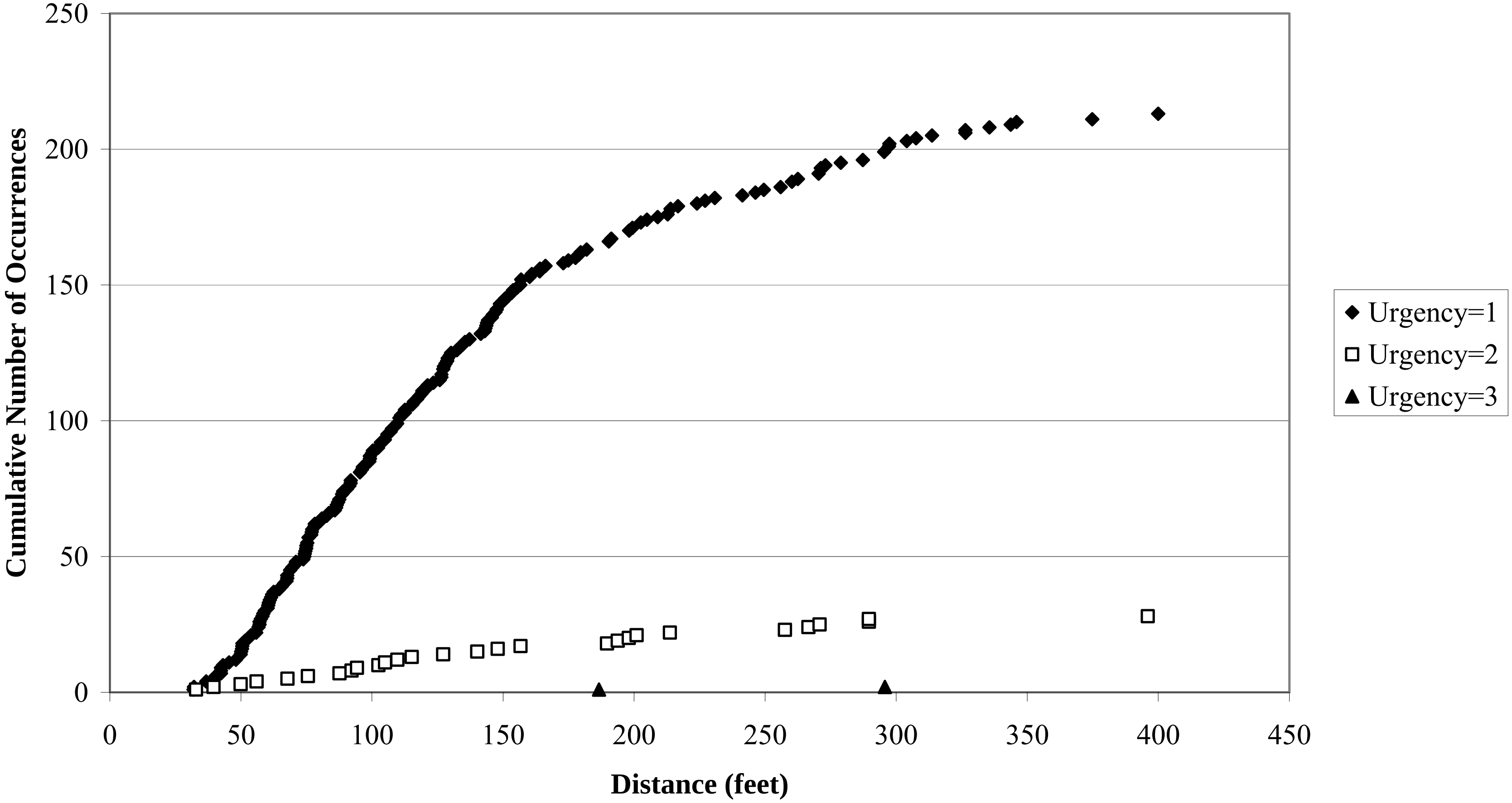

Figure 4.37. Distance to Rearward Vehicle for Sampled Events at Each Urgency Level in Which a Rearward Vehicle was Detected at t_0. (Note that sample size at urgency level 3 is small.)

Distance by Severity

The rearward distance for all 213 events for each severity level is presented in Table 4.43. Figure 4.38 illustrates distance at each severity level; no clear trends were present for this analysis. Figure 4.39 illustrates the cumulative number of occurrences for distance to the closest vehicle for all 213 events and the distance to the closest vehicle for events at each severity level.

Table 4.43. Descriptive Statistics of Distance in Feet to Closest Rearward Vehicle for the Sampled Events and for Each Severity Level.

	Severity						
	1	**2**	**3**	**4**	**5**	**6**	**All**
N	23	75	8	1	105	1	213
Mean	190.36	102.96	106.34	60.60	152.43	297.20	137.62
SD	101.48	47.52	64.14	n/a	86.69	n/a	81.85
Min	48.10	31.90	56.00	60.60	32.10	297.20	31.90
Max	396.00	260.20	209.00	60.60	400.00	297.20	400.00
5th	51.69	41.80	56.56	60.60	50.16	297.20	47.06
25th	109.40	71.70	59.70	60.60	78.20	297.20	75.00
50th	152.00	96.20	81.20	60.60	133.50	297.20	116.00
75th	274.85	127.30	126.53	60.60	199.40	297.20	177.60
95th	342.07	184.72	207.57	60.60	323.86	297.20	300.04

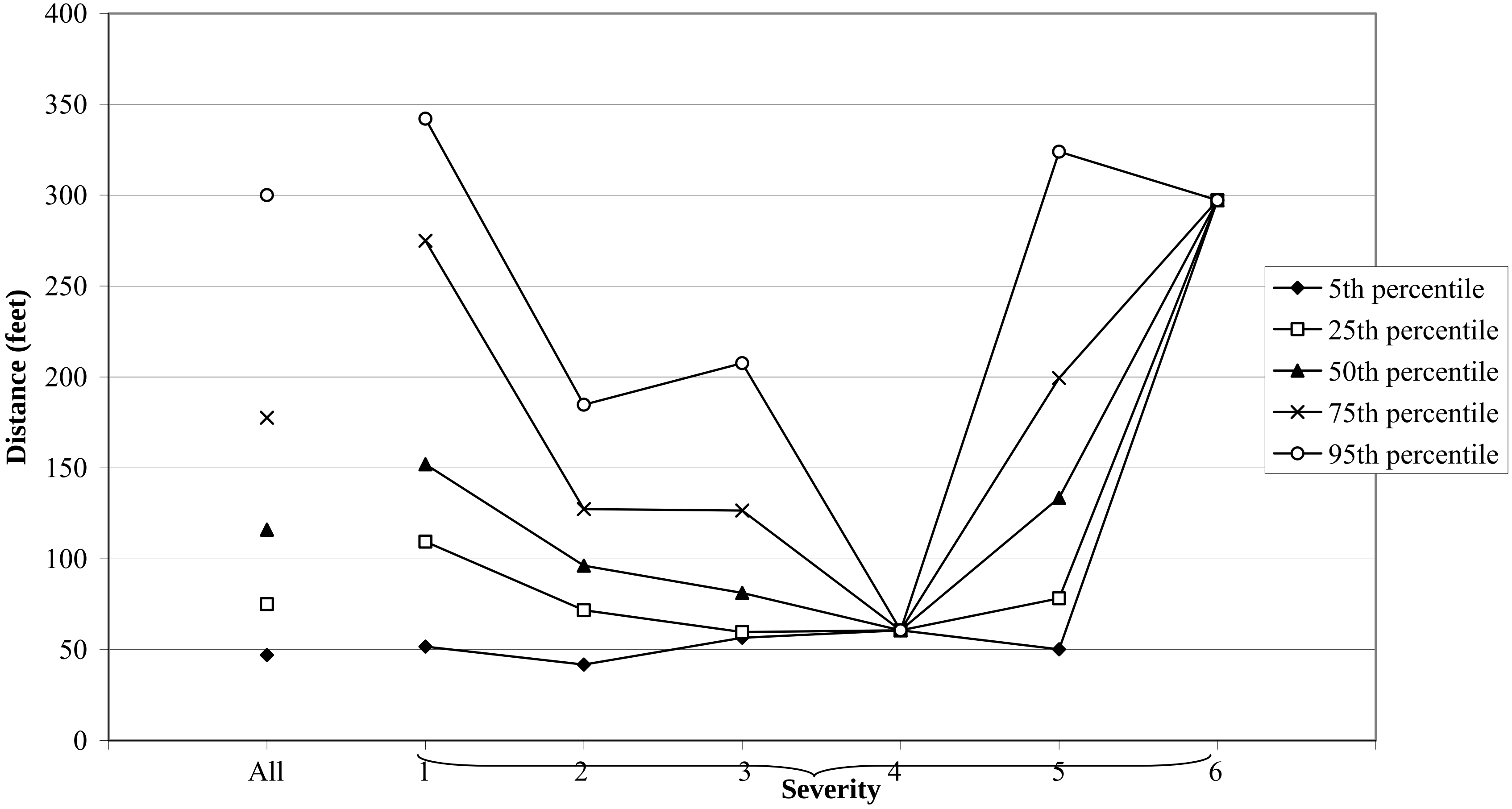

Figure 4.38. Distance Percentiles for the Sampled Rear Events and for Each Severity Level. (Note that data for severities 4 and 6 are for a single sample.)

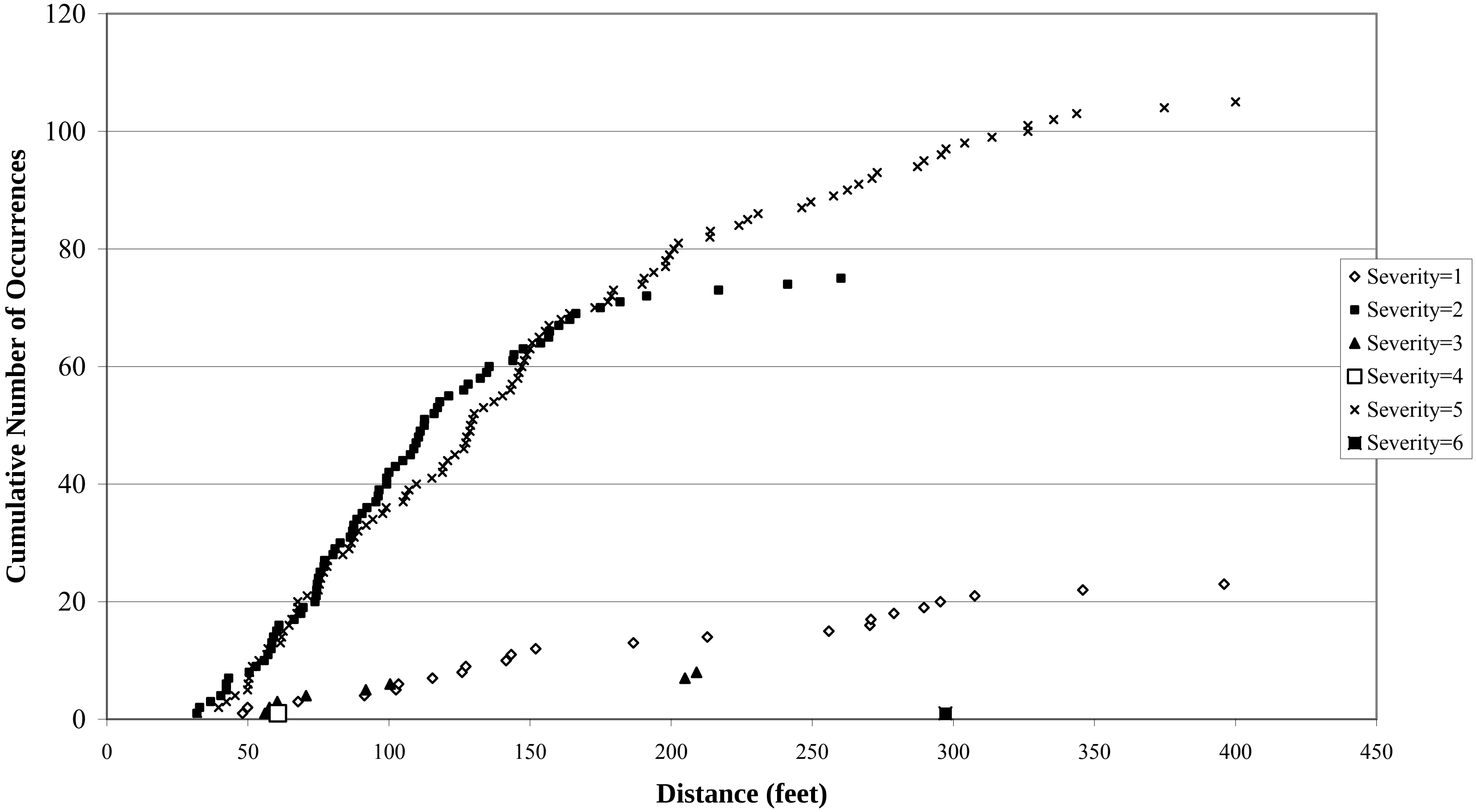

Figure 4.39. Distance to Closest Rearward Vehicle for the Sampled Events at Each Severity Level in Which a Rearward Vehicle was Detected at t_0. (Note that data for severities 4 and 6 are for a single sample.)

Time to Collision to Closest Rearward Vehicle

The TTC that drivers allow to the closest rearward vehicle relative to the SV was derived from input received from the left rear radar. Time to collision represents the time in seconds it would take for the rearward POV to collide with the SV, had the original route been maintained.

Time to collision was analyzed only for the 109 events in which a rearward target was present at t_0. Events were not analyzed in which targets were present but not detected at t_0 or if there was no target detected at all. Of the 109 events, 94 had a TTC data point. The remaining 16 events did not have TTC values, indicating that the POV had a velocity that was equal to or less than the velocity of SV at t_0.

Table 4.44 presents the descriptive statistics for these lane changes. Figure 4.40 illustrates the percentiles, the mean, and ±1 standard deviation from the mean relative to the SV for the 94 events. Figure 4.41 is a histogram of occurrences for closest following vehicle, and Figure 4.42 shows cumulative occurrences as a function of TTC. Notice that several lane changes have a TTC of 60 s. For these events, the vehicles likely had a very small relative velocity differential (i.e., -0.1 ft/s) that resulted in a very large TTC (e.g., 220 s). In these cases, the maximum was set at "60."

Table 4.44. Descriptive Statistics for TTC in Seconds to Closest Rearward Vehicle for Lane Changes at t_0 (Events in Which a POV was Present).

Sampled Lane Changes	
N	94
Mean	18.41
SD	14.69
Min	3.00
Max	60.00
5th %-ile	5.60
25th %-ile	9.53
50th %-ile	12.35
75th %-ile	22.60
95th %-ile	60.00

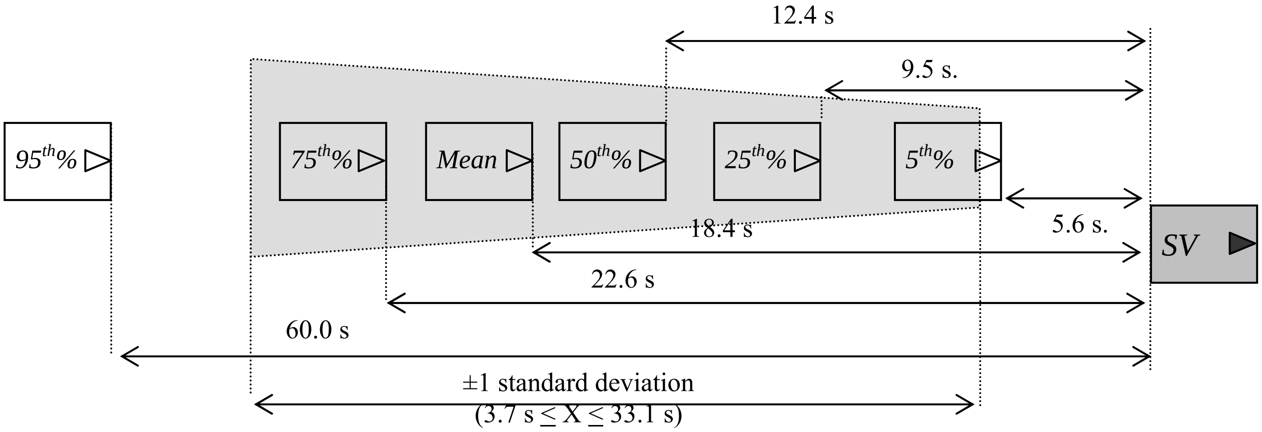

Figure 4.40. Percentile TTC to Closest Rearward Vehicle Relative to SV at t_0. (This diagram is a depiction of data and is not geometrically accurate.)

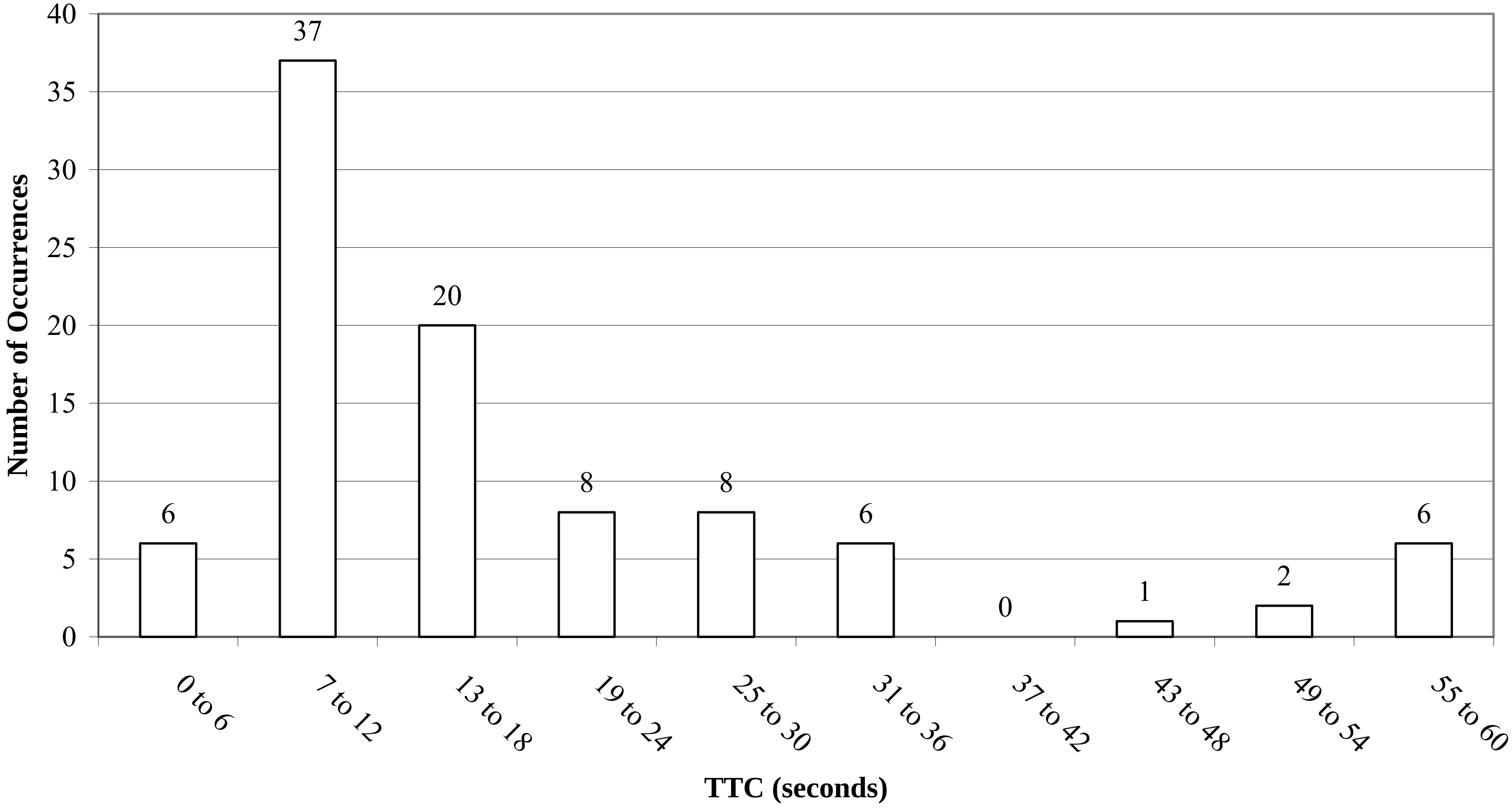

Figure 4.41. Frequency Distribution of TTC to Closest Rearward Vehicle at t_0 (N =93).

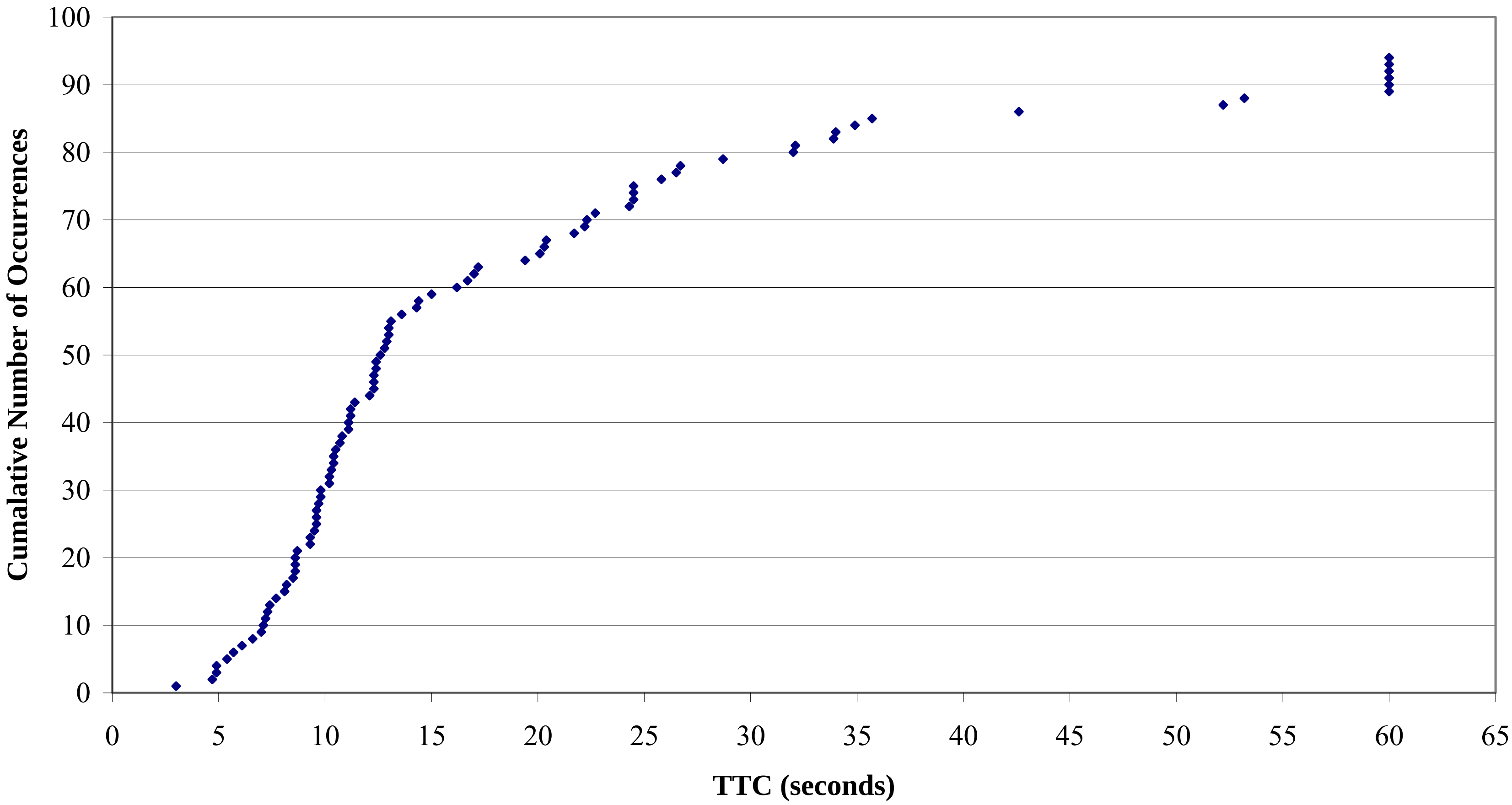

Figure 4.42. TTC to Closest Rearward Vehicle for the Sampled Events in Which a Rear Vehicle was Present at t_0 and TTC values were Available (N =94).

Time to Collision by Urgency

The number of events and additional descriptive statistics for each urgency level are listed in Table 4.45. Figure 4.43 illustrates TTC at each urgency level for the 94 events. The cumulative number of occurrences for TTC for the closest rearward vehicle for each urgency level can be understood by reviewing Table 4.44 and Figure 4.42 (graphing these events by urgency level turns out to be indistinguishable from the pattern depicted by Figure 4.42). The large majority (93%) of events had urgency ratings of 1. As a reminder, urgency ratings are predominantly based on the movement of forward vehicles; this subset of 94 events focused on lane changes in the vehicle of concern was the rearward vehicle.

In the majority of cases for percentiles, the TTC from the SV to the closest rearward vehicle decreases as the urgency rating of the lane change increases. There is only one event rated with an urgency of 3. The percentiles appear to increase in this event; however, with more observations, it is likely that the TTC would actually decrease.

Table 4.45. Descriptive Statistics of TTC in Seconds for Closest Rearward Vehicle for the Sampled Events in Which a Rearward Vehicle was Present for Each Urgency Level.

	Urgency			
	1	**2**	**3**	**All**
N	87	6	1	94
Mean	19.05	10.75	8.70	18.41
SD	15.05	4.45	n/a	14.69
Min	3.00	5.40	8.70	3.00
Max	60.00	17.00	8.70	60.00
5th	5.82	5.90	8.70	5.60
25th	9.60	7.88	8.70	9.53
50th	12.40	9.85	8.70	12.35
75th	24.40	13.85	8.70	22.60
95th	60.00	16.50	8.70	60.00

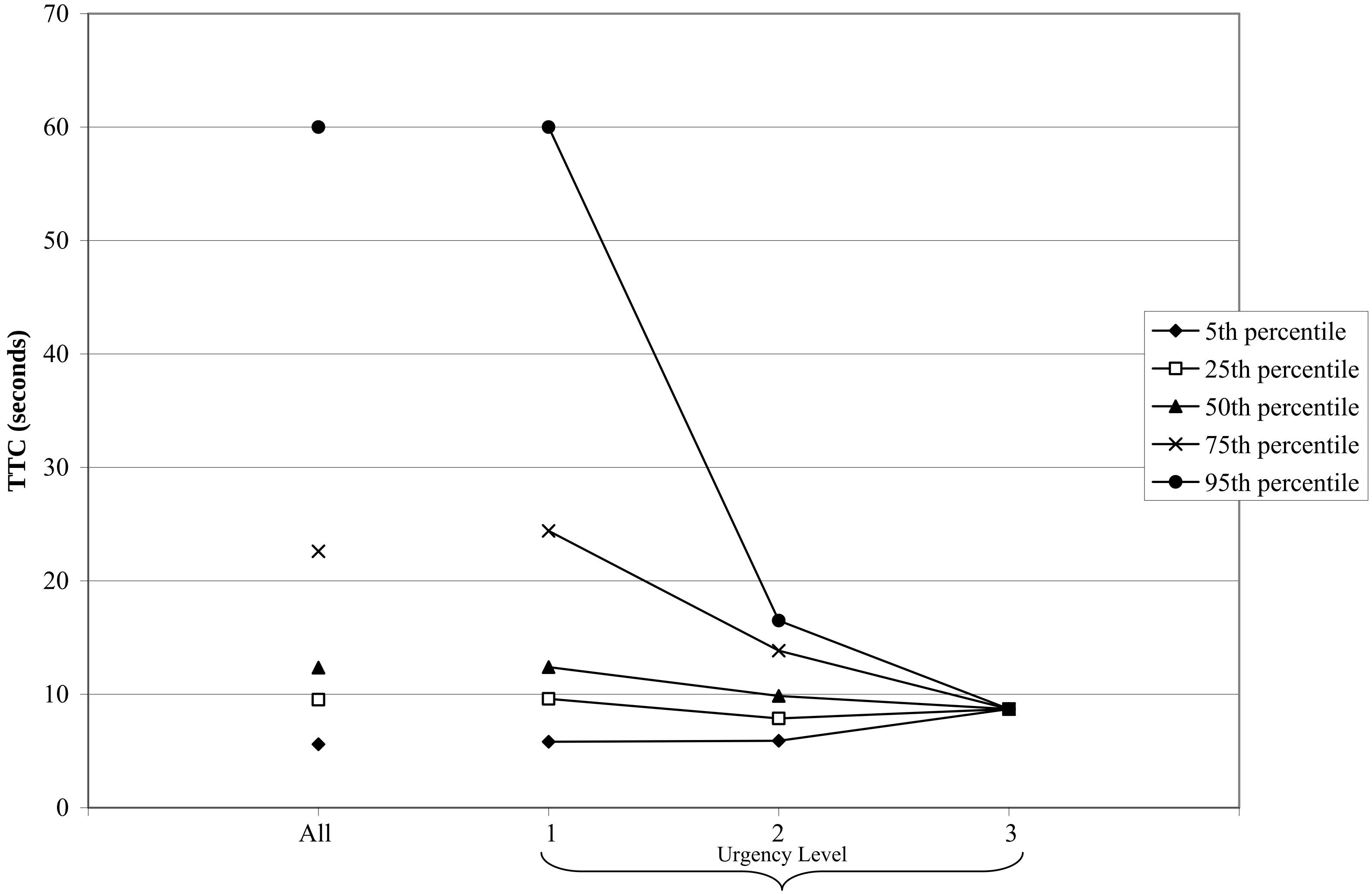

Figure 4.43. Rearward TTC Percentiles for the Sampled Events in Which a Rear Vehicle was Present at t_0 and TTC values were Available for Each Urgency Level (N =94). (Note that for urgency level 3 there is only one sample.)

Time to Collision by Severity

The rearward TTCs for the 94 events for each severity level are presented in Table 4.46. For severity ratings of 1 through 3, the mean and percentile value decrease as severity level increases. Note that only one event was rated with a severity of 4. For events rated with a severity of 5, the mean and percentiles appear to fall between those rated as severity of 2 and 3. It is likely that the pattern of an inverse relationship between TTC and severity rating would appear more clearly with a larger sample. With a larger sample, it is possible that the number of observation at each severity level would increase and the pattern would be more stable. The low number of observations causes this pattern to be difficult to see.

Figure 4.44 illustrates events by severity level. This figure closely resembles Figure 4.42; most events are rated with a severity of 2 and follow the same general pattern as the graph for all events. Figure 4.45 illustrates that TTC decreases for severity 1 through 3; for severity 5, the TTC values for the mean and percentiles appear to fall between those values for events rated with severity of 2 and severity of 3.

Table 4.46. Descriptive Statistics of TTC in Seconds to Closest Rearward Vehicle for the Sampled Events in Which a Rear Vehicle was Present at t_0 for Each Severity Level.

	Severity						
	1	**2**	**3**	**4**	**5**	**6**	**All**
N	7	65	6	1	15	0	94
Mean	25.66	19.84	6.33	22.20	13.41	n/a	18.41
SD	23.71	14.78	2.81	n/a	8.01	n/a	14.69
Min	6.60	5.40	3.00	22.20	4.70	n/a	3.00
Max	60.00	60.00	10.20	22.20	34.90	n/a	60.00
5th	7.23	7.12	3.48	22.20	6.52	n/a	5.60
25th	10.65	9.80	4.90	22.20	9.05	n/a	9.53
50th	15.00	12.90	5.30	22.20	10.30	n/a	12.35
75th	38.35	24.50	8.40	22.20	15.00	n/a	22.60
95th	60.00	58.64	9.98	22.20	27.62	n/a	60.00

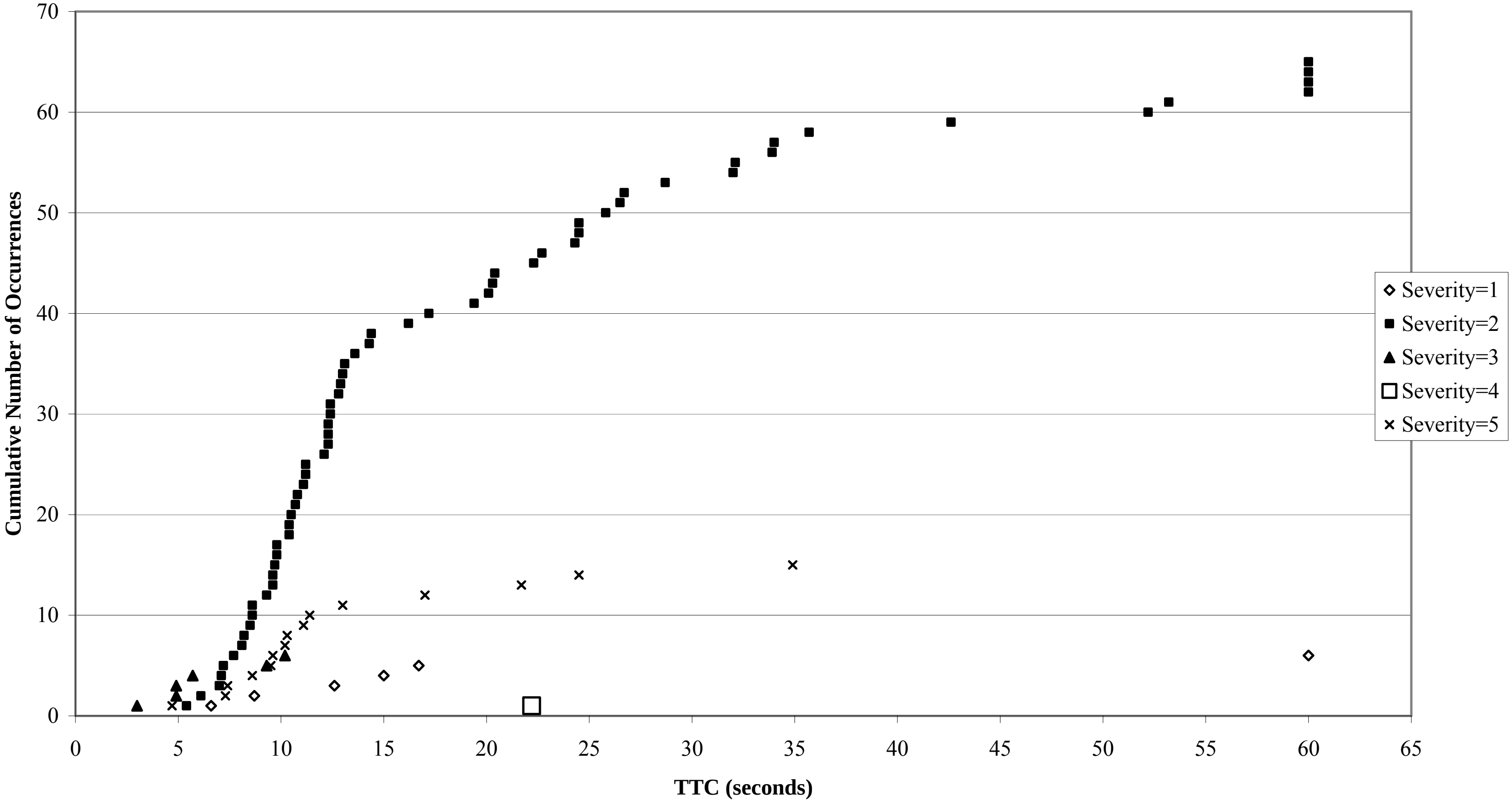

Figure 4.44. TTC to Closest Rearward Vehicle by Severity for the Sampled Events in Which a Rear Vehicle was Present at t_0 and TTC values were Available (N =94). (Note that for severity level 4 there is only one sample.)

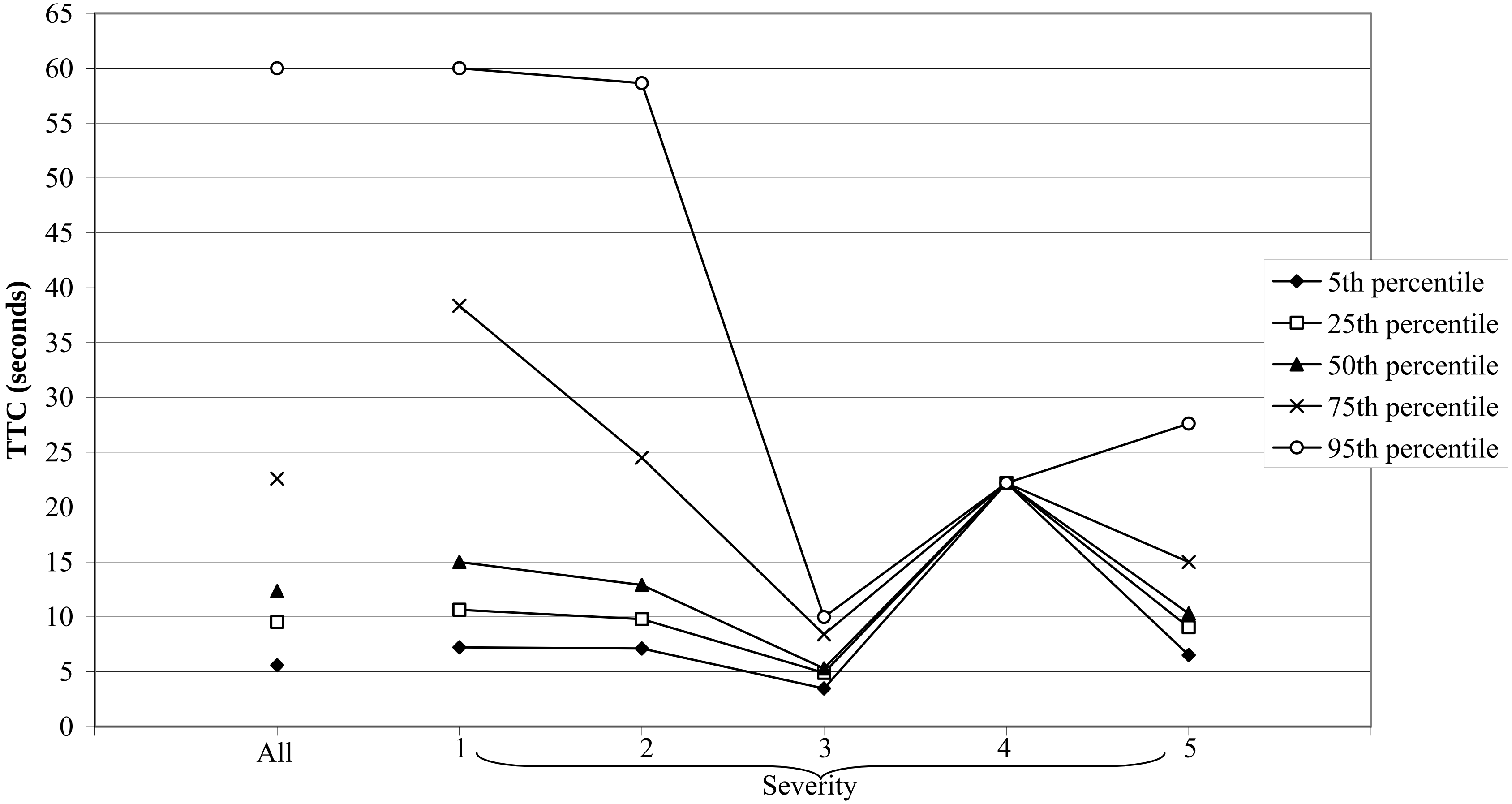

Figure 4.45. TTC Percentiles for the Sampled Events in Which a Rear Vehicle was Present and for Each Severity Level. (Note that for severity level 4 there is only one sample.)

Relative Velocity in Reference to Closest Rearward Vehicle

Relative velocity in reference to the closest rearward vehicle is important for CAS designers to understand. Relative velocity is measured by subtracting the velocity of the POV from the velocity of the SV, and it is negative in all 94 cases. This indicates that the rearward POV is moving at a faster velocity than the SV. For example, if the rearward POV is moving at 60 ft/s and the SV is moving at 50 ft/s, the relative velocity would be -10 ft/s. This information may influence the timing and urgency of issuing a CAS warning/alert. That is, if the relative velocity is low (such as -0.13 ft/s), an advisory alert may be issued (e.g., a visual alert). If the relative velocity is high (such as > -20.5 ft/s), then a more urgent warning may be issued, such as a combined visual and auditory alert to alert the driver to the presence of the approaching vehicle.

Relative velocity was analyzed only for the 94 events in which it was available. Table 4.47 presents the descriptive statistics for these lane changes. Figure 4.46 illustrates the percentiles, the mean, and ±1 standard deviation from the mean relative to the SV for the 94 events. Although distance is implied by this figure, relative velocity is independent of distance between vehicles. Figure 4.47 is a histogram of occurrences for closest following vehicle and Figure 4.48 shows cumulative occurrences as a function of relative velocity.

Table 4.47. Descriptive Statistics for Relative Velocity in Feet/Second Between the SV and the Closest Rearward Vehicle for the Sampled Lane Changes in Which a Vehicle was Detected at t_0.

Sampled Lane Changes	
N	94
Mean	-9.09
SD	7.12
Min	-37.20
Max	-0.20
5th %-ile	-22.03
25th %-ile	-12.03
50th %-ile	-7.70
75th %-ile	-3.95
95th %-ile	-0.86

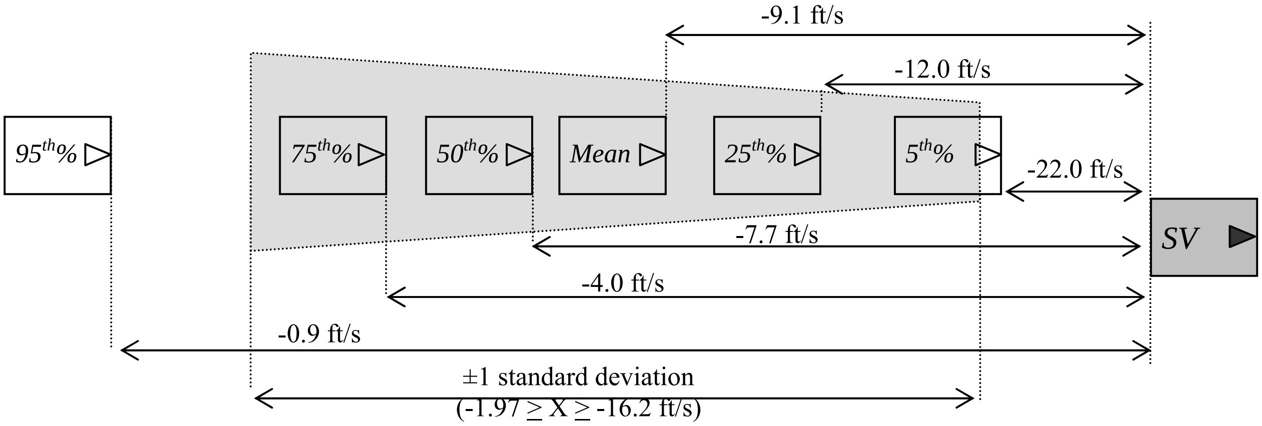

Figure 4.46. Percentile Relative Velocity to Closest Rearward Vehicle Relative to SV at t_0. (This diagram is a depiction of data and is not geometrically accurate.)

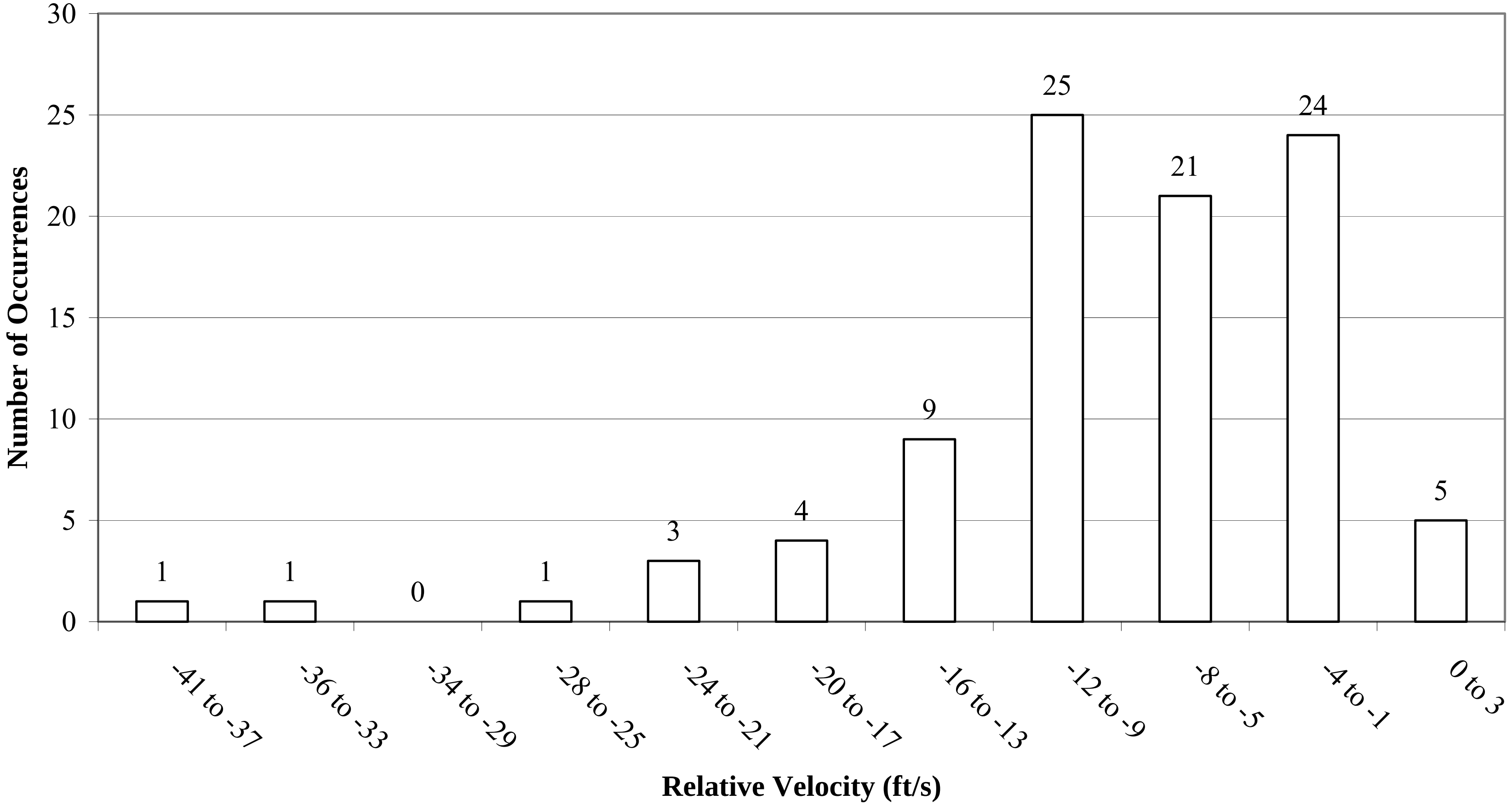

Figure 4.47. Frequency Distribution for the Sampled Events in Which a Rearward Vehicle was Detected at t_0 Showing Relative Velocity (N = 94).

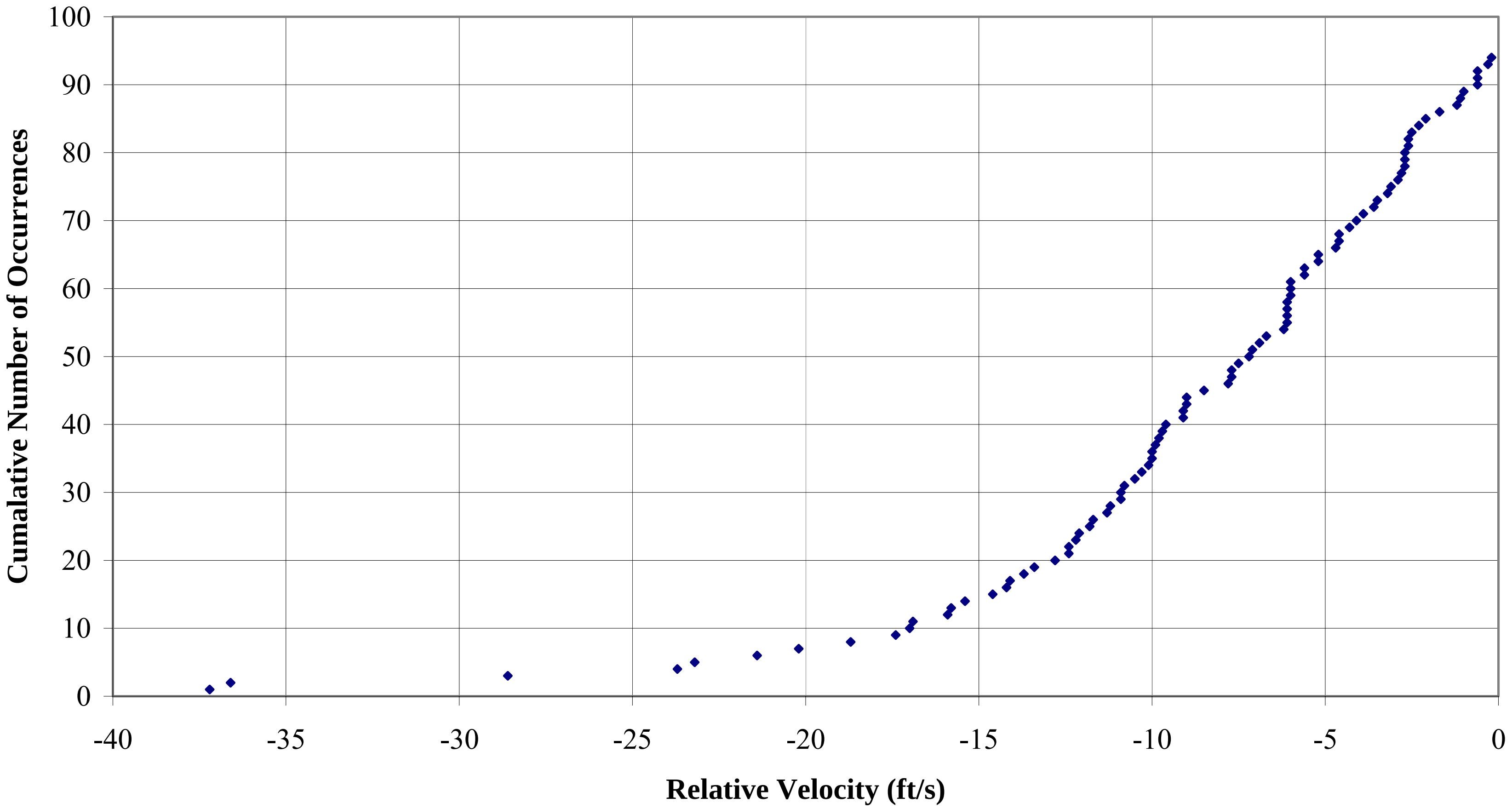

Figure 4.48. Relative Velocity Between SV and Closest Rearward Vehicle Detected at t_0 (N = 94).

Relative Velocity by Urgency

The relative velocity and descriptive statistics for each urgency level for the closest rearward vehicles detected at t_0 are listed in Table 4.48. Figure 4.49 illustrates relative velocity for all events at each urgency level, and Figure 4.50 illustrates the relative velocity between the SV and the closest rearward detected at t_0 vehicle at each urgency level. In most cases (except the 5th percentile), the relative velocity between the rearward POV and the SV decreases as the urgency of the lane change increases. That is, the more urgent the lane change is, the more likely the SV is willing to pull in front of a SV in which the disparity between vehicles is high (i.e., a high relative velocity such as –20 ft/s vs. -1.5 ft/s). However, this conclusion is tentative, given the low number of events with an urgency rating greater than 1.

Table 4.48. Descriptive Statistics of Relative Velocity in ft/s between the Closest Forward Vehicle for the Sampled Lane Changes and for Each Urgency Level.

	Urgency			
	1	**2**	**3**	**All**
N	87	6	1	94
Mean	-8.83	-10.78	-21.40	-9.09
SD	7.19	4.30	n/a	7.12
Min	-37.20	-17.00	-21.40	-37.20
Max	-0.20	-6.00	-21.40	-0.20
5th %-ile	-22.30	-16.30	-21.40	-22.03
25th %-ile	-11.50	-13.60	-21.40	-12.03
50th %-ile	-7.50	-10.15	-21.40	-7.70
75th %-ile	-3.55	-7.53	-21.40	-3.95
95th %-ile	-0.72	-6.30	-21.40	-0.86

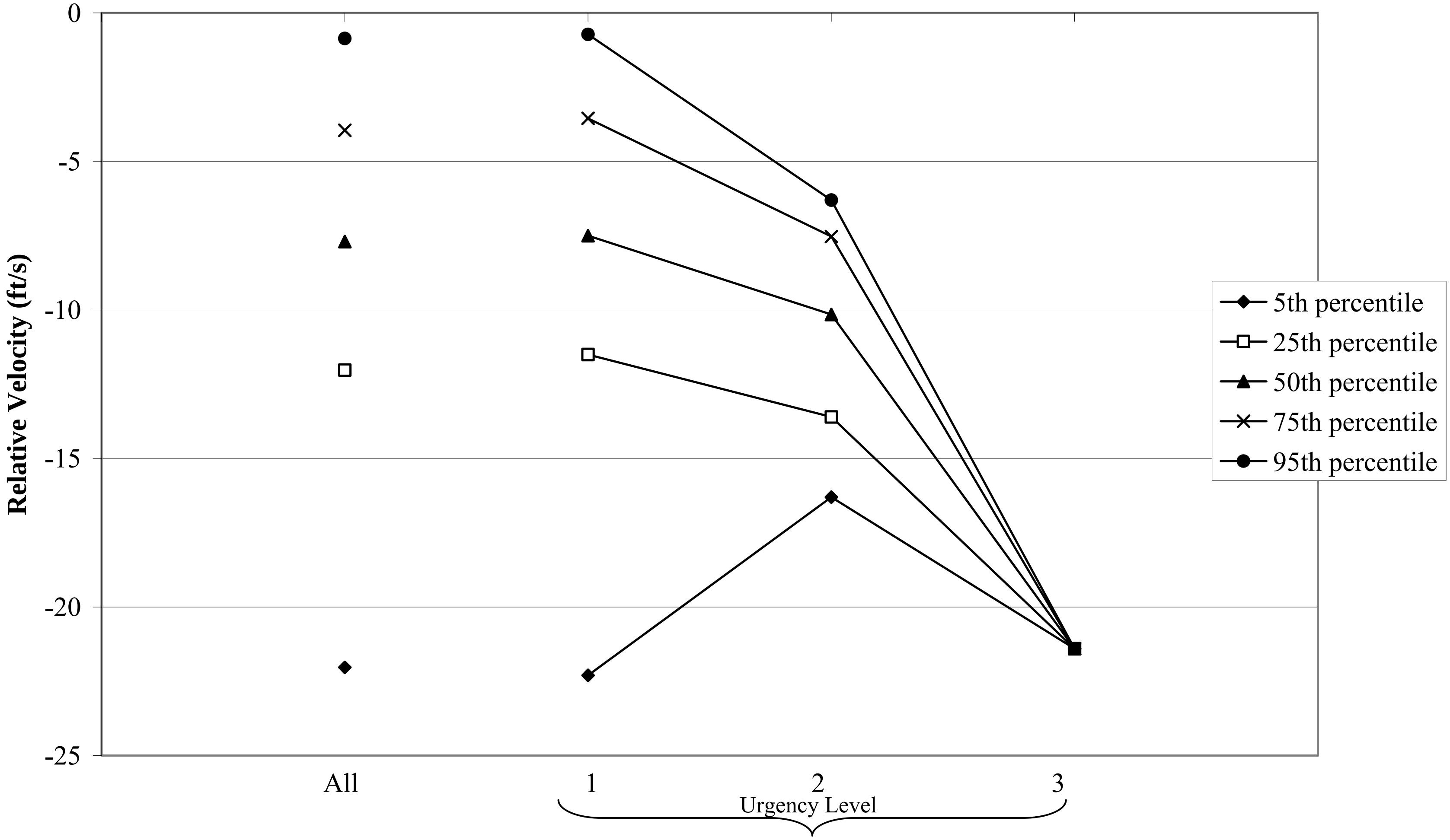

Figure 4.49. Relative Velocity Percentiles for Rearward Events in Which a Vehicle was Detected at t_0 at Each Urgency Level. (Note that for urgency level 3 there is only one sample.)

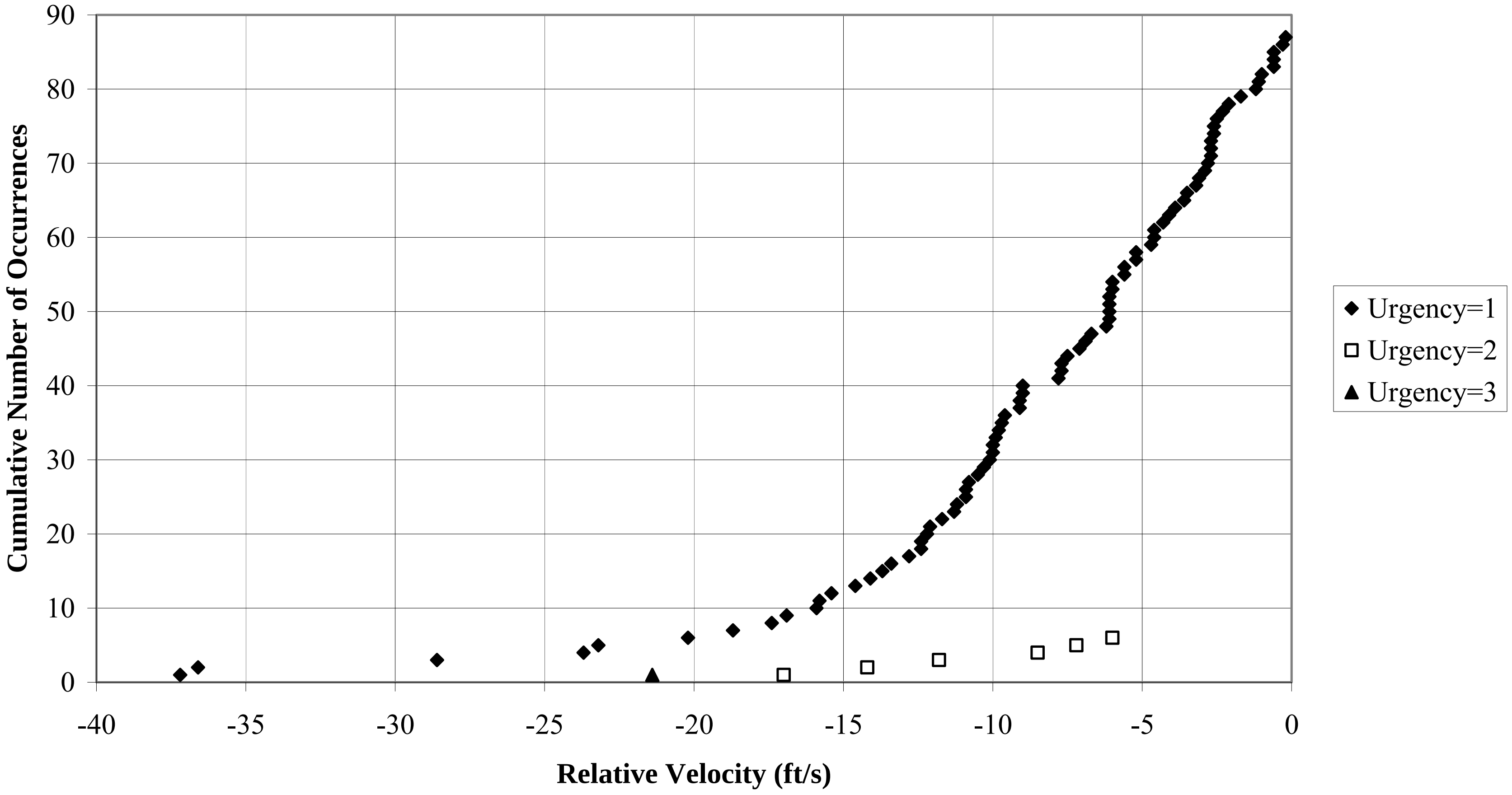

Figure 4.50. Relative Velocity Between SV and Closest Rearward Vehicle for Events at Each Urgency Level in Which a Rearward Vehicle was Detected at t_0.
(Note that for urgency level 3 there is only one sample.)

Relative Velocity by Severity

Table 4.49 lists the relative velocity for each severity level. Figure 4.51 illustrates relative velocity percentiles for events at each severity level, and Figure 5.52 illustrates the relative velocity for events at each severity level. There does not appear to be a clear relationship between relative velocity and severity. It is possible that the downward trend shown between events with a rating of 1 and those with a rating of 2 would continue with a larger data sample. This trend indicates that when the disparity between vehicles is high, the severity rating is low, which seems counterintuitive.

Table 4.49. Descriptive Statistics of Relative Velocity in Feet per Second to Closest Forward Vehicle for the Sampled Lane Changes and for Each Severity Level.

	Severity						
	1	**2**	**3**	**4**	**5**	**6**	**All**
N	7	65	6	1	15	0	94
Mean	-10.76	-8.49	-16.67	-2.70	-8.33	n/a	-9.09
SD	8.11	6.87	11.42	n/a	3.82	n/a	7.12
Min	-21.40	-37.20	-36.60	-2.70	-14.60	n/a	-37.20
Max	-0.30	-0.20	-6.00	-2.70	-2.10	n/a	-0.20
5th %-ile	-20.20	-19.90	-33.38	-2.70	-14.32	n/a	-22.03
25th %-ile	-17.15	-11.20	-20.83	-2.70	-11.05	n/a	-12.03
50th %-ile	-9.10	-7.10	-11.95	-2.70	-7.50	n/a	-7.70
75th %-ile	-5.10	-3.20	-10.28	-2.70	-5.85	n/a	-3.95
95th %-ile	-0.72	-0.68	-6.95	-2.70	-3.15	n/a	-0.86

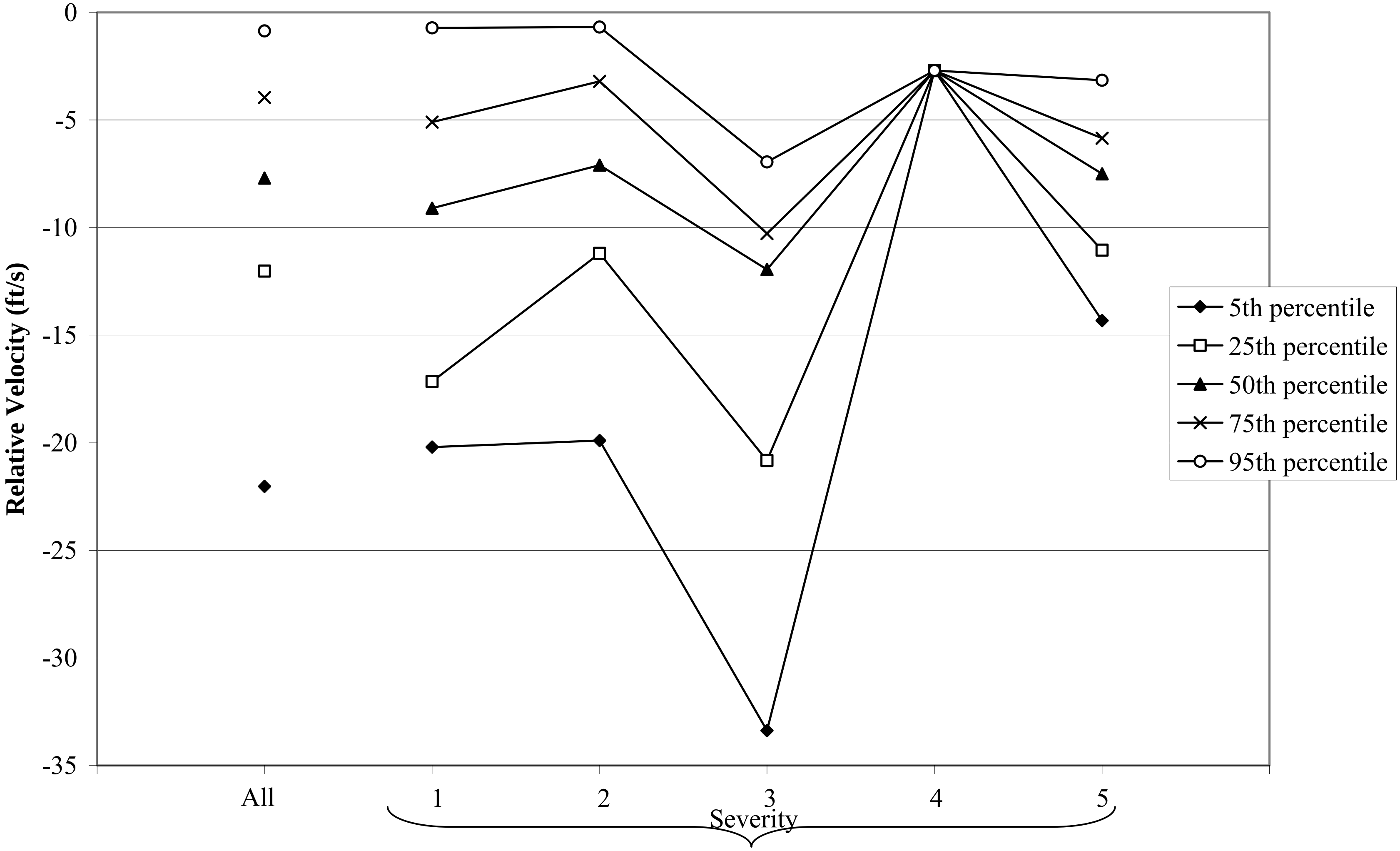

Figure 4.51. Relative Velocity Percentiles at Each Severity Level for Events in Which a Rearward Vehicle was Detected at t_0. (Note that for severity level 4 there is only one sample.)

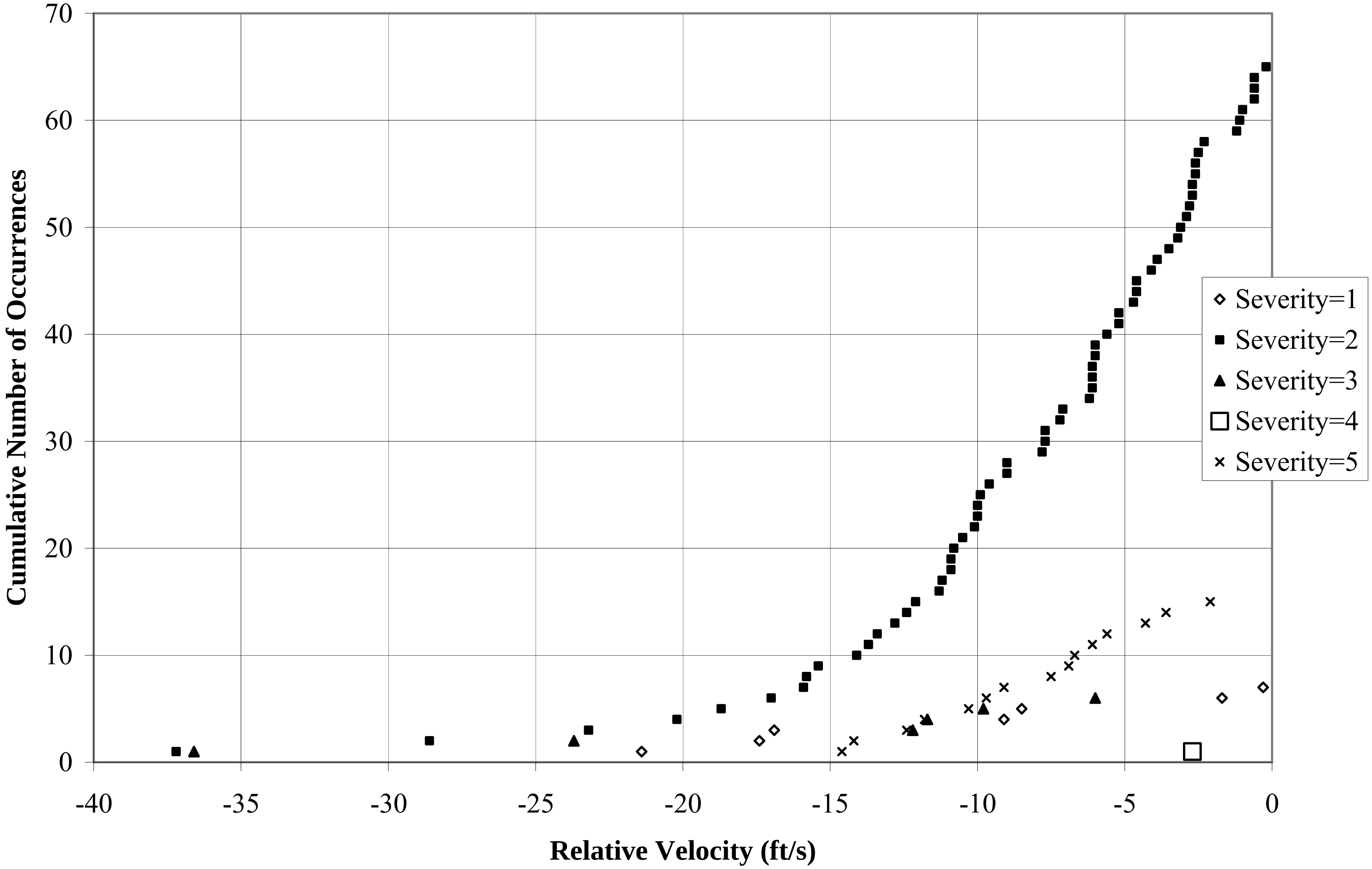

Figure 4.52. Relative Velocity Between SV and Closest Rearward Vehicle at Each Severity Level in Which a Rearward Vehicle was Detected at t_0.
(Note that for severity level 4 there is only one sample.)

The Safety Envelope

In an attempt to integrate the findings from both the closest forward gap and the closest rearward gap analysis, the concept of a safety envelope was developed. The safety envelope is a zone surrounding the subject vehicle in space and time and is measured at t_0. This concept could provide information about the driver's natural or innate go/no-go decision based on what is in front and behind the SV. The safety envelope was developed by combining the results from the forward and rearward area analysis.

To review, the forward area analysis involved the closest forward vehicle relative to (and in the same lane as) the SV, and the rearward area analysis involved the closest rearward *adjacent* vehicle relative to (in the destination lane of) the SV. For these analyses, forward and rearward area was reported in terms of distance, relative velocity, and TTC.

Distance

To investigate the concept of a safety envelope using distance to surrounding vehicles, data were first reviewed separately for both forward and rearward POV distance from the SV. Table 4.50 displays the descriptive statistics for all events in which a vehicle was present in either the front *or* rear of the SV. This table aids in understanding the relationship of distance from the POV to the SV.

Table 4.50. Distance in Feet for Forward *or* Rearward POV Events.

	Forward Distance	**Rearward Distance**
N (events)	434	109
Mean	121.39	100.73
SD	77.23	47.57
Min	23.50	31.90
Max	400.00	260.20
5th %-ile	39.64	42.40
25th %-ile	65.23	66.40
50th %-ile	96.40	91.90
75th %-ile	155.38	127.20
95th %-ile	299.90	195.24

Given that the safety envelope concept incorporates both the forward and rearward areas relative to the SV, event numbers were matched to determine cases where *both* a forward and rearward vehicle were present. Out of 500 events, vehicles were detected in both the front and the rear of the SV in 98 cases. Table 4.51 presents the descriptive statistics for this set of lane changes, and Figure 4.53 illustrates the 5th and 25th percentile and mean values in a graphical format. By comparing Table 4.50 to Table 4.51, one can see that even with fewer events to choose from, the values at each percentile are very similar. For example, the 5th percentile forward distance across 434 lane changes (Table 4.50) was 39.64 feet as compared to 44.10 feet for 98 lane changes (Table 4.51). Thus, it appears that the approach of considering only cases in which a vehicle is present in both the front and the rear is reasonable for estimating the safety envelope in terms of distance.

Table 4.51. Distance in Feet for Events in Which a Vehicle was Detected in *both* the Forward and Rearward Areas Simultaneously.

	Forward Distance	**Rearward Distance**
N (events)	98	98
Mean	119.52	103.24
SD	73.24	48.13
Min	24.00	31.90
Max	378.40	260.20
5th %-ile	44.10	42.40
25th %-ile	65.93	67.98
50th %-ile	96.40	93.25
75th %-ile	148.33	131.33
95th %-ile	283.63	202.20

Note that drivers tend to keep a consistent distance envelope in each direction at nearly all percentiles. From Table 4.51, one can observe that 95% of drivers studied had approximately 43 feet of space (or more) in the front and rear at the time the lane change began. For the purpose of this study, it appears that most drivers preferred to have a safety envelope of at least 40 feet around their vehicles at t_0.

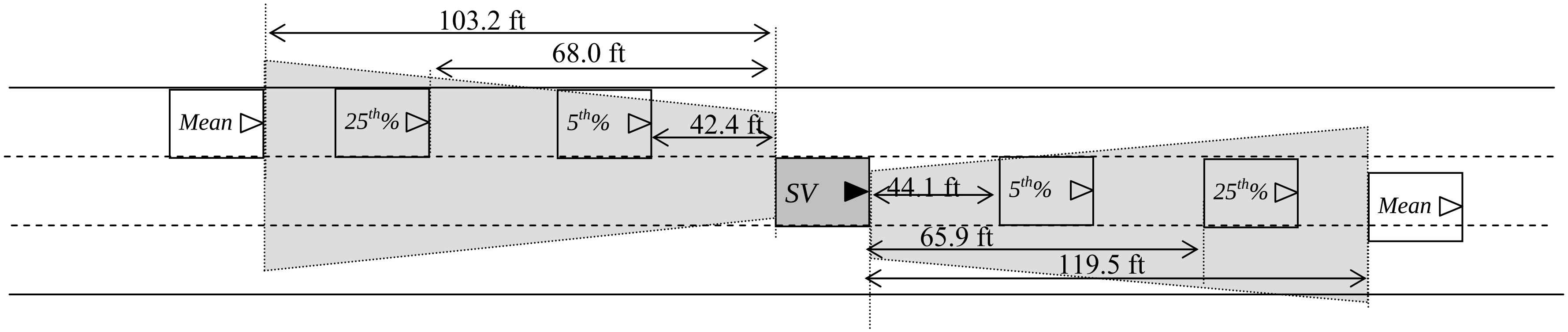

Figure 4.53. Distance Safety Envelope for Cases in Which a Vehicle was Detected in both the Forward and Rearward Area Simultaneously (Distance in Feet Shown for the 5th Percentile, 25th Percentile, and Mean Values).

Relative Velocity

The next investigation of the safety envelope concept used the dependent measure of relative velocity between the SV and the POV. In the following tables and figures, a large negative relative velocity indicates a high closing rate (i.e., the subject vehicle and the POV are closing on one another rather than pulling away from one another). For the case of a forward event, if the POV was moving at 50 ft/s and the SV (approaching the slow lead POV from behind) was moving at 65 ft/s, the relative velocity value would be -15 ft/s. If the value is positive, this would indicate that the SV was actually moving more slowly than the POV in the forward case. Relative velocity data were first reviewed for cases in which POVs were present in either forward and rearward positions relative to the SV. Table 4.52 displays the descriptive statistics for these events.

Table 4.52. Relative Velocity in Feet per Second for Forward *or* Rearward POV Events.

	Forward Relative Velocity	**Rearward Relative Velocity**
N (events)	434	109
Mean	-5.90	-7.09
SD	12.55	8.53
Max	-69.10	-37.20
Min	43.40	19.70
5th %-ile	-29.79	-20.92
25th %-ile	-9.28	-11.20
50th %-ile	-3.00	-6.10
75th %-ile	0.58	-2.60
95th %-ile	9.00	4.54

Forward and rearward distances were next matched by event number. Out of 500 events (434 forward and 109 rearward), there were 96 cases in which vehicles were detected in both the front and the rear of the SV for which relative velocity data were available; these events are described statistically in Table 4.53. Figure 4.54 illustrates the 5th and 25th percentile and mean values from Table 4.53 in a graphical format. By comparing Table 4.52 to Table 4.53, one can see that that even with fewer events to choose from, the values at each percentile are very similar. For example, the 5th percentile forward relative velocity across 434 lane changes (Table 4.52) was –29.79 ft/s as compared to –17.53 ft/s for 96 lane changes (Table 4.53). With fewer data points the relative velocity decreases; however, it appears that the approach of considering only cases in which a vehicle is present in both the front and the rear is reasonable for estimating the safety envelope. This case is also more representative of the concept behind the safety envelope.

Table 4.53. Relative Velocity in Feet per Second for Events in Which a Vehicle was Detected in *both* the Forward and Rearward Areas Simultaneously.

	Forward Relative Velocity	**Rearward Relative Velocity**
N (events)	96	96
Mean	-3.10	-7.83
SD	10.72	7.95
Min	-50.60	-37.20
Max	43.40	13.20
5th %-ile	-17.53	-20.50
25th %-ile	-7.15	-11.40
50th %-ile	-2.70	-7.00
75th %-ile	1.18	-2.88
95th %-ile	10.60	2.63

Ninety-five percent of drivers studied maintained a safety envelope of at least -20 feet per second relative velocity in each direction. Drivers will rarely choose to make a lane change when the closing rate between vehicles exceeds about 18 feet per second.

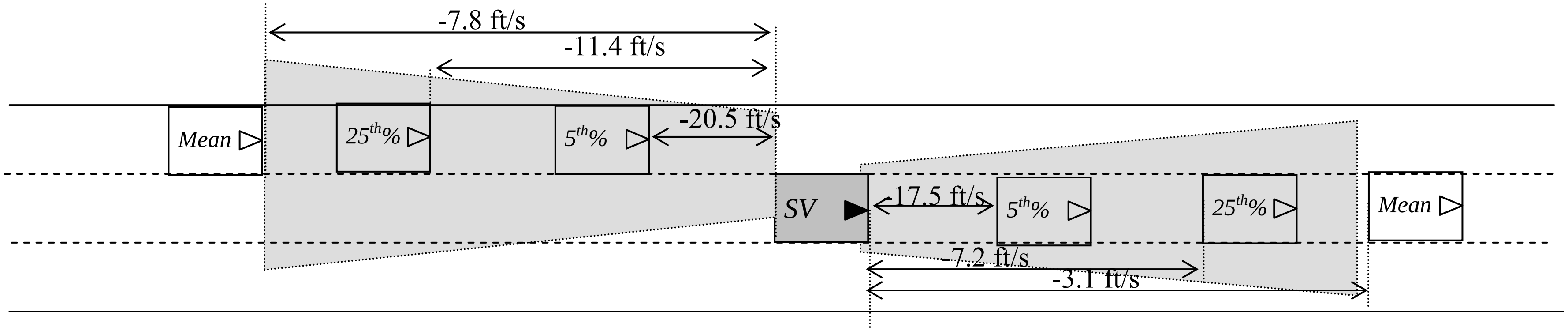

Figure 4.54. Relative Velocity Safety Envelope for Cases in Which a Vehicle was Detected in both the Forward and Rearward Position Simultaneously (Relative Velocity in ft/s Shown for the 5th Percentile, 25th Percentile, and Mean Values). (Note that the diagram is a depiction of velocity data, and not a geometrically accurate representation.)

Time to Collision

Both distance and relative velocity measures have limitations for use in the safety envelope concept. Considered independently, each measure may not be truly indicative of the potential risk of the situation at hand. For example, just because a vehicle is following another vehicle at a distance of 40 feet, it does not mean the driver is in a severe or urgent situation. Likewise, if a vehicle is following another vehicle at a short distance, and the closing rate is relatively low, there may not be enough information as to whether the SV driver is likely to perform a lane change maneuver. In fact, these two measures are very likely to interact. If a vehicle is 150 feet away but has a relatively high relative velocity, the driver of the SV might choose not to make a lane change. Similarly, if a vehicle is following closely but the relative velocity is low, the driver might choose to make a lane change.

Time-to collision is a measure that takes both distance and relative velocity into account. The interactive effects of distance and relative velocity are contained in the single measure TTC (calculated by dividing range by range rate, or distance by relative velocity). TTC seems a likely measure to be used in conjunction with a CAS; the CAS would monitor TTC as an indicator regarding go/no-go. This also supports the driver, in that he or she is monitoring the environment to make a go/no-go decision. Different levels of TTC could also be used to provide graded or “multiple-level” warnings as the TTC values decrease (e.g., Go, Caution, and No-Go).

Time to collision data were reviewed relative to vehicles forward of and rearward from the SV. Table 4.54 displays the descriptive statistics for all events in which a vehicle was present in either the front *or* the rear of the SV. Note that of the 434 cases in which a vehicle was present in front of the SV (Table 4.54), 123 had a TTC value that was less than or equal to 0, and these were not included in the table. TTC was not relevant in these cases because the POV ahead had a velocity equal to or greater than the SV. For the rearward targets, instances were counted that met three criteria: (1) a vehicle was detected in the rear left radar at t_0, (2) the detected vehicle had a TTC greater than 0, and (3) the detected vehicle was considered the POV in the event (i.e., was of relevance to the event in terms of being a potential threat to the driver).

Table 4.54. TTC in Seconds for Forward *or* Rearward POV Events.

	Forward TTC	Rearward TTC
N (events)	311	94
Mean	23.22	18.41
SD	19.36	14.69
Min	2.60	3.00
Max	60.00	60.00
5th %-ile	4.30	5.60
25th %-ile	8.60	9.53
50th %-ile	15.30	12.35
75th %-ile	32.30	22.60
95th %-ile	60.00	60.00

Event numbers were then matched to determine cases where *both* a forward and rearward TTC could be calculated. Out of 500 events (311 forward and 94 rearward), there were 60 cases in which vehicles were detected in both the front and the rear of the SV and for which a TTC could be calculated. Table 4.55 presents the descriptive statistics for this set of the 60 lane changes while Figure 4.55 illustrates the 5th and 25th percentile and mean values in graphical form. Tables 4.54 and 4.55 illustrate that, even with a fewer events to choose from, the values at each percentile are similar. It thus appears that the approach of considering only cases in which a vehicle is present in both the front and the rear is reasonable for estimating the TTC safety envelope.

Table 4.55. TTC in Seconds for Events in Which a Vehicle was Detected in both the Forward and Rearward Position Simultaneously.

	Forward TTC	Rearward TTC
N (events)	60	60
Mean	21.10	17.67
SD	17.88	12.17
Min	3.00	4.70
Max	60.00	60.00
5th %-ile	4.49	6.08
25th %-ile	7.60	9.45
50th %-ile	15.20	12.70
75th %-ile	25.45	23.10
95th %-ile	60.00	36.53

It is interesting to note that 95% of drivers studied had a TTC safety envelope of 4.5 to 6 seconds for both forward and rearward POVs at t_0. The TTC safety envelope concept can provide the criteria for the go/no-go decision of a CAS. This idea will be explained further in Chapter 5.

To summarize, the safety envelope that most drivers maintain can be described in terms of distance, relative velocity, and TTC. However, because distance and relative velocity interact in a dynamic fashion, the TTC safety envelope concept was developed to provide a measure which incorporates both distance and relative velocity information at t_0. For the TTC safety envelope, most drivers maintained at least of 4.5 seconds of TTC, with a mean of over 18 seconds. It should be noted that while TTC may provide the main information regarding a go/no-go decision, other aspects may need to be taken into account as well.

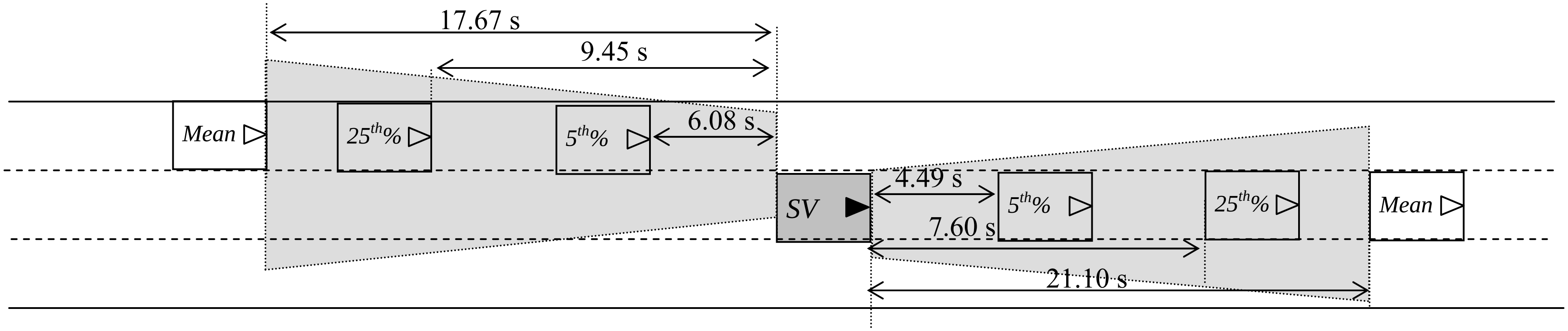

Figure 4.55. TTC Safety Envelope for Cases in Which a Vehicle was Detected in both the Forward and Rearward Position Simultaneously (TTC Values in Seconds Shown for the 5th Percentile, 25th Percentile, and Mean). (Note that the diagram is a depiction of TTC data, and not a geometrically accurate representation.)

CHAPTER 5: DISCUSSION AND CONCLUSIONS

Research Approach

The literature review revealed that most previous studies of lane changes collected smaller amounts of data and the data may not have been representative of naturalistic behavior for various reasons. The current study attempted to address these problems by collecting a large body of naturalistic data on lane changes. Sixteen commuters who normally drove ≥ 25 miles (40 km) in each direction participated; half commuted on an interstate and half commuted on a U.S. highway. Half of the participants normally drove an automobile and half normally drove an SUV. Participants were aged 20 to 64 with equal gender representation.

The two research vehicles were a sedan and an SUV. Each participant drove each vehicle for ten days. The data collection system included video, sensor, and radar equipment. The video system incorporated a five-channel video system 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.

The resulting data set contained 8,667 lane changes performed over 23,949 miles of data collection. There were 182 tapes of video data collected along with files containing corresponding sensor data. The full data set was analyzed using videotape derived data while a subset of 500 was analyzed in depth using combined video and sensor data. The data collection effort resulted in the largest and most complete known archive of lane change information to date.

Analysis of the Full Data Set

The full data set was analyzed using the videotapes to assign measures of severity, urgency, maneuver type, success/magnitude, and direction. Analysis of the full data set of 8,667 lane changes showed that the large majority of lane change maneuvers were uneventful; they were neither high in urgency nor high in severity. This is to be expected given that crashes are rare events, and lane changes crashes are a relatively rare subset of all crashes. No crashes of any type were observed during 10 months of data collection, and that the lack of a crash over 24,000 miles of driving is not surprising given crash frequencies per miles traveled. (Passenger vehicles had a crash rate of 1.9 per million vehicles miles traveled in 1997, thus the probability of a crash in this study was extremely small; Disaster Center, 2002.)

The contention that many lane change maneuvers are caused by a slower lead vehicle (Eberhard et al., 1994) is supported by the current research in that 37% of the observed lane changes were classified as resulting from slow lead vehicles. Drivers often change lanes in this situation to maintain their current speed by passing (Hetrick, 1997). Of all the lane changes rated ≥ 2 in severity, 55% 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 ≥ 2 in urgency, 78% were slow lead vehicle maneuvers. This may show that drivers feel comfortable with a relatively short TTC to the vehicle ahead (an urgency of 2 indicated a TTC of between 3.0 and 5.5 s at lane change initiation, while an urgency of 3 indicated a TTC of 3.0 s or less). Due to the high prevalence of the slow lead vehicle lane change, this type of lane change was analyzed in greater depth.

Analysis of the complete data set showed that more lane changes were completed by interstate drivers. Initially, the reason for this was thought to be the higher traffic on this interstate route. However, an examination of the normalized data, taking into account the number of lane changes per mile made by each participant, showed that the more likely reason was that the interstate drivers drove longer routes. Also, sedan drivers made significantly more lane changes than SUV drivers. In this case, an examination of the normalized data showed the difference to be true for the normalized data as well. It may be that sedan drivers spend more time in the right lane and make lane changes to pass, while SUV drivers drive faster and spend more time in the left (preferred) lane, resulting in fewer lane changes. It is possible that sedan drivers do not like to drive behind large vehicles (a common sight on this interstate) and therefore change lanes more often. Another possibility is that sedan drivers are more aggressive and make more lane changes to pass.

Participants drove a total of 23,949 miles (38,542 km) with an average commute of 37.4 miles (60.2 km). Over all participants, there was an average of 2.76 miles (4.44 km) between lane changes (0.36 lane changes/mile or 0.22 lane changes/km).

Additional analyses on the full data set included urgency and severity distributions for frequency and duration, direction distributions for frequency and duration, and success/magnitude distributions for frequency and duration. Interesting findings from these analyses included:

- Over 90% of lane changes were rated as low in both severity and urgency.
- The slow lead vehicle lane change was the most common type of lane change maneuver at 37% of all lane changes.
- Most lane changes were single lane changes (83%) followed by passing maneuvers of $\leq$ 45 seconds (12%).
- Lane changes to the left made up the majority of events at 55%.
- It was observed that drivers tended to stay in the right lane and usually moved to the left to pass; drivers rarely passed on the right.
- The great majority of slow lead vehicle lane changes were to the left (92%).

A similar set of distribution analyses was conducted for the category of slow lead vehicle lane changes, since this was the most common maneuver type. These analyses showed similar trends to those found for the full data set.

Analyses of the In-Depth Sample of 500 Lane Changes

A sample of 500 lane changes was selected for in-depth analyses using a combination of sensor and video data along with a customized computer program. The sample of 500 events was selected to include all of the higher severity and most of the higher urgency lane changes. These analyses provided additional insight into the behaviors, both prior to and at t_0, associated with riskier lane changes. The additional variables that were investigated in-depth for this sample of 500 included:

- Steering
- Lateral acceleration
- Velocity
- Braking
- Turn signal use
- Eye glance location probability
- Eye glance link value probability
- Mean single glance time
- Distance to forward and rearward POVs
- Relative velocity to forward and rearward POVs
- TTC to forward and rearward POVs

The steering, lateral acceleration, and velocity measures did not prove very meaningful as predictors or indicators of lane change behavior, although there was some evidence that higher speeds at t_0 are associated with more critical passing maneuvers. The mean velocity for all 500 lane changes at t_0 was 59 mph. Average velocity at t_0 was slightly higher on the interstate routes than on the U.S. highway routes.

Examination of the braking data showed that brakes were applied in only 5% of cases at t_0. The two most common cases where brakes were used were for the slow lead vehicle lane change and the exit/prep exit lane change. In the first case there is a velocity differential between the vehicles motivating the lane change, so the driver of the SV may need to apply the brakes to maintain a safe distance while passing. In the second case, the driver of the SV is anticipating the need to reduce velocity on the exit ramp.

Turn signal use was analyzed both independently and as a function of lane change direction. A surprisingly low percentage of turn signal use was found overall, although there was also a large between-subjects variance in the percentage of turn signal use. Overall, turn signals were used only 44% of the time, with signals used more often for left lane changes (48%) than for right lane changes (35%). It was hypothesized that drivers making a right lane change have often just passed a slow lead vehicle and therefore have a greater degree of situational awareness than drivers anticipating a left lane change. Thus, the drivers may feel that it is not as important to signal their intentions when moving to the right. Turn signal use is important from a design standpoint, in that some researchers have advocated linking the display of a lane change CAS to the activation of the turn signals. These results show that if the CAS were linked to turn signal use in this manner, it would be activated less than half the time prior to t_0, assuming the driver does not change turn signal behavior.

Eye glance data were available for all 500 lane changes, including glance location probabilities, link value probabilities, and mean single glance times. Glances were analyzed for the three seconds prior to t_0. The most important finding from the eye glance analysis is that for every lane change analyzed, there was at least one glance in the forward direction during the three seconds prior to t_0. Forward glances also had a relatively long mean single glance time at 0.8 s. The highest link value (glance transition) probability was between the forward view and the center rear view mirror. The probability of transitioning between these two locations was 0.53; the next highest probability was for a transition between the forward and left mirror locations (link value probability of 0.47). However, the probability of a glance transition between the forward view and the right mirrors was much smaller at 0.02.

Eye glance analyses were conducted separately for left and right lane changes, anticipating that the patterns would be distinct for lane changes in these two directions. 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. For right lane changes, the most likely glance locations 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 probabilities between forward and right mirror and between forward and right blind spot were also relatively high at 0.12. These results provide information as to the preferred location for a lane change CAS.* Some researchers have advocated placing such a system in the side mirrors. However, in order to take advantage of driver's natural glance tendencies, and assure that drivers see the CAS, the best location would be in the forward view, with the second most preferred location being the rear view mirror. Placement in the side mirrors would not be preferred, especially for lane changes to the right.

Eye glance patterns were also investigated for lane changes made in SUVs versus sedans. Differences in window size and field of view between the two vehicles led to speculation that a driver's scan patterns might change when using the different vehicle types. For this reason, an analysis of eye glance patterns was conducted comparing the SUV and sedan events. The analysis showed that both the mean single glance times and the glance probabilities (probability of a glance to that location within the three seconds prior to t_0) were nearly the same for every glance location studied. Consequently, despite the differences in window size and field of view between the vehicle types, drivers looked at the same locations with equal probability and for the same lengths of time.

The next areas of data analysis were attempts to separately model the forward and rearward areas with regard to POVs as drivers begin a lane change. These analyses were conducted by examining the data for distance to closest vehicle (forward or rearward), the velocity relative to the closest vehicle, and the TTC to the closest vehicle. For the most part this attempt was successful, although there were some limitations with this approach. The first limitation was the lack of side radar to capture vehicles that were very close to the SV, especially in the proximity zone (including the blind spot). The second limitation was that the severity and urgency ratings were based to a large degree on distance, TTC, and relative velocity, so there was a confound in trying to then analyze urgency and severity by these measures (lack of independence). Nonetheless, the data are a fair representation of the more critical lane change cases for which a CAS might be useful. Data were reported in the form of percentile values for distance, relative velocity, and time to collision. Forward and rearward safety envelopes were then diagrammed. The minimum acceptable values that 95% of drivers feel comfortable with when changing lanes are as follows:

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* The principal idea here is that the driver's natural scan pattern should be used to locate a CAS display. Of course, other ideas regarding location have been suggested.

- Distance of about 40 feet frontward and rearward.
- Relative velocity (closing rate) of less than 20 ft/s (both forward and rearward).
- TTC of between 4 and 6 seconds for POVs ahead of the SV, or approaching in the fast approach zone of the destination lane.

Note that the distance and relative velocity measures interact in a dynamic driving situation. If a vehicle is 150 feet away but has a high relative velocity, the driver of the SV might choose not to make a lane change. Likewise, if a vehicle is following closely but the relative velocity is low, the driver might choose to make a lane change. Time-to collision is a measure that takes both distance and relative velocity into account; the interactive effects of distance and relative velocity are thus contained in the single measure. Not only does TTC consider these two measures, but it seems a likely measure to be used in conjunction with a CAS. That is, the CAS would monitor TTC as an indicator regarding go/no-go. This also supports the driver in that he or she is monitoring the environment to make a go/no-go decision. Different levels of TTC could also be used to provide graded or "multiple-level" warnings as the TTC values decrease (e.g., Go, Caution, and No-Go). For these reasons, the TTC version of the safety envelope seems to be the most promising with regard to future development of lane change CAS. It would be expected, however, that certain supplements would be required.

Factors to Be Considered in System Design

This section of the report integrates various aspects of the in-depth analyses such as glance patterns, turn signal use, and the safety envelope to present preliminary concepts or recommendations for designers of lane change collision avoidance systems. Recommendations were developed based on the available data for the 500 in-depth analyses. The purpose is to provide guidance for CAS design (e.g., how and when to warn a driver if another vehicle is present in the blind spot). Recommendations are presented for the following five topics: presentation mode, triggering criteria, location/placement, turn signals, and integration with other CAS. These recommendations were developed based on drivers' natural inclinations in terms of eye glance patterns and turn signal use and on the assumption that a lane change CAS should not disrupt these natural patterns. Other approaches to the design problem might involve changing the driver's behavior in some way, but these approaches are not considered here. Nonetheless, designers using other design approaches should still find the data presented in this report to be useful.

Presentation Mode

Given the low percentage of turn signal use reported for this study, it is not recommended that a lane change CAS be presented with turn signal use. Even for drivers who do use turn signals, previous research indicates that some drivers activate the turn signal after beginning the lane change maneuver (Hetrick, 1997). The alternatives are that the lane change CAS should either:

1) Be always on, ready for the driver to check when planning a lane change, or
2) Displayed when requested by the driver, with an appropriate time-out feature.

Triggering Criteria

The warning triggering criteria can be developed based on analysis of the data including TTC and the presence of vehicles in the FAZ or PZ. The warning criteria are important so that drivers receive timely and accurate warnings with a minimum number of false alarms. The criteria could also be used to present graded warnings to the driver (e.g., Go, Caution, No-Go).

Talmadge et al. (1997) concluded that an appropriate lane change warning criterion would be 3 seconds for most drivers, based on an evaluation of TTC. For example, a warning light might be activated given a 3 second TTC to one or more surrounding vehicles. However, based on this study, a 3 second TTC criterion may not be adequate. The 5th percentile TTC value for vehicles forward of the SV was 4.49 s and 6.08 s for rearward. Namely, participants made lane changes with a TTC as low as 4.49 s for a small number of cases. These findings are somewhat limited in that the radar coverage did not account for vehicles next to or very close to the SV, especially in the proximity zone (including the blind spot). In other words, vehicles very close to the SV may have been missed due to limitations of the radar or the angle at which the radar units were aimed. Based on the current data, it appears that warnings should be issued at approximately 5 seconds TTC, regardless of position of the closest vehicle (forward or rearward). This should be considered as a starting point for testing of potential CAS. Given the previous recommendation of 3 seconds TTC by Talmadge et al. (1997), it may be discovered that CAS warning values as low as 3 seconds may be adequate. Since it is known that most drivers habitually look in the forward view, rearview mirror, and left mirror during the 3 seconds prior to t_0 (for left lane changes), it seems logical that a warning should be issued with *at least* 3 seconds TTC, so the driver will have time to comprehend, understand, and react to alerts.

Location/Placement

In terms of lane change CAS location, the most logical place would be in the forward view, since all drivers have at least one glance to the forward view during the three seconds prior to the lane change. This assumes that the designers of such systems would want to take advantage of drivers' natural scan patterns, and not rely upon driver retraining. The format of the warning/alert could include a variety of possibilities such as a simple LED display mounted in the dash or on the instrument panel (possibly positioned to reflect upward onto the windshield). Head-up displays offer advantages in that such a display could have multiple purposes, to which other warning and information systems might be linked. In addition, other modes of displays should be considered such as the use of audio or tactile displays. All of these possibilities should be considered, since drivers spend much of their time looking at the forward view.

However, if the system is always "on," having it located in the forward view could be distracting to drivers or it might be seen so often that it is ignored. To avoid this problem, request buttons could be placed on the left and right of the steering hub. These would activate the display, which would then be timed out. As an alternative, the next best location would be the rearview mirror, since drivers had a high proportion of glances to this location for both left and right lane changes. Drivers frequently glance at the rear view mirrors during normal driving as well, so there might still be a problem with drivers ignoring a system that was always on. Other potential locations include the left and right side mirrors, since drivers have a relatively high proportion of glances to these locations in preparation for a lane change. However, the right mirror is not used nearly as often for lane changes to the right as the left side mirror is for lane changes to the left.

Turn Signals

Due to the apparent split in opinion of how turn signals should interact with CAS warnings, a recommendation on turn signals is warranted. At issue is the question of whether CAS warnings should be tied to the use of turn signals. If warnings are tied to turn signal activation, then it is likely that the CAS could use signal activation as a signal of driver intent. However, it must be remembered that turn signals were activated prior to t_0 less than 50% of the time even for the relatively high severity and urgency cases analyzed here. In addition, turn signals are used for *turning*, where no lane changes are required.

Integration with other CAS

Findings from this effort may be beneficial to designers of forward collision warning systems or intelligent cruise control systems. For example, the data for TTC and relative-velocity at t_0 might provide input parameters for these types of systems. Also, the implementation of warnings/alerts for lane change CAS should complement other CAS warnings/alerts.

These preliminary recommendations should help in the development of prototype lane change CAS. The final design would of course be determined based upon additional experimentation to determine optimal location and modality, as well as the design philosophy.

Discussion of the Experimental Approach

The data archive resulting from this study is unique in its scope. It should be kept in mind by users of the data archives and results that the data were collected in a certain place and manner. All of the lane changes occurred in a hilly section of southwest Virginia that varies between rural, suburban, and urban. Traffic densities on the interstate route were relatively high, but probably lower than those found in most urban areas. It is also possible that a higher level of urgency and severity would have been recorded had the experiment taken place in a large urban location. For example, drivers in these areas may have forward and rearward safety envelopes that are smaller than those reported here; due to higher traffic density, drivers may learn to accept smaller gaps when changing lanes.

Another major aspect of the research technique is that the sampling plan deliberately focused on the more severe and urgent lane changes. The safety envelope, forward area analysis, rearward area analysis, turn signal use, and eye glance patterns reported here are thus generally applicable to the more severe and urgent cases. However, it should also be kept in mind that these lane changes were deliberately sampled with the intent of providing guidance for those lane changes for which a collision avoidance system would be most useful (i.e., those cases in which there are POVs present with a short TTC, high closing rate, or short headway distance).

Another aspect of the data collection technique that should be noted was the absence of side radar sensors on the experimental vehicles. The lateral distance to vehicles alongside the SV was unknown. Also, for many lane changes in which the POV was in or near the PZ (blind spot), radar data were unavailable (however, video data were available, so it was always known when a vehicle was in this location, even if the exact parameters were unknown).

The final aspect has to do with the vehicle speed data. Since the intent was to capture lane changes at highway speeds, the data processing system began recording when speed reached 40 miles per hour and cut off when speed dropped below 30 miles per hour. Thus no data were collected on lane change behavior below 30 miles per hour.

Future Research Directions

The data for both the full data set and the in-depth sample were archived with the intent that the data would then be available to answer other research questions. The archive consists of a library of raw videotape data (182 tapes), raw sensor data (~24 GB of data on 5 CD-ROMs), reduced data packets for the 500 sampled lane changes (on 1 CD-ROM), and digitized video for the 500 sampled lane changes (on 5 CD-ROMs). Given the size and quality of the data archive, future projects may take advantage of the archive to answer other research questions relating to naturalistic driving behavior. Examples of such topics include light vehicle/heavy vehicle interactions from the light vehicle point-of-view, distraction measures related to cell phone use, and baseline measures of driver headway maintenance or car following behavior. One advantage of this archive is that it contains an audio stream, so cell phone conversations can be analyzed for cognitive loading of the driver.

Conclusions

This research effort provided valuable insight into the nature and severity of lane changes in a naturalistic driving environment. There were 8,667 lane changes observed over 23,949 miles of driving, making this data collection effort the largest undertaken for the study of lane changes. Analysis of the full data set resulted in many interesting findings regarding the frequency, duration, urgency, and severity of lane changes in regard to maneuver type, direction, and other classification variables. A subset of the full data set was then analyzed in greater depth using the sensor data collected by the instrumented vehicle. The sampled lane changes were generally of the more severe and urgent types since these are the cases in which a lane change CAS is likely to be of greatest help. Variables analyzed for the sampled data included turn signal use, braking behavior, steering behavior, eye glance patterns, and forward and rearward area analysis. The concept of a safety envelope for lane changes was then developed using the forward and rearward area analyses. Finally, the data were used to provide recommendations for designers of lane change CAS in terms of display location. Overall, the research described here provides valuable insight into the behaviors and parameters associated with lane changes, while the data archive has the potential to address other questions related to driving behavior.

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APPENDIX A: TELEPHONE SCREENING FORM

Driver Screening and Demographic Questionnaire Date __________

Good day. My name is Erik Olsen and I am a researcher with the Virginia Tech Transportation Institute in Blacksburg, VA. The project is a driving study with commuter drivers using instrumented vehicles.

This study will involve you driving a car and then an SUV or vice versa for two weeks each as you commute to and from work. Each vehicle will be equipped with data collection equipment. All data shall only be used by VTTI researchers. Does this sound interesting to you?

Next, I would like to ask you several questions to see if you are eligible to participate. If there is a question you are uncomfortable with, you do not have to answer it.

Name: _________________________ Gender: MALE FEMALE
Address: ____
Home Phone: __________________ Work Phone: __________________ BTTC______

1. In what age bracket are you? (must be between 20 and 65 years old)
   - 20-29 ____
   - 30-39 ____
   - 40-49 ____
   - 50-59 ____
   - ≥ 60 ____

2. Do you have any health conditions or physical disabilities, including but not limited to night blindness, sleep disorders, or diabetes that affect your ability to drive safely?
Yes _____ No _____ If yes, what are they? ___________________________

3. Do you have a valid driver's license? Yes _____ No _____

4. How long have you been driving? ______

5. What is the make, model, and year of the car you currently drive? ______________________

6. Do you drive to work each day? Yes _____ No _____ What days? ________

7. Do you normally drive to/from work alone? Yes _____ No _____

8. What is the specific route with mileage that you drive to/from work?
____
____
____

9. Have you had any moving violations in the past 3 years? If so, please explain.
Yes _____ No _____ ____
____

10. Have you been involved in any accidents within the past 3 years? If so, please explain.
Yes _____ No _____ ____
____

11. Have you had any DUI convictions? Yes _____ No _____ (Must not have any)

12. Do you have car insurance? Yes ____ No ____

13. Do you ordinarily wear prescription glasses while you drive? Yes ____ No ____
How about sun glasses? Yes ____ No ____

14. Would you be willing and able to drive without wearing sunglasses during the time you are driving our vehicles? Yes ____ No ____

15. Have you previously participated in any experiments at the Virginia Tech Transportation Institute? If so, can you briefly describe the study? Yes ____ No ____
____
____

16. (Females only) Are you currently pregnant? Yes _____ No _____
If yes, when are you expecting? ___________

17. This study will involve your using our vehicles to commute to and from work. Do you have a convenient, safe place to keep the vehicle at home? (e.g., garage, driveway, street)

Thank you for answering these questions. At this time you are/are not considered eligible for our study. (If eligible): At this time I anticipate that we will have you start the study on ______. The next step is to schedule an orientation meeting. How does ______ work for you?

(If not eligible): At this time for _________ reason, it appears that you are not eligible for this study. Thank you for your time.

APPENDIX B: INFORMED CONSENT

INFORMED CONSENT FORM FOR PARTICIPANTS

NATURALISTIC HIGHWAY DATA GATHERING STUDY

Investigators: Walter Wierwille, Thomas Dingus, and Erik Olsen

I. The Purpose of this Research

The purpose of this research is to gather naturalistic data on ordinary drivers using instrumented vehicles. Most data are gathered with an experimenter present in the vehicle, which may lead to driving behavior that differs substantially from the way drivers drive under ordinary circumstances. Naturalistic data are needed as a foundation for new driver support systems, such as collision warning and avoidance systems. Unless such data are available, it is difficult to determine how best to design such systems in a way which optimizes the driver/vehicle interface.

II. Procedures

You are being asked to drive each of two instrumented vehicles in your daily commute to work. These vehicles contain sensors and data processing that can capture your normal driving. Small video cameras are also mounted in the vehicle. One of these cameras will be directed toward your face while you are driving. The equipment has been installed in such a way that you will hardly be able to notice it presence. It will not interfere with your driving, and there is nothing special that you will need to do in regard to the equipment.

One of the vehicles is a Ford Taurus and the other is a Ford Explorer. Each vehicle will be lent to you for a period of approximately two weeks and is to be substituted for the vehicle you would ordinarily drive back and forth to work. We ask you not to drive the research vehicles at other times, unless you have an emergency.

We would like to take a drive with you to familiarize you with the handling and layout of the Explorer. This is done as a safety precaution. Similarly, we would like to take a familiarization drive with you in the Taurus.

As a participant in this study, you are requested to perform the following duties:

1. Carefully read this informed consent form and then sign it if you agree to participate.

2. Fill out a driver questionnaire, which requests information on your health, the type of vehicle you most often drive, and additional information, such as how long you have been driving. (Assuming that your responses meet our criteria for participation, we will attempt to schedule you for full participation.)

3. Receive instruction and take on-the-road test drives in the Explorer and the Taurus.

4. Drive as you ordinarily would on your trips back and forth to work. The only difference is the vehicle you would drive. You need not “perform”. Just drive as you ordinarily would.

5. Keep the vehicle provided to you locked when not in use, preferably in a reasonably secure place. Try to maintain reasonable security for the vehicle while it is in your possession.

6. Participate in two different portions of the study. In one portion, you will drive one of the vehicles (either the Taurus or the Explorer) to work for about two weeks. Later, you will drive the other vehicle for about two weeks. In some cases there may be an interval of time between the two sessions.

7. Drive by yourself back and forth to work. We are particularly interested in single- occupant driving, so you are requested not to carry passengers except in an emergency.

8. Fill out a post-drive questionnaire regarding your participation. You will do this one time at the end of your participation.

III. Risks and Discomforts

There are some minor risks to which you will be exposed in participating in this experiment. Known risks are listed here.

1. There is the risk of an accident resulting from your driving back and forth to work. This risk is the same as you face in the vehicle you ordinarily drive.

2. There is the slight additional risk of an accident resulting from driving a vehicle less familiar to you than your everyday vehicle. This additional risk in roughly equivalent to borrowing or renting a car or an SUV for your commute back and forth to work. This risk is expected to subside as you become familiar with each of the research vehicles used in this experiment.

1. The following precautions will be taken to ensure that risks are minimized:

1. You agree to use the seat belt and shoulder strap restraint in the vehicle whenever the vehicle is in motion.

2. The two vehicles used in this experiment are modern vehicles with airbags and other safety equipment found on newer vehicles.

3. All of the data gathering equipment will be secured in the vehicle so that it does not present a hazard. The equipment will not obstruct your view out the windows or through the rear-view mirrors. The equipment will also be unobtrusive.

4. You will be given instruction and test drives in both the Explorer and the Taurus to help familiarize you with these vehicles.

IV. Benefits to You

You will be paid a gratuity for your participation and you will also have vehicles provided for your commute to and from work for approximately four weeks in total. You will also be reimbursed for the approximate cost of gasoline used during your commuting in the vehicles provided. There are no other known direct benefits to you. No promises or guarantee of benefits other than those listed in this informed consent form have been made to encourage you to participate. You may however enjoy driving the research vehicles, and it is likely that your participation in this experiment will help provide a better understanding of naturalistic driving behavior and how future safety improvements might be developed.

V. Extent of Anonymity and Confidentiality

The information gathered in this experiment will be treated with confidentiality. It will be used for research purposes only, and only by qualified researchers. Your name and other identifiers will be removed from the overall data set and in any resulting publications.

As indicated, video will be recorded while you are driving. The video includes an image of your face, so that we can determine where you are normally looking. The video will be treated with confidentiality and kept secure. It will be shared only with other qualified researchers, and not published except as noted in the following paragraph.

If at a later time we wish to use the video information for other than research purposes, say, for public education, or if we wish to publish (for research or for other purposes) your likeness or other information from the study that identifies you either directly or indirectly, we will only do so after we have obtained your permission.

Your data will be pooled with that of at least eight other participants. (The expected number of participants is likely to be between twelve and sixteen.)

VI. Compensation

You will receive a gratuity for participating in this experiment. For each day in which you commute to work in one of the instrumented vehicles, you will receive $10. If you save your receipts for gas, you will be reimbursed for the amounts spent. Therefore, under ordinary circumstances, if you complete the experiment, you will receive $200, that is, $10 times 20 days. Reimbursement for gas will be added to this amount. You will receive payment of your gratuity at the end of your participation. Reimbursement for gas will also be made at that time.

It is possible that a data gathering equipment malfunction may occur during some portion of your participation. If this should occur, we may have to temporarily suspend the experiment to service the data gathering equipment. While the equipment is out of service, you will be paid $4 per commuting day and you will have to use your regular vehicle. You may then be asked to extend your participation for an extra day or two, or possibly more to make up for the equipment problem. If you choose to do so, you will be paid an additional $10 for each additional commuting day of participation in which you drive one of the instrumented vehicles.

VII. Medical Treatment and Insurance

If you should become injured in an accident, the medical treatment available to you would be that provided to any driver or passenger by emergency medical services in the vicinity where the accident occurs.

The vehicle you will be driving is insured for automobile liability and collision/comprehensive through Virginia Tech and the Commonwealth of Virginia. There is medical coverage for you under this policy. The total policy amount per occurrence is $2,000,000. This coverage would apply in case of an accident, except as noted below.

Under certain circumstances, you may be deemed to be driving in the course of your employment, and your employer's worker's compensation provisions may apply in lieu of the Virginia Tech and Commonwealth of Virginia insurance provisions, in case of an accident. The particular circumstances under which worker's compensation would apply are specified in Virginia law. If worker's compensation provisions do not apply in a particular situation, the Virginia Tech and Commonwealth of Virginia insurance provisions will provide coverage.

A Virginia Tech automobile accident report form is located in the glove compartment of the vehicle you will be driving and outlines what you should do if you become involved in an accident and are not incapacitated.

VIII. Freedom to Withdraw

As a participant in this research, you are free to withdraw at any time without penalty. If you choose to withdraw, you will be compensated in accordance with the terms in Section VI. of this document.

IX. Approval of This Research

Before this experiment begins, the research must be approved by the Institutional Review Board for research involving human subjects at Virginia Tech as well as the sponsor’s human use review panel. You should know these approvals have been obtained.

X. Participant’s Responsibilities

If you voluntarily agree to participate in this study, you will have the following responsibilities while driving the research vehicles:

1. To be free of any illegal substances and to refrain from the use of alcohol and other substances that may impair your driving ability,

2. To conform to the laws and regulations of driving on public roadways,

3. To drive as you ordinarily would, but subject to 1. and 2. above,

4. To wear your seatbelt at all times while driving the vehicle,

5. To maintain reasonable security of the research vehicle in your possession,

6. To allow the experimenters to gain reasonable access to the research vehicle in your possession for purposes of diagnosing difficulties and downloading data, and,

7. To inform one of the experimenters if you encounter difficulties or have questions.

XI. Participant's Permission

I have read and understand this informed consent form and conditions of my participation. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent to participate.

If I participate, I understand that I may withdraw at any time without penalty. I agree to abide by the rules of this project.

______________________________________ ____________________________
Participant's Signature Date

Should I have any questions about this research or its conduct, I may contact:

Walter Wierwille, Project Principal Investigator	(540) 231-1500
Thomas Dingus, Director, Virginia Tech Transportation Institute	(540) 231-1500
Erik Olsen, Graduate Research Assistant	(540) 231-1500
David Moore, Chairman, Institutional Review Board	(540) 231-4991

APPENDIX C: NATURALISTIC LANE CHANGE FIELD DATA REDUCTION, ANALYSIS, AND ARCHIVING

Definitions and Graphical Depictions of Lane Change Categories (Severity, Type, Success, and Magnitude) August 1, 2001

The following material was used in reviewing the entire set of all lane changes/passing events collected during data collection. Note that some of the information here was changed after all events were identified (e.g., the rating scales were changed to the severity and urgency scales; some of the classifications were changed).

Video Tape Labeling Conventions

All video tapes are labeled with Project Name, Subject and Tape Number, Research Vehicle, Route Driven, Driver's Normal Vehicle, Begin Date (when data collection began for that tape), and Researcher's Name. Figure C-1 illustrates the tape labeling conventions used for the video tape labels.

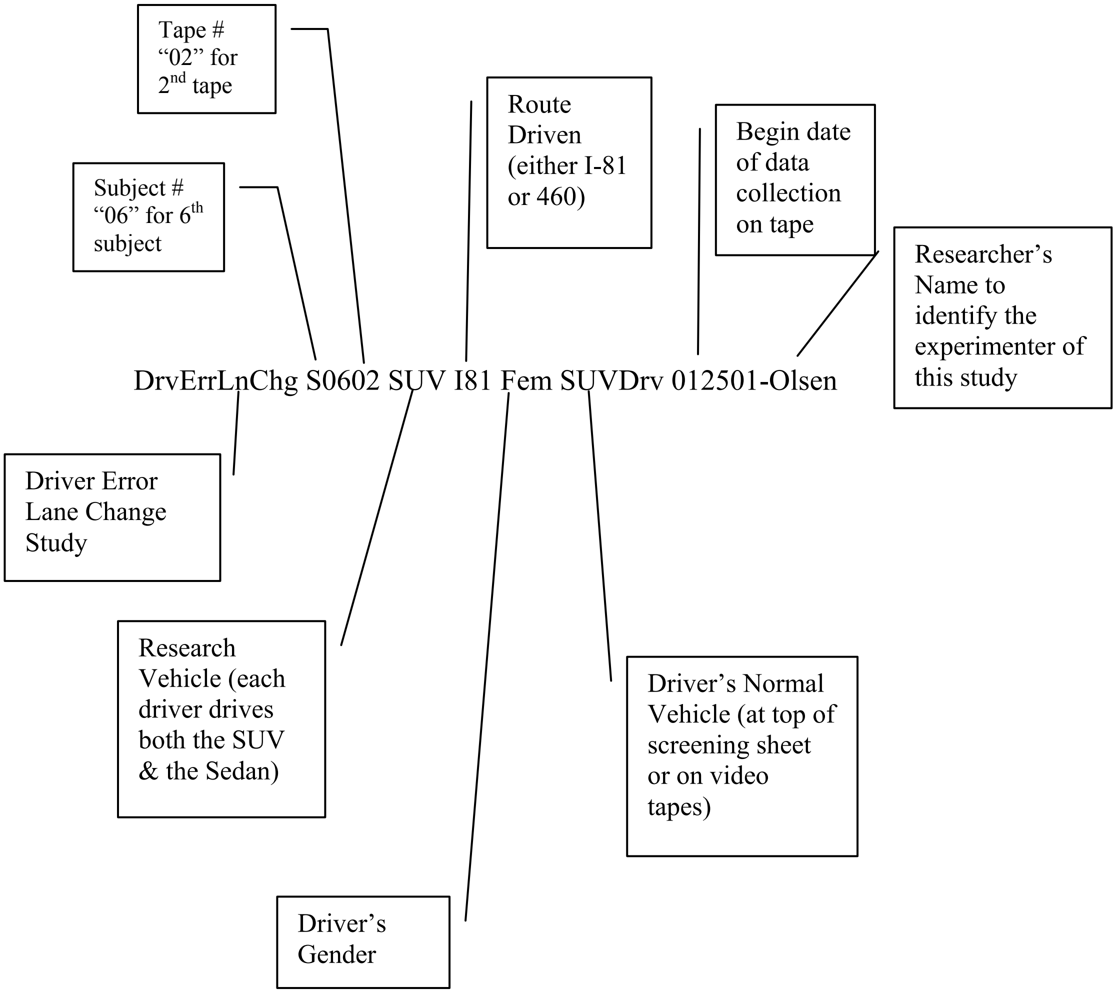


Figure C-1. Video Tape Labeling Conventions.

Zip Disk Labeling Conventions

All zip disks are labeled with Project Name, Subject Number, Research Vehicle, Route Driven, Gender, Driver's Normal Vehicle, Begin Date and End Date (when data collection began/ended for that zip), and Researcher's Name. Figure C-2 illustrates the zip labeling conventions used for the zip disk labels.

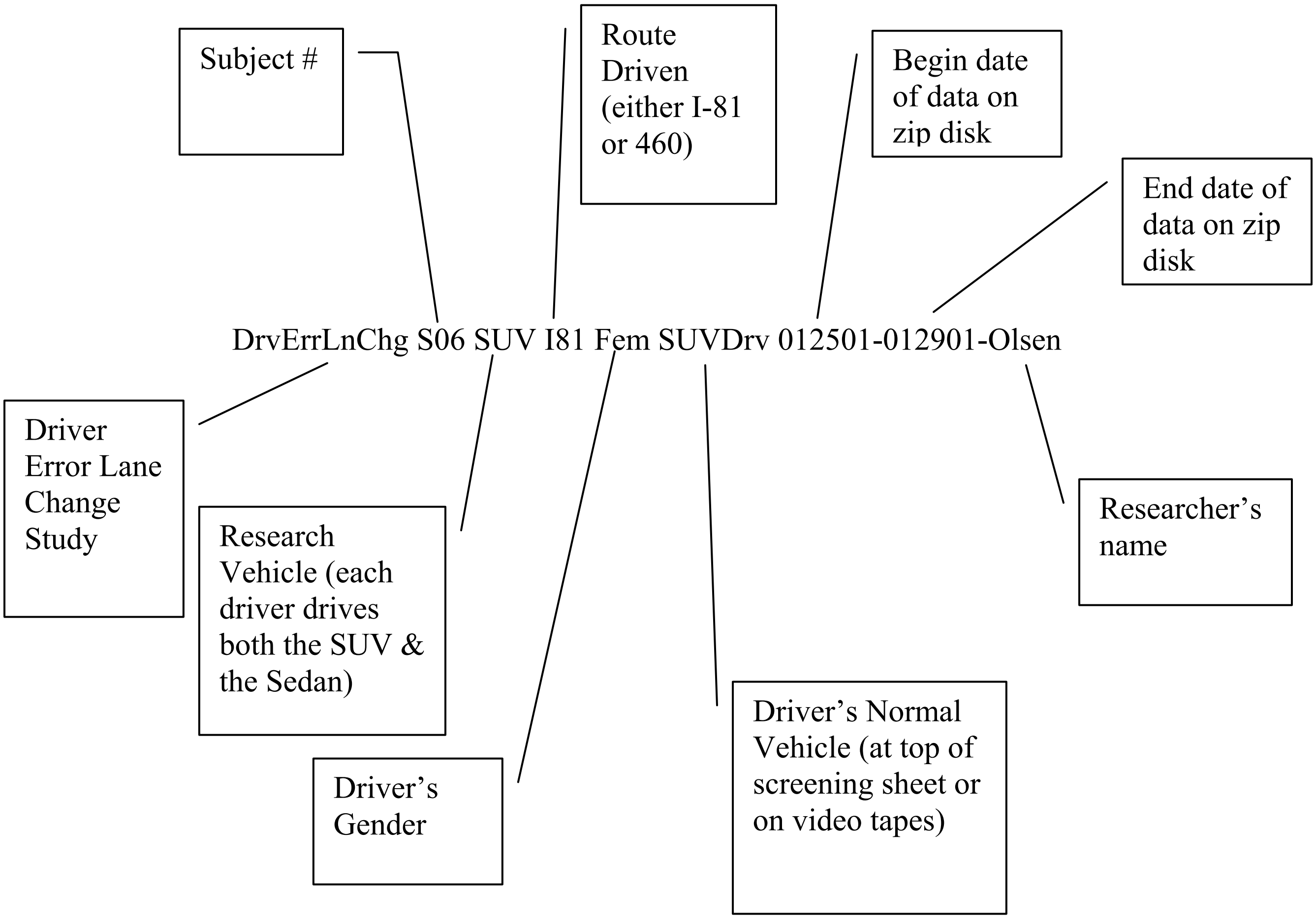


Figure 2. Zip Disk Labeling Conventions.

Lane Change Start and End Points

In terms of video analysis, a lane change will be considered to start when it is obvious on the videotape that the driver has begun steering into the lane change. This can usually be seen quite easily using the lower right hand quadrant of the video, which shows the right and left rear views. As the driver makes the initial steering move, the center line and side markers, which have been stable in the image, will begin to shift to one side or the other. With practice, multiple reviewers can learn to pinpoint this frame of the videotape within 0.1 seconds of one another.

The lane change will be considered to have ended at the point at which the driver has settled into the new lane. This can usually be seen using the lower right hand quadrant of the video, which shows the right and left rear views. As the driver settles, the center line and side markers, which have been steadily changing, will settle into a stable pattern. Sometimes the driver will overcompensate and then steer back to settle into the new lane. In this case, the lane change ends after the overcompensation correction ends and the driver is settled into the new lane. Watching the videotape in real time will allow the analyst to see when this is happening. Occasionally when a driver is passing a slower vehicle (especially a truck), he or she will hug the outside road marker while passing and then settle into the center of the lane. If a driver appears to be doing this, the lane change will be considered to have ended when the driver is settled into the "edge of the road" pattern (in other words, do not continue the lane change all the way through the "edge of the road" phenomenon until the point where the driver shifts back into the center of the new lane after passing). For a passing maneuver (lasting less than 45 seconds), the lane change will be considered to have ended when the subject vehicle is settled back into its original lane.

If there are any questions about lane change start and end points, ask one of the senior researchers. Note that there is some natural variation in how abruptly lane changes begin and end, even with the same driver. For a lane change which is gradual, the movement of the center and side markers is not always obvious, especially when viewing the tape in slow motion.

Duration

For each event identified, the duration will be calculated. For example, when entering data into the Excel spreadsheet, a duration column exists where the End synch number is subtracted from the Begin synch number for that event and then divided by 10 (e.g., Duration =(F2-E2)/10. This results in a value in seconds.

Road Type

Interstate (i)	I-81 or I-581
US hwy (us)	US460 or US11
Other (o)	Passing maneuver on any other road type, mark for future decision

Subjects who drive on one type of road for the majority of their commute may drive on another type for a short part of the commute. Try to classify each lane change into the correct category.

Direction of Maneuver

Right (r)	Driver moves from the left to the right
Left (l)	Driver moves from the right to the left

Success/Magnitude Categories

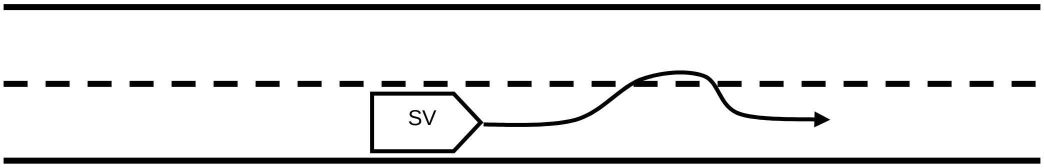
All events will be categorized in one of the following categories:

Category	**Definition**
Single (s)	Single lane change, ends in adjacent lane (by definition, successful).
Multi (m)	Multiple lane change, does not end in original lane or adjacent lane (by definition, successful).
Pass (p)	Dual lane change/passing maneuver, ends in original lane, ≤ 45 seconds duration (by definition, successful).
Partial (u)	Lane change that was not completed (by definition, unsuccessful).

Graphic Definitions for Lane Change Success/Magnitude

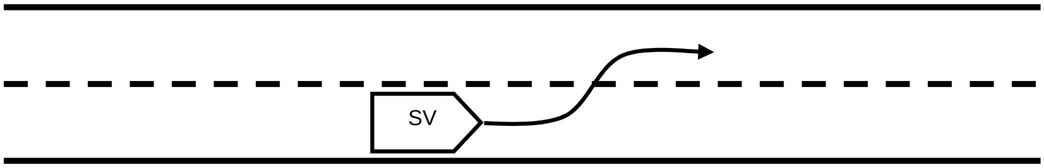
Classification name: partial (U for "unsuccessful")

Classification definition: Subject vehicle reverts to original lane before completing lane change (SV never settles in new lane). The presence or absence of POVs is irrelevant to this classification scheme.



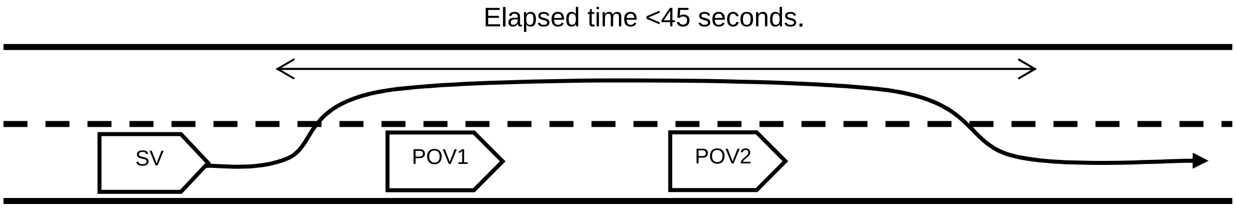
Classification name: single (S)

Classification definition: The SV changes lanes and settles in an adjacent lane. The presence or absence of POVs is irrelevant to this classification scheme.



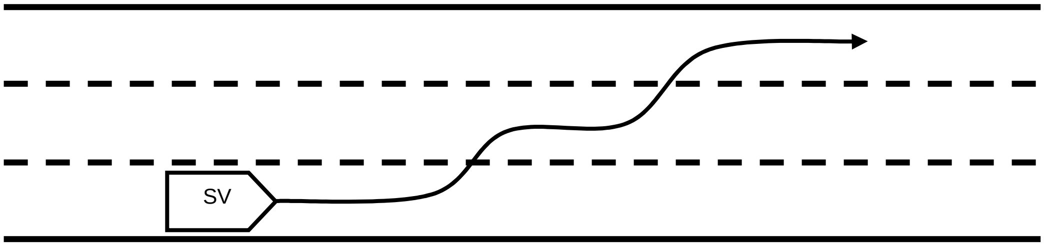
Classification name: pass (P)

Classification definition: The SV changes lanes and reverts back to the original lane within 45 seconds. Most often this maneuver is due to slow POVs ahead, and the SV will pass one or more of these POVs during the course of the passing maneuver.



Classification name: multi (M)

Classification definition: A multiple lane change in which the SV does not end up in the original lane (as opposed to a passing maneuver, in which the SV returns to the original lane). The presence or absence of POVs is irrelevant to this classification scheme.



Notes

A column for notes exists to allow notation of unexpected events or question for later review.

Lane Change Type Classifications (Revised 7/31/01)

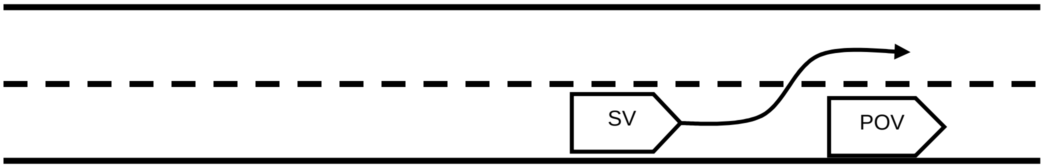
Lane Change Types

LC Type	**Description**
Slow lead veh	Lane change to pass a vehicle which is moving slower than the SV's preferred speed.
Return	Lane change to return to preferred driving lane.
Enter	Lane change to enter road (e.g., from on-ramp).
Exit/prep exit	Lane change associated with exiting.
Tailgated	Vehicle tailgating/approaching quickly.
Merging veh	Vehicle entering roadway causing SV to change lanes.
Rough/obst avoid	Maneuver to avoid obstacle or rough road surface.
Lane drop	End of driver's lane (e.g., road goes from 3 to 2 lanes).
Added lane	Addition of a lane (e.g., road goes from 2 to 3 lanes).
Unintended	Unintended lane deviation (e.g., distraction in car).
Other	Lane change for any other reason or for no discernible reason.

Graphic definitions for lane change types (not updated to reflected 7/31 changes from Table above)

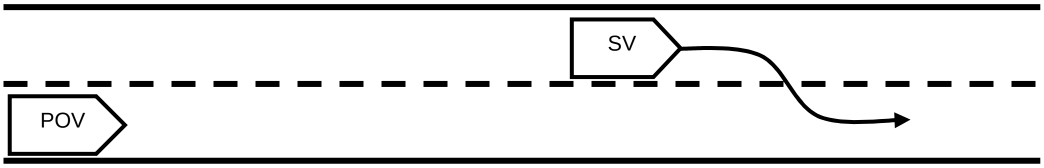
Classification name: slow lead vehicle

Classification definition: Lane change due to slow principal other vehicle (POV) in front.



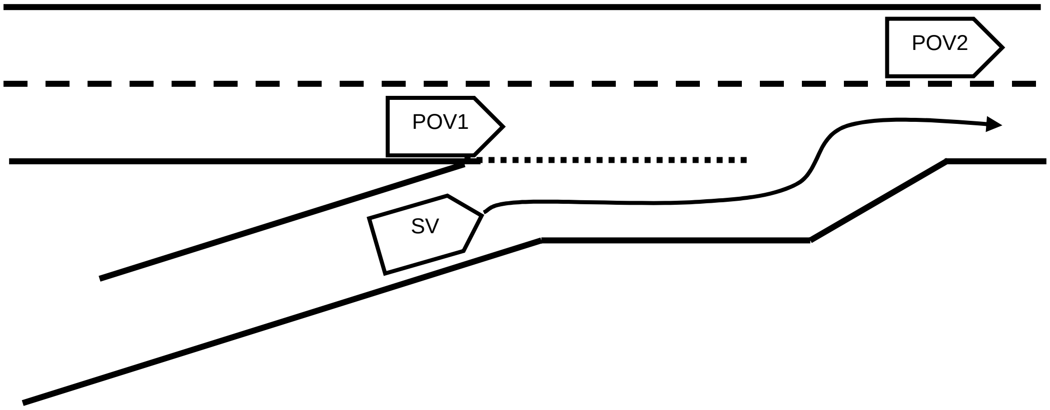
Classification name: return

Classification definition: Lane change to return to original lane after deviating from it for any reason.



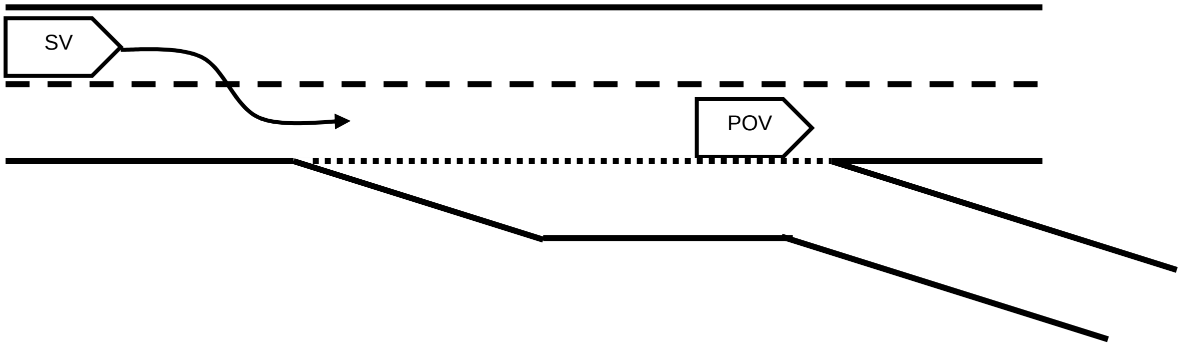
Classification name: enter

Classification definition: Lane change to enter the main highway. The TTC to POVs already on the highway are accounted for in the severity ratings.



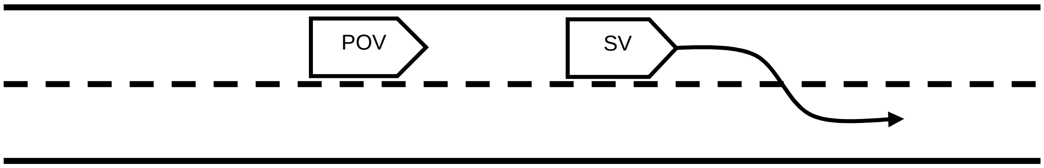
Classification name: exit/prep exit

Classification definition: Lane change to exit or to prepare to exit the main highway. The TTC to POVs are accounted for in the severity ratings.



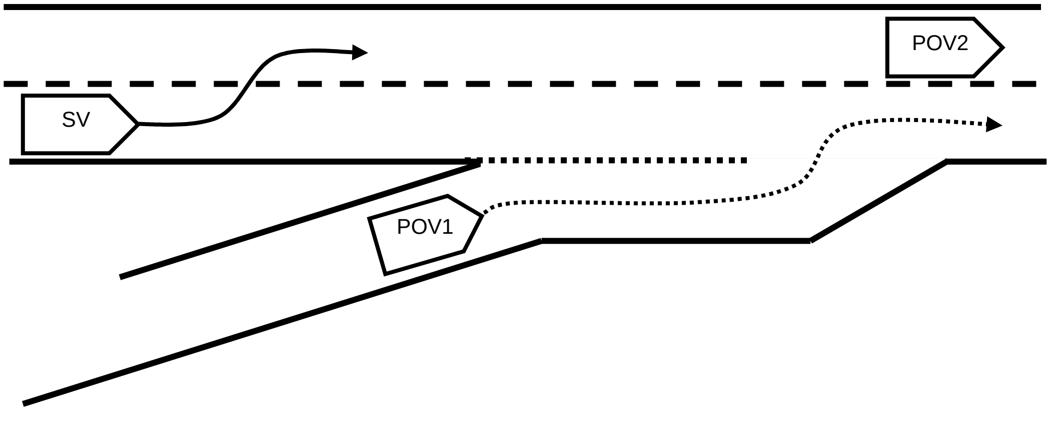
Classification name: tailgated

Classification definition: Lane change due to POV tailgating/approaching quickly; usually occurs while in the left lane. Driver of SV may make lane change while POV is still at a considerable distance/TTC. If, in the analyst's judgment, this is the true reason for the lane change, use this classification rather than any of the returning to original lane classifications. The TTC to POVs are accounted for in the severity ratings.



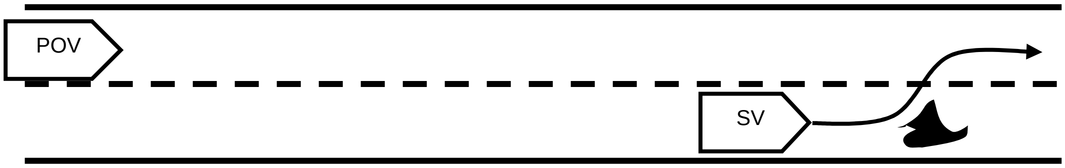
Classification name: merging veh

Classification definition: Lane change to allow POV to enter the main highway. The TTC to POVs are accounted for in the severity ratings.



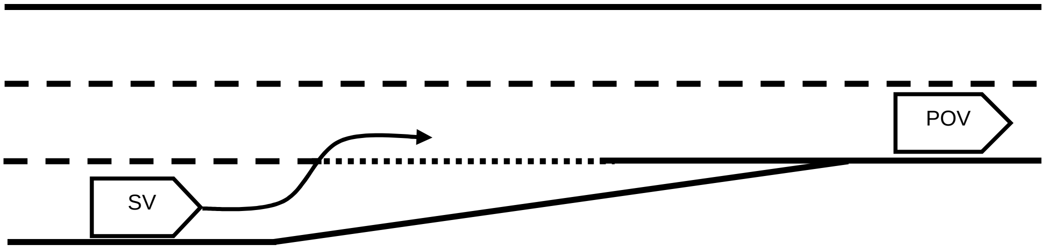
Classification name: rough/obstacle avoidance

Classification definition: Lane change due to road surface or obstacle in road. The TTC to POVs are accounted for in the severity ratings.



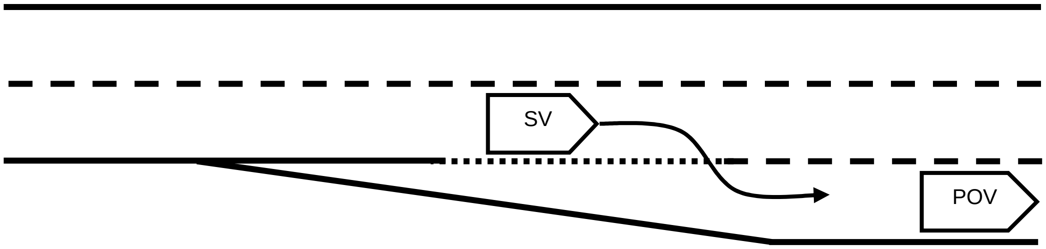
Classification name: lane drop

Classification definition: Lane change due to end of SV's lane (e.g., road goes from 3 to 2 lanes). The TTC to POVs are accounted for in the severity ratings.



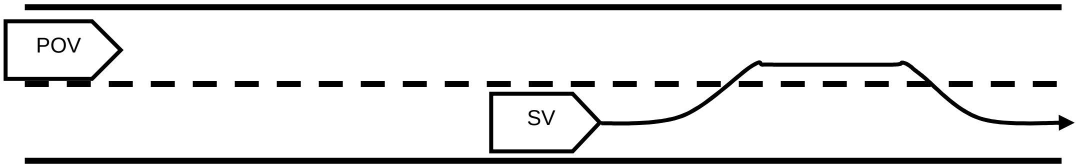
Classification name: added lane

Classification definition: Lane change due to the addition of a lane (e.g., road goes from 2 to 3 lanes). The TTC to POVs are accounted for in the severity ratings.



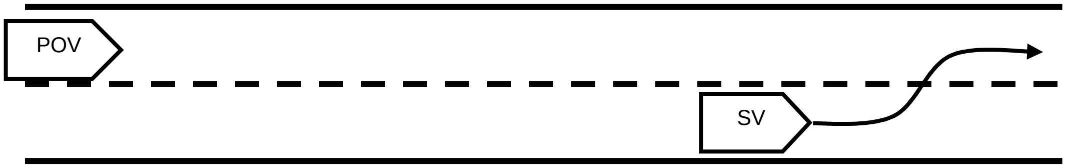
Classification name: unintended

Classification definition: Unintended lane deviation due to distraction, drowsiness, poor driving, etc.; often only a partial lane change. The TTC to POVs are accounted for in the severity ratings.



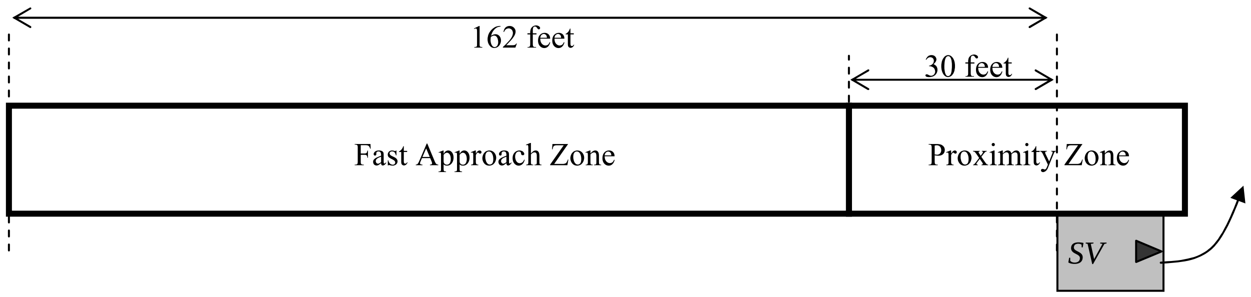
Classification name: other

Classification definition: Lane change for no discernible reason. The TTC to POVs are accounted for in the severity ratings, and POVs can be in any lane position relative to the SV.



Conflict Severity Rating: A lane change conflict, by definition, requires that there be a vehicle present in the lane into which the driver of the SV wishes to move.

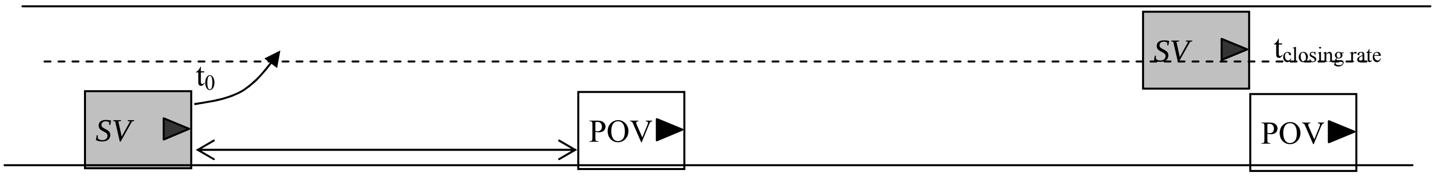
Rating	Description
7	Crash of any type
6	Emergency action/unplanned sudden maneuver required to avoid a collision with a vehicle (or object) in the adjacent lane into which the driver of the SV was attempting to move.
Ratings 5 through 1 are assessed at initiation (Start Synch) of the attempted lane change.	
5	POV in the proximity zone.
4	POV in the fast approach zone with time to reach closest end of zone, T_r[†], $\leq$ 1.0 sec.
3	POV in the fast approach zone with time to reach closest end of zone in the range $1.0 < T_r \leq 3.0$ sec.
2	POV in the fast approach zone with time to reach closest end of zone in the range $3.0 < T_r \leq 5.0$ sec.
1	POV in the fast approach zone with time to reach closest end of zone, T_r, > 5.0 sec, including case where there is no vehicle in the adjacent lane.



[†] T_r is the time required for a POV to reach the front end of the fast approach zone. (This point is 30 ft behind the SV.)

Urgency Rating: Each type classification can be placed in one of the following categories, according to the urgency of the SV's relationship to vehicle(s) in same lane or opposite adjacent lane (the lane opposite the one into which the SV intends to move):

Rating	**Description**
4	Critical incident/crash: Physical contact/collision occurs with a vehicle (or object) in the same lane as the SV or the opposite adjacent lane; or a sudden maneuver (braking or swerving) is required to avoid such a collision.
3	Forced: The lane change has a high degree of urgency due to fast closing rate* (TTC ≤ 3s) and/or close headway/tailway/distance to vehicle in the same or opposite adjacent lane.
2	Urgent: The lane change is somewhat urgent due to moderate closing rate (5.5s ≥TTC > 3s) and/or moderate headway/tailway/distance to vehicle in the same or opposite adjacent lane.
1	Non-urgent: The lane change is not urgent, because of a zero or negative closing rate (TTC > 5.5 s) with vehicle in the same or opposite adjacent lane, and/or long headway/tailway/distance, and/or lack of vehicles in the same or opposite adjacent lane.



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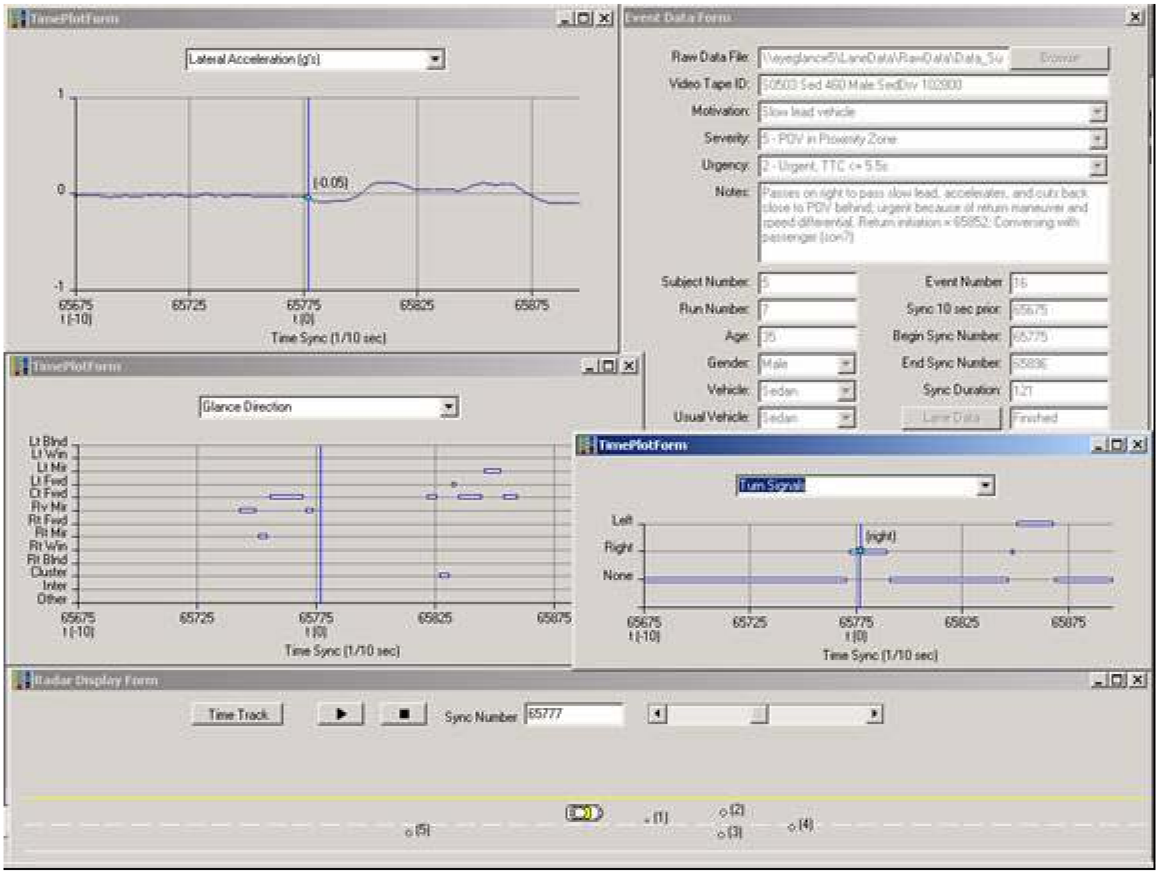
[*] Closing rate between vehicles is the number of seconds (time) it would take for vehicles to collide if the rear vehicle did not maneuver. In other words, it is the time from the initiation (Start Synch) of the lane change to the time when the front bumper of the SV is parallel with the rear bumper of the POV (e.g., when the POV is in front of the SV).

APPENDIX D: USER MANUAL FOR LANE CHANGE DATA REDUCTION PROGRAM



Raw Data File: \\eyeglance5\LaneData\RawData\Data_Su

Video Tape ID: 50503 Sed 460 Male SedDrv 102800

Motivation: Slow lead vehicle

Severity: 5 - POV in Proximity Zone

Urgency: 2 - Urgent, TTC <= 5.5s

Notes: Passes on right to pass slow lead, accelerates, and cuts back close to POV behind; urgent because of return maneuver and speed differential. Return initiation = 65852. Conversing with passenger (con7)

Subject Number: 5

Run Number: 7

Age: 35

Gender: Male

Vehicle: Sedan

Usual Vehicle: Sedan

Event Number: 16

Sync 10 sec prior: 65675

Begin Sync Number: 65775

End Sync Number: 65836

Sync Duration: 121

Finished

Sync Number: 65777

May 1, 2002

Event Analysis Protocol Overview

This document explains how to view events using the Lane Change Data Reduction Program, as used to analyze the sample of 500 lane change events from the total database. This program was created by Brian Leeson of VTTI to allow analysts to identify and characterize lane changes collected from on-road vehicles. The data collected used three hardware systems. The hardware systems collected numerous data including eye behavior (i.e., allowing extraction of location and duration of eye glances prior to and during maneuvers), driver-vehicle performance measures (steering wheel behavior, number and average length of lane changes, vehicle velocity, and turn signal usage), and driving performance data related to lane-changing behavior (azimuth, gap, and gap closing rate to other vehicles fore and aft).

Considered separately, these data are difficult to interpret. For example, one could imagine attempting to use a spreadsheet to make sense of various data sources.

The Lane Change Data Reduction Program allows the analyst to gain insight as to what is taking place during a specific maneuver by integrating the three types of data. Such integration allows the analyst to identify, review, categorize, and rate maneuvers. To assist in this task, a customized system was developed for review of all data types in conjunction with the composite video. The program can read raw data files consisting of radar and vehicle data for a desired lane change or passing event.

The following pages explain how to view events created by the program. It can be read without access to actual data files to gain a general understanding of how it works.

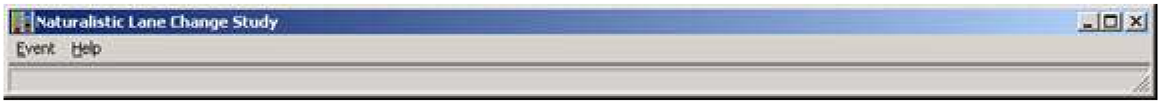
Running the Program

To allow the Lane Change Program to operate (to display analyzed events):

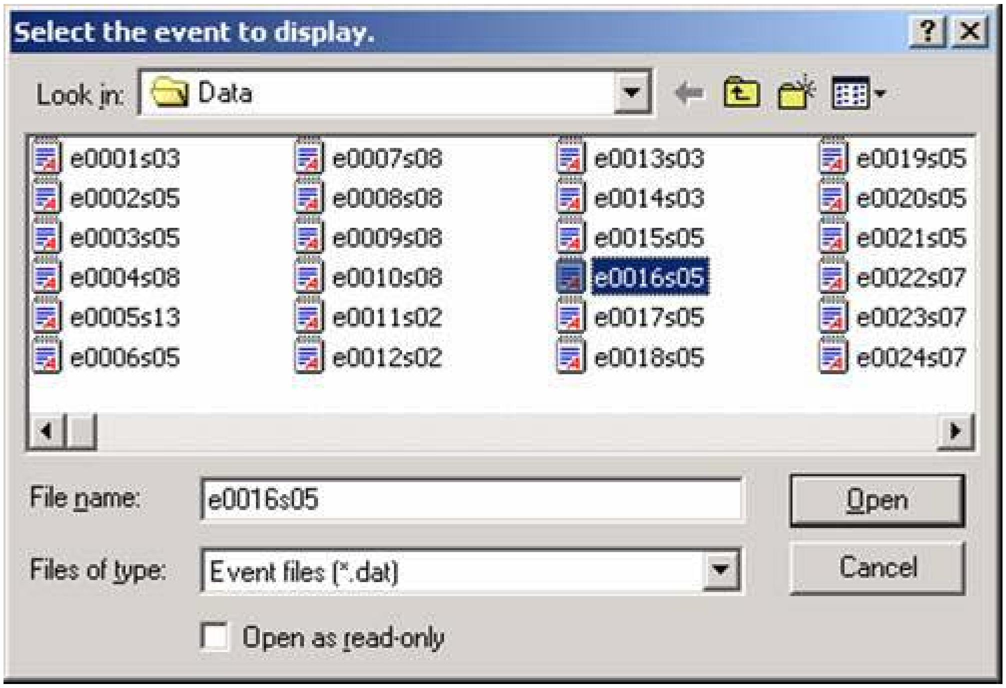
1. Place the Lane Change CD into the CD drive. The following directories and files exist:
   - “Data” contains .dat files created by the Lane Change Program (e.g., "e0001s03.dat"). Files include 0001 through 0517. Files 0034, 0114, 0141, 0146, 0148, 0197, 0259, 0262, 0276, 0277, 0283, 0308, 0361, 0413, 0421, 0424, 0430 are included but data were not available to fully analyze these events.
   - “Frames” is an empty directory required for the program to run.
   - “RawData” is empty, but exists to store subdirectories for each subject, e.g., "Data_Subject2"). These subdirectories are not required to display events. However, when data were originally entered, each subdirectory contains further subdirectories for that subject for each data collection session, e.g., "data_100500_0201_SUV" corresponding to data collected on October 5, 2000 for Subject#2, tape #1 in the SUV). Each of these subdirectories contained a series of .dat files created during data collection, e.g., "V002_01.dat" created on 10/5/00 at 9:40 AM corresponding to the first data collection run for that data collection session. **All that is needed to display these events are the data files in the "Data" directory, created by the Lane Change program when they were originally entered.**
   - borlndmm.dll (Application Extension)
   - cp3240mt.dll (Application Extension)
   - drwtsn32 (log file)
   - LaneChange (Application File)
   - Sedan (Horizontal Bitmap file)
   - Sedan2 (Vertical Bitmap file)
   - softdata.tmp (temp file)
   - SUV (Horizontal Bitmap file)
   - SUV2 (Vertical Bitmap file)
   - vcl35 (bpl file)

2. Run the LaneChange Program by clicking on the Lane Change Application icon within the LaneData directory on the CD.

Displaying Events



1. Select "Display Event" from the Event menu on the Lane Change menu bar.
2. Select an event to view, such as "e0016s05" (event #16, subject 5) from the Data directory (within the LaneData directory).



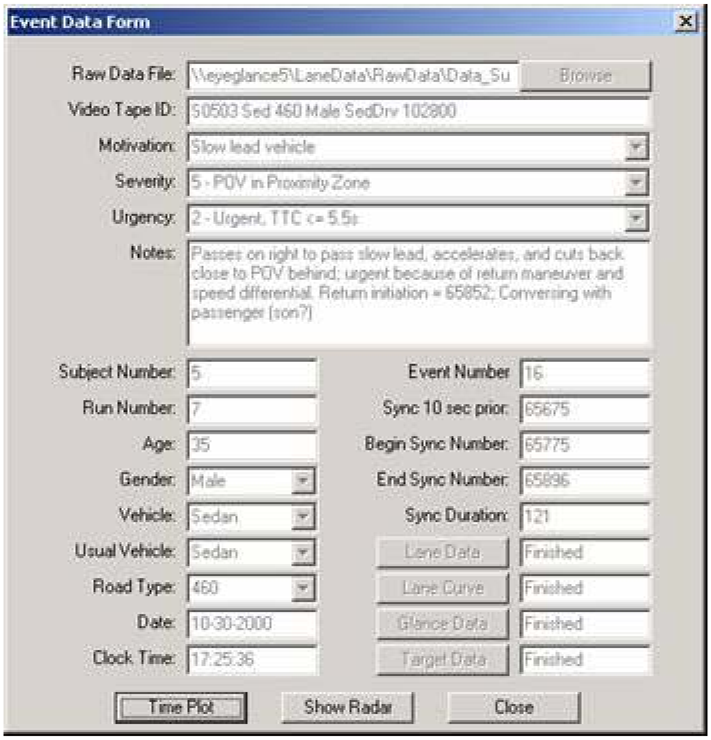
Look in: Data

File name: e0016s05

Files of type: Event files (*.dat)

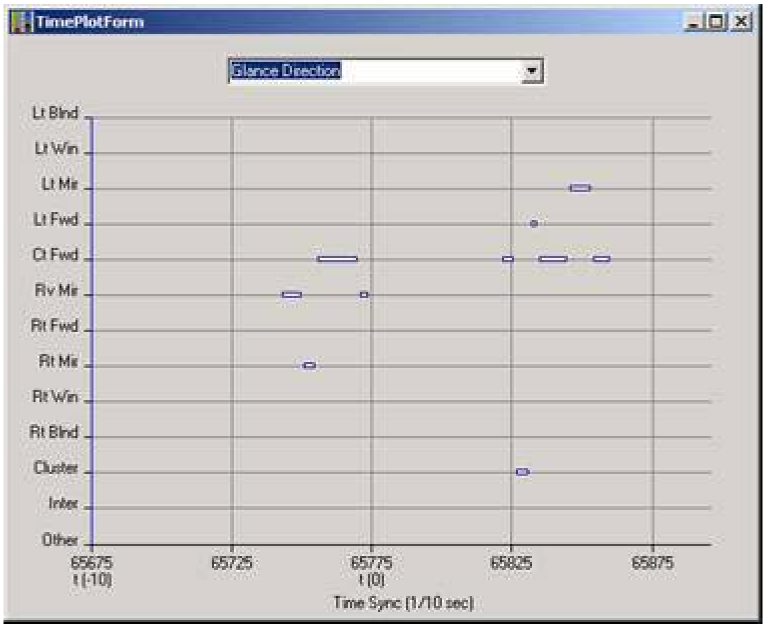
☐ Open as read-only

3. Click on Open. The Event Data Form will open:



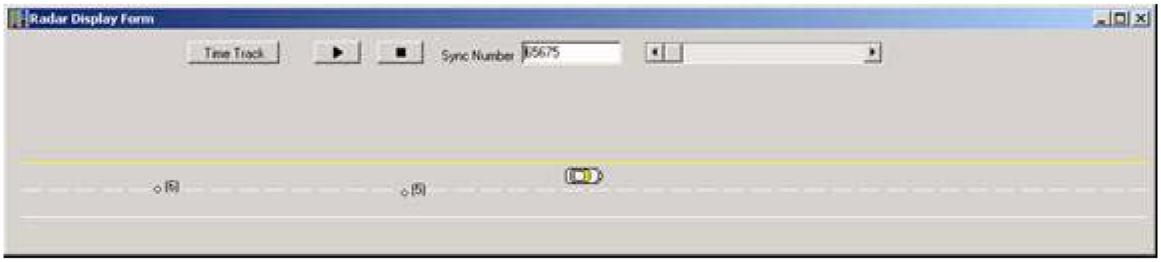
Raw Data File: \\eyeglance5\LaneData\RawData\Data_Su
Video Tape ID: 50503 Sed 460 Male SedDrv 102800
Motivation: Slow lead vehicle
Severity: 5 - POV in Proximity Zone
Urgency: 2 - Urgent, TTC <= 5.5s
Notes: Passes on right to pass slow lead, accelerates, and cuts back close to POV behind; urgent because of return maneuver and speed differential. Return initiation = 65852; Conversing with passenger (son?)
Subject Number: 5
Run Number: 7
Age: 35
Gender: Male
Vehicle: Sedan
Usual Vehicle: Sedan
Road Type: 460
Date: 10-30-2000
Clock Time: 17:25:36
Event Number 16
Sync 10 sec prior: 65675
Begin Sync Number: 65775
End Sync Number: 65896
Sync Duration: 121
Lane Data: Finished
Lane Curve: Finished
Glance Data: Finished
Target Data: Finished

4. Click on the "Time Plot" button in the Event Data Form window to see the TimePlotForm (time graph):



Glance Direction

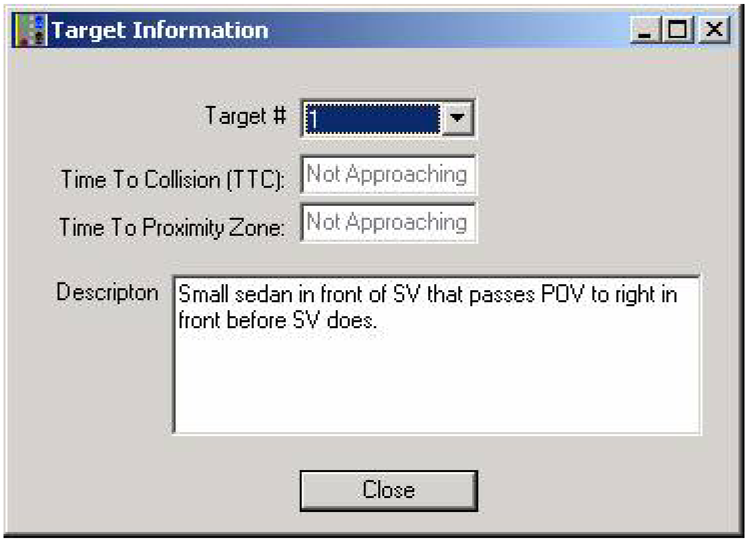
5. And the Radar Display Form (bird's eye view of the subject vehicle and surrounding radar targets):



Sync Number 05675

6. The TimePlotForm has a pull-down menu to see various parameters:
   - Glance Direction
   - Subject Vehicle Speed (mph)
   - Steering Wheel Angle (rad)
   - Lateral Acceleration (g's)
   - Accelerator Position
   - Brake Position
   - Turn Signals
   - Absolute Target Speed (mph)
   - Relative Target Speed (ft/s)
   - Target Distance (ft)
   - Target Angle (degrees)

Note: When either the Target Distance or Target Angle item is selected, a Target Information window will appear. This window provides descriptive information including TTC, time to Proximity Zone about the identified target. Information for each target is available by changing the Target # in the pull-down menu at the top of this window.



Target # 1

Time To Collision (TTC): Not Approaching

Time To Proximity Zone: Not Approaching

Descripton: Small sedan in front of SV that passes POV to right in front before SV does.

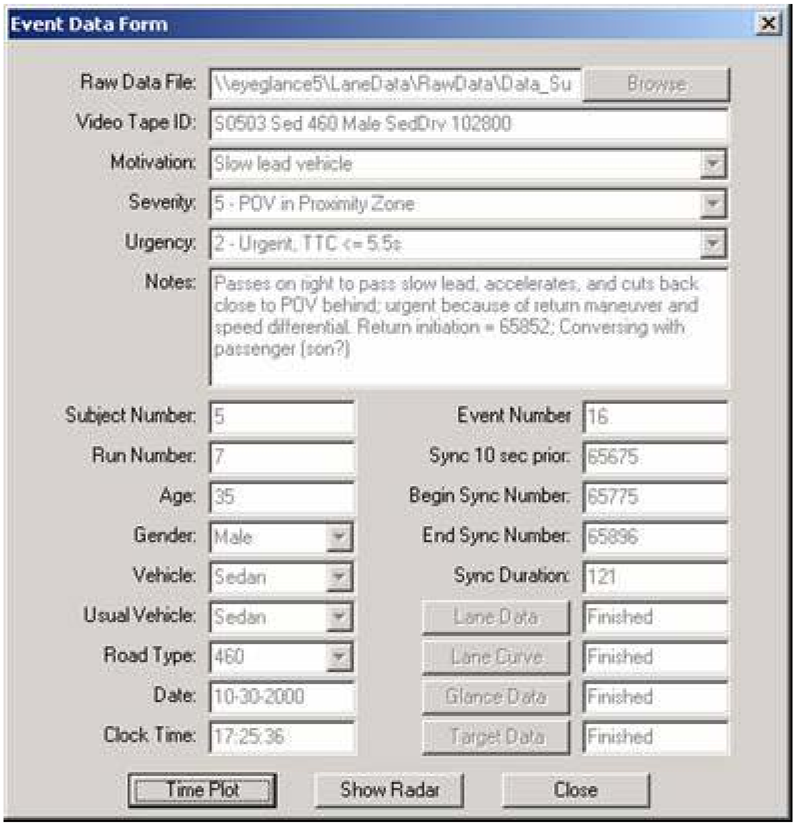
7. Select a pull-down menu item as desired.
    - To see multiple items at once, click on the Time Plot button again and a new TimePlotForm (graph) will pop up on top of the previous.
    - Reposition the new graph as desired.

8. The Radar Display Form has simple play and stop buttons and a scroll bar for controlling the movement of the event over time. Notice the synch numbers corresponding to time (1 synch = 1/10 second)

9. The time track button can be toggled to see the radar tracks for a particular target.

Description of Lane Change Program Forms

The Event Data Form includes relevant data for the event as shown below:



Raw Data File: \\eyeglance5\LaneData\RawData\Data_Su
Video Tape ID: S0503 Sed 460 Male SedDrv 102800
Motivation: Slow lead vehicle
Severity: 5 - POV in Proximity Zone
Urgency: 2 - Urgent, TTC <= 5.5s
Notes: Passes on right to pass slow lead, accelerates, and cuts back close to POV behind; urgent because of return maneuver and speed differential. Return initiation = 65852; Conversing with passenger (son?)
Subject Number: 5
Run Number: 7
Age: 35
Gender: Male
Vehicle: Sedan
Usual Vehicle: Sedan
Road Type: 460
Date: 10-30-2000
Clock Time: 17:25:36
Event Number 16
Sync 10 sec prior: 65675
Begin Sync Number: 65775
End Sync Number: 65896
Sync Duration: 121
Lane Data: Finished
Lane Curve: Finished
Glance Data: Finished
Target Data: Finished

The event Start Sync is the Begin Sync Number, on the middle right side of the form.

The Video Tape Number[*] is entered into the "Video Tape ID" field in the Event Data Form of the Lane Change program

Notes are entered into the "Notes" field in the LaneChange program.

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[*] See the Video Tape Labeling Convention section at the end of this document.

- Start Synch reflects the first sign of lateral movement (beginning of lane change).
- End Synch reflects the “settling point” of movement (end of lane change).

The following pull down menu items were also selected during analysis:

- Motivation (lane change type) as follows:

Motivation	**Description**
Slow lead veh	Lane change to pass a vehicle moving slower than the Subject Vehicle’s (SV) preferred speed.
Return	Lane change to return to preferred driving lane.
Enter	Lane change to enter road (e.g., from on-ramp).
Exit/prep exit	Lane change associated with exiting.
Tailgated	Vehicle tailgating/approaching quickly.
Merging veh	Vehicle entering roadway causing SV to change lanes.
Rough/obst avoid	Maneuver to avoid obstacle or rough road surface.
Shoulder	Moving off paved surface/out of travel lanes for any reason.
Lane drop	End of driver’s lane (e.g., road goes from 3 to 2 lanes).
Added lane	Addition of a lane (e.g., road goes from 2 to 3 lanes).
Unintended	Unintended lane deviation (e.g., distraction in car).
Other	Lane change for any other reason or for no discernible reason.

- Severity: A lane change conflict, by definition, requires that there be a vehicle present in the lane into which the driver of the SV wishes to move.

Rating	**Description**
7	Crash of any sort.
6	Emergency action/unplanned sudden maneuver required to avoid a collision with a vehicle (or object) in the adjacent lane into which the driver of the SV was attempting to move.
Ratings 5 through 1 are assessed at initiation (Start Synch) of the attempted lane change.	
5	POV in the proximity zone.
4	POV in the fast approach zone with time to reach closest end of zone, T_r[†], $\leq$ 1.0 sec.
3	POV in the fast approach zone with time to reach closest end of zone in the range $1.0 < T_r \leq 3.0$ sec.
2	POV in the fast approach zone with time to reach closest end of zone in the range $3.0 < T_r \leq 5.0$ sec.
1	POV in the fast approach zone with time to reach closest end of zone, T_r, > 5.0 sec, including case where there is no vehicle in the adjacent lane.

[†] T_r is the time required for a Principal Other Vehicle (POV) to reach the front end of the fast approach zone. (This point is 30 ft behind the SV.)

- Urgency: Each type classification can be placed in one of the following categories, according to the urgency of the SV's relationship to vehicle(s) in same lane or opposite adjacent lane (the lane opposite the one into which the SV intends to move):

Rating	**Description**
4	Critical incident/crash: Physical contact/collision occurs with a vehicle (or object) in the same lane as the SV or the opposite adjacent lane; or a sudden maneuver (braking or swerving) is required to avoid such a collision.
3	Forced: The lane change has a high degree of urgency due to fast closing rate[*] (TTC ≤ 3s) and/or close headway/tailway/distance to vehicle in the same or opposite adjacent lane.
2	Urgent: The lane change is somewhat urgent due to moderate closing rate (5.5s ≥TTC > 3s) and/or moderate headway/tailway/distance to vehicle in the same or opposite adjacent lane.
1	Non-urgent: The lane change is not urgent, because of a zero or negative closing rate (TTC > 5.5 s) with vehicle in the same or opposite adjacent lane, and/or long headway/tailway/distance, and/or lack of vehicles in the same or opposite adjacent lane.

Lane Data includes synch numbers associated with event beginning, inside crossing of the lane line, outside crossing of the lane line and end of the event.

Lane Curve is data that was entered based on a visual estimation of the road curvature based on the video.

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[*] Closing rate between vehicles is the number of seconds (time) it would take for vehicles to collide if the rear vehicle did not maneuver. In other words, it is the time from the initiation (Start Synch) of the lane change to the time when the front bumper of the SV is parallel with the rear bumper of the POV (e.g., when the POV is in front of the SV).

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