REDUCING SIDE-SWEEP ACCIDENTS WITH VEHICLE-to-VEHICLE COMMUNICATIONS

by

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ABSTRACT

This dissertation present contributions to the understanding of the causes of a side-sweep accidents on multi-lane highways using computer simulation. Side-sweep accidents are one of the major causes of loss of life and property damage on highways. This type of accident is caused by a driver initiating a lane change while another vehicle is blocking the road in the target lane.

Our objective in the research described in this dissertation was to understand and simulate the different factors which affect the likelihood of side sweep accidents. For instance, we know that blind spots, parts of the road that are not visible to the driver directly or through the rear-view mirrors are often a contributing factor. Similarly, the frequency with which a driver checks his rear-view mirrors before initiating the lane change affects the likelihood of the accident. We can also have an intuition that side-sweep accidents are more likely if there is a significant difference in the vehicle velocities between the current and the target lanes. There are also factors that can reduce the likelihood of the accident: for instance, the signaling of the lane change by the driver can alert the nearby vehicles about the lane change, and they can change their behaviors to give way to the lane changing vehicle. The emerging technology of vehicle-to-vehicle communication offers promising new avenues to avoid such collisions by making vehicles communicate the lane change intent and their positions, such that automatic action can be taken to avoid the accident.

While we can have an intuition about whether some factors increase or reduce accident rate, these factors interact with each other in complex ways. The research described in this dissertation developed a highway driving simulator specialized for the accurate simulation of the various factors which contribute to the act of lane change in highway driving. We are modeling the traffic as seen from the lane changing vehicle, including the density, distribution and relative velocity of the vehicles on the target lane. We are also modeling the geometry of the vehicle, including size, windows, mirrors, and blind spots. Moving to the human factors of the simulation, we are modeling the behavior of the driver with regards to the times of checking the mirrors, signalling and making the lane change decision. Finally, we are also modeling communication, both using the traditional way using the turn signals, as well as through means of automated vehicle to vehicle communication.

The detailed modeling of these factors allowed us to perform extensive simulation studies that allow us to study the impact of various factors on the probability of side-sweep accidents. We validated the simulation models by comparing the results with the real-world observations of the National Highway Traffic Safety Administration. One of the benefits of our model is that it allows the modeling of the impact of vehicle to vehicle communication, a technology currently in prototype stage, that cannot be studied in extensive real world scenarios.

To my family for their support, kindness and love.

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CHAPTER 1: INTRODUCTION

This chapter, discusses the importance of simulating the traffic scenarios leading to a side-sweep accident. We discuss the importance of reducing side-sweep accidents, the impact of driver awareness. We describe the problem statement of the dissertation, the challenges we faced, our contributions and finally, the applications that might benefit from the simulation architecture created.

1.1   Objectives

Accidents on highways are one of the major sources of loss of life in modern society. Driving a vehicle on a busy multilane highway while attempting to change lanes occasionally can be hazardous. That is because due to the blind-spots, the drivers may not see the vehicles in the adjoining lanes. Significantly more lives have been lost in highway accidents than in terrorism or wars. Part of the reason for this is that Americans spend a significant time on the roads—the average commute is 30 min (NHTSA) [LK94].

Every vehicle has a blind-spot. Some of the contribution factors are: improperly adjusted side and rearview mirrors, the dimensions and the configurations of the side and rearview mirror and the rear and front windshields. Any technology that makes driving safer, faster or cheaper would have a significant human and commercial impact. Whereas, in recent years, significant research focus (and press coverage) has been dedicated to self-driving vehicles, there is no imminent

transition to fully self-driving infrastructure. In fact, fully autonomous vehicles are not legal for highway driving—they require human supervision. Even if fully autonomous vehicles become commercially available in the next decade, the vast majority of vehicles on the highway will remain human-controlled, with the mix of vehicles changing only gradually towards more autonomy. What we are going to see, in the foreseeable future, is a mix of vehicles with various sensing, actuation and communication technologies, and various degrees of automation based on these. Just like with today's cars, drivers will have a choice of turning on or off these technologies, as well as reacting or not reacting to messages coming from them.

It is quite possible that this proliferation of technology mixtures will make driving in the following decades even more unpredictable and cognitively challenging than in the current situation, where uncertainty arises only from the driver's behavior. In the real world this is a very tedious task to accomplish. For example, data published by the National Highway Traffic Safety Administration (NHTSA) [LOW04] is based on the observation of one hundred drivers' (100) road experiences during a 12-month period of time, but this sample is too small order to formulate a standard set of rules.

To understand the traffic of the future, the only feasible approach is to study it through the means of simulation [YQY11, KGN12, QHC13, GW13, KLY12, LJL14, BB16a]. When conducting experiments on real systems would be impossible or impractical where it is possible in simlation. In conducting simulations [SGB05, GWA10, AT13], it is possible to generate a large

amount of data with several permutations and combinations with respect to multiple attributes for analytical purposes.

In order to understand the impact of a new technology, we need to study it through a simulation that models not only the technology itself, but the overall environment, visibility, traffic structure as well as the cognitive state, reaction time and so on of the drivers. However, It is not enough to model where a vehicle is and how fast it moves. We need to model the surrounding vehicles, what each of the drivers know, their decision making processes, and their low-tech and high-tech means to communicate with each other.

Furthermore, it is imperative to understand the impact due to the magnitude of the blind-spot in correlation with other attributes such as vehicle density, velocity, frequency of the driver looks before lane change (driver update time) and the percentage of the number of drivers look before changing the lane. In order to define the uniform set of rules, it is vital to collect a large number of statistics and all these attributes need to be taken into consideration. Let us consider the case of side-sweep accidents, which will be the running subject of the remainder of this dissertation.

Overall, we conclude that side-sweep accidents can have complex sources. Technological solutions, such as sensor improvements and V2V communication can improve several steps of this process, but they will always need to be seen as playing a specific part of a system. Our objective in this dissertation is to present the design of a simulator that takes into account all the factors of the lane change scenario. We will then use this simulator to study the potential of technological solutions such as V2V communication in reducing the frequency of the side-sweep accidents.

1.2 The Physical and Cognitive Context of a Lane Change

Why do side-sweep accidents occur? Side-sweep accidents occur during driving on multi-lane highways when a vehicle initiates a lane change, a follower vehicle is blocking the other lane. In the simplest approximation, the cause of the accident is *lack of awareness*—the driver of the lane changing vehicle is not aware that there is a blocking vehicle in the other lane [YEM95, RT00]. This lack of awareness might be due to either the driver neglecting to check the appropriate side mirror, or the blocking vehicle was in the driver's blind spot. The accidents might also be due to a *misprediction* of the driver that the blocking vehicle would be safely behind it at the time of the lane. The cause of the side-sweep accident is the incorrect decision made by the driver of the lane changing vehicle, due to lack of information: the driver did not know about the blocking vehicle. This misprediction might be due to a misjudgment of the relative speed of the vehicles, or the blocking vehicle had accelerated since the most recent driver lookout. Driver fatigue, environmental conditions such as icy and wet roads are also contribution factors.

To avoid side-sweep crashes, drivers are instructed to ensure that there is no blocking vehicle by visual inspection, looking both through the rear view and side mirrors as well as turning his or her head in the direction of the target lane [Kni12]. Moving towards more complex causes, a possible cause of the side-sweep accident might be a *a failure of communication*. The lane changing vehicle might have communicated its intention to change lanes, either with the turning signals or vehicle to vehicle (V2V) communication, but this signal had not been seen or received by the blocking vehicle.

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Let us now investigate why the driver was not aware of the blocking vehicle. The simplest explanation is that the driver did not look or check the mirrors. NHTSA research revealed that 17% of drivers failed to check their left mirrors, left windows, and center mirrors during the last 8 s prior to initiating a left-lane change. Furthermore, 36% of drivers failed to check their right mirrors, right windows, and center mirrors during the last 8 s prior to initiating a right-lane change [BB15, BB16b, LOW04]. Side-sweep accidents lead to a side collision, but the resulting loss of control can create further collisions [YEM95, RT00]. Side-sweep accidents account for 4%–10% of all crashes [FLK09, FKS12, TCE00, WK94].

Even for drivers who do check the mirrors, a significant number of drivers do not make a strong effort to turn their head and make a visual inspection. As many vehicles have significant blind spots, it is possible that the blocking vehicle exists even if it does not show up in the mirror [MG08]. The size of the blind spot depends on the geometry of the vehicle, the size and adjustment of the mirrors, as well as other means of inspecting the target lane (such as side-view cameras or blind spot sensors).

Another factor comes into the picture when we consider that conditions might change between the last time a driver looked at the target lane versus when the lane change is initiated. For instance, an accelerating vehicle might enter into the blocking zone without the driver being aware of it. The ability to accurately assess whether the lane will be free at the moment of the initiation of the lane change requires that the driver makes a prediction of the way that the traffic will evolve. This prediction might be impaired in conditions of poor visibility and drowsiness [BH08, HEF10].

Visibility can be impacted by the factors such as atmospheric conditions and the blind spots [KI08]. Enhancing driver attention and minimizing the size of the blind spots of cars can help overcome lack of visibility issues [KKA12]. Another way to monitor drowsiness is proposed by integrating intelligent control systems into vehicles to include the human driver control loop [BH08].

Finally, the cause of the accident might be an *incorrect mental modeling*. The lane changing driver might judge that the blocking vehicle's driver will slow down to give way, but instead, that driver chooses to accelerate, relying on the lane changing driver see him and abandoning the action.

1.3 Reducing the Number of Side-Sweep Accidents

There are several ways in which the number of side-sweep accidents can be reduced [HXX04, RRE13, HS12, BB16a]. *Early warning systems* improve the driver's awareness of potential blocking vehicles or obstacles [LCF12]. Systems such as side detection sensors recognizing objects on either side of the vehicle and alert drivers of the presence of vehicles during lane changes to avoid side-sweep accidents [SHT12, Car05, DDS14]. For these systems, it remains the responsibility of the driver to make a correct decision, such as canceling the lane change.

Another class of systems, *early intervention systems*, provide limited automatic assistance to the driver by intervening even *after* the decision has been made [CC09, RZF10, ARR08, ANL07, YCW09, YCL08, Lee11]. This assistance may be in the form of slowing the vehicle to a stop and/or controlling steering to help the driver stay in the proper lane.

Another important class of methods for reducing the number of side-sweep accidents is by improving the coordination and communication between drivers. This communication does not necessarily need to be mediated through technology. By using its turning lights, the driver can communicate his intention to change lanes to the following vehicles. Following vehicles can also infer this intention from implicit means from the behavior of the driver. Communication in the other direction is also possible: the blocking vehicle might warn the driver initiating a dangerous lane change by honking.

These communication methods might not always work. The fault may be with the initiator (neglecting to use or deploying the lane change signals too late), or with the fault of the receiver (not noticing or ignoring the lane change signal). Even if communication was successfully received, this may not be a clear agreement for the procedure to follow. The signaling driver might expect that the following driver might slow down and give way upon receipt of the signal, while the driver of that vehicle might choose to accelerate instead.

V2V communications are novel networking technologies that extend traditional means of communication between vehicles. V2V technologies might enable many novel driving behaviors such as convoy formation [KB05]. For the purpose of this research, we will restrict our attention to communication between the lane changing and the follower vehicle. The first advantage of V2V communication is that it allows more information to be transferred than the single-bit turning signals. Furthermore, V2V communication can ensure that a transmission has been received by the

destination vehicle (although this might not guarantee that the driver of the vehicle receives and also understands the signal).

As with any communication technologies, V2V communication does not guarantee that the appropriate actions for the avoidance of the accident will be made. To perform lane changes safely and quickly, ideally coordinated action from both the lane changing and the following vehicle is needed. However, as new technologies are adapted by drivers gradually, it is likely that, in the foreseeable future in most encounters, only one of the vehicles will be augmented with automated response technology. As we shall see in our experiments, even this might improve the accident rate.

1.4 Driver Awareness

Most accidents occur because the driver was not aware of the obstacle in the immediate vicinity due to poor visibility and drowsiness [BH08, Rec, HEF10, HEF10]. Visibility can be impacted by factors such as atmospheric conditions and blind spots [KI08]. Enhancing the driver attention and minimizing the size of the blind spots of cars might overcome lack of visibility issues [KKA12]. Driver drowsiness can be monitored by integrating intelligent control systems into vehicle to include the human-driver control loop [BH08].

Traditional Means of Awareness: The traditional way to be aware of another vehicle in the adjoining lane is the use the side-view (left and right) mirrors, rearview mirror and visual inspection by turning the head and looking back [Kni12]. Properly adjusted mirrors are vital to enhance the

angle of view thereby reducing the blind-spot and providing the driver with a better view of the other vehicles before changing the lane. The problem with the traditional means of awareness is that there is no room for errors as there is no early warning system, if the driver make a mistake by not seen the other vehicle because of the blind-spot [MG08].

Technological Means of Awareness: Developing technological means of awareness can improve passenger safety by mitigating the injuries and preventing accidents[HXX04, RRE13, HS12]. There are two types of technological solutions: early warning systems[LCF12] and early intervention systems systems[CC09, RZF10, ARR08, ANL07, YCW09, YCL08, Lee11].

Collision warning systems use side detection sensors to recognize objects on either side of the vehicle and to alert drivers the presence of vehicles during lane changes to avoid side-sweep accidents [SHT12]. Collision intervention systems go beyond collision warning by providing limited automatic assistance to the driver during potential crash situations. This assistance may be in the form of slowing the vehicle to a stop and or controlling steering to help the driver to stay in the proper lane. However, for the foreseeable future, the main decision maker will remain the human driver.

1.5   Problem Statement

The problem addressed in this research is primarily focuses on side-sweep accidents with the objective of developing a framework through which we can evaluate the safety of vehicles in lane change situations. In this research, first, we focus on the visual inspection by the driver through

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the rear and side view mirrors (the old fashion way), next the benefits of signaling before lane changing and finally, the effect of novel technology, in particular V2V, on the frequency of side-sweep accidents. In order to obtain realistic and useful results, the simulator needs to satisfy a number of requirements.

First, it needs to realistically model the traffic conditions of multi-lane highway driving, including the geometry of the road, the overall and relative speed of the vehicles, and the distribution of the vehicles in the traffic. The simulator should allow the modeling of various traffic conditions.

Second, the simulator needs to model the visibility of the drivers of the vehicles, including direct observation and observations through the mirrors. Occlusions by parts of the car (A, B and C pillars) and by other vehicles must be considered. The location, shape and size of the blind spot must be accurately modeled, and we should be able to repeat experiments with different blind spot sizes.

Finally, the simulator needs to model driver behavior [LTB15], in particular not only whether the driver can see the blocking vehicle, but also whether it will check its mirrors, as well as the temporal relationship of the decision making with regards to the sighting.

There is special interest in the ways in which the attributes (itemized list given below) affects the information that reaches the driver and the way this information impacts the decisions of the driver.

- Relative velocity

- Vehicle density and frequency

- The duration of the interval of the driver look outs

- Geometry of the vehicle and the configuration of the side, left and right, and rear view and mirror angles of the mirrors, and

- Size and the orientation of the blind-spots because of the side-view mirror adjustments

Most of the literature in this domain focuses on automobile blind-spots with respect to side-sweep accidents but do not address the above stated attributes. In this research, however, focus is to comprise these attributes in the modeling framework to mimic the real world scenarios and observe the outcome.

1.6 Challenges

There are several challenges simulating the automobile blind-spot simulation with respect to side-sweep accidents and incorporating vehicle conditions in the simulation can be tedious and challenging. Some of the challenges are discussed below.

(a) Vehicle conditions: Accidents can occur because of vehicle conditions (i.e., flat tire) at the time of the accidents.

(b) Environmental conditions: Accidents can occur because of environmental conditions (i.e., fog, rain, icy roads) at the time of the accidents.

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(c) Human mental conditions: Accidents can occur because of driver condition (i.e., poor eye sight, mental status) at the time of the accidents.

(d) Mimicking various size and shapes of vehicles: It is difficult to simulate the multiple vehicle sizes because the simulator can accommodate only one car size (driver car)

(e) Limited number of default input simulation parameters: It is difficult and impractical to incorporate all the attributes in the simulation; for example, some of the above stated variables (environmental, mental, and vehicle conditions) are not incorporated,

(f) Mean time to change lane: How to rationalize and incorporate in the simulation that an average time a motorist takes to change a lane safely,

(i) Vehicle design configurations: There are many types of shapes and sizes of vehicles; therefore, it is impossible to mimic all the configurations with respect to driver visibility (i.e., side and rear view mirror sizes and location),

(j) Real world data sample size is too small: Data published by National Highway Traffic Safety Administration (NHTSA), is based on the observation of one hundred drivers' (100) road experiences during a twelve 12-month period of time; this sample is too small for the comparison purposes with the simulation model data and draw some rational conclusions.

Some of the research have already addressed some subsets of the problem. According to NHTSA findings, 83% of the single lane changes with a mean duration time of 6.28 seconds. However, these findings does not comprise the relative velocity or the vehicle density because these two

attributes can impact at the same time during the lane change. Side-sweep accidents account about 4 to 10 percent of crashes according to transportation researchers. However, the research does not provide a detail breakdown; therefore, it is a tedious factor for statistical comparison among the simulated and the real world data.

1.7 Contributions

The contributions presented in this dissertation are enumerated below: The contributions presented in this dissertation are enumerated below:

- Develop a simulator to simulate and evaluate the automobile blind-spots in side-sweep accidents.

- Simulate in detail the situational awareness and behavior of the driver, including the visibility with respect to the blind-spots of the vehicle as well as the times of checking the mirrors and initiating a lane change impacting the side-sweep accidents.

- Estimate the time it takes to change a lane and the frequency of side-sweep accidents in various conditions such as traffic density and relative velocity of vehicles.

- Investigate the impact of the spatial dimensions and angle of orientation of automobile blind-spots during side-sweep accidents.

- Study the position of the blind-spots, which depends on the geometry of the windows and mirrors of the vehicle.

- Understand the correlation between the magnitude and the orientation of the blind-spots and the frequency of side-sweep accidents in various conditions (e.g., traffic density and relative velocity).

- Investigate the impact of using the turning signals before changing the lane on the frequency of side-sweep accidents.

- Investigate the benefits of V2V communication when changing the lane on the frequency of side-sweep accidents.

1.8 Applications

Applications that might benefit from the blind-spot simulation system are listed below:

- *Education and training:* The simulation model can be used for education and training purposes. For example, the areas of interest is to perform *what-if* analysis of simulating blind spots while calibrating the simulation model for various attributes such as driver lookup frequency, duration between the lookups, vehicle velocity, side and rear view mirror angles and closely mimicking the actions taken by the drivers or simulator operators.

- *Identifying learner behavior:* In such education and training scenarios, the simulation model can be employed to identify when and where the learner behavior is deviating from the normal or acceptable behavior. The discrepancies can be used to evaluate the performance

of the learner. After recalibrating the simulation model can provide important feedback to the driver such that the weaknesses or mistakes can be addressed.

- *Traffic school:* In addition to normal education and training, the simulation model can be used to train and educate the drivers after traffic violations to reduce the side-sweep accidents.

- *Evaluating lane change time:* Using the simulation model, we can estimate the time it takes to change a lane and the frequency of side-sweep accidents in various conditions such as traffic density and relative velocity of vehicles.

1.9   Outline

The remainder of this dissertation is organized as follows.

Chapter 2 contains a comprehensive literature review of related research.

Chapter 3 discusses the vehicle simulation model as applied to mirrors and the presence and position of blind spots, scenarios of turn signals and V2V communications.

Chapter 4 discusses the information gathering behavior of human drivers, i.e. the ways in which they collect information about the surrounding traffic before they make a decision about a lane change and describes a model of the algorithm human drivers use to decide about a lane change.

Chapter 5 discusses and analyses the results of the simulation studies.

Chapter 6, the conclusions of the study and presentation of future works.

CHAPTER 2: LITERATURE REVIEW

This chapter describes much of the related work that has been conducted on side-sweep accidents with respect to blind-spots, and it identifies the pertinent areas that need more research. Although the literature review is comprehensive in identifying the areas relevant to the side-sweep accidents such as simulator architecture framework, driver lookout statistics, driver awareness about the vicinity, vehicle blind-spot as observed by the driver and technological means of awareness of the blind-spots. But all these research needs are not addressed by this dissertation.

2.1 What are the Side Sweep Accidents?

Basically, a side-sweep accident is, when there are two-vehicles travel parallel to each other and because of the blind-spots one driver is unaware of the other while attempting to change the lane. A blind spot in a vehicle is an area around the vehicle that cannot be directly observed by the driver while in control of the steering wheel, under existing circumstances [LB10, Pla06, JKI00]. Lane changes can occur for a variety of reasons. For example, attempt to overtake the slower vehicle in the front; permit the vehicle approaching faster from behind or simply wants to exit from the highway. Side-sweep accidents can occur for several reasons. For example, [OLW02] suggests that the driver did not see or was unaware of the presence of another vehicle or crash hazard lanes. According to [Kni93], 75% of lane change and merge crashes involve a recognition

failure by the driver. Another factor is the driver impairment due to alcohol [RT00] or mental condition [WLL98, MME09] and road conditions at the time of the accident [MME09]. Furthermore, not adjusting the rear view mirror also contributes to the size of the blind-spots resulting side-sweep accidents [Pla06].

2.2   Importance of Reducing Side-Sweep Accidents

To enhance the vehicle safety factors, it is imperative to study the correlation between the vehicle blind-spots and side-sweep accidents, which account for 4 to 10 percent of crashes according to transportation researchers [FLK09, FKS12, TCE00, WK94]. According to the 2009 National Automotive Sampling System General Estimates System, 7.44% of all car accidents are caused by improper lane changes [FLK09]. Therefore, the best solution is to make aware of the blind-spots with respect to side-sweep accidents, thereby, the driver can make an informed decision before changing the lane.

2.3   Importance of Side-Sweep Accident Simulation

Modeling and simulation comes into play an important role in side-sweep accidents [YQY11, KGN12, QHC13, GW13, KLY12]. Simulation is performed, when conducting experiments on real systems would be impossible or impractical. Furthermore, conducting simulations [SGB05,

GWA10], it is possible to generate large amount of data with several permutations and combinations with respect to multiple attributes for analytical purposes.

The architecture framework of the simulator is based on Object Oriented concepts, and each vehicle is an object. Simulation model is dynamically designed. For example, attributes such as side, rear and front view angles, relative velocity and vehicle density can be dynamically changed.The simulator models in detail the situational awareness and behavior of the driver, including the visibility, windows, mirrors, and blind spots of the vehicle as well as the times of checking the mirrors and initiating a lane change [BB15, BB16b]. The simulator is designed with proper scales of dimensions with respect to the road infrastructure and a variable medium size passenger vehicles [xxxb, xxxa]. Improving the accuracy of microscopic highway simulation through agent based modeling of the conscious aspect of the driver behavior is discussed by [LB10]. The importance of combination of driving simulation and computer modeling is the development direction of accident analysis [KLY12], can provide the necessary basis for conditions by the in-depth data analysis of traffic accidents. The advantage of linear and continuous model of car following model is discussed by [KGN12] and based on the relative distance and relative acceleration of each instant, the simulation model predicts the future behavior of the leader vehicle and according to this behavior, the acceleration of the follower vehicle is controlled. Reconstruct side pole impact accidents by computer simulation is discussed by [QHC13]. In this method, first the motion of the vehicle before impact is reconstructed, and then construct the impact between the vehicle and the pole, these two steps is repeated to obtain a reasonable simulation results.

2.4 Driver Awareness of Vicinity and Blind-Spots Avoidance

As discussed [BH08, Rec, HEF10], most accidents occur because the driver was not aware of the obstacle in the immediate vicinity area due to poor visibility and drowsiness [HEF10]. Driver awareness about the immediate vicinity can be either traditional or technological means or both. As discussed by [Kni12], the traditional way is to properly adjust the side and rear view mirrors and visually inspecting the lane by turning back and forth before changing the lane. But there are major issues with the traditional means on awareness since there is no room to rectify the errors![MG08]. Also, it is possible to implement a solution in order to minimize the traffic accidents because of the blind-spot [Kni12].

Seat belts and airbags are mealy a means to mitigate the injuries caused by an accident, but they do not provide any early warning systems. Developing the technological means of awareness for side-sweep warnings can help to enhance passenger safety by mitigating the injuries and preventing accidents[HXX04, RRE13, HS12, KKA12]. There are two types of technological solutions: early warning systems[LCF12] and early intervention systems[CC09, RZF10, ARR08, ANL07, YCW09, YCL08, Lee11, TCE00].

[LJJ11, LCF12] discussed a vision-based real-time gaze zone estimator based on a driver's head orientation and this method can helps during the day as well as night times. While overtaking and changing the lane can be a risk; therefore, [MG08] propose an aid system based on image processing to help the driver in these situations [RRE13, CC09]. [ANL07, RZF10, YCW09] discusses the inter-vehicle cooperation based on wireless mobile ad hoc network while changing the lanes

in order to avoid or reduce the side-sweep accidents. [BH08] discusses the controlling drowsiness of the driver by integrating intelligent control systems into vehicle to include the human-driver control loop. In order to overcome the visibility issues because of the shadows, occusions and poor light conditions; video image detector method is proposed by [Lee11]. [SHT12, JKI00] proposed collision avoidance system be installed on vehicle's rear-end window of preceding vehicle. In order to avoid intersection accidents, the situation analysis method for driver assistance is proposed by [HS12]. [KI08] proposed, adjusting side-view mirrors dynamically in order to enhance the visibility when the driver is in the process of changing the lane.

2.5   Lane Changing Times

Lane change is a behavior that frequently occurs when vehicles are operating on high-traffic urban roads. Previous research and field observation show the duration of lane change ranges from 1.0s to 16.5s [WB70, MSR10, TZ07, CTA94, FG90, HWG00, Het, TGG97]. It is important to study the execution of lane changing and find out the influence factors leading to the different duration of lane change. For example, some of the facts can be vehicle density, relative velocity, type of a vehicle, driver's competency, city streets and highways. Findings based on the previous research are summarized in the following table. It is important to study the execution of lane changing and find out the influencing factors leading to the different duration of lane change. As can be observed, the lane change time depends on the various road conditions such as urban, highway driving as well as type of a vehicle, for example, passenger or heavy.

Table 2.1: Lane Change Duration as Reported by Various Sources.

Source	Min-Max Duration	Notes
Worrall (Worrall et al. 1970)	2.3s-4.1s	
Finnergan (P.Finnegan et al. 1990)	4.9s-7.6s	including visual search time
Chovan (D.Chovan et al. 1994)	2.0s-16s	
Tijerina (Tijerina et al. 1997)	3.5s-6.5s	City streets
Tijerina (Tijerina et al. 1997)	3.5s-8.5s	Highway
Hetrick (S.Hetrick 1997)	3.4s-13.6s	City and highway segments
Hanowski (Hanowski et al. 2000)	11.1s-16.5s	Local short-haul truck, speed 45mph
Todelo (Toledo 2007b)	1.0s-13.3s	Heavy vehicles and passenger cars.
Moridpour (Moridpour et al. 2010b)	1.6s-16.2s	Heavy vehicles
Moridpour (Moridpour et al. 2010b)	1.1s-8.9s	Passenger cars

2.6 Technological Means of Awareness

Technological solutions, such as sensor improvements or collision warning systems and V2V communication can improve several steps of this process.

The technological means of awareness for side-sweep warnings can help to enhance passenger safety by mitigating the injuries and preventing accidents[HXX04, RRE13, HS12]. There are two types of technological solutions: early warning systems[LCF12] and early intervention [CC09] systems[RZF10, ARR08, ANL07, YCW09, YCL08, Lee11]. Vehicle that are designed for collision warning systems are equipped with side detection sensors to recognize objects on either side of the vehicle and to alert drivers the presence of vehicles during lane changes to avoid side-sweep accidents [SHT12]. Another class of systems, *early intervention systems*, provide limited automatic assistance to the driver by intervening even *after* the decision has been made [CC09, RZF10,

ARR08, ANL07, YCW09, YCL08, Lee11]. This assistance may be in the form of slowing the vehicle to a stop and/or controlling steering to help the driver stay in the proper lane.

V2V communications are novel networking technologies that extend traditional means of communication between vehicles. V2V technologies might enable many novel driving behaviors such as convoy formation [KB05, BH08, YCW09, YCL08, Lee11, HXX04, RRE13, SHT12, HS12, KI08, CC09].

CHAPTER 3: SIMULATION MODEL

Our group at University of Central Florida (UCF) have significant experience in developing traffic simulators to study various aspects of human driving behavior. The UCF Lane Change Simulator (LCS), to be described below, concentrates on modeling in detail the circumstances of a lane changing car in multi-lane highway traffic.

In contrast to simulators that model the overall flow of the traffic, the LCS concentrates on a single car and its driver's decisions as it moves in traffic. The traffic flowing around the car assumes a Poisson arrival model of the vehicles. Various assumptions about the density and relative velocity of the vehicles in adjacent lanes can be specified as parameters to the simulator. Although photo-realistic visualization is not an objective for LCS, its simple graphical interface allows us to inspect the particular circumstances under which the lane change decision is made.

As the awareness of the lane changing vehicle's driver of a potential blocking vehicle is a critical aspect of the success of a lane change and the avoidance of a side-sweep accident, LCS focuses extensively on correct modeling of the driver visibility and blind spots.

In this chapter, the blind-spots orientations, simulation model architecture and data sets are described which were used to simulate the automobile blind-spots presented in this thesis. As established in Chapter 1, the areas of interest are to perform *what-if* analysis of simulating blind-spots while calibrating the simulation model for various attributes such as driver lookup frequency,

duration between the lookups, vehicle velocity, side and rear view mirror angles, and closely mimicking the actions taken by the drivers or simulator operators. In Section 3.1 orientation and the spatial dimensions of the blind-spots are described. In Section 3.2 simulation model architecture is described.

In Section 3.3 the model input parameters are introduced, and the output is discussed. In Section 3.4 the driver status model described. In this section, there is an elaboration on how does the driver acquire the information, and how does it impact the behavior of cautious human drivers. Lastly, in Section 3.6, there is an elaboration on the possible scenarios of vehicle collisions and finally, in Section 3.7 the lane change algorithm is presented.

3.1   Blind Spot Spatial Dimensions And Orientation

The simulation model assumes that the vehicle always is in the middle lane heading from left to right and there are blind spots on the left and right sides as well as the back side of the car. Figure 3.1 delineate the blind spots of a passenger *car* with respect to left, right and rearview mirrors and d1, d2 and d3 are the distances from the eye-points of the driver to the left, right, and rearview mirrors and rearview windows, respectively. As shown, there are four blind spots and two are because of left and right view mirrors, and the other two are behind the vehicle because of the rearview mirror and rearview window. The magnitudes of the left, right and rear view mirrors' viewing areas are dependent on the dimensions of the angles α_1, α_2 and α_3.

As shown in the figure, the magnitudes of the blind spots on the backside of the vehicle can depend on the dimensions of the rearview mirror and window. For example, a combination of smaller rearview and/or window can expand the size of the blind-spot and on the other hand combination of larger rearview and/or window can contract the size of the blind-spot. Therefore, properly adjusted mirrors (rear and sides view) are vital to enhance the angle of view with a better glean by providing the driver with a superior view of the other vehicles in the adjoining lanes. Figure 3.1, describes the blind spot simulator with optimized left and rearview mirror angles. Please note: the optimized means properly adjusted the left and rearview mirrors.
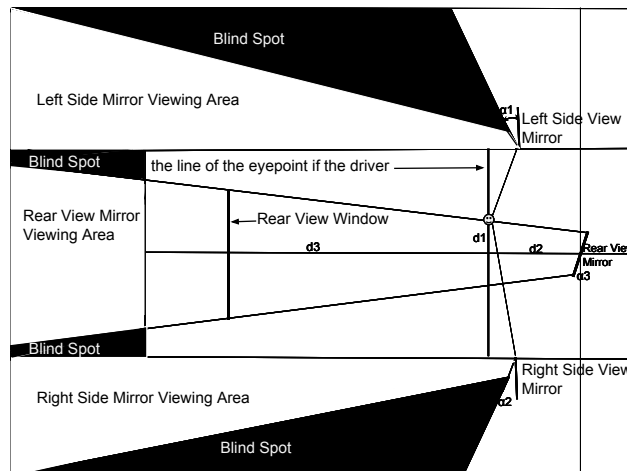
Figure 3.1: Blind Spot Simulator with Optimized Left and Rearview Mirrors.

Figure 3.1 is considered as the representation of ideal state or the most optimal positions of the blind spots on the left side of a vehicle. In this state, the left and rearview mirrors are optimally adjusted in order to view the maximum area to minimize the blind spots: left side (highlighted in

black) and rear (tiny area left blind spot and rear) of the vehicle. As shown, the shape of the blind spot is triangular and one side is somewhat perpendicular to the vehicle.
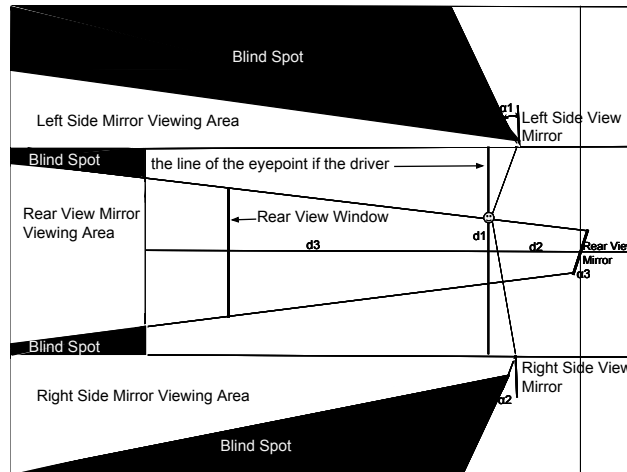
Figure 3.2: Blind Spot Simulator - Left View Mirror not Properly Adjusted.

With comparison to the ideal situation, Figure 3.1, Figure 3.2 show the left view mirror is not properly adjusted, resulting a lager blind spot is highlighted in black, and the shape has become more rectangular. Furthermore, the orientation of the blind spot has changed because one side has become more parallel and another side has become more perpendicular towards the vehicle. D1, d2 and d3 are the distances from the eye-points of the driver to the left, right, rearview mirrors and rearview windows respectively. With comparison to the ideal situation, Figure 3.1, Figure 3.3 shows the rear view mirror is not properly adjusted resulting in a lager blind spot right behind left side of the vehicle. This can be because of several reasons. For example, vehicle dynamics and combination of not properly adjusted or the smaller size of the rearview mirror and/or the smaller size of the rearview window can expand the size of the blind-spot [GVC12].
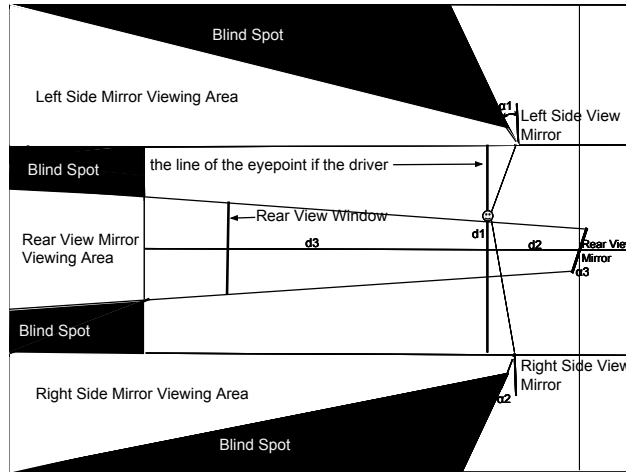
Figure 3.3: Blind Spot Simulator - Rearview Mirror not Properly Adjusted.

On the other hand, a combination of properly adjusted and a larger rearview mirror and/or rearview window can contract the size of the blind-spot. D1 is the distance of eye-point of the driver to the center of the vehicle; d2 is the distance of eye-point of the driver to the rear view mirror, and d3 is the distance of eye-point of the driver to the rear view window.

3.2   Model Architecture

We designed the UCF LCS to model in detail the events immediately preceding a lane change. Most traffic simulators take the perspective of the overall highway, and are interested in the overall traffic metrics such as throughput, average speed, average time to destination, and the evolution of the traffic over timespans of hours. The UCF LCS, in contrast, is only interested in the vehicles in close proximity to the lane changing vehicle and a short timespan of tens of seconds necessary for the lane change maneuver. We shall need to ensure that the traffic near the lane changing vehicle

is modeled realistically. We are not interested, however, in the vehicles before they enter and after they leave the zone of the lane changing vehicle.

The simulator had been implemented in Java, and it has been designed such that every aspect of the traffic model, vehicle geometry and road geometry can be specified in parameters. For the simulation study described in this paper, we fixed the road and overall vehicle geometry to correspond to average sizes of US highways and a mid-size four door vehicle, respectively. We retained these as default parameters, however, the mirror adjustments can be done.

Photorealistic visualization was not part of the objectives while designing our simulator. We found, however, that a simple graphic rendering can help us understand the various scenarios. Figures 3.4, 3.5, 3.6 and 3.7 show a series of screenshots from the '"warm up" phase of the scenario. In general, it is difficult to initialize a traffic simulator to a random point in the traffic, as in normal traffic the position of every vehicle is determined by its history of interactions with other vehicles. Thus, like many simulators, LCS uses a "cold start" approach. It starts with an empty highway and a specific arrival rate of the vehicles (in our case, Poisson arrival with a specific average cars per minute) and lets the dynamic interactions between the vehicles stabilize. The '"measured part" of the simulation, in our case the lane change intent, will happen after the traffic has stabilized. This warm up process is shown in the screenshots in Figures 3.4, 3.5, 3.6 and 3.7.

The architecture framework of the simulator is based on *Object Oriented concepts*, and each vehicle is an object [BB15]. Simulation model is dynamically designed. Meaning the configurations of the simulation can be changed to perform a *what-if* analysis of simulating blind spots of

varying initiating conditions of particular scenarios by input variables. For example, input variables such as side, rear and front view angles, driver lookout time and frequency, relative velocity, and vehicle density, can be dynamically changed [BB15] the output of the simulation model. The simulator is designed with proper scales of dimensions with respect to the road infrastructure and a medium size passenger vehicles [xxxb, xxxa]. In the model, the vehicle arrival is discrete and is based on the Poisson arrival time, and the model assumes that lane changes occur instantaneously: for a shift to the left lane, a vehicle, which has been previously in the middle lane, at time *t* disappears from the middle lane and appears in the left lane [BB15]. Figures 3.4, 3.5, 3.6 and 3.7 show the several snapshots of the blind spot simulator architecture provided as examples. The simulator consists of three lanes (Figures 3.4) and the lines separate each of the lanes. The vehicle is in the middle lane heading from left to right depicted as a grey rectangular object, which represents the driving vehicle. Figure 3.5 displays the approaching vehicles from the left as well as the right sides of the car, and the vehicle left side of the car just about to cross the blind spot. Figure 3.6 shows the car is in the blind spot; last, (Figure 3.7) shows the vehicles passing from the left as well as from the right side of the car.

Initially, the simulator background is painted in black, but the color changes accordingly after configured with configurable attributes such as frontview, rearview, and sideview angles, and the remaining background display in black color. For example, the front darker grey area represents the front view, 180 angle, the lighter gray represents the rear view mirror, with 60 angle and finally, the left and right side view mirrors are represented in color white, each of which has a 45 angle. Hence,

these angle parameters are merely examples and the simulator can be configured dynamically to any angle value. After these parameters are passed in the simulator, the blind spots represent the remainder of the background, which appear in black. Because of the relative velocity, the driving vehicle in the middle is stationary, and the other vehicles move from left to right. The simulations can be performed to run constant or variable relative vehicle velocities with configurations of different vehicle densities (i.e., cars per minute - CPM)) while simulating side-sweep accidents because of changing lanes from middle to left or right lanes. In this research, simulations were performed to observe the correlation between the different constant relative velocities with respect to variable CPM while merging to left lane. Also, this figure depicts the vehicles approaching from the left and right side of the middle vehicle, and a vehicle on the left lane that is crossing the blind spot appears in white color is displayed in the Figure 3.6. In the model, the vehicle arrival is discrete and is based on the Poisson arrival time.
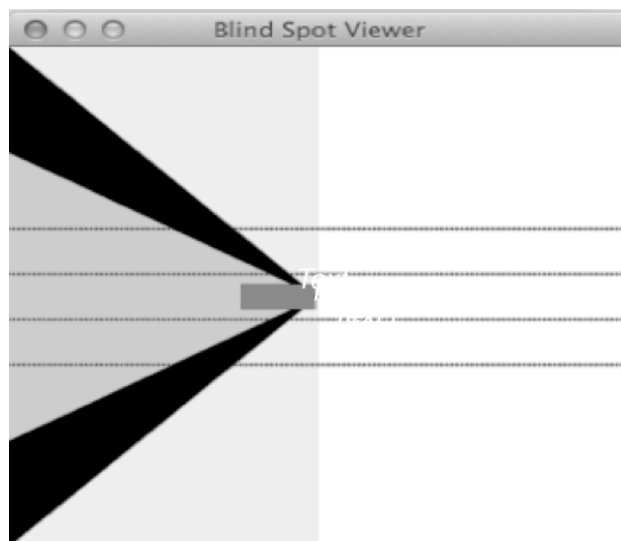
Figure 3.4: Snapshot

31
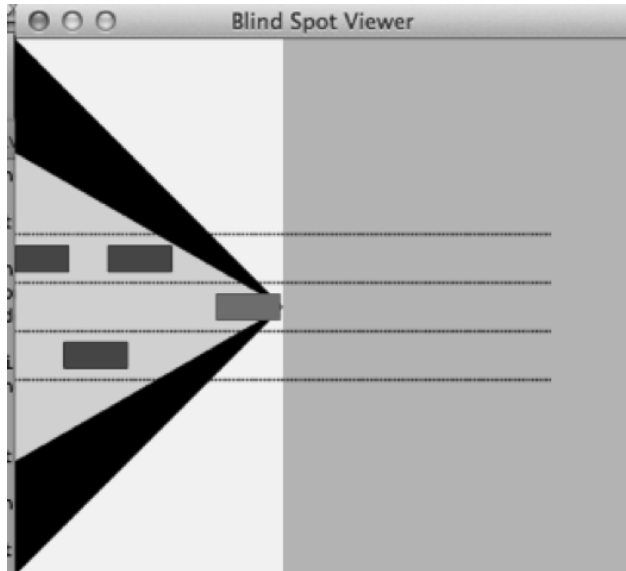
Figure 3.5: Cars approaching from behind
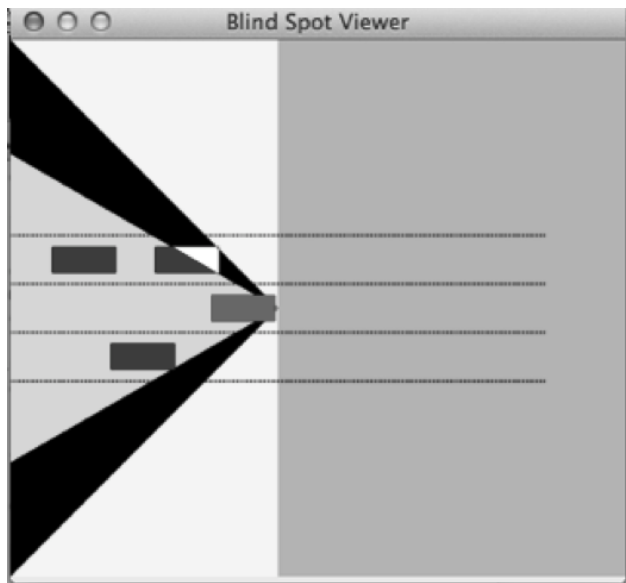
Figure 3.6: Car is on the blind spot
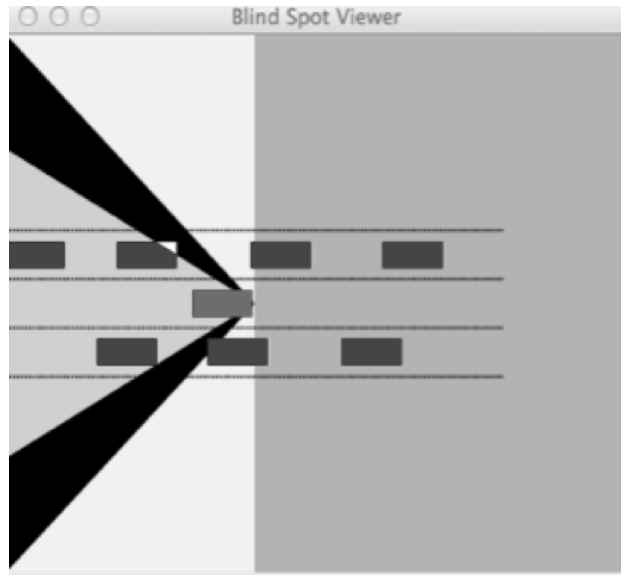
Figure 3.7: Cars passing

3.3 Model Input Parameters

In the following, we report the results of several simulations of the scenarios described in Section 3.5. There were several types of simulations being performed to derive the mean averages. Each experiment was run with 300 iterations. On Average, 15 cars per minute (CPM) or 900 cars for an hour were ran. After each iteration, the experiment initialization variables were reset to their initial values before the next iteration. After iterations for each experiment, the data for each iteration was derived to calculate the averages. The figures' plots are based on these averages.

At the start of the simulations, the simulator was initialized with default parameters as stated in Table 3.1. The simulation was run for 30 s; this was the ramp-up period. Afterwards, this period

and during the steady state environment, data was collected with respect to several data points as discussed in the following section.

For the study, experiments were run using the simulation model based on specifications published by the study done by National Highway Safety Administration and published the findings under the title "A Comprehensive Examination of Naturalistic Lane-Changes" [LOW04]. This simulation model assumes the driver is always driving in the middle lane and changes the lane whenever it is necessary either to the left or right lanes. Therefore, in order to observe the side-sweep accidents because of blind spots, separate simulations are being performed for changing the lanes for left as well as for right. This experiment only analyzed the results merging from middle to the left lane. The input parameters of the simulation are summarized in Table 1.

Traffic volume or density: This parameter indicates the traffic density or cars per Minute (CPM). For example, 15 CPM is equivalent to 900 cars averagely for an hour but the vehicle arrival is based on Poisson Distribution.

Driver velocity: This is the velocity of the driving car.

Relative velocity: This is the relative velocity of the passing vehicles in the adjoining lane.

Probability of driver lookouts: This is the default value of the percentage of the driver checks the adjoining lane before the lane change.

Driver updates time: This is the default value of how often the driver checks the adjoining lane before the lane change.

Table 3.1: Default input parameters of the simulation

Parameters	Values
Traffic parameters	
Traffic density	5-25 cars per minute
Velocity of the lane changing vehicle	65 mph
Relative velocity of vehicles on the target lane	1-6 mph
Vehicle geometry	
Vehicle length	192 inches
Field of view left and rear view	15 , 60
Driver model	
Probability of driver checking mirrors	0.83
Driver update times	3-8 sec
Minimum spacing ratio between cars	2 times length
Turn signal parameters	
Maximum turn signal wait time	20 sec
Driver wait time	2-16 sec
Driver percentage using the turn signals	10%-100% sec
Probability of the following driver slowing down	0.9
V2V parameters	
V2V communications probability	0.90
V2V transmission range	100-400 inches

Field of view: These are the default value of the side and rearview mirrors.

Vehicle dimensions: Average length (inches) of a mid size car.

Lane change time: Once the driver decides to change the lane, change immediately.

Minimum space between vehicles: Simulator maintains two car spaces between the cars.

Random number of cars: This parameter randomize the vehicle arrival pattern, which is based on Poisson Distribution. For example, setting this parameter to 0.1 the vehicle arrivals is based on uniform distribution compared to discrete distribution setting it to 1.0. However, the average number of cars remains the same.

3.4   Driver Status Model

Generally, automobile drivers can be categorized into one of two areas: cautious or reckless. How does the information gathering occur, and how does it impact the behavior of cautious human drivers? In particular, what are the ways in which they collect information about surrounding traffic before they make a decision about a lane change? While driving, a driver gathers information about his or her surroundings in three different ways: strategic, tactical, and operational [Ped04, BM09].

- The strategic level: This is the highest or the conceptual level where general goals such as route choice, navigation, and timing are set.

- The tactical level: The driver maneuvers at tactical level, with particular focus on how context information influences or reacts driver's performance. Also, the tactical level involves decision making related to the management of current driving activity (e.g., maneuvering).

- The operational level: This level involves vehicle handling or executive actions which implement the maneuvers decided at the tactical level. This level is performed almost without conscious thought and the driver looks forward continuously and checks mirrors only at intervals. For example, at time T1, a curious driver may be checking in the mirror and contemplating to changing lanes, and T2 is the time to make a definite decision to change the lane. The time lapse between T1 and T2 depends on the factors such as traffic conditions, driver competence, weather conditions, etc. At time T3, the driver is looking in the mirrors, sides and rear, and speculating the lane change. On the other hand, a reckless driver does not pay any attention to any of the above stated chronological events and may change the lanes back and forth without any regard to traffic laws, rules, and regulations or the whether conditions. This could be high-risk maneuver, and lane change could be with or without a crash.

Pertaining to the simulation, there are three types of simulation models: Driver Attention, Driver Visibility and Driver Decision Mental models.

3.4.1 Driver Attention Model

This model facilitates us to model how often or the frequency of a driver looks into the rear view mirror, side view mirrors, or forward before changing lanes. As displayed in Figure 3.8, the two arrows represent the lanes. The bottom arrow represents the middle lane and the top arrow represents left lane. Because of the lane changing algorithm only discusses the lane change from middle to left lane, the right lane is not shown. The vehicles represent as blocks and travel from left to right in the left lane, (i.e., top lane); this lane is adjacent to the middle lane. The vehicle traveling process is based on Poisson arrival times of events, which are independent of each other's vehicles. The states S1, S2, S3 and S4 represent the different circumstances of the mental status of the driver whom may be contemplating and looking around to change the lanes during the time periods T_{LL-2}, T_{LL-1}, T_{LL} and T_X respectively. A cautious driver, during state S1, the driver has begun to look in the mirror(s) checking to see whether a vehicle is approaching immediately behind in the left lane (time T_{LL-2}). At this time, no decision is made whether to change the lane or continue to stay in the same lane. During state S2, the first decision is made to change the lane and look in the mirrors (time T_{LL-1}). During the state S3, the second decision is made; looking back in the mirrors and just about to change lanes (time T_{LL}). Last, state S4 represents the lane changing time (time T_X). These events analogous to the number of times (frequency) a driver looks back and forth before change the lane. Also, shown in Figure 3.8, is the time the driver spends or loses (T_{LL} - T_{LL-2}) while looking or contemplating during the lane change.

38
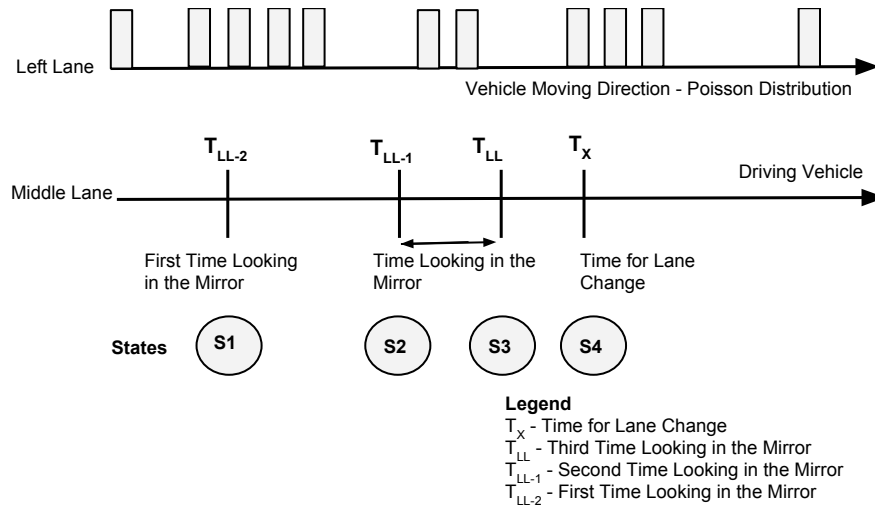
Figure 3.8: Lane changing scenarios

Figure 3.9, depicts the state transition diagram where the consideration of the system, which may be described as being any one of set N distinguished states where a state could be in S1 to S6. States S1, S2, S3 and S4 are already discussed and S5 represents the state after a successful lane change; however, S6 represents the state where a crash can occur. Competent or a prudent driver may decide to change the lane at state S2 as indicated by an arrow; however, there could be a higher probability of an accident compared to the lane change at state S3. This is an example for a person who looks less frequently or did not see a vehicle in the adjoining lane due to a larger blind spot. Also, Figure 3.9 represents all the possible scenarios that can occur among the states. For example, the driver may decide not to look again and instead may decide to change lanes abruptly. This scenario is reflected as a move directly from states S2 and S3, however, state S5 with a lower probability of a successful lane change at state S2 compared to state S3. A move from S2 to S6 where a higher probability of a crash, compared to a move from S3 to S6. Loopback arrows, for

example S1, represent when the driver decides to stay instead of changing lanes and the arrow from
S1 to S2 represents moving to the next state.
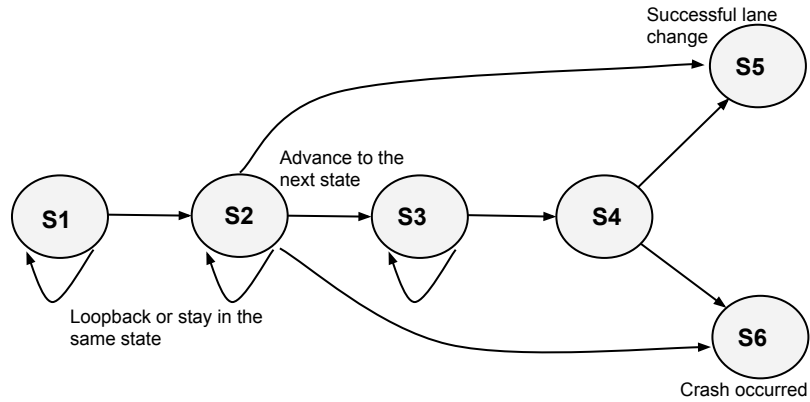
Figure 3.9: State transition diagrams

3.4.2 Driver Visibility Model

This model facilitates us to model the visibility type: forward, rear, left or right mirrors, and the
way in which the driver becomes aware of other vehicles and obstacles before lane change. The
visibility model allows us to specify and simulate the distance at which the driver considers the
safe distance of an approaching vehicle from behind before change lane. As shown in Figure 3.10,
the times T1 and T2 are correspondent to states S2 and S3 respectively, and the blind spot area
is enclosed by the two dark, black, thick vertical lines. For instance, Figure 3.10 displays the
visibility scenarios of states S2 and S3 where a driver decides to change lanes.

40
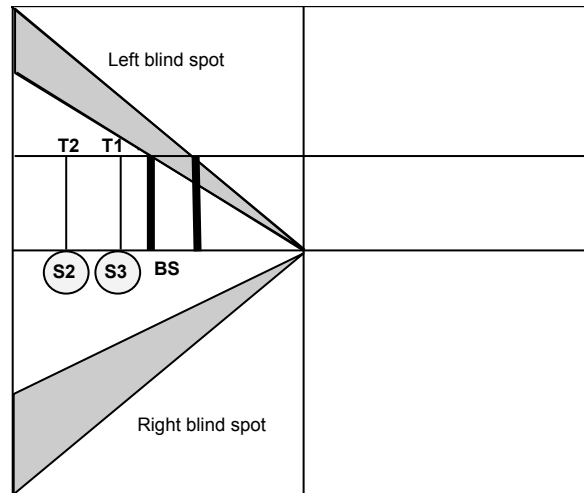
Figure 3.10: Driver Decision Mental Model

Furthermore, other attributes can be simulated such as the occlusion of visibility by large vehicles and model-limited visibility conditions: the BS angle size, frequency, and the duration of the driver lookouts. The default assumption is that the sufficient visibility occurs, the simulation with the probability of 83% and 64% of the drivers look left or right, lanes respectively, 8 second before the lane change. All the vehicle sizes are heterogeneous, mid size passenger cars.

3.4.3   Driver Decision Mental Model

Driver mentality is based on the driver competency, environmental conditions and the traffic congestions at the time of the lane change, condition of the vehicle that you are driving among others. This model facilitates need to model the basics of the decisions: if it is safer to change lanes based on what the driver sees before changing lanes because this may not be the same as what the driver

sees after changing lanes. The lane algorithm describes the model of human drivers use to make decisions during a lane change. Using this framework, an experimental study of lane change is described. The Figures 3.8 and 3.9 already displayed the events that could occur with respect to a driver's thought process when a vehicle travels in the middle of a highway while attempting to change from middle to the left lane.

3.5 Drvier Scenarios

Before we proceed further, we need to clarify what a "crash" situation means in our simulations. While we do model the conscious behavior of the drivers, we cannot realistically model reactive actions that take place at time scales of milliseconds, such as sudden evasive actions, where several inches in the position of the vehicle might make the difference. We will say that if a vehicle initiates a lane change while another vehicle blocks the lane, we will count this as a '"potential crash situation". In practice, it is possible that the crash will be avoided through a quick evasive action by the follower vehicle or a last second cancellation of the lane change by the driver. While the number of the near-crashes will be overall higher than the actual crashes, whether a given encounter ends up in a crash or near-crash is primarily a probabilistic event. Our models will predict the potential crash situations, and thus the number of real crashes will be proportionally a smaller fraction of these.

Scenario 1—Reckless driver: In this baseline scenario, the driver of the lane changing vehicle will initiate a lane change if there is no vehicle in his direct line of sight. If there is a vehicle in the

direct line of sight, the driver will wait, continuing to drive at a constant speed without initiating a lane change. As the reckless driver will not check the blind-spot or the mirror, if there is a vehicle behind the car, the vehicles will get into a crash situation. While this represents an unusually high number of potential crashes, it allows us to set the baseline for other scenarios.

Scenario 2—Average driver: In this scenario, we aim to model the behavior of a typical driver based on highway administration statistics. Such a driver, once he decides to perform a lane change, will periodically check its mirrors, with a certain probability. Based on NTHSA data, this interval is 8 s and the probability $p = 0.83$. If the driver does not see a vehicle in the mirrors or in the direct line of sight, it initiates a lane change. If the driver sees a vehicle in the mirror and this vehicle is either blocking the lane or, based on its current speed, will be blocking the lane at the moment of the lane change, the driver will wait. Note that for Scenario 1 and 2 we did not assume any action taken by the driver of the following or blocking vehicle, as this driver is not aware of the intention of changing lanes.

The average driver might still get into crash situations. One reason might be that it missed checking the mirrors (according to the statistics, the drivers check them only 83% of the time). Another reason might be that the driver might have checked the mirror at a moment when the blocking vehicle was in a blind spot and the driver did not track the vehicle from a previous sighting.

Scenario 3—Driver using turn signals: In this scenario, the behavior of the driver from scenario 2 is augmented with the fact that the driver uses the turn signal before changing lanes.

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While in previous cases the drivers of the following vehicles were not active participants, in order to model this scenario, we need to know the action taken by the driver of the following vehicle.

There are several important parameters of this scenario. The first one is whether the follower driver took action upon seeing the signal. The normal action to take upon seeing the signal is a moderately strong braking. This action might not be taken, either because the driver did not see the signal or chooses to ignore it. Another parameter is the number of seconds before the initiation of the lane change that the driver turned on the turn signal? If the signal is turned on only immediately before the lane change, there might not be sufficient time for the following driver to slow down and clear the lane for the lane changing vehicle.

What do we expect from the lane change signal? First, we expect a reduction of the number of crash situations, since even in situations where the average driver might have crashed, the crash could have been avoided due to the action of the following driver.

Second, we expect that, on average, the time to change lanes will be reduced, since, by the action of the following driver, the lane changing driver might find a slot into which he/she could change lanes more quickly. For the same reasons as before, there is no guarantee that there is a no crash situation even in the case of the use of the turn signal.

Scenario 4—V2V communication with active control in the lane changing vehicle: For this scenario, we assume that the vehicles have V2V communication technology such as Dedicated Short Range Communication (DSRC). We assume that, using this technology, the following vehicle can make its presence and speed known to the lane changing vehicle using short-range V2V

communication. Furthermore, the lane changing vehicle is equipped with a device that prevents the driver from initiating a lane change if the on-board algorithm judges that, given the existence of the following vehicle and the relative velocities at the moment of the lane change, a collision will occur.

Let us consider what we expect such a system to achieve. First, the system should obtain better information about the status of the target lane than visual inspection by the driver. The V2V system will listen all the time and blind spots will not prevent the communication. Furthermore, by directly transmitting the velocity of the following vehicle, the overall system can have better information about the relative speeds. In general, it is not easy for drivers to estimate the relative speeds of the vehicles from short glances in the mirror.

Nevertheless, equipping a vehicle with this technology will not immediately mitigate all possibilities for a side-sweep accident. To begin with, not all vehicles will be immediately equipped with this technology. Second, V2V communication is limited by the transmission range of the V2V radios, which can be further limited by environmental conditions. If the following vehicle is significantly faster than the lane changing one, and the transmission range is small, it might happen that the V2V-based notification arrives too late to prevent a side-sweep collision.

Note that many other possible scenarios exist. V2V communication can be also implemented with an intelligent decision making factor in the follower vehicle instead of the lane changing one. In another scenario, we can assume the existence of an intelligent agent in both vehicles, which might negotiate a coordinated course of actions. Multi-vehicle coordinated action using vehicle-

to-infrastructure (V2I) communication is also a possibility. Exploring these and similar scenarios, however, is beyond the scope of this research.

3.6   Time To Collision

During a lane change, depending on the relative velocity of two vehicles heading in the same direction, there is probability that a collision can occur. The time to collision (TTC), depends on these two variables: BS, relative velocity, and the distance between the vehicles. For example, if the first or the front vehicle velocity (v1) is 100 feet/second, and the second vehicle velocity (v2) coming from behind is 130 feet/second, then, the relative velocity is -30 feet/second (v1 - v2), and the distance between the two vehicles is 60 feet (d), then, it takes 2 seconds (t) for the collision to occur.

Model assumes that lane changes occur instantaneously: for a shift to the left lane, a vehicle, which has been previously in the middle lane, at time *t* disappears from the middle lane and appears in the left lane. This opens up the possibility that a car coming from behind in the new lane with a higher velocity cannot break sufficiently quickly and collides with the lane-changing car. The model assumes the vehicles approaching from behind, left or right lane, proceeding at a constant velocity has the responsibility of the lane changing car to ensure that the rear left vehicle j-1 has sufficient buffer distance (b_max) such as that it can decelerate (â) before hitting the lane-changing vehicle.

$$\hat{a}_{2-1}(t) \geq -b_{max}$$

If this condition is not satisfied, the vehicle concludes that it is not safe to change lanes because changing the lane may result in a collision.

3.7 Lane Change Algorithm

The lane change algorithm discussed in this research is applicable to a cautious driver and not for a reckless driver. The rational behind the lane change algorithm is based on the following chronological steps provided in the algorithm with some assumptions, prudent driver, normal environmental conditions, the driver is always in the middle lane, and the lane change occurs either to the left or to the right lane. The lane change algorithm is given below Algorithm 1 and also summarized in Table 3.2 and Table 3.3.

Algorithm 1 Lane Change Algorithm

```
 1: for 83% of the drivers check lane in 3 - 8 sec intervals do
 2:     if The driver decides to change the lane then
 3:         Check left lane for vehicles in close proximity and velocity
 4:         if True stays back then
 5:             Check again in 3 - 8 sec intervals
 6:         end if
 7:         if The driver does not see a vehicle, change lane then
 8:             either Successful
 9:             or Unsuccessful
10:             - if there was a vehicle in the blind-spot
11:             - if proximity was a factor
12:             - if velocity was a factor
13:         end if
14:     else if 17% of the drivers do not check when changing the lane then
15:         either Successful
16:         or Unsuccessful
17:         - if there was a vehicle in the blind-spot
18:         - if proximity was a factor
19:         - if velocity was a factor
20:     end if
21: end for
```

Table 3.2: Lane Change Algorithm

Driver Status	The State
Driver in the middle lane checks the adjoining left lane periodically. A cautious driver's checking probability is 0.83 and 1-8 second intervals [LOW04]. The frequency of checking times depends on the attributes such as traffic and environmental conditions with a minimum of two instances before deciding to change lanes Figure 3.8	1. At state (S1), the driver for the first time is contemplating to change lane. If the driver decides not to change the lane then stays at the same lane as indicated by loopback arrow, Figure 3.9 2. At state (S2), the driver is more certain to change the lane. If the driver see a vehicle, then continue to stays at state (S2) as indicated by loopback arrow (Figure 3.9) 3. If not at state (S2) change the lane as indicated by the arrows (Figures 3.9 and 3.10 - T_2): if successful state S5 or if unsuccessful state (S6)
Next, after 1-8 seconds, the driver takes a second look at state (S3). This scenario is reflected in Figure 3.9. In Figure 3.10 this is indicated as just before the blind spot at time T_1. This process repeats every 1-8 seconds until change the lane	1. If the driver see a vehicle then stays back at state (S3), and there is no lane change, this is indicated by the loopback arrow 2. If the driver does not see a vehicle change lane: if successful state (S5) or if unsuccessful state (S6) 3. On the other hand, if the driver does see a vehicle then checks the proximity and the velocity between the driving car and the one immediately behind 4. If the car is too close to change the lane, then the driver stays in the lane but check after 1-8 seconds. If the conditions are good then the lane change occurs or continue to stay in the lane until the next appropriate occasion arrives 5. Lane change could be successful (S5) or unsuccessful (S6)
Successful lane change (S5) scenarios	1. If the driver did not see a vehicle because of the blind spot then change lane thinking that there is no vehicle after few seconds later at time Tx (S4) 2. There was no vehicle in the close proximity 3. During the lane change, the simulation model checks whether there is a vehicle in the blind spot

Table 3.3: Lane Change Algorithm

Driver Status	The State
Unsuccessful lane change (S6) scenario	1. During the lane change the simulation model check, if there is a vehicle in the blind spot 2. There was no vehicle in the close proximity 3. If there is a vehicle then the lane change is unsuccessful or a vehicle crash

CHAPTER 4: MODEL OUTPUT and DATA ACQUISITION

This section includes the several data points and methods of data acquisitions with respect to simulation outputs. The study reviewed the data acquisition methods of lane changing scenarios with respect to frequency, velocity, CPM, spatial dimensions and angle of orientation of BS on side sweep accidents. At the start of the simulations, the simulator was initialized with default parameters as stated in Table 3.1. For example, initially, CPM and BP angles were set to 5 and 5° respectively and the simulations were performed. The simulation was run for 30 seconds; that was the ramp-up period. After words, that period and during the steady state environment, data was collected respect to several data points as discussed in the following section. Several types of simulations were ran with different permutations and combinations. For example, simulations were run while incrementing BS angle by 5° increments until 25°. Next, CPM was incremented by 5, and the simulations were repeated and then the results were recorded. The simulations was repeated until CPM was equal to 25. Likewise, several simulations were run with various configurations of BS angles.

4.1   Frequency

Table 4.1 provides a summery of statements pertains to the model output on the frequency of side-sweep Accidents.

Table 4.1: Frequency of Side-Sweep Accidents

Scenario	Observations
The impact on side-sweep accidents due to relative velocity and vehicle density	1. Observe the correlation between the number of side-sweep accidents with respect to the relative velocity. 2. Observe the correlation between the number of side-sweep accidents with respect to vehicle density.
Number of successful and unsuccessful lane changes	1. Observe the correlation between the successful lane change and the duration to change the lane due to relative velocity. 2. Observe the correlation between the successful lane change and the duration to change the lane due to the vehicle density. 3. Unsuccessful lane changes also can be analyzed. For example, an accident can occurr because of a planned lane change or changing the lane abruptly.
Number of vehicles passed between the driver's first look and when the lane change was actually occurred	1. Number of vehicles passed while the driver contemplates to change the lane.
Time to change the lane	1. How long the driver has to wait before changing the lane due to the higher relative velocity and the vehicle density.

4.2 Angle Of Orientation

The Table 4.2 provides itemized statements are some of the highlights of the data acquisitions of the model output parameters on angle of orientation of side-sweep Accidents.

Table 4.2: Angle Of Orientation

Lane Changing Statistics	Observed Outcome
Lane changing statistics as a function of blind spot angle and cars per minute	1. evaluated the percentage of successful lane changes with respect to combination of the angle and cars per minute. 2. evaluated the percentage of uncheck unsuccessful lane changes with respect to combination of the angle and cars per minute. 3. analyzed the successful Vs. unsuccessful lane changes. 4. estimated the average time (sec) for successful lane changes as functions of cars per minute (CPM) and relative velocity.
Lane changing statistics as a function of relative velocity and cars per minute	1. Compared and analyzed the successful lane changes with respect to relative velocity 1 mph and 3 mph. 2. Compared and analyzed the unsuccessful lane changes with respect to relative velocity 1 mph and 3 mph.
Lane change statistics comparison with respect to side and rear view mirror blind spot angles	1. Comparison between successful and unsuccessful lane changes with respect to side-view and rearview mirror angles. 2. Correlation among number of cars passed, number of time stayed-back and time to change the lane with respect to blind spot angle.
Orientation of the blind spot	1. Orientation or the shape of the BS is based on the side and rearview mirrors adjustments. 2. Evaluated the various attributes such as successful, unsuccessful, number of stay-back before 1 ane change. The duration of the stay-back could affect because of relative velocity and congestions.

There are several types of simulations being performed to derive the mean averages and then to observe outputs. Model output is categorized into three areas:

In this experiment, we studied the impact of successful lane change solely based on the visual inspection.

- Simulating the impact of blind-spots on the frequency of side-sweep accidents

- The automobile blind-spots' spatial dimensions and angle of orientation on side-sweep accidents

In this experiment, we studied the impact of the presence of the turning signal to the success of the lane change.

- The impact of the turn signal duration

- The rate of successful lane changes as a function of the driver wait time.

In this experiment, we studied the impact of the presence of the vehicle-to-vehicle communication with respect to the success of the lane change.

- The impact of V2V transmission range and relative velocity

- The line of view of the driver with the left mirror improperly adjusted.

- The Impact of the Blind Spot When V2V Communication Is Present

CHAPTER 5: DATA ANALYSIS AND RESULTS

In this section, a description of the simulation output results is provided as established in the previous sections. There are several types of simulations being performed to derive the mean averages and then to observe the following results of the model outputs. Model output results are categorized into two areas:

- Simulating the Impact of Blind-Spots on the Frequency of Side-Sweep Accidents

- The Automobile Blind-Spots' Spatial Dimensions and Angle of Orientation on Side-Sweep Accidents

- The Impact of the Turning Signal

5.1 Frequency

Using this simulator, several studies were performed to estimate the time it takes to change a lane and the frequency of side-sweep accidents in various conditions such as traffic density and relative velocity of vehicles and then analyzed the results such as driver wait time, unsuccessful lane changes, number of times the driver stayed back before lane changes. All the following test scenarios, the left view mirror angle size was adjusted to 15°, the driver looks every 8 sec.

(lookout frequency) before the changing the lane and 83% of the drivers check before changing

the lane (probability = 0.83) and 17% of the drivers do not check before changing to the left lane.

5.1.1 Correlation between the relative velocity and the driver waiting
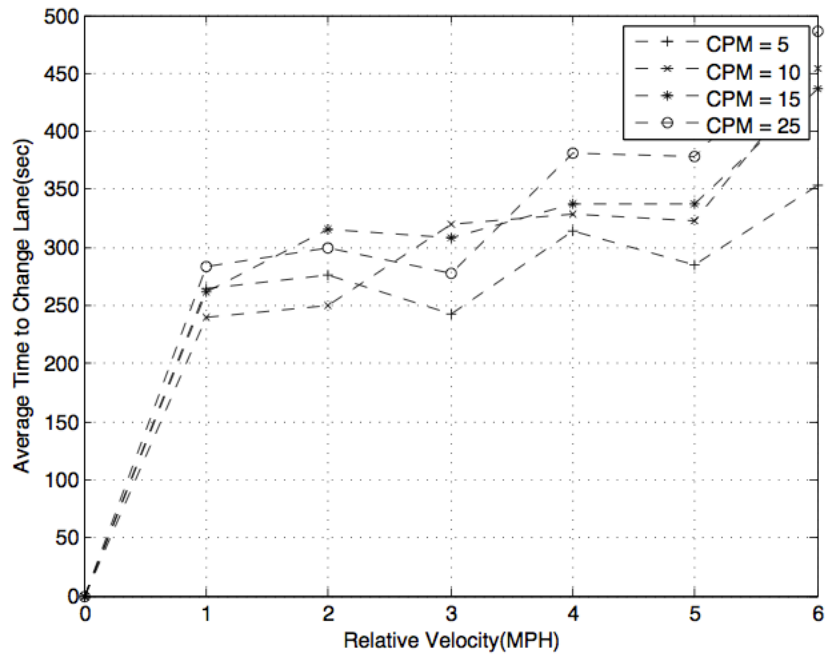
Figure 5.1: Correlation between the relative velocity and the Driver waiting time before changing the lane.

Figure 5.1 displays the correlation between the relative velocity and the driver waiting time before

changing the lane. As displayed, the average driver waiting time remains the same until the relative

velocity approaches 3 mph and then the waiting time increases along with the increasing relative

velocity particularly after 4 mph. As observed, the time to change the lane increases exponentially

along with increasing relative velocity. Higher the relative velocity, it is necessary to wait a longer time period, until there is an ample proximity for the driver in the middle lane to change the lane safely before the other car, behind in the left lane, catches up with the car in the middle lane, which intends to change the lanes. Furthermore, regardless of the vehicle congestion on the adjoining lane, the lane change time increases along with the ascending velocity; however, it is compounded by the higher vehicle congestion. For example, at CPM is 25 (1500 cars for an hour) waiting period at its highest.

5.1.2   Correlation between the relative velocity and vehicle density

Figure 5.2 displays the correlation between the relative velocity and the traffic volume. As displayed, the average number of cars passed by averagely between two-to-three approximately, and remains the same until the relative velocity approaches 3 mph. Then, there is a sharp increase along with the increasing relative velocity, particularly after 4 mph. Because of the higher relative velocity, the time to change the lane increases exponentially and the passing number of vehicles increases incrementally, as displayed in Figure 5.1, resulting in a longer period to change the lane safely. As the vehicle velocity increases, the time to change the lane increases with the ascending velocity; however, it is compounded by the higher vehicle congestion.
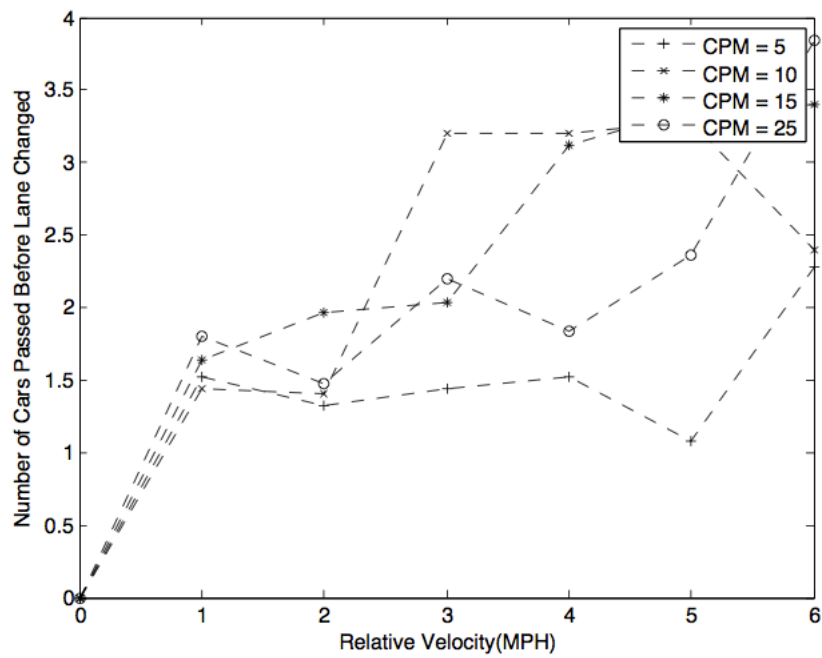
Figure 5.2: Correlation between the relative velocity and vehicle density.

5.1.3   Correlation between the number of successful and unsuccessful

As shown, accident rate is approximately 2% to 3% until the relative velocity approaches 3 mph and increases sharply along with the velocity and vehicle density.

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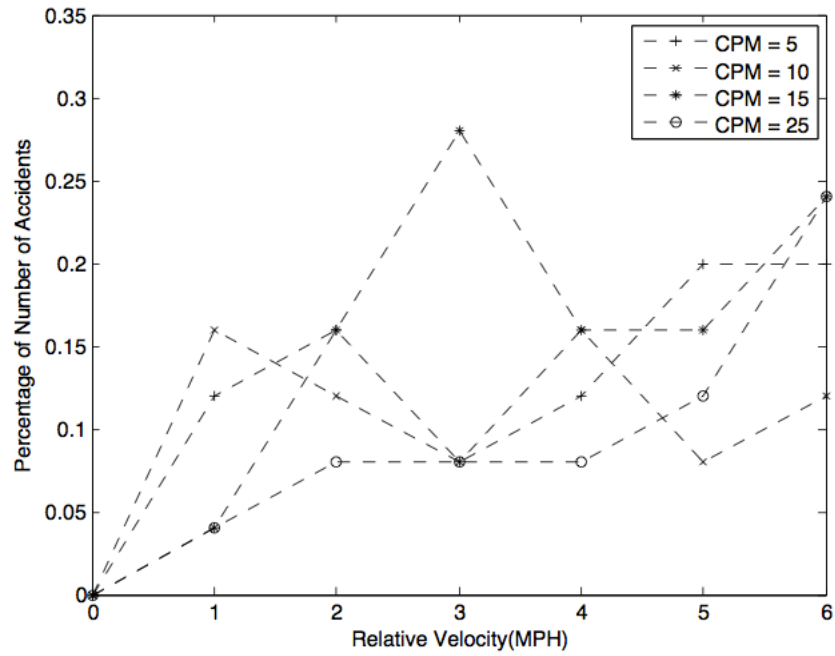
Figure 5.3: Correlation between the number of successful and unsuccessful lane changes with respect relative velocity.

Figure 5.3 displays the correlation between the number of successful and unsuccessful lane changes with respect to relative velocity.

5.1.4   Correlation between the number of times stayed back before lane changes
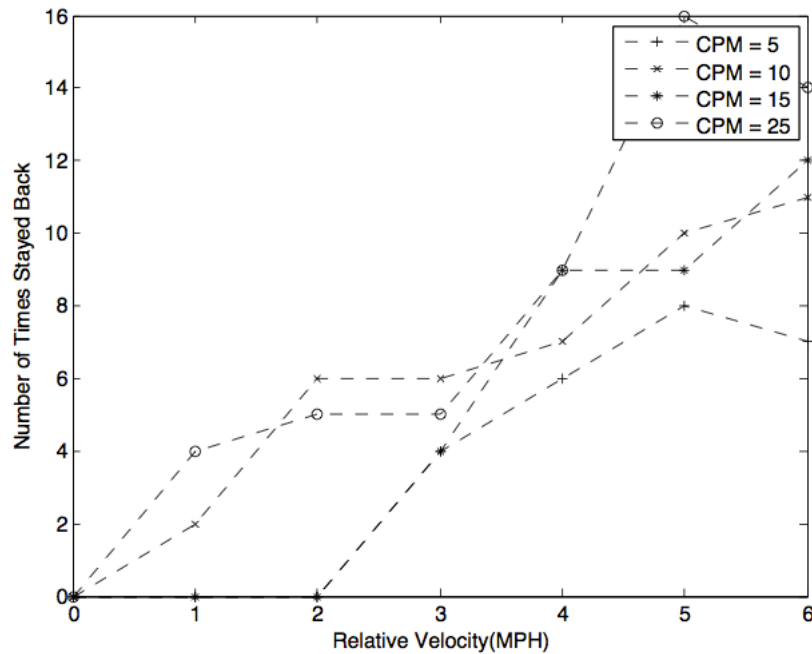
Figure 5.4: Correlation between the number of times stayed back before lane changes with respect relative velocity.

Figure 5.4 displays the correlation between the number of attempts to change to the left lane and the relative velocity. The driver was contemplating to change the lane and makes an attempt to change instead of changing abruptly. It can be observed if the relative velocity is between 1 to 2 mph the number of attempts are relatively low, but increases along with the increasing velocity. Based on the above outputs (Figure 5.1, Figure 5.2, Figure 5.3, Figure 5.4) it is possible to generalize some of the observations. Attempting to change lane is relatively safer until the relative velocity is approximately 3 mph, even if the vehicle congestion does not change. It can also be true that at

a constant velocity while increasing vehicle density, attempting to change lane is relatively safer until the relative velocity is approximately 3 mph.

5.2 Angle of Orientation of Side-Sweep Accidents

This section discusses the impact of the spatial dimensions and angle of orientation of automobile blind spots during side-sweep accidents. Using this simulator, a study was performed to evaluate the correlation between the magnitude and the orientation of the blind spots, the frequency of side-sweep accidents in various conditions (e.g., traffic density and relative velocity) and time to change the lane. All the test scenarios discussed in this section, the left angle size varies from 5° to 25°, relative velocity is 1 mph, duration between looks 8 sec, driver lookout frequency probability was set to 0.83.

5.2.1 Lane Change Scenario1: Observations as a Function of Blind Spot Angle and Cars per Minute

This section includes the several simulation outputs with respect to lane change scenarios as a function of cars per minutes (CPM) and blind spot angle (BS).
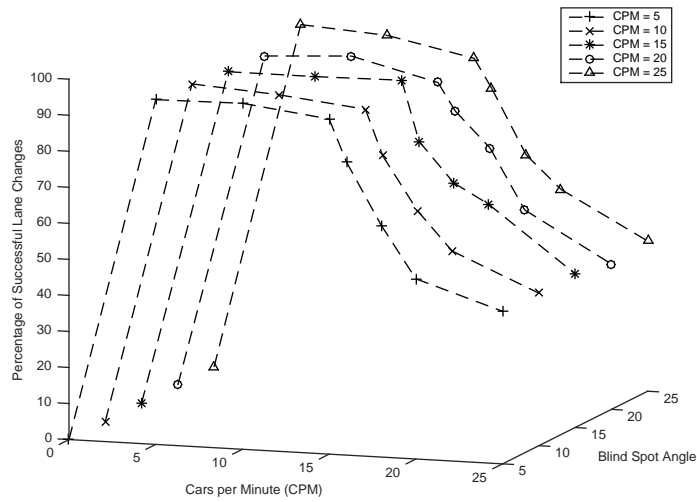
Figure 5.5: Percentage of Successful Lane Changes as a Function of Cars per Minute (CPM) and Blind Spot Angles.

Figure 5.5 displays the percentage of successful lane changes as a function of vehicle congestion or CPM and the blind spot angle . As displayed, CPM scales from 5 (300 cars per hour) to 25 (1,500 cars per hour) and blind spot angle scale from 5° to 25° while the relative velocity is to set to 1 mph. As observed, the successful lane changing patterns are similar if the blind spot angles are 5° and 10° and somewhat change as the angle increases. Also, it could be observed, that after 16°, the percentage of successful lane changes will begin to diminish regardless of the CPM, particularly when the blind spot angle is greater than 20°; then, the successfulness of lane change diminishes rapidly.
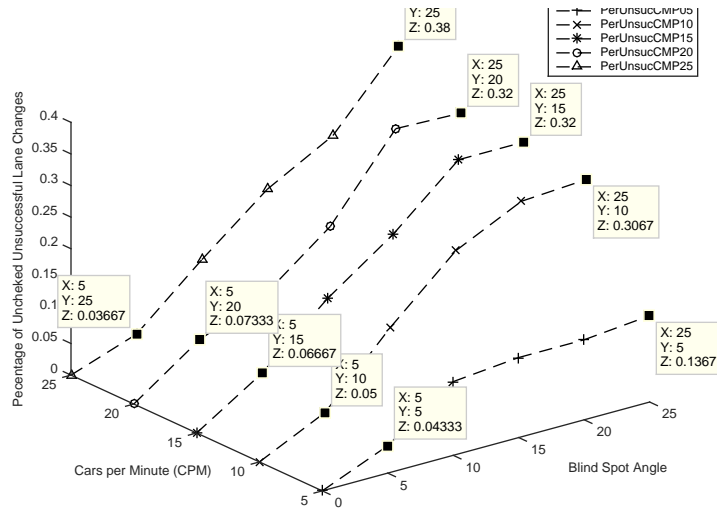
Figure 5.6: Percentage of Uncheck Unsuccessful Lane Changes with Respect to Vehicle Congestion and Relative Velocity.

Figure 5.6 displays the percentages of unsuccessful lane changes as a function of number of cars as well as the blind spot angles. As displayed, the unsuccessful lane change percentages are somewhat similar when the angle is around 5°, but increases rapidly along with the increasing blind spot angle and vehicle congestions. For example, particularly it should be observed that the unsuccessful lane change rate increases along with the increasing angle. Also, it is compounded by the increasing vehicle congestions.
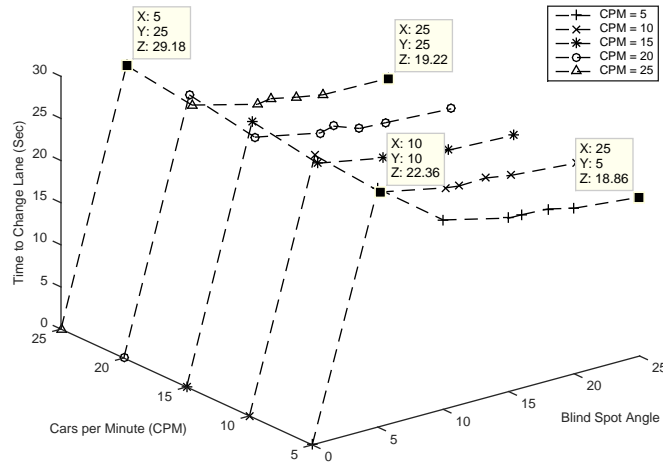
Figure 5.7: Average Time (sec) for a Successful Lane Changes as Functions of Cars per Minute (CPM) and Blind Spot Angles.

Figure 5.7 displays the driver wait time to change the lane as a function of CPM and the blind spot angle. Driver wait time with respect to lane changing scenario can be summarized as follows:

When the driver is contemplating the lane change, first, the driver must check to see if there are vehicles present in the left lane (if changing from right to left) and, if it is true, then, stay-back and check again after 8 sec. Next time, if there are no vehicles, then check the distance between the driving car and the one immediately behind. If there is a car and it is too close, then, wait until the conditions get better to change the lane. Repeat this process every 8 sec until the driver changes lane.

As displayed in the figure, the coordinates x, y, and z represent the blind spot angle, CPM and *lane change time (sec)* respectively. As observed, the lane changing patterns vary regardless

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of the size of the blind spot angle and the CPM. The average wait time to change the lane is approximately 22 sec when the blind spot angle is 5° and CPM is 5. However, it takes 29 sec when the blind spot angle is 5° and CPM is 25. Hence, it takes more time to change the lane at a higher vehicle congestion. That is because the time difference the driver sees more vehicles at higher CPM compared to a lower CPM and the driver tends wait a longer period before changing the lane. It was also observed that the average wait time to change the lane gradually decreases as the the blind spot angle increases. That is because of a larger blind spot; the driver may not see many vehicles and tends to assumes that there are no other vehicles and changed the lane. In addition, it was observed that the lane change time does not depend on and has a relatively minor variation with respect to the size of the blind spot at higher CPM.
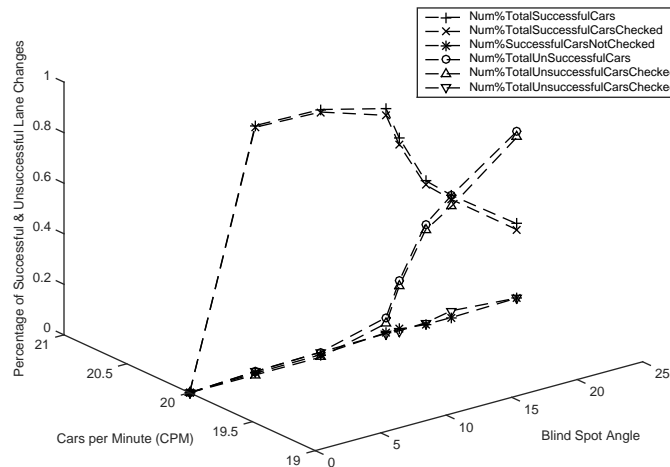

Figure 5.8: Analysis of Successful and Unsuccessful Lane Changes as Functions of 20 Cars per Minute (CPM) and Blind Spot Angles.

Figure 5.8 displays the correlation between the number of successful and unsuccessful lane changes as a function of 20 CPM and blind spot angle. As shown, it is fairly consistent and safer to change lane until the blind spot angle is 15°; thereafter, the successful lane change rate begins to diminish rapidly. However, unsuccessful lane change rate increases. As displayed, there are six graphs in the figure. Successful lane change (percent of total successful cars) consists of two components: *check* and *not check* before lane change. *Check* means the driver checks to see whether there are vehicles present in the adjoining lane before change lane, and *not check* means may not check and simply change the lane. Likewise, unsuccessful lane change (percent of total unsuccessful cars) consists with two components: *check* and *not check* before lane change. As observed, the unsuccessful lane change is virtually consists of the *check* component and not from the *not check* component. This can be because of the larger blind spot angle (>15°) resulting the low visibility and the driver may have not seen the vehicles in the adjoining lane; the tendency of a vehicle crash increases exponentially.

5.2.2   Lane Changing Scenario2: Observations as a Function of Relative Velocity and Cars per Minute

This section includes the several simulation outputs with respect to lane changes as a function of cars per minutes (CPM) and relative velocity. As already stated, CPM and relative velocity were initially set to 5 and 1 mph respectively. The simulation was performed while incrementing CPM

by 5 and until 25 and the relative velocity by 1 mph until 5 mph. The simulation was repeated with

respective inputs, and the results were recorded.
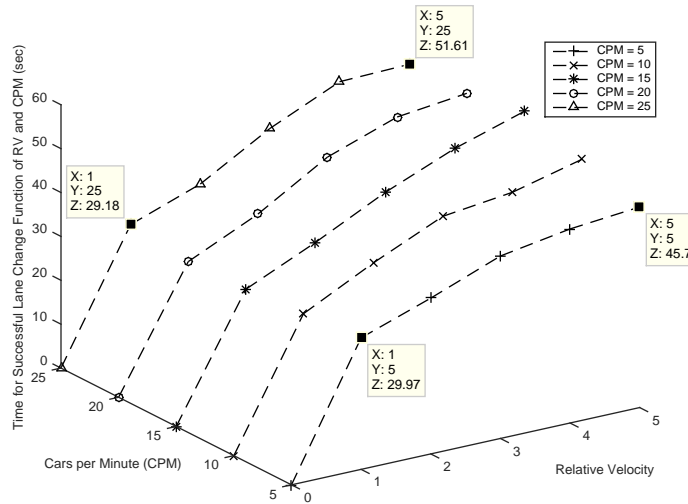
Figure 5.9: Average time (sec) for a Successful Lane Changes as a Function of Cars per Minute (CPM) and Relative Velocity.

Figure 5.9 displays the driver wait time as a function of CPM and the relative velocity before

changing the lanes (Relative Velocity Varies from 1 mph to 5 mph, Duration between Looks 8 sec,

Driver Lookout Frequency Probability is 0.83). Because of the higher relative velocity, the time to

change the lane increases exponentially, resulting in a longer period to change the lane safely. As

displayed, the average time to change lane does not depends on the CPM when the relative velocity

is 1 mph but increases more rapidly along with the increasing relative velocity. For example, if

the relative velocity is 5 mph, then, it takes 45 sec when CPM is 5 and 51 sec when CPM is 25.

This is because of two reasons: (1) the driver see more vehicles and (2) the shorter time period

to change the lane at a higher relative velocity. For example, during a lane change, depending

on the relative velocity of two vehicles heading in the same direction, there is probability that a collision can occur. The time to collision, depends on these two variables: (1) relative velocity and (2) the distance between the vehicles. Suppose the first or the front vehicle velocity (v1) is 100 feet/second, and the second vehicle velocity (v2) coming from behind is 130 feet/second, then, the relative velocity is -30 feet/second (v1 - v2), and the distance between the two vehicles is 60 feet, then, it takes 2 seconds for the collision to occur.

Figure 5.10: Comparison between Successful Lane Changes with Respect to Relative Velocity 1 mph and 3 mph.

Figure 5.10 displays, the overall successful lane change (percent of total successful cars) consists of two components: *check* and *not check* (Blind Spot Left Angle Size Varies from 5° to 25° and Cars per Minute 20, Duration between Looks 8 sec, Driver Lookout Frequency Probability is 0.83). It was observed the overall lane changing patterns are very similar regardless of the relative velocity (i.e., 1 or 3 mph). As the blind spot angle approaches more than 15°, the successful lane

change percentage begins to diminish. However, after further analysis, it was discovered that there is an intrigue, distinct difference with regard to discrete components of the overall successful lane changing patterns (1 and 3 mph). For example, as shown in the figure, if the relative velocity 3 mph, then, the dominant component of the successful lane change is *check*. In fact, the total successful lane is merely 100% of the *check* and *not check* is virtually 0%. As shown in Figure 5.10, this can be because of a higher relative velocity; the driver tends to be more cautious and takes more time and looks more frequently before deciding to change the lanes. Moreover, further analysis revealed that the *number of times stayed back* and *time to change lane* as much as two times if the relative velocity is 3 mph compared to 1 mph respectively. This is because of several reasons:

- at a higher velocity, the drivers maintain a longer distance between the cars,

- the driver tends to look more frequently,

- thereby, number of *checks* before lane change is higher, and

- more vehicles passed by.

Conversely, if the relative velocity was 1 mph, the successful lane change is composed of *check* as well as *not check* components. Therefore, the total successful lane changes consists of mainly the *check* component according to simulation output. Because at a lower relative velocity (1 mph), there are not many vehicles passing; drivers are less frequently checking, and they may not have to wait a longer period of time when changing lanes. Furthermore, unlike at a higher relative velocity (i.e., 3 mph) the overall successful lane change is a factor of both *check* and *not check* components.

The rate begins to diminish if the blind spot angle is more than 15°. The *not check* component diminishes much more rapidly.
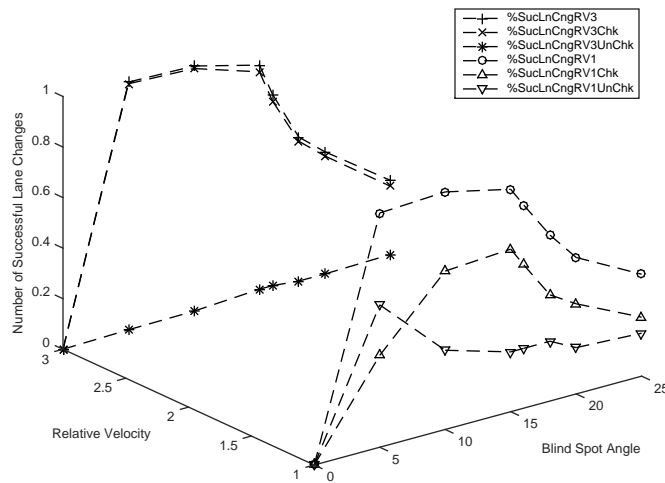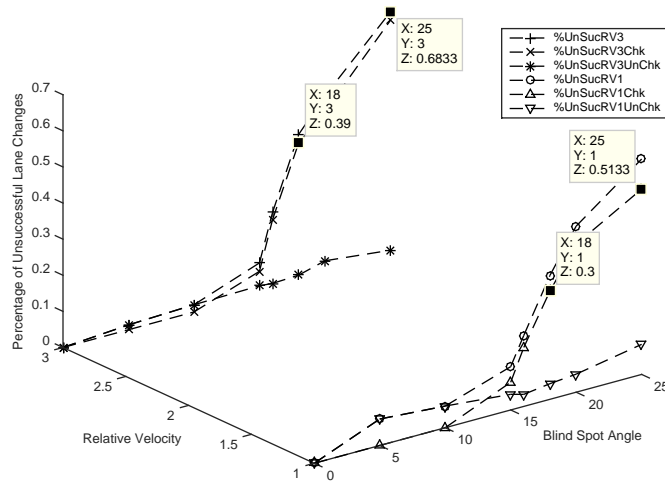

Figure 5.11: Comparison between Unsuccessful Lane Changes with Respect to Relative Velocity 1 mph and 3 mph.

Figure 5.11 displays the unsuccessful lane change (percent of total unsuccessful cars) (Blind Spot Left Angle Size Varies from 5° to 25° and Cars per Minute 20, Duration between Looks 8 sec, Driver Lookout Frequency Probability is 0.83). It was observed, that the main component of the unsuccessful lane change is the *check* before lane change. Comparing the unsuccessful lane change percentages with respect to relative velocity 1 and 3 mph, it was observed, that if the blind spot angle is greater than 15°, then, because of the limited visibility of the vehicles in the adjoining lane, the tendency of a vehicle crash increases exponentially. For example, as shown when the relative velocity is 1 mph (y =1) and the blind spot angle is 18° (x=18), the percentage of unsuccessful lane change is approximately 30% (z=30); whereas, it is approximately 39% (z=39) if the relative

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velocity is 3 mph. That is about 9% increases between the two velocities. Likewise, comparing the unsuccessful lane change percentage between the two velocities when the blind spot angle is 25°, the result is worse for the unsuccessful lane change percentages. For example, 1 mph 51% compared to 68% 3 mph; that is increase of 17%. Furthermore, it was observed that the *not check* component does not change along with blind spot or relative velocity and has minimal impact on the unsuccessful lane change percentage.
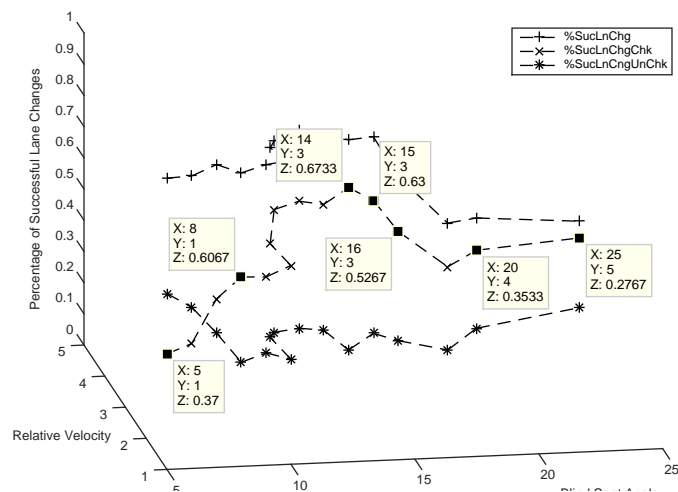
Figure 5.12: Successful and Unsuccessful Lane Change with Respect to Relative Velocity and Blind Spot Angle.

Figure 5.12, shows the overall successful lane change rate along with *check* and *not checked* components (Default Lookout Frequency 8 sec Vs. 4 sec - Left Angle Size 15°, Duration Between Looks 8 sec, Driver Lookout Frequency Probability is 0.83). According to the simulation output results, when the blind spot angle is around 5° and relative velocity is around 1 mph, the *not checked* component mainly contributed to the successful lane change. This can be because of the

slower relative velocity and smaller blind spot angle where the driver is able to see better and may not be checking frequently. As the blind spot and the relative velocity increases, it was observed that the driver may tend to be more cautious, resulting the *check* component vastly contributes to the successful lane change. Furthermore, when the blind spot angle is around 14° (x = 14) and relative velocity is 3 mph (y = 3), the *check* component is optimized 67% (z = 67); however, as the blind spot angle as well as relative velocity increases, the successful lane change rate starts to diminish.

5.2.3   Lane Change Scenario3: Comparison with Respect to Relative Velocity and Blind Spot Angle

Two previous sections provide an analysis of lane changing scenarios of relative velocity and blind spot with respect to CPM. This section provides a comparative analysis of lane changing attributes such as *successful lane change, number of attempts made before the lane change* and *time to change the lane* with respect to relative velocity and blind spot angle. In the first analysis, the blind spot angle scales from 5° to 25° and relative velocity is set to 1 mph and the second analysis, the relative velocity scales from 1 mph to 5 mph and blind spot angle is set to 5° and compare the simulation output. In both the analysis, the CPM is set to 25.

Blind spot left angle scales from 5° to 25°, relative velocity scales from 1 to 5 mph, cars per minute 25, duration between looks 8 sec, driver lookout frequency probability is 0.83. The attribute *attempts* represents the number of times the driver attempts to change lane.

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Table 5.1: Lane change statistics comparison with respect to blind spot and relative velocity

Increasing blind spot Angle, relative velocity = 1 mph				Increasing Relative Velocity, Blind Spot = 5°			
Angle	Attempts	Per. Suc.	Time	Velocity	Attempts	Per. Suc.	Time
5	42	0.96	29	1	42	0.96	29
10	11	0.95	22	2	18	0.87	35
15	6	0.90	20	3	12	0.80	44
20	4	0.55	19	4	9	0.73	51
25	3	0.43	19	5	7	0.62	51

As shown in the Table 5.2.3, as the blind spot angle and relative velocity increases, the number of attempts decreases; whereas, with respect to the blind spot the attribute's values decrease more rapidly. Same is true for the *successful lane change rate* (Percent Successful - Per.Suc) as well as *time to change the lane*. That is because the driver may not see the vehicles in the adjoining lane because of a larger blind spot angle. Likewise, with the increasing relative velocity, *number of attempts* and *successful lane change rate* (Percent Successful - Per. Suc) begins to diminish. However, when compared to blind spot environment, they do not decrease very rapidly. On the other hand, *time to change lane* is quite reciprocal in the opposite directions.
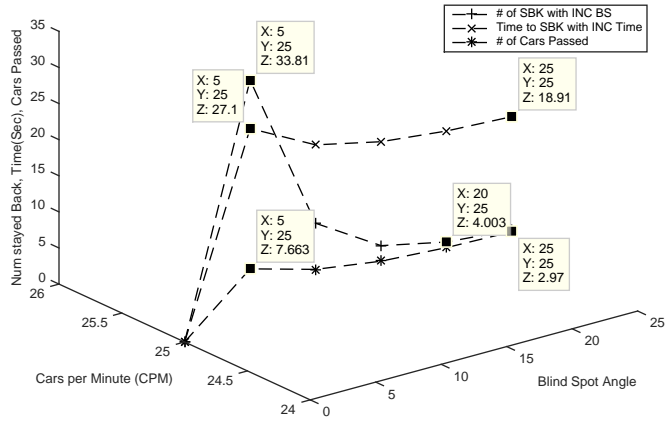
Figure 5.13: Correlation among Number of Cars Passed, Number of Times Stayed Back and Time to Change the Lane with Respect to Blind Spot Angle.

Note: Blind Spot Left Angle Size Varies from 5° to 25°, Constant Relative Velocity 1 mph and

Cars per Minute 25, Duration between Looks 8 sec, Driver Lookout Frequency Probability is 0.83.
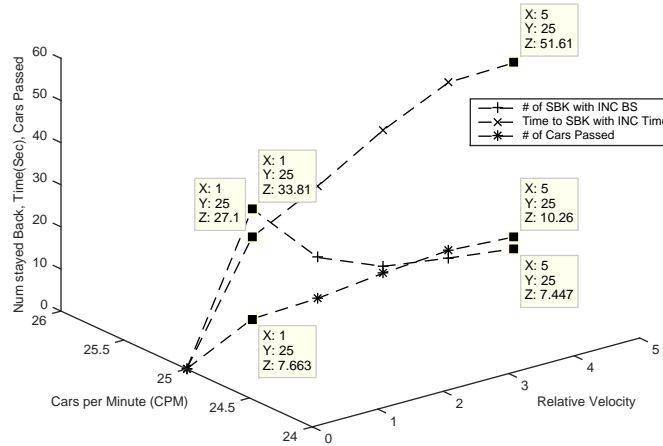
Figure 5.14: Correlation among Number of Cars Passed, Number of Time Stayed Back and Time to Change the Lane with Respect to Relative Velocity.

Note: Relative Velocity Varies from 1 mph to 5 mph, Constant Blind Spot Angle 5° and Cars per Minute 25, Duration between Looks 8 sec, Driver Lookout Frequency Probability is 0.83.

Figures 5.13 and 5.14 display two different scenarios of *time to change the lane*. The first scenario, Figure 5.13 displays the variable blind spot with constant relative velocity. The second scenario, Figure 5.14 displays the variable relative velocity with constant blind spot angle. Initially, all the variables are equal (blind spot angle is 5° and relative velocity is 1 mph), the output data points were equal. However, the blind spot and relative velocity scale, the *time to change the lane* with respect to relative velocity increases rapidly compared to blind spot. For example, it takes as much as three times to change the lane at a higher relative velocity, compared to a larger blind spot

Table 5.2: The parameters for simulating the impact of the turn signal wait time

Parameters	Values
Traffic parameters	
Probability of the driver using the turn signal	0.1 - 1.0
Maximum turn signal wait time	20 sec.
Driver wait time	16 sec.
Probability of the following driver slowing down	0.1

angle (18 Vs. 51 sec). That is because of a greater number of stay-backs as a result of more cars

passed by (3 Vs. 7) at a higher relative velocity.

5.3   The Impact of the Turning Signal

In this experiment, we studied the impact of the presence of the turning signal to the success of the

lane change. The simulation parameters are described in Table 5.2. There are two scenarios are

discussed:

- The Impact of the percentage of using the turning signal

- The impact of the turn signal duration

5.3.1   *The impact of the percentage of using the turning signal*

In general, drivers are advised to signal "ahead of time", that is, to allow the signal

to be on for a certain amount of time before initiating a lane change. To verify this

Table 5.3: The parameters for simulating the impact of the turn signal duration

Parameters	Values
Traffic parameters	
Probability of the driver using the turn signal	0.9
Maximum turn signal wait time	20 sec.
Driver wait time	2-20
Probability of the following driver slowing down	0.1

assumption, we run a series of experiments varying the turn signal wait time. Table 5.3

shows the parameters for the simulation. These largely echo the ones from the previous

experiment, with the probability of turn signal use set to 90%.

Figure 5.16 shows the experimental results. As expected, the benefits of the turn signal

need to be compounded with an appropriate wait time - activating the turn signal and

immediately starting a lane change keeps the success rate essentially where it is without

any turn signal at all.
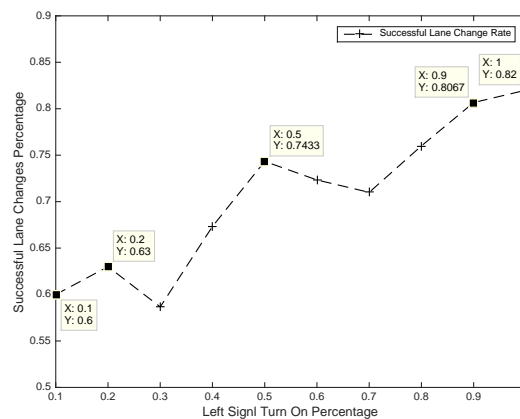
Figure 5.15: Left lane change turn signal percentage and the successful rate.

Figure 5.15 shows the simulation results for various probabilities of the driver using the turn signal in addition to checking the side view mirrors. As expected, the number of successful lane changes increases with the use of the turn signal. Drivers who do use the turn signal 10% of the time succeed about 95% of the time to change lanes in the allotted time frame, while those who always use it succeed almost 100% of the time. We observe that this increase is higher than what we would expect from the very small percentage of the drivers who slow down when seeing the signal. The cause of this is that even if several cars pass by without giving way, the driver only needs one left lane driver to give way to him.

5.3.2 The impact of the turn signal duration
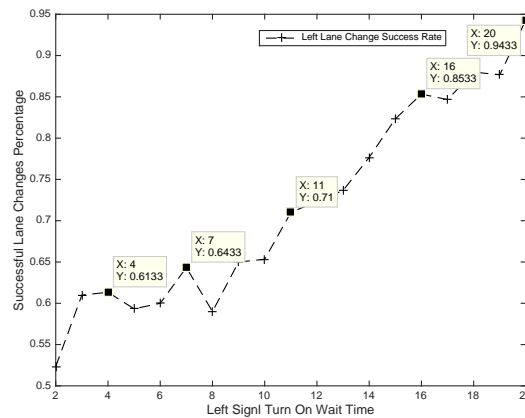
Figure 5.16: The rate of successful lane changes function of the driver wait time.

In this experiment we assumed that the driver turns on the signal up to 20 s, and attempt to change the lane within this period. The lane change is successful if the driver can make the lane change in this interval—if the lane change is unsuccessful, the driver needs to continue waiting for an opportunity.

As expected, the number of successful lane changes increases along with the longer waiting period. For example, the drivers who do use the turn signal and then waits 16 s to try to make a lane change 85% of the successful compared to 71% of the time who waits 11 s.

5.4   Vehicle to Vehicle Communication

In this set of simulation studies, we consider the case described in Scenario 4, which is a case of V2V communication where the following vehicle communicates its location and velocity to the lane changing vehicle. Table 5.4 lists the common simulation parameters for the simulation studies in this section.

5.4.1   The impact of V2V transmission range and relative velocity

In the first set of experiments, we varied both the relative velocity and the V2V transmission range. Figure 5.17A shows the experimental parameters for these simulation runs. The relative velocities had been studied for 1–5 mph faster compared to the current lane.

Table 5.4: Experimental parameters of V2V transmission range and relative velocity

Parameters	Values
Traffic parameters	
Probability of left lane car being equipped with V2V technology	100%
V2V transmission range	167–400 (inches)
Relative velocity of vehicles on the target lane	1–5 mph

For all relative velocities, we repeated the simulation for V2V transmission ranges between 167 and 400 inches. As expected, the higher the transmission range, the higher the probability of a successful lane change. At a transmission range of 400 inches (about two car lengths), the fraction of successful lane changes approaches 100%. Table 5.4 and Figure 5.18 summarize the statistical dispersion of the data with respect to Mean (M), Standard Deviation (S) and Variance (V). The data shows that the standard deviation and the variance get smaller as the range between the two vehicles increases.
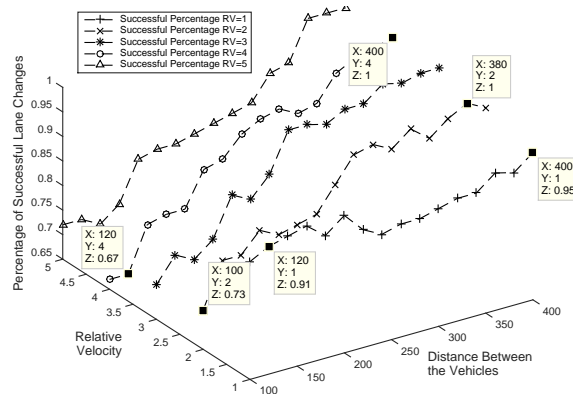
Figure 5.17: The impact of relative velocity and V2V transmission range on the rate of successful lane changes.

Table 5.5: Statistical Dispersion of the Data with Respect to Mean, Standard Deviation and Variance.

	Distance = 100			Distance = 140			Distance = 200			Distance = 300			Distance = 380		
RV	M	S	V	M	S	V	M	S	V	M	S	V	M	S	V
1-5	.746	.084	.007	.79	.084	.007	.856	.043	.002	.934	.378	.0014	.976	.027	.0007
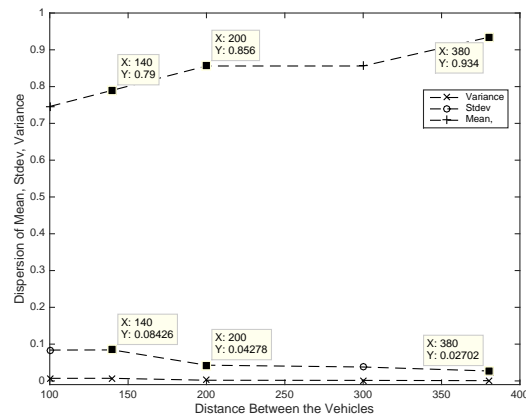
Figure 5.18: Statistical Dispersion of the Data with Respect to Mean, Standard Deviation and Variance.

Smaller standard deviation and variance values indicate that the data points tend to be very close to the mean. In other words, by maintaining the proper distance between the two vehicles, it is possible to reduce the side-sweep accidents at a higher relative velocity.

5.4.2   The impact of the blind spot when V2V communication is present

One of the major sources of side sweep accidents is the presence and size of blind spots. While drivers can check the presence of a vehicle in a blind spot by turning in the appropriate direction but in general a lot more drivers fail to do so compared to those who that fail to check the mirror. This problem is magnified when the mirrors are improperly adjusted (see Figure 5.19). This creates larger-than-optimal blind spots (compare with Figure 3.1 which shows the optimal adjustment).
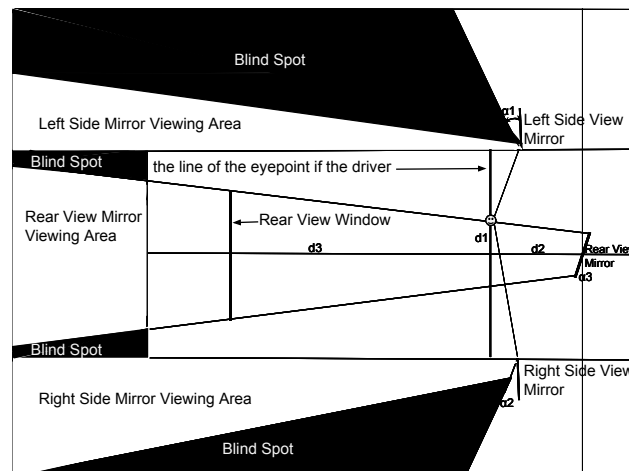
Figure 5.19: Blind Spot Simulator - Left View Mirror not Properly Adjusted.

We conjecture that V2V communication along the line described in Scenario 4 mitigates the problem. To verify this assumption, we run a series of experiments with the V2V communications enabling and varying the size of the blind spot from 5 to 40 de-

grees. The effective percent of time V2V communications is a variable. During these experiments, it is set to 90%.

In other words, 15 CPM is equivalent 900 cars for an hour; therefore, average 810 (900 * 0.90) number of left line cars with V2V per experiment. As expected the V2V communication largely mitigates the presence and size of the blind spot, with the results being uniformly high with little to no impact seen from the size of the blind spot as display in Figure 5.20.
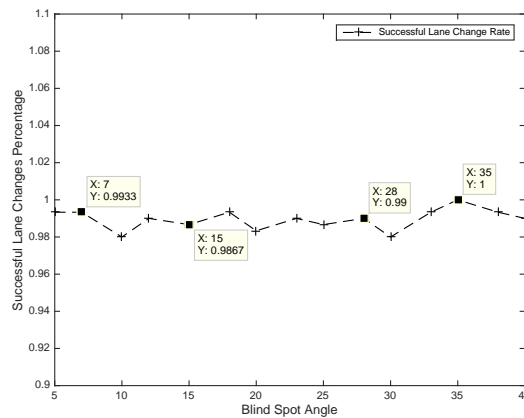
Figure 5.20: The fraction of successful lane changes function of the angle of the blind spot in the presence of V2V communication.

5.4.3   The impact of driver attention when V2V communication is present
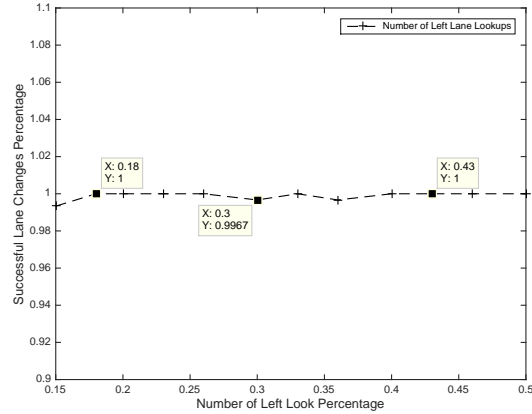
Figure 5.21: The fraction of successful lane changes function of the probability of the driver looking before initiating the change, in the presence of V2V communication.

Another known cause of side sweep accidents is the lack of attention of the driver. A measure of this value is the probability of the driver looking to the left when initiating a lane change. In previous work [BB16b] we found this impact to be quite significant. Figure 5.21 shows the impact of the look percentage on the success of the lane change when V2V communication is enabled.

As expected, V2V communications largely compensate for the inattention of the driver - the driver's look probability has an essentially unobservable impact on the accident rate.

CHAPTER 6: CONCLUSIONS AND FUTURE RESEARCH

In this research, we presented a simulation model for lane changing vehicles, with a special focus on side-sweep accidents. Simulation modeling analysis can significantly contribute to factors that will enhance driver safety because of side-sweep accidents. In this study, the blind spot simulation model facilitates the *what-if* analysis of simulating blind spots in the real world by varying initiating conditions of driving scenarios. This simulation model can take into account many detailed aspects of the lane change processes, such as the vehicle and road geometry, blind spots, driver behavior as well as communication technologies. Through a series of simulation studies, we considered the impact of traditional and novel communication technologies. In traditional communications, it is common sense for an experienced driver to take every precaution in changing lanes safely, but accidents can occur because of blind spots.

We model the traditional way of communicating driver intent through turn signals and the response of the following drivers. We also model modern approaches of V2V communication where the following vehicle notifies the lane changing vehicle of its position and speed, and the automation in the lane changing vehicles overrides the driver's lane change intent if there is a danger of collision. We found that the existence of V2V

communication can largely compensate for driver inattention and large blind spots created by incorrectly adjusted mirrors in the vehicle.

In this research, the lane changing scenarios were analyzed with constant vehicle velocity. In future research, the observations and the results obtained from the simulations pertaining to the scenarios with respect to variable velocities and the impact of the spatial dimensions of the automobile blind spots on the side-sweep accidents will be analyzed.

In the following section, we analyzed and produced the results of these scenarios and provided a comparative analysis of the results with respect to traditional and non traditional communication technologies.

6.1 Traditional Communication - Without Using the Turn Signals

We found that some of the experimental results are comparable with the National Highway Traffic Safety Administration (NHTSA) finding but there are major differences particularly with respect to lane change time. This can be due to two input parameters:

∗ Relative velocity

∗ Vehicle density

As previously stated, according to NHTSA finding, 83% of the single lane changes with a mean duration 6.28 seconds without a discussion about the relative velocity

or the vehicle density at the time of the lane change. This research has taken into consideration these two input parameters and can be very vital for the comparison purposes of the results obtained from the simulation and NHTSA.

The default simulator parameters in this research are based on the real-world observations published by the National Highway Traffic Safety Administration [3, 5, 9]. For example, checking the left windows, and center mirrors during the last 8 seconds prior to initiating left-lane changes, 17% of drivers failed to check their left mirrors. It has been observed that most of the side-sweep accidents are because of reckless lane changes. The default value (probability = 0.17) or 17% of the drivers who do not look back before lane changes seems to be high. Changing this probability to 0.93 from 0.83, only 7% of the drivers do not look back, yields better results. Next, changing the probability to 0.98 from 0.83, only 2% of the drivers do not look back, yields even better results. Last, changing the driver update time to 4 sec from default 8 sec received the best results.
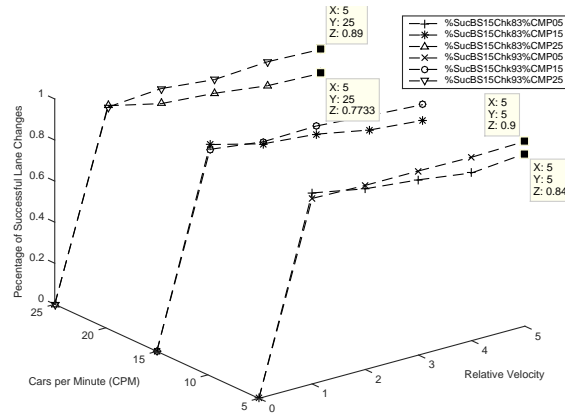
Figure 6.1: Percentage of Successful Lane Change Comparison as a Function of Driver Lookout Frequency Probability.

Figure 6.1 displays the percentage of successful lane changes compared to default driver lookout frequency probability 0.83 (default - Left Angle Size 15°, duration between Looks 8 sec) Vs. 0.93. As indicated, the lane change successful percentages improve when the driver lookout frequency probability increase from 0.83 to 0.93 for each and every scenario. The spatial dimensions of the blind spot is a constant.

 * Scenario1: Cars per minutes is set to 5

 * Scenario2: Cars per minutes is set to 10

 * Scenario3: Cars per minutes is set to 15

As shown, increasing the driver lookout probability, in each and every scenario the successful lane percentages increased irrespective of the relative velocity and CPM. For example, when CPM equals to 5 and 25, at 5 mph relative velocity, the lane change successful percentages increased by about 6% and 12% respectively. This indicates

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that by increasing the driver lookout frequency contributes to enhance the successful

lane change regardless of the vehicle congestion.
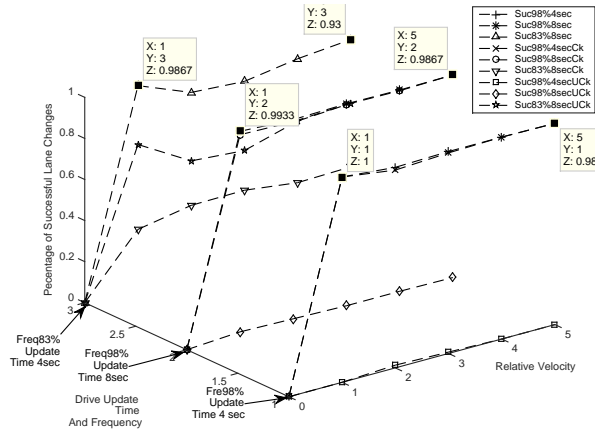
Figure 6.2: Driver Update Time and Frequency Comparison with Default Values.

Figure 6.2 displays the following three scenarios where the default driver update time

8 sec Vs. 4 sec, constant CPM 5 and left angle size 5°, default driver lookout frequency

probability is 0.83 Vs. 0.98.

* Scenario1: Overall successful lane change percentage along with *check* and *not
  check* components with default driver lookout probability of 0.83 and increase
  update time to 4 sec from 8 sec (default),

* Scenario2: Overall successful lane change percentage with *check* and *not check*
  components with enhanced the driver lookout probability of 0.83 (default) to 0.98
  but no change the update time: default 8 sec, and

∗ Scenario3: Overall successful lane change percentage along with *check* and *not check* components witch enhanced the driver lookout probability of 0.83 (default) to 0.98 an increase in the update time: 4 sec from 8 sec.

As shown in the figure, the Scenario1 (lookout probability 0.83 and update time 4 sec) has the relative velocity is at 1 and 5 mph; the overall lane change successful percentage is approximately 98% and 93% respectively, and also the overall successful percentage consists with both *check* and *not check* components. Although, the successful lane change percentage has gone down at relative velocity 5 mph, by comparison with the default values, (the driver lookout probability 0.83 and update time 8 sec, See Figure 6.1), this is a remarkable improvement (84% Vs. 93%). Next, increasing the lookout probability to 0.98 from 0.83 and no change to the driver update time (4 sec), (Scenario 2: Lookout probability 0.98 and update time 8 sec), it was observed that the overall successful percentage increase to 99% from 98% and the overall successful percentage virtually consists of *check* component and not from the *not check* component. That is because of the enhanced driver lookout probability (0.98); 98% of the drivers check the adjoining lane before changing lanes. Lastly, when both are enhanced (Scenario 3: Lookout probability to 0.98 and update time 4 sec), the results were 100% and 98% successful lane change at relative velocity 1 and 5 mph respectively, and *not check* component has virtually disappeared. That is because 98% of the drivers check every 4-sec interval before changing lanes.

The above output results are based on two variables, driver lookout frequency and update time, and the following conclusions are reached. While both the variables contribute toward enhancing successful lane changes, the smaller driver update time interval contribution is more significant compared to driver lookout frequency. This indicates that checking the adjoining lane is imperative before initiating the lane change. Checking in shorter time intervals can enhance the success of a lane change, significantly.

Some other observations and conclusions:

* As based on the output of Figure 5.5, it can be observed and considered that $16°$ angle is a demarcation point regardless of the size of the blind spot angle and CPM at relative velocity 1 mph. The percentage of successful lane changes will begin to diminish more significantly. If the blind spot angle is greater than $20°$.

* As observed in Figure 5.6, the unsuccessful lane change percentages are somewhat similar when the angle is approximately $5°$, but they increase rapidly along with the increasing blind spot angle and vehicle congestion.

* As displays in Figure 5.7, the driver waiting time and lane changing patterns are very similar regardless of the size of the blind spot angle and the CPM. Also, the average wait time to change the lane gradually decreases as the the blind spot angle increases. That is because of a larger blind spot, the driver may not see many vehicles and tends to assumes that there are no other vehicles.

∗ As displays in Figure 5.9, because of the higher relative velocity, the time to change the lane increases exponentially, resulting in a longer period to change the lane safely.

6.2 Traditional Communication - Using the Turn Signals

According to the simulation results, we can conclude that side-sweep accidents can be minimized, if the higher percentage of the drivers use the turn signal few seconds before initiating of a lane change. Table 5.2 and Figure 5.15 display the results of the *Turn Signal Percentage*. According to the results, there is direct correlation between the higher signal frequency and the successful lane change rates. Before a lane change, turning on the turn signals more frequently can alleviate the side-sweep accidents. Table 5.3 and Figure 5.16 show the results of the *Turn Signal Wait Time*. According to the results, there is direct correlation between the higher wait time and the successful lane change rate. Before a lane change, turning the turn signals on can alleviate the side-sweep accidents but increase the wait time.

6.3   Non Traditional Communication - Using the V2V Communication Technologies

In conventional systems such as unidirectional communications, signaling before changing lanes, the *Driver* is in control as opposed to the *Car*. As shown in Figure 6.1 and Figure 6.2 , side-sweep accidents can be reduced considerably by the combination of increasing the frequency and the duration of the driver lookouts but the collisions still can occur. During a lane change, in V2V communication the *Car* is in control as opposed to the *Driver*, therefore, in sudden lane changes, a V2V communication such as bidirectional communication system facilitates safety warnings to vehicles in the adjoining lanes (left or right) before they get too close, thereby, reducing the number of side-sweep accidents.

As discussed in the Chpater 5 section 4, we model several scenarios of V2V simulations and observed the results. For example, as expected we observed, at higher transmission range, the higher the probability of a successful lane change Table 5.4. Furthermore, as expected the V2V communication largely mitigates the presence and size of the blind spot, with the results being uniformly high with little to no impact seen from the size of the blind spot Figure 5.20 and Figure 5.21.

Lastly, this paper describes the simulation approach to the safety of lane change of highway traffic. In this research, the lane changing scenarios were analyzed with constant vehicle velocity. In future research, the observations and the results

obtained from the simulations pertaining to the scenarios with respect to variable velocities and the impact of the spatial dimensions of the automobile blind spots on the side-sweep accidents will be analyzed.

These results open up the possibility of several directions of future work. We are working on providing more detailed simulations that take into account the driver's behavior as it interacts with the automation. Another direction includes other V2V communication modes. In this paper, we assumed that the notifications flow from the follower vehicle to the lane changing one, while the lane changing vehicle has the automation that can override a dangerous command from the driver. Other possibilities which we did not consider in this research include the lane changing vehicle transmitting its intention to the follower as well as bidirectional communication models where the vehicles agree on a negotiated course of action.

Ideally, based on the simulations results, the combination of the two systems (unidirectional and bidirectional) the side-sweep accidents can be eliminated and enhance the driver safety. Based on these results, it can be concluded, vehicle-to-vehicle communication can enhance the driver safety during side-sweep accidents and it can be enhanced further in conjunction with higher frequency and duration of the using turn signals.

LIST OF REFERENCES

[ANL07]   Samer Ammoun, Fawzi Nashashibi, and Claude Laurgeau. "An analysis of the lane changing manoeuvre on roads: the contribution of inter-vehicle cooperation via communication." In *Intelligent Vehicles Symposium, 2007 IEEE*, pp. 1095–1100, 2007.

[ARR08]   J Diaz Alonso, Eduardo Ros Vidal, Alexander Rotter, and Martin Muhlenberg. "Lane-change decision aid system based on motion-driven vehicle tracking." *Vehicular Technology, IEEE Transactions on*, **57**(5):2736–2746, 2008.

[AT13]   Taimoor Abbas and Fredrik Tufvesson. "Line-of-sight obstruction analysis for vehicle-to-vehicle network simulations in a two-lane highway scenario." *International Journal of Antennas and Propagation*, **2013**, 2013.

[BB15]   Gamini Bulumelle and Ladislau Bölöni. "Simulating the impact of blind-spots on the frequency of side-sweep accidents." In *Proceedings of the Symposium on Theory of Modeling & Simulation: DEVS Integrative M&S Symposium*, pp. 235–241. Society for Computer Simulation International, 2015.

[BB16a]   Gamini Bulumulle and Ladislau Bölöni. "Reducing Side-Sweep Accidents with Vehicle-to-Vehicle Communication." *Journal of Sensor and Actuator Networks*, **5**(4):19, 2016.

[BB16b]   Gamini Bulumulle and Ladislau Bölöni. "A Study of the Automobile Blind-Spots' Spatial Dimensions and Angle of Orientation on Side-Sweep Accidents." In *Proc. of Spring Simulation Multiconference (SpringSim-2016)*, 2016.

[BH08]   Pinar Boyraz and John HL Hansen. "Active accident avoidance case study: integrating drowsiness monitoring system with lateral control and speed regulation in passenger vehicles." In *Vehicular Electronics and Safety, 2008. ICVES 2008. IEEE International Conference on*, pp. 293–298, 2008.

[BM09]   Ankatrien Boulanger and Annette Meng. "Reporting tool for effects of a single campaign." *Directorate-General for Energy and Transport, European Commission, Brussels*, 2009.

[Car05]   Arthur Carter. "The status of vehicle-to-vehicle communication as a means of improving crash prevention performance." Technical report, National Highway Transportation Safety Administration, 2005.

[CC09]   CT Chen and YS Chen. "Real-time approaching vehicle detection in blind-spot area." In *Intelligent Transportation Systems, 2009. ITSC'09. 12th International IEEE Conference on*, pp. 1–6. IEEE, 2009.

[CTA94]   JD Chovan, L Tijerina, G Alexander, and DL Hendricks. "Examination of lane change crashes and potential IVHS countermeasures. Final Report." Technical report, 1994.

[DDS14]   Ruina Dang, Jieyun Ding, Bo Su, Qichang Yao, Yuanmu Tian, and Keqiang Li. "A lane change warning system based on V2V communication." In *Proc. of 17th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, pp. 1923–1928, 2014.

[FG90]   Paula Finnegan and Paul Green. "Time to Change Lanes: A Literature Review." Technical report, 1990.

[FKS12]   Haneen Farah, Haris N Koutsopoulos, Mohammad Saifuzzaman, Robert Kölbl, Susanne Fuchs, and Doris Bankosegger. "Evaluation of the effect of cooperative infrastructure-to-vehicle systems on driver behavior." *Transportation research part C: emerging technologies*, **21**(1):42–56, 2012.

[FLK09]   GM Fitch, SE Lee, S Klauer, J Hankey, J Sudweeks, and T Dingus. "Analysis of lane-change crashes and near-crashes." *US Department of Transportation, National Highway Traffic Safety Administration*, 2009.

[GVC12]   Raymond Ghandour, Alessandro Victorino, Ali Charara, and Daniel Lechner. "Risk indicators anticipation based on the vehicle dynamics anticipation to avoid accidents." In *Intelligent Vehicles Symposium (IV), 2012 IEEE*, pp. 93–98. IEEE, 2012.

[GW13]   Ilan Grinberg and Yair Wiseman. "Scalable parallel simulator for vehicular collision detection." In *International Journal of Vehicle Systems Modelling and Testing*, volume 8, pp. 119–144. Inderscience Publishers Ltd, 2013.

[GWA10] Feng Guo, Brian M Wotring, and Jonathan F Antin. "Evaluation of Lane Change Collision Avoidance Systems Using the National Advanced Driving Simulator." Technical report, 2010.

[HEF10]   Xiaohui Hu, Russell Eberhart, and Brian Foresman. "Modeling drowsy driving behaviors." In *Vehicular Electronics and Safety (ICVES), 2010 IEEE International Conference on*, pp. 13–17. IEEE, 2010.

[Het]   Shannon Hetrick. *Examination of driver lane change behavior and the potential effectiveness of warning onset rules for lane change or "side" crash avoidance systems*. PhD thesis, Virginia Polytechnic Institute & State University.

[HS12]   Simon Herrmann and Frank Schroven. "Situation analysis for driver assistance systems at urban intersections." In *Vehicular Electronics*

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and Safety (ICVES), 2012 IEEE International Conference on, pp. 151–156. IEEE, 2012.

[HWG00] Richard J Hanowski, Walter W Wierwille, Sheila A Garness, Thomas A Dingus, Ronald R Knipling, and Robert J Carroll. "A field evaluation of safety issues in local/short haul truckin." In *Proceedings of the human factors and ergonomics society annual meeting*, volume 44, pp. 3–365. SAGE Publications, 2000.

[HXX04] Weiming Hu, Xuejuan Xiao, Dan Xie, Tieniu Tan, and Steve Maybank. "Traffic accident prediction using 3-D model-based vehicle tracking." In *Vehicular Technology, IEEE Transactions on*, volume 53, pp. 677–694. IEEE, 2004.

[JKI00] Hossein Jula, Elias B Kosmatopoulos, and Petros A Ioannou. "Collision avoidance analysis for lane changing and merging." *Vehicular Technology, IEEE Transactions on*, **49**(6):2295–2308, 2000.

[KB05] M.A. Khan and L. Bölöni. "Convoy driving through ad-hoc coalition formation." In *Proc. of IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS), San Francisco, California*, pp. 98–105, March 2005.

[KGN12] A Khodayari, A Ghaffari, M Nouri, S Salehinia, and F Alimardani. "Model Predictive Control system design for car-following behavior in real traffic flow." In *Vehicular Electronics and Safety (ICVES), 2012 IEEE International Conference on*, pp. 87–92. IEEE, 2012.

[KI08] Junpei Kuwana and Makoto Itoh. "Dynamic angling side-view mirror for supporting recognition of a vehicle in the blind spot." In *Control, Automation and Systems, 2008. ICCAS 2008. International Conference on*, pp. 2913–2918. IEEE, 2008.

[KKA12] Kemal Kaplan, Caner Kurtul, and H Levent Akın. "Real-time traffic sign detection and classification method for intelligent vehicles." In *Vehicular Electronics and Safety (ICVES), 2012 IEEE International Conference on*, pp. 448–453. IEEE, 2012.

[KLY12] Dongwook Kim, Junyung Lee, and Kyongsu Yi. "Development of a Combined Steering Torque Overlay and Differential Braking Control for Side Crash Prevention." In *Vehicular Technology Conference (VTC Spring), 2012 IEEE 75th*, pp. 1–5. IEEE, 2012.

[Kni93] Ronald R Knipling. "IVHS technologies applied to collision avoidance: Perspectives on six target crash types and countermeasures." In *Proceedings of the 1993 Annual Meeting of IVHS America: Surface Transportation: Mobility, Technology, and Society*, pp. 249–259, 1993.

[Kni12] I Knight. "A study of the implementation of Directive 2007/38/EC on the retrofitting of blind spot mirrors to HGVs." Technical report, 2012.

[LB10] Yi Luo and Ladislau Bölöni. "Towards a more accurate agent-based multi-lane highway simulation." In *Proceedings of International Workshop on Agents in Traffic and Transportation (ATT10), in conjunction with the 9th Joint Conference on Autonomous and Multi-Agent Systems (AAMAS 2010)*, pp. 13–20, 2010.

[LCF12] Bin-Feng Lin, Yi-Ming Chan, Li-Chen Fu, Pei-Yung Hsiao, Li-An Chuang, Shin-Shinh Huang, and Min-Fang Lo. "Integrating appearance and edge features for sedan vehicle detection in the blind-spot area." **13**(2):737–747, 2012.

[Lee11] In Jung Lee. "An accident detection system on highway using vehicle tracking trace." In *ICT Convergence (ICTC), 2011 International Conference on*, pp. 716–721. IEEE, 2011.

[LJJ11] Sung Joo Lee, Jaeik Jo, Ho Gi Jung, Kang Ryoung Park, and Jaihie Kim. "Real-time gaze estimator based on driver's head orientation for forward collision warning system." *Intelligent Transportation Systems, IEEE Transactions on*, **12**(1):254–267, 2011.

[LJL14] Ching-Fu Lin, Jyh-Ching Juang, and Kun-Rui Li. "Active collision avoidance system for steering control of autonomous vehicles." *IET Intelligent Transport Systems*, **8**(6):550–557, 2014.

[LK94] David M Levinson and Ajay Kumar. "The rational locator: why travel times have remained stable." *Journal of the american planning association*, **60**(3):319–332, 1994.

[LOW04] Suzanne E Lee, Erik CB Olsen, and Walter W Wierwille. "A comprehensive examination of naturalistic lane-changes." Technical report, National Highway Traffic Safety Administration, 2004.

[LTB15] Y. Luo, D. Turgut, and L. Bölöni. "Modeling the strategic behavior of drivers for multi-lane highway driving." *Journal of Intelligent Transportation Systems*, **19**(1):45–62, 2015.

[MG08] EN Mazzae and WR Garrott. "Light vehicle rear visibility assessment." *US Department of Transportation, National Highway Traffic Safety Administration. DOT HS*, **810**:909, 2008.

[MME09] Axel Malczyk, Edgar Mayr, Michael Ecker, Tobias Seebauer, Carla Weber, Lorenz Lampl, Matthias Helm, Martin Kulla, Linda Winkler, Florian Gebhard, et al. "Car crashes with polytrauma in southern Germany." In *21st International Technical Conference on the Enhanced Safety of Vehicles*, 2009.

[MSR10] Sara Moridpour, Majid Sarvi, and Geoff Rose. "Modeling the lane-changing execution of multiclass vehicles under heavy traffic conditions." *Transportation Research Record: Journal of the Transportation*

Research Board, **Transportation Research Board of the National Academies**:11–19, 2010.

[OLW02]   Erik CB Olsen, Suzanne E Lee, Walter W Wierwille, and Michael J Goodman. "Analysis of distribution, frequency, and duration of naturalistic lane changes." In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 46, pp. 1789–1793. SAGE Publications, 2002.

[Ped04]   Margie Peden et al. "World report on road traffic injury prevention." Technical report, 2004.

[Pla06]   George E Platzer Jr. "Compound automotive rearview mirror.", August 29 2006. US Patent 7,097,312.

[QHC13]   Chen Qiang, Zhao Hang, Yao Chun-de, Zou Tiefang, and Li Gen. "Reconstruct side pole impact accidents by computer simulation." In *Intelligent System Design and Engineering Applications (ISDEA), 2013 Third International Conference on*, pp. 1092–1095. IEEE, 2013.

[Rec]   Filter Based Boost Rectifier. "Paper ID Paper Title.".

[RRE13]   Osama Rizwan, Hamza Rizwan, and Masood Ejaz. "Development of an efficient system for vehicle accident warning." In *Emerging Technologies (ICET), 2013 IEEE 9th International Conference on*, pp. 1–6. IEEE, 2013.

[RT00]   Donald A Redelmeier and Robert J Tibshirani. "Are those other drivers really going faster?" *Chance*, **13**(3):8–14, 2000.

[RZF10]   Andreas Riener, Kashif Zia, Alois Ferscha, Cristina Beltran Ruiz, and Juan Jesus Minguez Rubio. "AmI Technology Helps to Sustain Speed While Merging-A Data Driven Simulation Study on Madrid Motorway Ring M30." In *Distributed Simulation and Real Time Applications (DS-RT), 2010 IEEE/ACM 14th International Symposium on*, pp. 111–120, 2010.

[SGB05]   Alrik L Svenson, Valerie J Gawron, and Timothy Brown. "Safety evaluation of lane change collision avoidance systems using the national advanced driving simulator." In *19th International Technical Conference on the Enhanced Safety of Vehicles, Washington, DC*, 2005.

[SHT12]   Yuichi Saito, Naohisa Hashimoto, Sadayuki Tsugawa, and Shin Kato. "Development on indicating system of information of deceleration intention to following vehicle-Suggestion and fundamental experiment." In *Vehicular Electronics and Safety (ICVES), 2012 IEEE International Conference on*, pp. 157–162. IEEE, 2012.

[TCE00]   Sam Talmadge, R Chu, C Eberhard, K Jordan, and P Moffa. "Development of performance specifications for collisions avoidance systems

for lane change crashes." Technical report, Transportation Research Board, 2000.

[TGG97] L Tijerina, WR Garrott, M Glecker, D Stoltzfus, and E Parmer. "Van and passenger car driver eye glance behavior during lane change decision phase, Interim Report." *Transportation Research Center Report, National Highway Transportation Safety Administration, Washington DC*, 1997.

[TZ07] Tomer Toledo and David Zohar. "Modeling duration of lane changes." *Transportation Research Record: Journal of the Transportation Research Board*, **Transportation Research Board of the National Academies**, 2007.

[WB70] RD Worrall and AGR Bullen. "An empirical analysis of lane changing on multilane highways." 303, Highway Research Record, 1970.

[WK94] Jing-Shiarn Wang and Ronald R Knipling. *Lane change/merge crashes: problem size assessment and statistical description*. US Department of Transportation, National Highway Traffic Safety Administration, 1994.

[WLL98] Christopher D Wickens, John D Lee, Yili Liu, and Sallie Gordon-Becker. "Introduction to human factors engineering." *Addison-Wesley*, 1998.

[xxxa] "Federal Highway Administration, Lane Width." http://safety.fhwa.dot.gov/geometric/pubs/mitigationstrategies/chapter3/3_lanewidth.cfm.

[xxxb] "Motor Vehicle Dimensions, The Engineering Society For Advancing Mobility Land Sea Air and Space." https://law.resource.org/pub/us/cfr/ibr/005/sae.j1100.2001.html.

[YCL08] Chung-Ping Young, Bao Rong Chang, Jian Lin Jr, and Ren-Yang Fang. "Cooperative collision warning based highway vehicle accident reconstruction." In *Intelligent Systems Design and Applications, 2008. ISDA'08. Eighth International Conference on*, volume 1, pp. 561–565. IEEE, 2008.

[YCW09] Chung-Ping Young, Bao Rong Chang, and Ting-Ying Wei. "Highway vehicle accident reconstruction using cooperative collision warning based motor vehicle event data recorder." In *Intelligent Vehicles Symposium, 2009 IEEE*, pp. 1131–1136. IEEE, 2009.

[YEM95] Stephen K Young, Carol A Eberhard, and Philip J Moffa. "Development of performance specifications for collision avoidance systems for lane change, merging, and backing. Task 2 interim report: Functional goals establishment." *US Department of Transportation, National Highway Traffic Safety Administration*, 1995.

[YQY11]   Wang Yi-zhi, Yuan Quan, and Li Yi-bing. "Modeling multi-view scenario of driving simulation on typical side-impact accidents." In *Consumer Electronics, Communications and Networks (CECNet), 2011 International Conference o*, pp. 470–473. IEEE, 2011.