CHALMERS
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Analysis and modelling of drivers' responses to safety-critical lane changes performed by heavy vehicles

Master's thesis in Automotive Engineering

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Gothenburg, Sweden 2019

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Cover: Image showing the scenario where a truck will change lane

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Abstract

According to the National Highway Transport Safety Administration (NHTSA), around 240,000-610,000 crashes due to lane change are reported to the police annually. In addition, over 300,000 lane change crashes remain unreported to the police. These high crash numbers indicate that lane change maneuvers pose a high risk to the lane changing and surrounding vehicles. Automated driving can possibly reduce lane change crashes or mitigate their consequences by promoting safer lane changes. In this context, this thesis mainly focuses on the analysis of safety critical lane change maneuvers using Naturalistic Driving Data from the SHRP2 database. The lane changes being considered in this thesis are performed by heavy vehicles, as observed from the perspective of a following vehicle equipped with forward facing camera. A total of 89 cases were found relevant for the scope of the study and manually annotated to extract variables which could describe the interaction between the heavy vehicles changing lane and the following passenger car. The annotated variables were used to quantitatively describe the lane change maneuver and to determine the factors responsible for the start of braking of the following passenger car. The results show that lateral motion of the heavy vehicle and a combination of lateral motion and blinking of the heavy vehicle are the main factor triggering the braking of the following car's driver. The speed difference of the following vehicle between the points when heavy vehicle starts its lateral motion and when the following vehicle starts to brake also has an impact on the braking of the following vehicle. These results have potential application for the design and testing on critical lane change maneuvers performed by an automated truck.

Keywords: Automated driving, Human Factors, Driver models, Heavy Duty vehicles, Automated Trucks

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Lastly, we are grateful to our friends and family for being themselves.

The findings and conclusions of this paper are those of the author(s) and do not necessarily represent the views of VTTI, the Transportation Research Board, or the National Academies

Göteborg, Sweden, 2019

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Nomenclature

The terminology used for this thesis is listed below:

ADAS	Advanced Driver Assistance System
DAS	Data Acquisition System
DOT	Department of Transportation
FHWA	Federal Highway Administration
GIDAS	German In-Depth Accident Study
GPS	Global Positioning System
LCV	Long Combination Vehicle
NDD	Naturalistic Driving Data
NDS	Naturalistic Driving Study
NHTSA	National Highway Transport Safety Administration
PHRP	Protecting Human Research Participants
POV	Principal Other Vehicle
SHRP2	The Second Strategic Highway Research Program
SV	Subject Vehicle
TTC	Time to Collision
VTTI	Virginia Tech Transportation Institute

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1
Introduction

1.1 Background

Since the rapid advancement in the automotive industry and affordable prices of owning a car, use of a personal car has become a primary mode of transportation. The act of driving has also diversified its application to not just normal commute, but also to racing sport and ride sharing services. Nevertheless, it is sad to note that this act of driving has also proven to be dangerous and caused many fatalities in the past. According to the World Health Organization's global report on road safety in 2015, about 1.35 million fatalities are recorded each year due to road traffic crashes [1]. Such an alarming rate of crashes and fatalities has inspired and driven researchers and auto manufacturers across the world to find measures to improve vehicular safety, thereby saving lives.

Today, we are constantly making a step ahead towards automation in many areas, and this could potentially reduce the errors caused by humans. Vehicle automation is one among them where research and development is progressing rapidly, with the vision of safer vehicles and thereby improving road safety. According to Eriksson et al., driving is a complex task which requires the continuous integration of perception, cognition and a response in the form of a decision-making process [8]. Vehicle automation aims at reducing the workload of the driving task on the driver by providing precautionary support to mitigate potential collisions. According to the Society of Automobile Engineers (SAE) [2], the automation of driving can be classified into six levels from 0-5. As shown in Figure 1.1, automation will be deployed in gradual levels, where level 1,2 and 3 involve driver assistance systems which can assist the driver in the driving task. Level 4 and 5 is where full automation is in place and the human driver is not required to carry out any of the driving tasks [2]. This is a gradual transition of the control from the human driver to the system. Therefore, up to Level 4 of automation, the driver will be expected to respond to a request to intervene when the automated system is unsupported [3].

SAE Level	0	1	2	3	4	5
Name	No Driving Automation	Driver Assistance	Partial Driving Automation	Conditional Driving Automation	High Driving Automation	Full Driving Automation

Figure 1.1: The different levels of automation, as suggested by SAE [2]

An Automated Driving System (ADS) is a system that is capable of performing all the driving tasks autonomously [2]. Automated driving features are, to an extent, already present in today's vehicles, in the form of Advanced Driver Assistance Systems (ADAS). Many auto manufacturers such as Ford, GM, BMW, Volvo, etc have already started rolling out ADAS features for production vehicles such as Adaptive Cruise Control (ACC), Forward Collision Warning(FCW), Automatic Emergency Braking (AEB), Lane Departure Warning (LDW), to name a few. In the recent past, ADAS features have become a common basic feature in most production vehicles. In fact, according to a journal published in the US [4], as of May 2018, at least 92% of the vehicles were installed with at least one ADAS feature. Vehicle automation has the potential to not only improve road safety, but also has potential applications in the mining and freight industries [5]. Volvo is already conducting tests and estimates that fully autonomous mining trucks will be fully operational by the end of 2019 for the transport of limestone on a five kilometer stretch through tunnels at a mine in Norway [9].

According to a study, heavy duty vehicles have a pronounced effect on the flow of traffic [10], and study of the behaviour of trucks can help in transportation research. In the context of automated driving, one of the functions of an automated truck will be to perform an automated lane change maneuver. A lane change maneuver is usually initiated by the driver in order to enhance the driving condition/situation, mostly when the lane ahead is occupied by a slow-moving vehicle or a lane [12]. In some other cases, the vehicle makes a change of lane in order to enter or exit a ramp, to maintain safe and comfortable distance to vehicle stopped on the shoulder of the highway, or in order to choose a desired exit route at a toll booth. Such an Automated vehicle (AV) will however have to interact with Human Driven Vehicles (HDV) whilst performing a lane change maneuver. In order to ensure a smooth interaction between these AVs and HDVs, it is essential to study the driver behaviour for different driving scenarios.

2
Literature Review

Researchers have estimated that lane change crashes account for about 4-10 percent of all crashes [11]. According to the National Highway Transport Safety Administration (NHTSA), between 240,000 to 610,000 lane changing crashes are reported to the police annually in US and at least 60,000 people are injured, and a significant amount of property is also damaged [12] [20]. Besides, investigations have revealed that an estimated 386,000 lane change crashes go unreported in the US [21] [20]. Lane change crashes account for between 0.5 to 1.5 percent of all motor vehicle fatalities, which is about 224 to 732 fatalities per year in the US [12] [20]. An analysis from the German In-Depth Accident Study (GIDAS) from 1985 to 1999 showed that an average of about 5% of crashes occurred while changing lanes [22]. Such a high number of fatalities is reason enough for researchers and industries to study about lane change maneuvers.

A lane change maneuver is performed by a vehicle in order to change its position to a new destination lane in order to enhance the driving comfort. Such a maneuver involves planning, recognition and performing the maneuver. Due to this, it is essential for the vehicle performing the lane change to assess the behaviour of the vehicles in the surroundings before initiating such a lane change maneuver. 75 percent of all lane change, or lane merge crashes involves a recognition failure by the driver (i.e., the driver “did not see” the other vehicle until the crash was unavoidable) [23]. According to the National Highway Transport Safety Administration (NHTSA)[24], truck drivers are five times more susceptible to die as compared to an average worker as an occupational hazard, and 70 percent of the fatal crashes that occur involving a truck is due to the distraction and inattentiveness of the truck driver [25]. Lane changes on highways can cause unpredictable disruptions in traffic flow and alter the safety gap between vehicles [26]. This can consequently cause an interference to advanced driver assistance systems (ADAS) and autonomous vehicles (AV), to maintain adequate gap in a car following situation. Lane change manoeuvres have been proven to be a major contributing factor to traffic disturbances, especially on multi lane freeways [28].

2.1 Lane Change Maneuver

According to the NHTSA, a lane change is ”a driving maneuver in which a vehicle moves from one lane to another where both the lanes have the same direction of

travel"[32]. This report also suggests that the scenarios where the vehicle makes a lateral movement onto the shoulder of the road are not to be considered as a lane change. A lane change is a sequential process and hence requires the definition for the beginning and the end of the process. Various theories have been suggested about the factors which determine the 'start' of a lane change. The most convincing and comprehensive of them is the one suggested by Lee et al (2004)[33]. This definition says that the beginning of a lane change can be determined by either of the following

- A driver initiating a steering input in order to change the direction of the vehicle
- A lateral movement of the vehicle begins, relative to the lane
- A driver fixates gaze to the forward view after glancing at the side mirrors.

Similarly, defining the end of a lane change is also essential to understand the completion of the maneuver. Lee et al suggested that a lane changed is termed as completed when it normalizes in its adjacent destination lane. Additionally, a 100-Car Naturalistic Study was conducted in Virginia by Chen et al [34] in order to determine the start and end of a lane change, identify whether a lead vehicle is present during a lane change and to compute minimum TTC for each such lane change maneuver. According to this study, the lane change starts when the leading edge of the vehicle meets the lane edge and ends when the vehicle is completely within the boundaries of the adjacent lane [34].

According to a report by the National Highway Safety Administration (NHTSA) in the USA, a lane change maneuver is defined as a deliberate and substantial shift in the lateral position of a vehicle [35]. Such a maneuver involves the driver to gather information and make decisions about the driving conditions and gauge if such a lane change maneuver is possible and legal. Some cues that could tell the driver of the possibility of a lane change are checking the rear view mirrors for any following vehicle, check for blind spot using the rear view mirrors, gauge the distance to the lead vehicle, looking at the adjacent lanes (mostly in multi-lane freeway situation) for any following vehicles and also recognize if there are any other roadway limitations to change lane.

Depending on the nature or intent to perform the lane change maneuver, Zhao et al [38] proposed a theory of classifying the lane change maneuver into mandatory and discretionary lane changes. According to this, a mandatory lane change is one which is required to be performed, for example in case of a ramp exit, lane drop, or to yield to traffic near a ramp. A discretionary lane change is one in which the lane change change is performed in order to enhance the perceived driving conditions. This means that most of the lane changes except for the ones which are mandatory because of an infrastructural blockage, are classified as discretionary lane changes. This study also shows that mandatory lane changes are more aggressive than discretionary lane changes for the simple reason that they usually arise out of urgency, and hence are more safety critical. However, Pan et al [39], proposed a slightly different version of understanding the difference between mandatory and discretionary lane

changes. According to that paper, a mandatory lane change is executed when the driver must change lane in order to follow a certain path to the destination. In other words, the driver has to perform the lane change to mandatorily navigate to his/her final destination. A discretionary lane change is a maneuver made by a driver in the look out for better driving conditions to gain speed or travel time advantage.

2.2 Naturalistic Driving Study (NDS)

According to a European Naturalistic Study - UDrive [13], a naturalistic driving study is "undertaken to provide insight into driver behaviour during every day trips by recording details of the driver, the vehicle and the surroundings through unobtrusive data gathering equipment and without experimental control." In other words, a NDS is the data collection of road users performing their daily activities in real time traffic. According TU Dresden "Naturalistic driving studies investigate real traffic situations and provide useful information for critical events, (near-) crashes as well as normal driving in mixed traffic situations. The derived information have a great importance for the system conception of (partially) automated driving functions and ADAS. " [7] NDS can be used to better understand the driver and interaction with the vehicle, the roadway, trafc in all driving conditions. [6]Some significant advantages of naturalistic driving data are to testing intelligent systems, understand crash causation, investigate driver behaviour, analyze mobility, traffic efficiency and to evaluate such intelligent systems [29]. Some of the largest naturalistic driving studies conducted in the past are :

- 100CAR - (VTTI, USA) [14]
- 400 Car - Australia [15]
- UDrive - Europe [16]
- EuroFOT - Europe [17]
- SemiFOT - Europe [18]
- SHRP2 - USA [19]

2.3 The Second Strategic Highway Research Program (SHRP2)

The Second Strategic Highway Research Program (SHRP2) Naturalistic Driving Study was initiated to identify and address the role of driver performance and driver behavior in traffic safety [31]. The SHRP2 Naturalistic driving study is one of the largest study conducted where nearly 3247 participants took part [31]. The recruited participants drove their personal car fitted with sensors as naturally as they would normally drive. The data was collected over a period of 2 years from six sites across the United States (Indiana, Pennsylvania, Florida, New York, North Carolina, Washington). During this period, a total of 8714 cases of crash and near crash events were recorded. Participants were recruited by the coordinated efforts

of The Virginia Tech Transportation Institute (VTTI) and the Washington State Department of Transportation (DOT). The Data Acquisition System (DAS) used for this naturalistic driving study consisted of forward radar, four video cameras, accelerometers, vehicle network information, Global Positioning System(GPS), on-board computer vision lane tracking, and data storage capability [31].

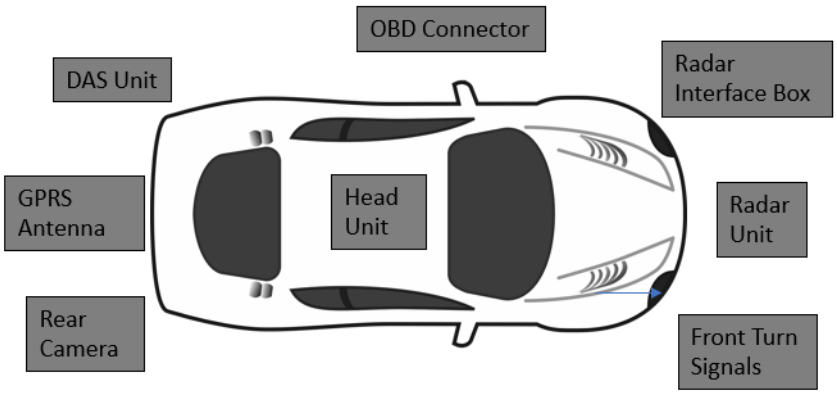

Figure 2.1: Schematic Diagram of the Data Acquisition System (DAS) [31]

As shown in Figure 2.1, the radar unit in SHRP2 was mounted at the front of the vehicle in order to record the information about the leading vehicle. The Head Unit (as seen in Figure 2.1) consists of four cameras which are located away from the driver's head, positioned away and behind the rear view mirror. This head unit also consists of accelerometers and a passive alcohol sensor. A rear facing camera and a data transmission system with a WiFi antenna are mounted on the rear window in order to capture the information of the following vehicle [31].

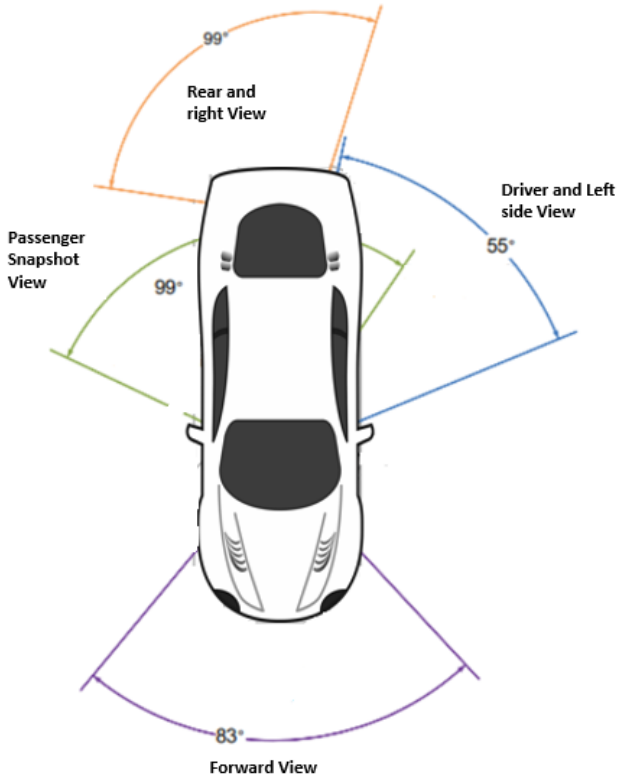

Figure 2.2: Field of View for the Data Acquisition System (DAS) [31]

Figure 2.2 shows the field of the view that was captured using the Data Acquisition System during the data collection stage from each vehicle mounted with sensors. From such instrumentation, it is possible to estimate different driver behaviour, environmental conditions and road characteristics that are extracted from crashes and near crashes. The data collected from SHRP2 is also intended to give a detailed understanding of driver behaviour and crash causation factors. With a broad set of stakeholders, the main goals of this naturalistic driving study included addressing the most critical needs in order to focus on meaningful targets to highway road users such as increasing safety, reducing congestion and improving road conditions for users [31].

2.4 Regulations in the USA

The road and vehicle regulations were used in the estimation of the speed of the heavy duty vehicle, during the data annotation stage from the video feed, as discussed in the methods section.

2.4.1 Length of a commercial vehicle

In the USA, the FHWA has set a guideline for automotive manufacturers to follow for the length of a commercial vehicle. The guidelines are laid out exclusively for

the maximum permissible length of the semitrailer or trailer, but does not set any guideline on the length of the cab. On the contrary, in Europe the guideline is set for the overall length of the truck, including the cab. This is also one of the noticeable reasons for the nose shaped cab in the USA, and flat faced cab in Europe for commercial trucks. As shown in Figure 2.3, the maximum permissible length of the semitrailer is 48 feet (14.63m) .

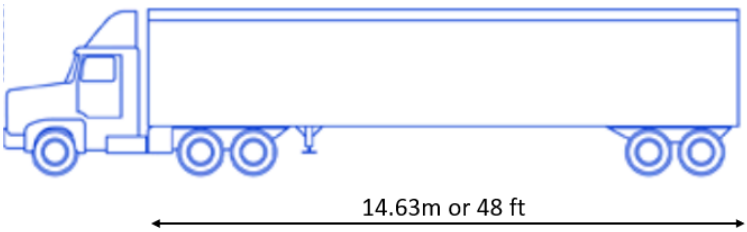

Figure 2.3: Length regulations for a truck with semitrailer combination [40]

On the other hand, for a truck with a trailer combination, the regulations are laid out for the semitrailer and the trailer individually. The maximum permissible length for the semitrailer and the trailer is 28.5 feet (8.69m) each when in a combination [40].

2.4.2 Lane Markings on highways

The lane markings on the expressways are set by the Federal Highway Administration of the Department of Transportation in the USA. Figure 2.4 shows that the distance between two lane markings is 9 feet (2.74m) and the length of each such lane marking is 3 feet (0.9m). Such standardization in the dimensions of the lane markings helps in the estimation of speeds and distances from the video feed.

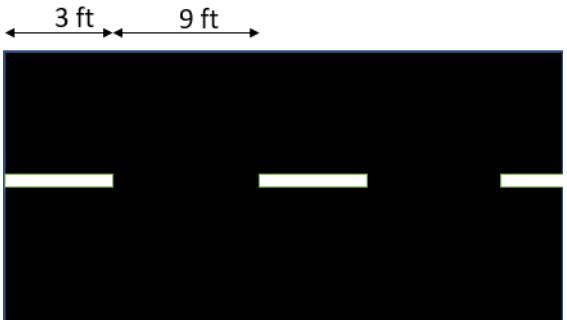

Figure 2.4: Figure shows the guidelines set by the FHWA of the USA for the lane markings along expressways in the USA [41]

2.5 Problem Statement

Various studies have been conducted in the past about modelling of the behaviour of a vehicle performing a lane change and how an automated vehicle should adapt

to the gap available around it before initiating a lane change maneuver [37]. Nevertheless, there is limited research into how the lane change performed by a vehicle (truck, in this case) affects the behaviour of the vehicles following it. A lane change maneuver performed by an automated truck will influence the reactions of the vehicle following it, in order to evade the situation to avoid a crash. Study of these responses is important to be able to enhance the systems in such automated vehicles, so that the automated vehicle does not perform a drastic lane change. The study of driver behaviour helps to model these variables, in order to enhance the automated systems in the trucks. In an era where automated trucks will be a common scenario on expressways, it is essential for the truck to perform a lane change that does not cause the following vehicle to perform a dangerous evasive maneuver. Automated trucks see its prime importance and efficiency in providing solutions for logistics and freight requirements and this will see large miles of highway driving. Hence, there is need to understand the behaviour of the following vehicle, so that the truck is efficiently adapting to the kinematics of the vehicles around it and causing the least disruption to traffic flow.

2.6 Aim

In this context of automated driving, this thesis mainly focuses on the analysis of safety critical lane change maneuvers performed by heavy duty vehicles, mainly trucks and truck with trailer combinations. Naturalistic Driving Data collected from instrumented cars as a part of the Second Strategic Highway Research Program (SHRP2) is used for this thesis. This data is collected from instrumented passenger cars fitted with forward facing cameras. The heavy duty vehicle performing the lane change is herein referred to as the Principal Other Vehicle (POV) and the following passenger car is called the Subject Vehicle (SV). Therefore, the lane changes being considered here are performed by heavy duty vehicles (POV) from the perspective of the following passenger car (SV). The evasive maneuvers of the driver of the SV are also analysed in order to understand what are the factors that triggered a response from the SV driver, as a reaction to the lane change performed by the POV ahead. In short, the main deliverables of this thesis can be summarized as follows.

- Characterisation of the lane change usually performed by truck drivers as a time sequenced event.
- Analysis of the interaction between the truck and the following passenger car at the time of lane change
- Analysis of the responses of the driver of the following car and the factors which trigger a reaction from this driver as a response to the lane change performed by the truck ahead.

3
Methodology

3.1 Definition of Lane Change

After studying from previous literature, a definition of a lane change specific to this thesis was formulated. As described earlier, for this thesis, a lane change was categorized as a mandatory lane change only if the lane change was to be performed due a lane closure as a result of an infrastructural blockage. The rational behind this was that an automated truck should be able to plan ahead and make the decision for a lane change without disrupting the flow of vehicles around it. Therefore, all other lane changes (eg., lane merging, lane entry/exit) were categorized as discretionary lane changes. The data used for this study is collected from forward facing cameras on passenger cars, herein referred to as the Subject Vehicle or SV. The cameras record the lane change performed by a heavy duty vehicle, herein referred to as the Principal Other Vehicle or POV. According to this, a lane change, either mandatory or discretionary, can be defined as a lateral maneuver in which a vehicle makes a lateral movement from its present lane in order to reach the adjacent lane.

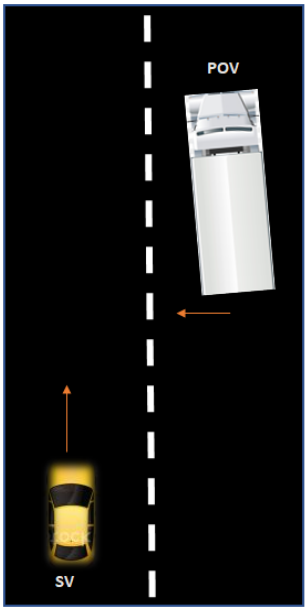

Figure 3.1: A depiction of the lane change scenario where the POV is performing the lane change and data is collected from the perspective of the following Subject Vehicle.

As shown in Figure 3.1, the lane change being considered is performed by a heavy duty vehicle. The start of a lane change is marked as the time when the first front wheel of the POV comes in contact with the lane boundary (herein referred to as T_1). The lane change is completed when all the wheels of the POV have crossed the lane boundary and reached the adjacent destination lane (herein referred to as T_c).

3.2 Stages of a Lane Change

After multiple iterative times of viewing and analysing the videos of lane change maneuvers, we noticed a pattern in the sequence of a lane change maneuver. Therefore it was hypothesised to divide the lane change maneuver into a sequence of time series events, based on the crossing of the wheels of the POV across the lane boundary. This would help us to understand the nature of the lane change and the time taken during each stage of the lane change maneuver. The lane change can be sequentially divided as shown in Figure 3.2. The explanation of each of the time series and the variables annotated during each time step is explained in detail in the later sections, but is as shown below.

- The time when the POV initiates a lateral movement (T_0)
- The time when the first front wheel of the POV touches the lane boundary (T_1)
- The time when first rear wheel of the last axle of the POV touches the lane boundary (T_2)
- The time when the second rear wheel of the last axle of the POV touches the lane boundary (T_3)
- The time when the lane change of the POV is completed (T_c)

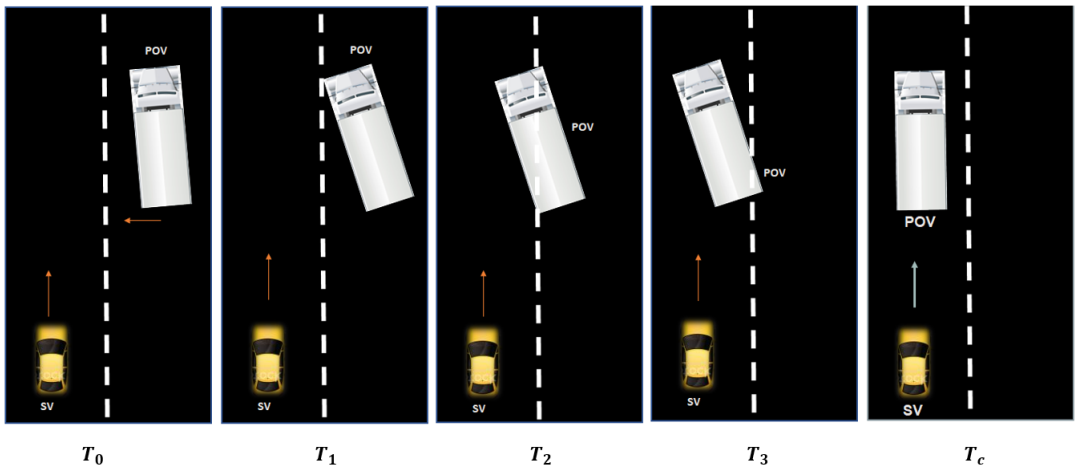

Figure 3.2: Figure shows the sequence of events during a lane change maneuver formulated for this thesis. T_0 is the time when the POV initiates the first lateral movement. T_1 is the time when the first front wheel of the POV touches the lane boundary. T_2 is the time when the first rear wheel touches the lane boundary. T_3 is the time when the second rear wheel touches the lane boundary. T_c is the time when the lane change is completed

3.3 Data

3.3.1 Data Access

Data privacy agreements are in place with the participants to ensure security of data. Since the data collected concerns the data collected from human research participants, the data access is granted only after the completion of a Protecting Human Research Participants (PHRP) online training. On completion of this training about the sensitive factors to consider while dealing with human research participants, the user becomes a 'Qualified Researcher'. Successively, the qualified researcher is given full access to the videos. Nevertheless, these videos do not reveal any personal or sensitive data about the participants. Each video feed is clipped for a length of 30 seconds by researchers/annotaters at VTTI over a period of time, and some variables which help filter out different scenarios have also been annotated based on a dictionary. All collected data is aggregated onto an interface (as shown in Figure 3.3) and available to be disseminated for research purposes.

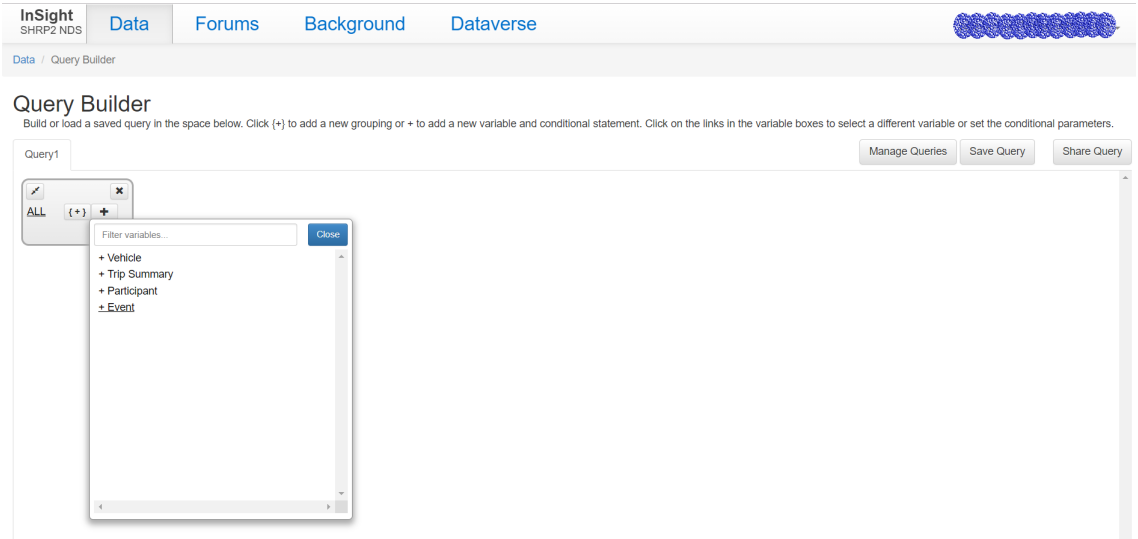

Figure 3.3: Image of the interface of SHRP2 data, where a query is set up using filters to get the desired event [31]

Note that work is a combination of using the SHRP2-insight database and using SHRP2 data under a data licence agreement (project) between Chalmers and VTTI, and required ethical considerations have been made.

3.3.2 Data Selection

Query Set up

Since this data set contains large amounts of data and many events in different scenarios, there is a need to filter out the required cases needed for this study.

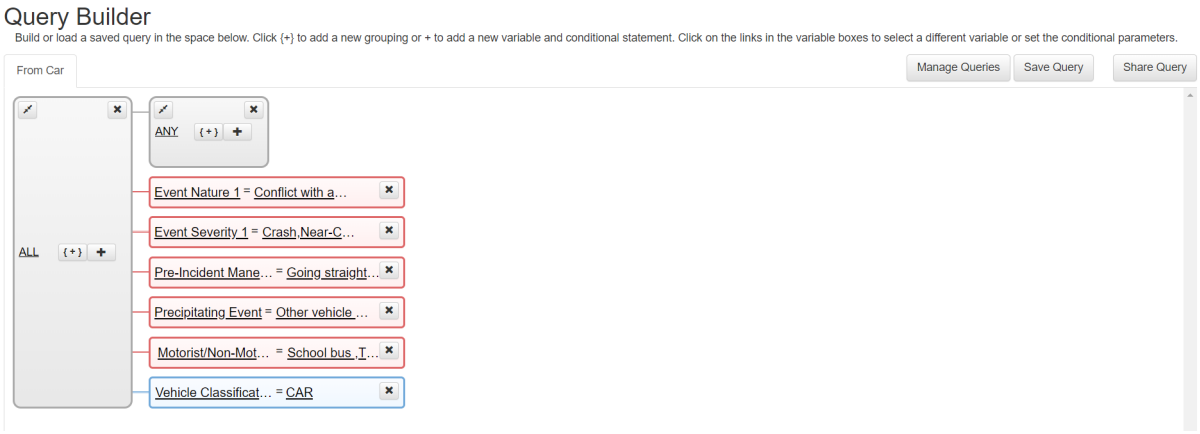

Figure 3.4: Image of the Query Builder and the filters applied to arrive at the relevant lane change scenarios [31].

By means of a Query Builder (as shown in Figure 3.4), the data set can be filtered based on certain variables which have previously been annotated by VTTI. A dictionary of all the variables used by VTTI is available to be used by researchers who gain access to this data. The variables used for this thesis are shown in Table 3.1.

Table 3.1: Variables used to set up query

Variables for Query set-up	**Short Description**
Event Nature 1	Suggests the nature of the conflict event
Event Severity 1	Suggests the severity of the conflict event (crash, near crash, etc)
Precipitating event	State or action of the driver that caused the sequence of events under analysis
Pre-incident maneuver	Last action performed by driver before the occurance of the Precipitating event
Motorist/Non-motorist/Animal/Object 2	Specifies the other vehicle/object involved in the conflict (POV)
Vehicle classification	Specifies the subject vehicle category (SV)

The SHRP2 data set consists of various crash and near crash events recorded over a period of time. This data set was then filtered by setting a query using variables (as shown in Figure 3.4).

Event Nature

This variable accounts for the "nature of the other vehicle involved in the conflict, during a crash or a near crash event." Since this study required to analyze the lane change behaviour of a vehicle performing a lane change, the following filters were relevant to include during set up of query. The full list of sub categories under this are in the Appendix A.1.

- Conflict with a lead vehicle
- Conflict with vehicle in adjacent lane

- Conflict with merging vehicle

Event Severity

This variable accounts for ”the severity of the event or incident” that is under analysis. ”The categorization is made based on the outcome of the event (crash, near crash, crash relevant, non conflict). According to this, a crash is defined as any contact made by the subject vehicle with another object or vehicle, which is either moving or stationary. The contact also includes with roadside barriers, objects on or off the roadway, pedestrians, cyclists, or animals. A near crash is defined as a circumstance when a vehicle has to perform a swift and urgent evasive maneuver in order to avoid a crash [44].” For this study, only crash and near crash events were considered.

Precipitating event

This variable accounts for ”the state or action of the subject vehicle or any other object that initiated the sequence of events that led to the event” under analysis. ”This variable takes into account the kinematic measure of the vehicle but does not account for driver behaviour factors such as driver distraction or fatigue [44].” See Appendix A.2 for the detailed list of filters and their explanations. The following filters were chosen for this study.

- Other vehicle lane change - left, sideswipe threat
- Other vehicle lane change - right, sideswipe threat
- Other vehicle lane change - left other
- Other vehicle lane change - right other
- Other vehicle lane change - left in front of subject
- Other vehicle lane change - right in front of subject
- Other vehicle - in crossover

Pre-incident maneuver

This variable accounts for ”the last action performed by the driver of the subject vehicle just before or at the time of the precipitating event [44].” Similar to the precipitating event, this variable does not account for the actions of the driver inside the vehicle, but is only a vehicle kinematic measure. See Appendix A.3 for the full list of the sub categories. Among all the listed variables, for this study, the following filters were used to set up the query. The reason for this inclusion is to be able to account for different states of the subject vehicle (travelling straight, merging or negotiating) at the time when the POV initiates a lane change.

- Going straight, constant speed
- Going straight, accelerating
- Going straight, but with unintentional "drifting" within lane or across lanes
- Decelerating in traffic lane
- Starting in traffic lane
- Turning left
- Negotiating a curve

- Changing lanes
- Merging
- Passing or overtaking another vehicle

Motorist/Non-motorist/Animal/Object 2

This variable accounts for "the nature of the Principal Other Vehicle that is involved in the event" under analysis . "This object restricts the subject vehicle to be able to perform an evasive maneuver [44]. " See Appendix A.4 for the full list. For this study, truck with semitrailer, truck with trailers and buses are filtered using the query.

Vehicle classification

This variable accounts for the nature of the Subject Vehicle, based on the body style [45]. The scope of this study is limited only to analyze the reactions of a car driver, and hence only car is filtered using the query.

3.3.3 Data Reduction

On selection of the variables to set up the query, as shown in Table 3.1, a filtered number of events were obtained which was ready to be viewed and analyzed. This filtering yielded a total of 126 cases, based on the set filters. Further, each of these individual cases were viewed and analyzed carefully, in order to understand if it fit in the scope of the thesis or not. One primary consideration during this phase was that the thesis focused on studying the lane changes performed by heavy duty vehicles, primarily trucks, and therefore the lane changes performed by the Subject Vehicle could not be considered. Since another primary focus was to understand the reactions of the SV driver, the lane changes which did not trigger a reaction from the driver of the SV was considered unfit. After careful analysis of all the videos, it was noticed that certain events did not fall in the scope of the thesis and was therefore excluded. The exclusion criteria for these events are discussed in the further section. Nevertheless, after such an exclusion, the entire data set was reduced to a total of 87 relevant lane change events, which fit into the scope of this thesis.

3.3.3.1 Exclusion criteria for data

Even after applying the desired filters, certain events were found which did not fit into the scope of the thesis and these events were excluded. The main rationale here was to understand and argue if an analysis of the event would yield results about the reactions of the driver of the SV.

Table 3.2: Table showing the reason for exclusion of a particular case, the number of cases excluded and the reason for such an exclusion

Number of events	Reason for exclusion	Explanation
8	SV's lane merged	Mostly in a highway driving scenario where the SV's lane merges and it looks like the POV performed a lane change, but actually since the SV's lane ended, the SV had to drive into the POV's lane.
7	SV performs the lane change	Most often in a highway driving scenario where the SV performs the lane change in the direction of the POV. Since the thesis aims at studying the reactions of the following SV, these events do not help to understand how the SV reacted, when the POV performed the lane change.
5	POV drifts close to lane boundary	As seen from the video, a fully loaded POV drifts in the direction of the SV, mostly in a curved road scenario, but doesn't even touch the lane boundary. This does not classify as a lane change for this thesis.
3	Turning at an intersection	In a slow moving scenario, SV tries to overtake the POV from the left, but the POV in turn makes a left run at an intersection. The SV thereby waits and then makes a turn as well. This does not help to understand driver's responses as both vehicles are at low speeds and in urban driving conditions.
2	SV and POV are in the same lane	During these events, the SV and POV are initially in the same lane and then simultaneously perform the lane change to an adjacent lane. This does not help to study the reaction of the SV driver as the lane change is initiated by the SV itself.
2	Unclear video	Very poor quality of camera and radars make it impossible to understand or decipher anything from the video.
1	POV is a car	In this event, the SV reacts by braking due to the sudden maneuvers performed by a POV which is a car. This car performs such a sudden maneuver because of a lane change performed by its POV, which is a truck.
1	SV drift close to lane boundary	The SV drifts close to the lane boundary making it look like a lane change.

3.3.4 Data Annotation

After filtering the data for relevant cases, the next part of the thesis was to identify, different variables that would describe the lane change maneuver. In other words, these variables would have to recreate the entire lane change scenario in the absence of a video feed. There were two types of variables that were identified, variables annotated by VTTI and variables manually annotated from the dataset. Variable identification was an iterative process and the video feeds of the 89 lane changes were watched multiple times to identify variables which could describe the situation. Some of the example of the variables annotated manually were the speed of SV and POV at different stages of the lane change, the longitudinal distance and relative speed between the SV and POV etc as shown in Section 3.3.4.1. On the other hand incident type, traffic density, road alignment are some example of Variables annotated by VTTI which is discussed in Section 3.3.4.2

3.3.4.1 Manually annotated variables

Since the variables available from the SHRP2 database was limited, there was a need to manually annotate certain variables which could help to recreate the entire lane change maneuver. Estimation techniques were used (discussed in later sections) to estimate the speed of the POV during the different stages of lane change. Some other variables that were useful to describe the scenario were direction of lane change, the motivation for the POV to perform a lane change, etc. It is to be noted that this

was an iterative process, where the videos were watched multiple times in order to come to a conclusion.

Table 3.3: Table shows an overview of the variables that were manually annotated from the data

POV Vehicle type
Lane change direction
Number of lanes
Number of wheels of the POV
Blinker activation (Yes/No)
POV lane change motivation
Intentional / Unintentional Lane Change
Completed / Aborted Lane Change
Mandatory / Discretionary Lane Change
Overshadowing Maneuver (Yes/No)
Duration of overshadow (D_{os})

POV vehicle type

Depending on the type of vehicle performing the lane change, i.e, the POV was categorized. The main focus of this thesis was to look at the lane changes performed by trucks, and hence only heavy duty vehicle were considered. More precisely, the categories were formulated based on their axles and size. The classification is shown in Table 3.4.

Table 3.4: Table showing the categorization of the type of POV

Type of vehicle	**No. of vehicles**
Single Unit Vehicles (Two-axles, Four-Tire)	3
Single Unit Trucks (Two-Axle, Six-Tire)	10
Three-Axle Single-Unit Truck	2
Five-Axle Single Trailer Truck	57
Six or more-Axle Single Trailer Truck	5
Bus	12

Lane change direction

Based on the direction of lane change performed by the POV, the lane change is classified as Left-to-Right and Right-to-Left lane changes. Left-to-Right lane changes are usually performed to enable ramp exits or in order to complete an

overtaking of a slow lead vehicle. Right-to-Left lane changes are usually performed in order to overtake a slow lead vehicle or during ramp entry scenarios.

Number of lanes

At the time of the incident (i.e., the lane change maneuver), the number of lanes in the highway are noted. The main motivation behind annotating this variable is to understand the scope that the SV had in order to perform an evasive maneuver. It would also be helpful to understand and relate this variable to single or multiple lane changes performed by the driver of the POV.

Number of wheels of the POV

This variable accounts for the number of wheels of the POV under consideration. This was manually annotated by looking at the video feed. The variable also find relation to the length of the vehicle and thereby a relation to the time taken to complete a lane change.

Blinker activation

A lane change maneuver is initiated by showing intent to the vehicles following it, by means of activating a blinker. Blinker is a strong indication to the following vehicle to be cautious of the lane change and be able to adapt its speed to the situation. Hence, this variable takes into account if the POV activated the blinker or not before initiating a lateral movement in order to perform the lane change maneuver.

POV lane change motivation

After careful understanding and analysis of the videos, the motivation for the POV to perform the lane change was formulated. From the video, for some cases it was observed that there was noticeable motivation for the POV to perform a lane change. Nevertheless, the most common motivations were ramp entry/exits, to overtake a slow leading vehicle, lane closure/lane merging, desired exit at toll booth.

Intentional / Unintentional Lane Change

Based on the intention of the driver to initiate the lane change maneuver, lane changes can be classified into intentional lane changes and intentional lane changes. Intentional lane changes are the ones where the driver intentionally initiates the lateral movement of the vehicle within its lane, in order to reach the adjacent destination lane. An unintentional lane change is most often the case when the vehicle drifts into the other lane. This is often noticed in a road curve scenario for long combination vehicles. Sometimes, drowsiness and driver inattention are also factors which cause such an unintentional lane change. Most common technique of finding cues for such driver distraction are by the use of eye trackers to study the gaze behaviour of the drivers. Fixation points can reveal relevant information about the driver attention patterns and the cause of distraction.

Completed / Aborted Lane Change

Before a vehicle initiates a lane change, it is essential to gauge the kinematics of the vehicle surrounding the vehicle, so as to cause minimal disruptions in traffic flow. In most cases, the vehicle is able to successfully transition from its own lane to its destination/target lane. When a vehicle has normalized in its destination lane, it can be classified as a completed lane change maneuver. In some cases, the vehicle notices another following vehicle approaching at a high speed or notices a vehicle in its blind spot after initiating the lateral movement. In such cases, the driver aborts the lane change and returns to its original lane. In some other cases, the video feed ends in between the completion of the lane change, and hence it is difficult to gauge if the driver would have completed the maneuver later or not. Such lane changes have been classified as "Incomplete" lane changes.

Mandatory / Discretionary Lane Change

A vehicle, on a normal basis, initiates a lane change maneuver in order to avoid an obstruction in its road ahead. Based on the need for the vehicle to perform such a lane change, the maneuvers can be classified as mandatory and discretionary lane changes. Various literature suggests different definitions of the same, but the most relevant combination of them was used for this thesis. A mandatory lane change is one where the lane ahead is closed or blocked (mostly, infrastructural) and the vehicle has to forcibly change lane in order to avoid a collision. Most often, this is an unavoidable maneuver and sudden. Hence, these lane changes cause larger effects on the vehicles following. Discretionary lane changes are initiated by the driver of the vehicle at his/her own discretion. Even the scenarios where the driver had to perform a sudden maneuver to take a ramp exit are considered as discretionary, keeping in mind the fact that such a maneuver are the ones that need to be eliminated for an automated truck to perform.

Overshadowing Maneuver

After manually watching all the videos that involved a lane change, it was noticed that in many cases the truck would initiate a lane change and intrude into the SV's lane but eventually ends up aborting or delaying the lane change on noticing a fast approaching vehicle from behind. It was also noticed that even though the POV aborted the lane change in some cases, the SV was forced to perform an evasive maneuver anyways. Such an intrusion by the POV caused reaction from the SV by braking or steering. In other cases when the POV completed the lane change, there was a lateral intrusion into the SV's lane for a time period to allow the SV to pass or evade the POV and then the POV would complete the lane change. Such a maneuver when the POV makes a two step maneuver before finally reaching the destination lane is termed as an overshadowing maneuver. This variable accounts for the cases whether there was an overshadowing maneuver or not.

Duration of overshadow (D_{os})

As described in Section 3.3.4.1, an overshadowing maneuver is of importance for this study. This variable accounts for the time for which the POV performs an overshadowing maneuver. For the cases which has an overshadowing maneuver, the start of an overshadowing maneuver is defined by the time when the vehicle cuts in to the SV's lane. The end of an overshadowing maneuver is marked by the time when the POV has stopped intruding into the SV's lane, for both completed and aborted lane changes.

Time Series

The lane change of the POV is categorized into a time series of events (See Figure 3.2). The video was annotated for the time stamps during the maneuver for both the POV as well as the SV.

Table 3.5: Table showing the time sequences of the lane change maneuver that were manually annotated from the individual videos for each case.

The time when the POV initiates a lateral movement (T_0)
The time when the first front wheel of the POV touches the lane boundary (T_1)
The time when first rear wheel of the POV touches the lane boundary (T_2)
The time when the second rear wheel of the POV touches the lane boundary (T_3)
The time when the lane change of the POV is completed (T_c)
The time when the POV activates the blinkers (T_{blink})
The time when the SV brakes (T_b)
The time when the SV steers (T_s)

The time when the POV initiates a lateral movement (T_0)

Initially, the SV and the POV are travelling in adjacent lanes and the POV is the lead vehicle. The first stage of a lane change is the initiation of a lateral movement of the POV in the direction of the SV's lane. The time instant when the POV initiates this lateral movement is denoted and referred to as T_0. Another indication of the initiation of a lane change is the activation of blinkers. The time instant when the POV activates the blinkers has also been annotated and is discussed in the later sections. At T_0, the video was annotated for certain variables manually.

- Speed of the SV (kph) - The speed of the subject vehicle when the POV initiates a lateral movement in the direction of SV's lane is extracted from the time series data.
- Speed of the POV (kph) - Since the POV (truck) is the leading vehicle and had no sensor systems in it, the data was available only for the SV. Hence, the speed of the POV was calculated using estimation techniques. That is, the distance between two lane markings (as shown in Figure 2.4) is 12 feet. That includes 3 feet for the lane marking and 9 feet between two lane markings. The video feed contains time stamp recorded continuously. The time the POV takes to pass three such lane markings are noted. The speed of the POV is now computed with a simple speed-distance formula.
- Longitudinal distance between SV and POV at the time instant when the POV begins the lateral movement is also estimated. Similar to the speed calculation previously, the time taken for the SV to go from its position at T_0 to the point where the POV was at T_0 is found from the difference in the time stamp of the video feed. During this time, the average speed of the SV is also calculated from the data. Thereby, the distance is also calculated using a simple speed-distance formula. This method does not account for the acceleration of the SV

during this short traverse. This absolute longitudinal distance could possibly provide some insights about how close the SV and POV were when the POV initiated the lateral movement.
- Lateral distance between POV and the lane boundary at the time when the POV initiated a lateral movement. According to the FHWA, the width of a lane on the expressway is 3.6m, and the permissible width of the truck is 2.4m, which leaves 1.1m on either side if the POV is in the middle of the lane. A rough estimate is made on remaining gap based on how close the POV is to the lane boundary.
- Relative speed between the SV and the POV at T_0.
- Overlap between SV and POV - An approximate value (in percentage) of the lateral and longitudinal overlap that existed between the SV and the POV at the time when the POV initiated a lateral movement was noted. These values of overlap were noted as an approximate percentage of the length of the body overlapping.

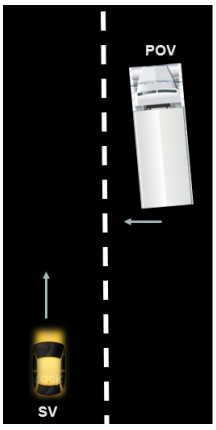

Figure 3.5: Graphical representation of the time when the POV first starts a lateral movement (T_0)

The time when the first front wheel of the POV touches the lane boundary (T_1)

After initiation of a lateral movement towards the SV's lane, the POV has to cut in to the SV's lane. This time instant when the first wheel comes in contact with the lane boundary, or the cut-in point is referred to as T_1 (as shown in Figure 3.6. At T_1, the video was annotated for certain variables manually.

- Speed of the SV (kph) - The speed of the subject vehicle when the POV touches the lane boundary is noted. This speed data was extracted from the time-series data.
- Speed of the POV (kph) - The speed of the POV at the time instant when it first touches the lane boundary (or the cut-in point) is noted. The speed is calculated using estimation methods, similar to T_0.
- Longitudinal distance to the cut-in point (D_{cut-in}) - The longitudinal distance from the SV to the point where the POV cuts in is noted. This distance is a safety relevant indicator of how close by the SV was when the POV cuts in to

SV's lane. This variable was calculated using similar estimation methods as for T_0.

- Overlap between SV and POV - An approximate value (in percentage) of the lateral and longitudinal overlap that existed between the SV and the POV at the time when the POV cuts in was noted. A lateral overlap would suggest if the SV was in a possible blindspot when the POV cuts in to the lane boundary. The longitudinal overlap would suggest if both the vehicles were in the same lane or adjacent lanes at this time instant. These values of overlap were noted as an approximate percentage of the length of the body overlapping.
- Relative speed between the SV and the POV at T_1.

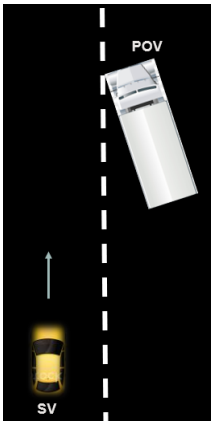

Figure 3.6: Graphical representation of the time when the POV first makes contact with the lane boundary (T_1)

The time when first rear wheel of the POV touches the lane boundary (T_2)

The next time instant annotated for is time when the first rear wheel of the POV touches the lane boundary (as shown in Figure 3.7) and is denoted and referred to as T_2. At T_2, the video was annotated for certain variables manually.

- Speed of the SV (kph) - The speed of the subject vehicle when the first rear wheel of the POV touches the lane boundary is noted. This speed is extracted from the time-series data.

- Longitudinal distance between the SV and the POV - The longitudinal distance between the rear of the POV and front of the SV at the time instant when the first rear wheel of the POV touches the lane boundary is also noted using similar estimation methods as done for T_0.

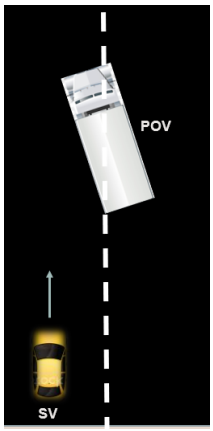

Figure 3.7: Graphical representation of the time when the first rear wheel of the POV touches the lane boundary (T_2) .

The time when the second rear wheel of the POV touches the lane boundary (T_3)

The last step before the completion of lane change is for all the wheels to cross the lane boundary into the destination lane. This time instant when the second or last rear wheel crosses the lane boundary is herein denoted and referred to as T_3 (as shown in Figure 3.8). At T_3, the video was annotated for certain variables manually.

- Speed of the SV (kph) - The speed of the subject vehicle when the second rear wheel of the POV touches the lane boundary is noted. This speed data was extracted from the time-series data.

- Longitudinal distance between SV and POV - The longitudinal distance between the rear of the POV and front of the SV at the time instant when the second rear wheel of the POV touches the lane boundary is also noted using similar estimation methods as done for T_0.

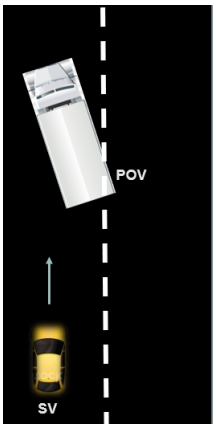

Figure 3.8: Graphical representation of the time when the second rear wheel of the POV touches the lane boundary (T_3)

The time when the lane change is completed (T_c)

For this study, the lane change is defined as a complete lane change when all the wheels of the POV have reached the destination lane (as shown in Figure 3.9). This time instant when all the wheels have crossed the lane boundary and the vehicle normalizes in its destination lane is termed as lane change completion time, denoted as T_c. At this time instant, the speed of the POV is also calculated using estimation methods as used for the calculation of the speed of the POV at T_0.

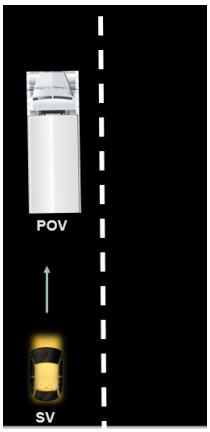

Figure 3.9: Graphical representation of the time when all the wheels of the POV is in the SV's lane ,i.e., the lane change is completed. (T_c)

The time when the POV activates the blinkers (T_{blink})

A very strong cue that shows the intent before starting a lane change maneuver is the activation of blinkers. As a thumb rule, all vehicles performing a lane change should blink adequately before starting a lateral movement. Since this was considered an important parameter to study the responses of the SV, the time of blinker activation of the POV was annotated and is herein denoted and referred to as T_{blink}. At this time instant, the speed of the SV (in kph) is also extracted from the SHRP2 data.

The time when the SV brakes (T_b)

The variables until now accounted for the characteristics during time instances for the POV. When the POV performs a lane change, the SV reacts by performing an evasive maneuver in order to avoid a collision. Such a reaction is of prime importance for this study and therefore the time instant when the SV braked as a response to an activity of the POV was noted. The start of braking was calculated when the speed of the SV reduced significantly and this is also verified from the video.

The time when the SV steers (T_s)

Another evasive maneuver usually performed by drivers to evade a collision is to steer away from the problem. Since this response was also considered interesting for this study, the time instant when the SV steered as an evasive response to movement

of the POV was noted. This time instant is calculated from a change in the yaw rate recorded and is a measure of the steering angle.

Duration of evasive maneuver of the SV

As a response to the lane change performed by the POV and depending on how critical the event is, the SV engages in an evasive maneuver in order to avoid a collision. This variable accounts for the duration taken by the SV in order to perform such an evasive maneuver. The start of this evasive maneuver is defined as the start of braking or steering (whichever comes first). The end of the evasive maneuver is defined as the end of the braking or steering, whichever comes last such that the SV has returned to its original state of driving before the event.

Lateral Intrusion

A vehicle begins a lane change manoeuvre by initiating a lateral movement towards the lane edge. Sometimes, the driver attempts a lane change manoeuvre but aborts the lane change on noticing a fast approaching vehicle at its blind spot or on realizing that the lane change may be too safety critical, and therefore aborts the lane change. Such an act is a lateral intrusion into the SV's lane and also causes an evasive response from the SV driver. The following three variables accounts for this intrusion factor.

a. Duration for which POV intrudes into SV's lane(D_{li})

This variable accounts for the duration for which the POV intruded into the SV's lane, for aborted lane changes. The start of intrusion is marked by the time instant at which the one of wheels of the POV enters into the SV's lane and the end is marked when the POV returns back into its original lane. The difference from the time stamps is the duration for which the POV caused an intrusion into the SV's lane.

b. Maximum lane intrusion by POV into SV's lane (Approximate in %)

This variable accounts for the maximum lateral distance of the lane that the POV intruded. This is a approximate estimated value as a percentage of the lane intruded, since the width of a lane is constant on the highway. This variable could provide valuable information on how much allowance it gave the SV in order to perform an evasive maneuver.

c. Time at max. intrusion

This variable accounts for the time instant at which the maximum lateral intrusion occurred.

3.3.4.2 Variables annotated by VTTI (SHRP2)

After collection of large scale data from all the vehicles during the SHRP2 data collection program, data reductionists were recruited by the Virginia Tech Transportation Institute (VTTI) in order to reduce and set baselines for the cases. These researchers also annotated different variables in order for it to be used by researchers across the world. Such a labour intensive work has been helpful in being able to filter out the scenarios based on the desired parameters.

Table 3.6: Variables annotated from the SHRP2 dictionary [44]

Incident Type
Precipitating Event
Evasive Maneuver
Traffic Density
Weather Condition
Surface Condition
Day/Night
Locality
Road Alignment

Incident Type

This variable accounts for "the type of conflict that the SV engages in, based on the severity and type of the other vehicle involved in the event." For the full list of categories, See Appendix A.6. For this study, the variable **Sideswipe, same direction (left or right)** was considered as the most important and interesting variable as it involved the changed of a vehicle's position from one lane to another.

Precipitating Event

See Section 3.3.2 for detailed information on the definition of Precipitating event. Among all the filters available (See Appendix A.2), the ones chosen for this study was the lane change in front of the subject, and a left or right sideswipe threat [44].

Evasive Maneuver

This variable accounts for "the reaction of the driver in terms of the evasive maneuver that the SV driver engaged in, in order to avoid a collision. This is as a response to the act performed by the POV." This data is collected as a combination of the vehicle kinematic measure and the video feed. For this study, the categories used were braked, steered,and brake steer.

Traffic Density

This variable accounts for "the level of traffic that was present at the time of the start of the Precipitating event in the SV's lane." The categorization (See Appendix

A.5 for full list of categories) is made based on the number of vehicles that were present in the SV's lane and in the same direction of travel.

Weather Condition

This variable accounts for "the weather condition at the time of the start of the Precipitating event." Accordingly, the classification is made as one of Clear/Party Cloudy, Overcast, Wind Gusts, Fog, Mist/Light Rain, Raining, Snowing, Sleeting, Rain & Fog, Snow/Sleet & Fog or No adverse condition

Surface Condition

This variable accounts for "the type of roadway surface condition that would affect the vehicle's coefficient of friction at the start of the Precipitating Event. Includes weather-related surface conditions as well as non-paved surface descriptions."

Day/Night

This variable accounts for "the time of day, based on the lighting in the environment." During the manual annotation of the videos, it was noticed that the POV sometimes failed to notice the approaching SV during poor lighting conditions and therefore this variable was thought of to be interesting for the analysis and to understand if the lighting had any effect on the brake reaction time of the SV driver..

Locality

This variable accounts for "the surroundings at the time of the Precipitating Event that may or may not influence the traffic flow." From the list of categories in the dictionary, the data set was categorized into Urban, Rural and Highway.

Road Alignment

This variable accounts for "the curvature of the roadway in the direction of travel of the SV at the time of the Precipitating Event." Based on this the road alignment is categorized as Straight, curve left or curve right [44].

4

Results

This section presents the results obtained from the analysis of the data. 89 lane change events were analyzed and studied in detail. Based on the need for the initiation of the lane change, the lane changes were classified as mandatory or discretionary lane changes. Out of the 89 cases, 95%(85 cases) were discretionary and the remaining 5% (4 cases) were mandatory lane changes, as shown in Figure 4.1. Out of the discretionary lane changes, over 50% of the initiated lane changes were completed, nearly 27% of them were aborted and 20% of them were classified as incomplete lane changes. The reason to classify them as 'incomplete' lane changes was because the videos on the SHRP2 web interface were snipped for 30 seconds. Therefore, some videos ended before it was clear if the lane change was completed or aborted.

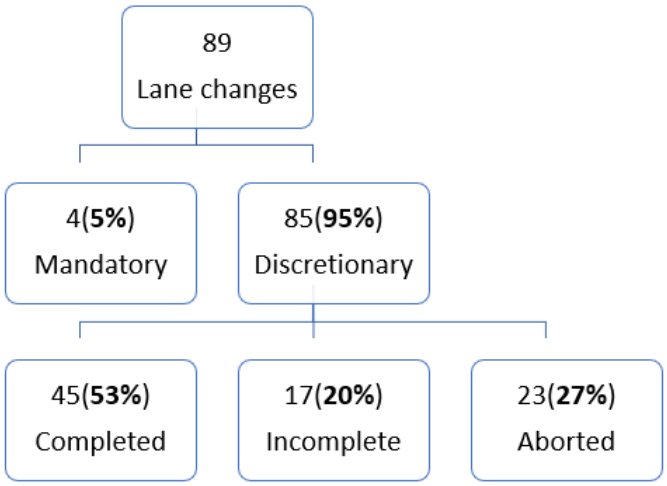

Figure 4.1: Lane change classification based on the lane change completion

Figure 4.2 gives more information about the discretionary lane changes and how they were classified. Among the 85 discretionary lane changes, 71% of the lane changes were from right-left direction with the remaining being left-right direction. For a right-left lane change, in 70% of the cases, the principle other vehicle (POV) indicates the intention to make a lane change by blinking. However, in the left-right lane changes, only 56 % of the vehicles blinked. It was noticed that there were higher number of cases when the POV used the blinker to show intention, as compared to a left-right lane change.

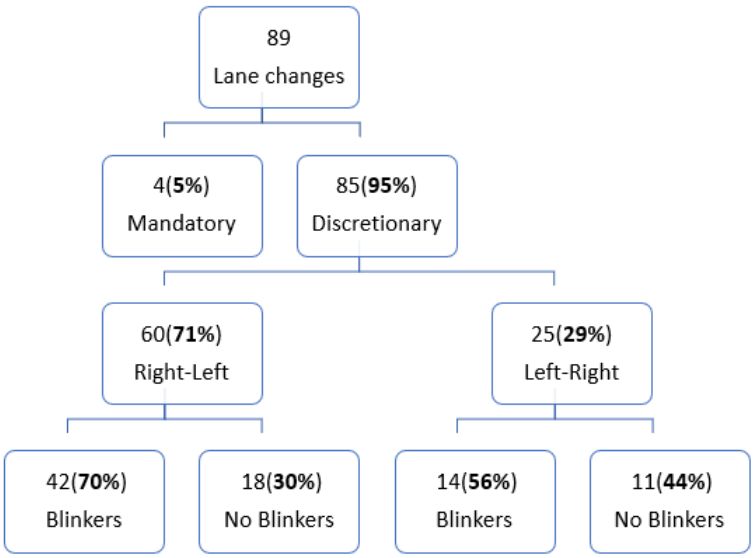

Figure 4.2: Lane change classification based on the direction and blinking

Figure 4.3 gives information about the evasive maneuver performed by the subject vehicle (SV) due to the lane changes performed by the POV. Out of the 60 cases of right-left discretionary lane changes, 60% of the vehicles braked to avoid a crash with the POV, 33% of the vehicles braked & steered to avoid the crash, and 6% of the vehicles only steered to avoid a crash. On the other hand, in left-right lane changes, 60% of vehicles braked & steered, and the remaining 40% only braked. Higher number of vehicles braked & steered while performing a lane change in the left-right direction, as compared to the right-left lane change.

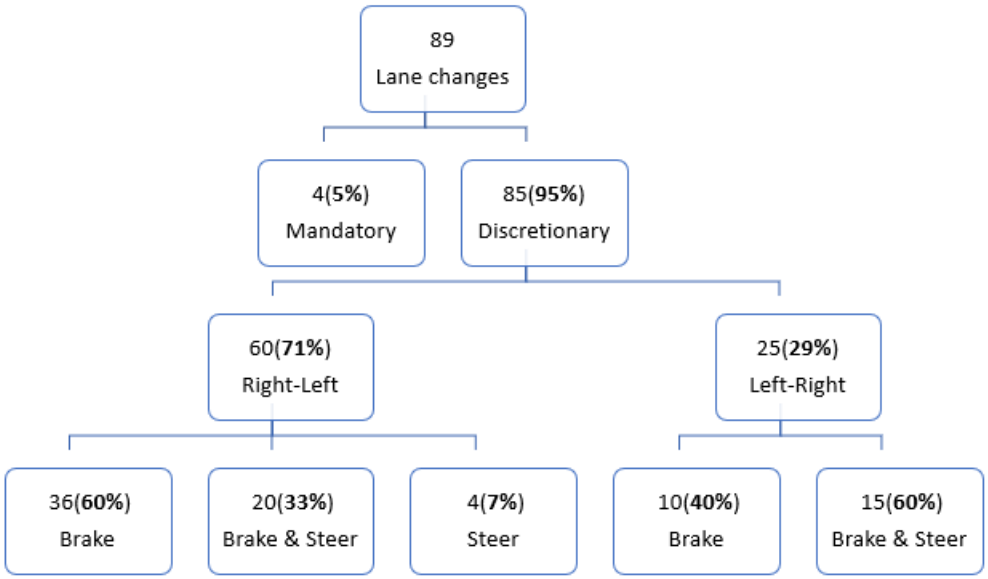

Figure 4.3: Lane change classification based on the direction and evasive action

4.1 Quantitative description of the lane change

Table 4.1 shows the average time duration to complete a lane change by different types of vehicles, based on the number of axles. This duration is the time from when the POV makes the first lateral movement (T_0) till the POV is comfortably in the SV's lane (T_c). The number of cases reported in the Table 4.1 against each type of vehicle corresponds to the number of vehicles completing a lane change. The actual number of vehicles under each category of vehicle are in Table 3.4. Two axle (both four and six tires) and three axle vehicles take less than 4 seconds to complete a lane change while five and six or more axle truck take more than 6 seconds to complete the lane change. This can be attributed to the fact that shorter length of vehicle will mean shorter duration to complete the lane change.

Table 4.1: Average lane change time duration for different types of vehicles

Type of vehicle	**No. of cases**	**Average Lane Change time (s)**
Single Unit Vehicles (Two-axles, Four-Tire)	1	2.3
Single Unit Trucks (Two-Axle, Six-Tire)	6	3.8
Three-Axle Single-Unit Truck	1	2.7
Five-Axle Single Trailer Truck	30	6.2
Six or more-Axle Single Trailer Truck	3	6.1
Bus	7	6.6

Table 4.2 shows the time duration taken by different types of vehicles from the first lateral movement (T_0) till the first front wheel touches the lane boundary (T_1). It is observed that the number of cases in the Table 4.2 is almost equal to the actual number of cases under each vehicle type reported in Table 3.4. This means that in most of the cases investigated in this study, the vehicle makes a lateral motion and touches the lane boundary. The average time duration for single unit trucks (four and six tires), three axle and five axle trucks were around 2 seconds. The average time is the shortest for six or more axle trucks. Most of the six or more axle trucks were travelling close to the lane boundary and therefore had a short time duration to complete this stage (T_0-T_1).

Table 4.2: Average $T_0 - T_1$ time duration for different types of vehicles

Type of vehicle	**No. of cases**	**Average T_0 - T_1 duration(s)**
Single Unit Vehicles (Two-axles, Four-Tire)	3	1.8
Single Unit Trucks (Two-Axle, Six-Tire)	9	1.8
Three-Axle Single-Unit Truck	2	1.5
Five-Axle Single Trailer Truck	55	2.1
Six or more-Axle Single Trailer Truck	5	0.8
Bus	12	1.2

Figure 4.4 shows a histogram of time duration to move from first lateral movement (T_0) to the front wheel touching the lane boundary (T_1). The average time duration from the first lateral movement (T_0) to the front wheel touching the lane boundary (T_1) was 1.92 seconds, while 70% of these events were completed in less than 3 seconds.

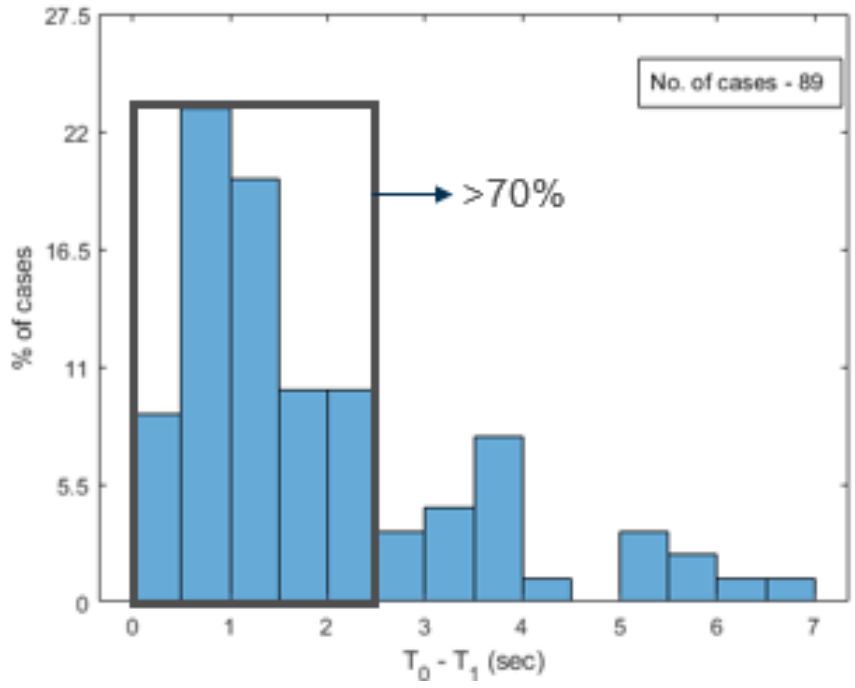

Figure 4.4: Histogram of time duration to move from first lateral movement (T_0) to the front wheel touching the lane boundary (T_1)

Table 4.3 shows the time taken by different vehicle types to move from when the front wheel touches the lane boundary (T_1) until the first rear wheel of the last axle

touches the same lane boundary (T_2). Two axle (six tire) and three axle trucks move from T_1 to T_2 in less than 0.4 seconds. The average time duration for two axle vehicle (four tire) is 0.03 seconds and the lower value is due to the fact that the wheels of the vehicles in those cases were very close to the lane boundary and front and rear wheels touched the lane boundary almost simultaneously. The average time duration in case of buses is close to one second. Nearly 50% of the buses were travelling in the urban locality and therefore were at lower speeds. Besides, the buses in the highways were travelling at lower speeds compared to the speeds of the trucks in other categories. Due to lower speeds of the buses, their average time duration to move from T_1 to T_2 was higher.

Table 4.3: Average T_1-T_2 time duration for different types of vehicles

Type of vehicle	**No. of cases**	**Average T_1 - T_2 duration(s)**
Single Unit Vehicles (Two-axles, Four-Tire)	3	0.03
Single Unit Trucks (Two-Axle, Six-Tire)	9	0.1425
Three-Axle Single-Unit Truck	2	0.33
Five-Axle Single Trailer Truck	48	0.85
Six or more-Axle Single Trailer Truck	4	0.82
Bus	12	0.95

Figure 4.5 shows a histogram of time duration to move from the front wheel touching the lane boundary (T_1) to the first rear wheel of the last axle touching the same lane boundary (T_2). The average time from the front wheel touching the lane boundary (T_1) to the first rear wheel of the last axle touching the lane boundary (T_2) was 0.6 seconds and 85% of the lane changes had the time duration below 1.25 seconds. Overall, the time duration T_1-T_2 is shorter than T_0-T_1.

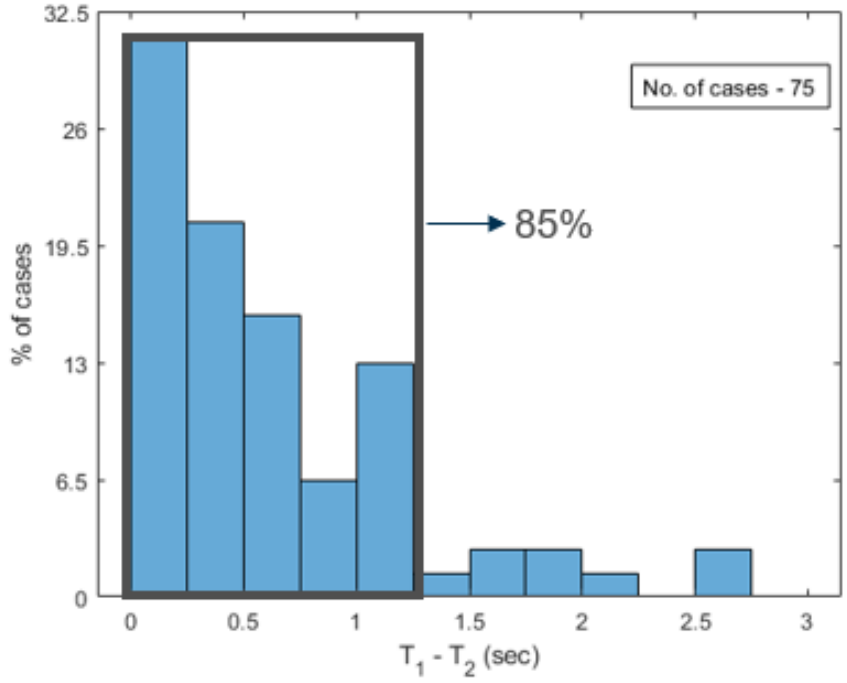

Figure 4.5: Histogram of time duration to move from front wheel touching the lane boundary (T_1) to the first rear wheel of the last axle touching the same lane boundary (T_2)

Figure 4.6 represents the time duration from first lateral movement (T_0) to the first rear wheel of the last axle touching the same lane boundary (T_2) and from the front wheel touching the lane boundary (T_1) to first rear wheel of the last axle touching the same lane boundary (T_2) for all the cases. From the Figure 4.6, the points representing the time duration T_1 -T_2 appear to be more compressed and closer to zero compared to the points representing the time duration T_0-T_2. For some cases, the points representing the time duration T_1-T_2 are almost equal to zero and this is due to the fact that the front and the rear wheels of the corresponding vehicle touch the lane boundary almost simultaneously.

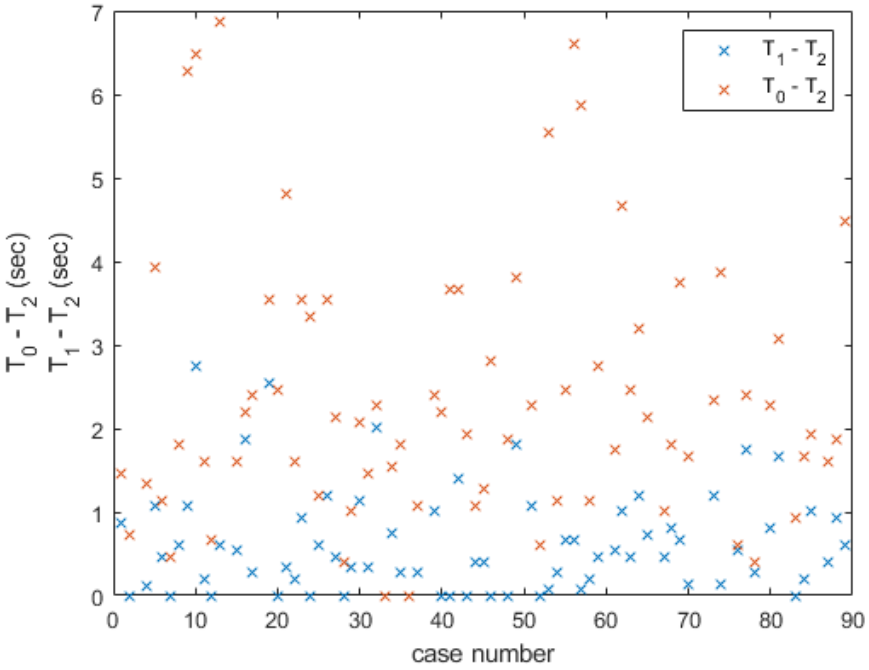

Figure 4.6: T_0-T_2 and T_1-T_2 for different cases

Table 4.4 shows the time taken by different types of vehicles to move from first rear wheel of the last axle touching the lane boundary (T_2) to the last rear wheel of the last axle touching the lane boundary (T_3). This time duration is longer compared to T_0-T_1 and T_1-T_2. One of the possible reasons for the longer time duration during T_2 to T_3 is that the cab part of the vehicle is already in the destination lane and the POV driver already starts to counter-steer the vehicle.

Table 4.4: Average $T_2 - T_3$ time duration for different vehicle types

Type of vehicle	**No. of cases**	**Average T_2 - T_3 duration(s)**
Single Unit Vehicles (Two-axles, Four-Tire)	1	1.7
Single Unit Trucks (Two-Axle, Six-Tire)	5	2.5
Three-Axle Single-Unit Truck	1	1.6
Five-Axle Single Trailer Truck	25	4
Six or more-Axle Single Trailer Truck	3	3.8
Bus	8	3.7

Figure 4.7 shows a histogram of time duration to move from the first rear wheel of the last axle touching the lane boundary (T_2) to the last rear wheel of the last axle touching the lane boundary (T_3). The average time duration for the POV to move from the first rear wheel of the last axle touching the lane boundary (T_2) to the last rear wheel of the last axle touching the lane boundary (T_3) was 3.6 seconds, while 80% of the lane changes had the time duration from T_2-T_3 around 5 seconds.

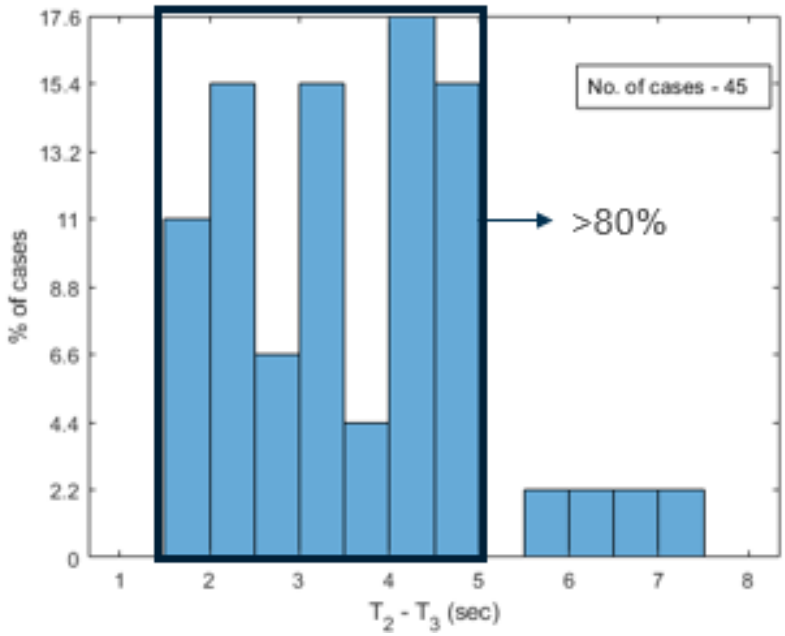

Figure 4.7: Histogram of time duration to move from the first rear wheel of the last axle touching the lane boundary (T_2) to the last rear wheel of the last axle touching the lane boundary (T_3)

After analysing different stages of lane changes, the activation of blinkers by the POV was studied. Table 4.5 represents the number of cases in which the POV blinked before or during the lane change maneuver.

Table 4.5: Number of cases blinking and not blinking before or during a lane change for different vehicle types

Type of vehicle	Blinking	No Blinking	Total cases
Single Unit Vehicles (Two-axles, Four-Tire)	3	0	**3**
Single Unit Trucks (Two-Axle, Six-Tire)	3	7	**10**
Three-Axle Single-Unit Truck	0	2	**2**
Five-Axle Single Trailer Truck	39	18	**57**
Six or more-Axle Single Trailer Truck	4	1	**5**
Bus	9	3	**12**
Total	**58**	**31**	

Table 4.6 gives insights about the first action undertaken by the POV driver - either lateral movement or blinking - before starting the lane change maneuver. From the table, there are almost equal number of cases in which the POV made the lateral movement first or blinking first.

Table 4.6: Number of cases blinking first or making a lateral movement first during a lane change for different vehicle types

Type of vehicle	Lateral movement first	Blinking first
Single Unit Vehicles (Two-axles, Four-Tire)	0	3
Single Unit Trucks (Two-Axle, Six-Tire)	2	1
Three-Axle Single-Unit Truck	-	-
Five-Axle Single Trailer Truck	19	20
Six or more-Axle Single Trailer Truck	1	3
Bus	3	6
Total	**25**	**33**

4.2 Interaction between the SV and POV

Figure 4.8 shows a histogram of the longitudinal distance between the rear of the POV and the front of the SV at the time when POV initiates the first lateral movement (T_0) and when the front wheel touches the lane boundary (T_1). Over 70% of the cases have the longitudinal distance less than 30m when POV initiates

the first lateral movement (T_0). However, this distance reduces to below 15m for over 70% of cases when the front wheel of the POV touches the lane boundary (T_1).

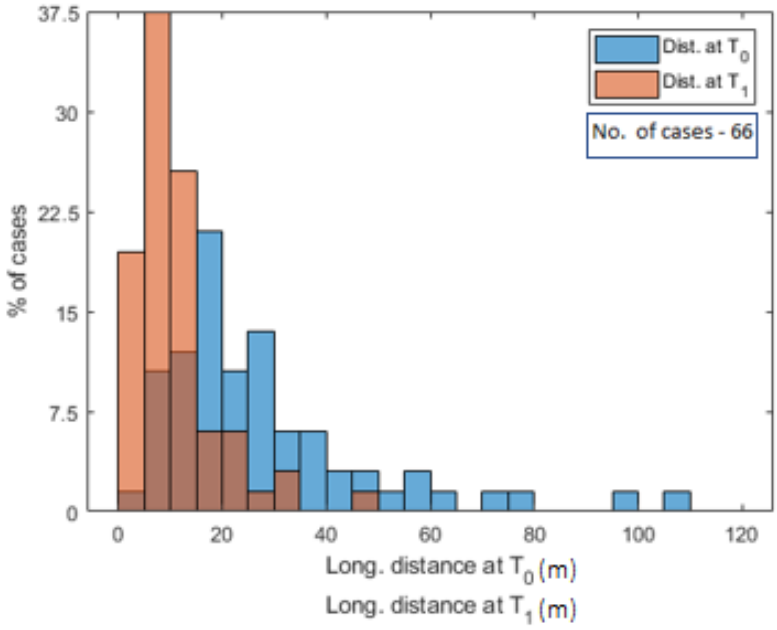

Figure 4.8: Histogram of longitudinal distance between SV and POV at T_0 and T_1

Figure 4.9 shows a histogram of the relative speed between the POV and SV at the time when the POV initiates the first lateral movement (T_0) and when the front wheel touches the lane boundary (T_1). For over 75% of the cases, this relative speed was below 40 kph at both T_0 and T_1.

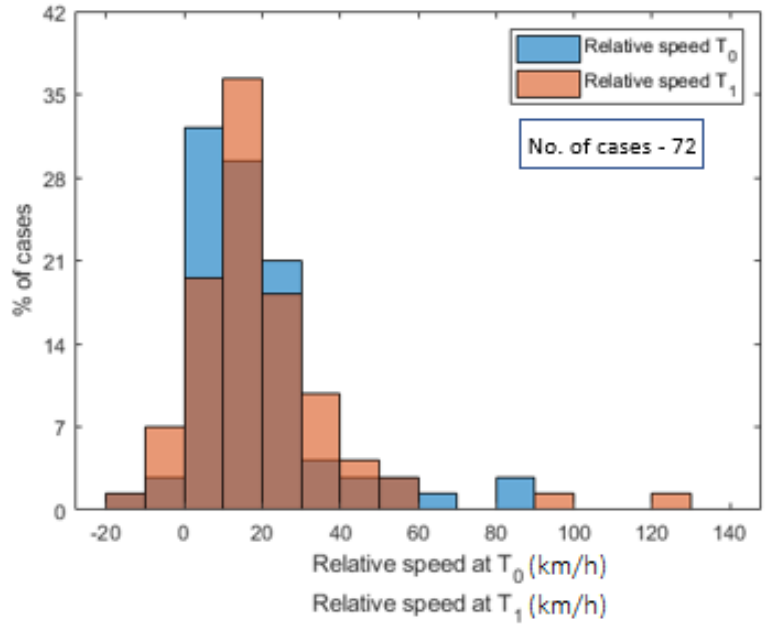

Figure 4.9: Histogram of relative speed between SV and POV at T_0 and T_1

4.3 Factors influencing the evasive maneuver of the SV during a lane change

Table 4.7 shows the number of vehicles that performed their first evasive maneuver as braking, steering or both. In as many as 67% of all the cases, the first evasive maneuver of the SV drivers was braking. However, there were four cases where the drivers braked and steered simultaneously. An important note to be made is that this Table 4.7 represents only the first evasive maneuver performed by the SV drivers.

Table 4.7: First evasive maneuver performed by the SV driver

First evasive maneuver	No. of cases
Brake	65
Steer	20
Brake & steer	4

The Figure 4.10 shows the plot of the start of first evasive maneuver of SV after the first lateral movement of the POV (T_0) vs the time duration POV takes to complete T_0-T_1. Most of the points in the plot indicate that the first evasive maneuver of the SV is braking which is in agreement with the Table 4.7. However, few event of braking and steering could not be captured in the plot as it was not possible to determine the start of the evasive maneuver.

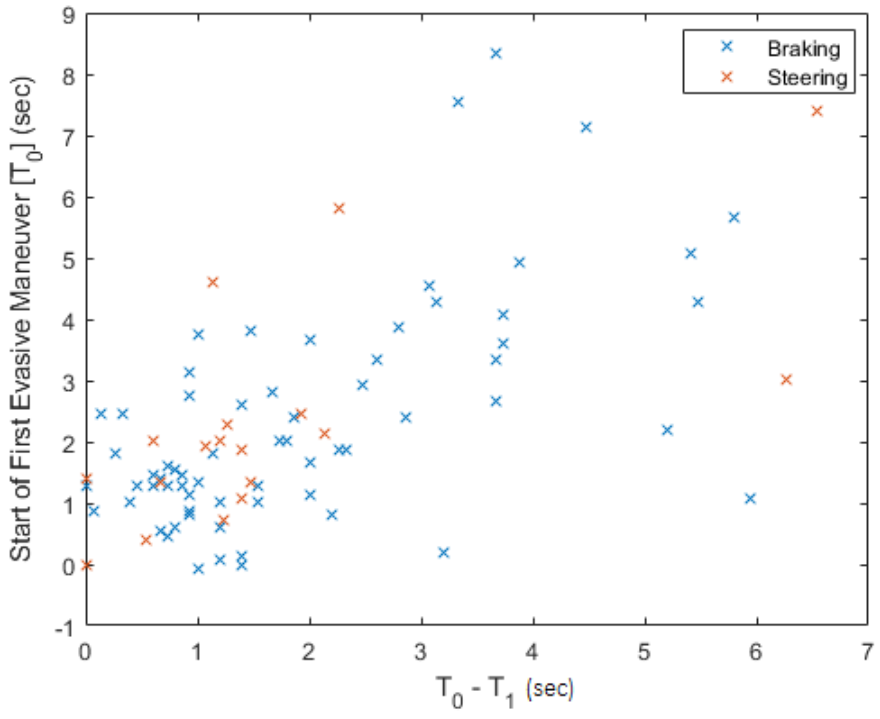

Figure 4.10: Plot of first evasive maneuver Vs $T_0 - T_1$ time duration

Table 4.8 shows the average brake reaction time for the SV drivers as a function of different types of vehicles changing lane. Brake reaction time (BRT) is the time duration between the first lateral movement (T_0) of the POV and the start of braking maneuver (T_b) of the SV. The SV drivers require on average below two seconds to brake, regardless of the type of vehicle changing lane. Nevertheless, the brake time is over two seconds when the POV is a five-axle single trailer trucks.

Table 4.8: Average BRT (T_b-T_0) for different vehicle types

Type of vehicle	**No. of cases**	**Average BRT(s)**
Single Unit Vehicles (Two-axles, Four-Tire)	3	1.7
Single Unit Trucks (Two-Axle, Six-Tire)	9	1.9
Three-Axle Single-Unit Truck	2	1.4
Five-Axle Single Trailer Truck	55	2.3
Six or more-Axle Single Trailer Truck	5	1.5
Bus	11	1.7

Figure 4.11 shows a histogram of the brake reaction time (BRT) of the SV drivers. Nearly 85% of the cases had BRT below three seconds and the cases where the BRT were above five seconds were mostly cases in which the surrogate time to collision (TTC) measured between SV and POV at T_0 was large. The time to collision (TTC) was called surrogate since the SV and POV were in two adjacent lanes when measured.

Also, some cases had multiple lane changes and therefore the first lateral movement (T_0) of the POV didn't draw any evasive maneuver from the SV. Finally, for one case, the timing of the evasive maneuver was before the first lateral movement (T_0) of the POV. A possible reason for this could be blinking of the POV before making the lateral movement.

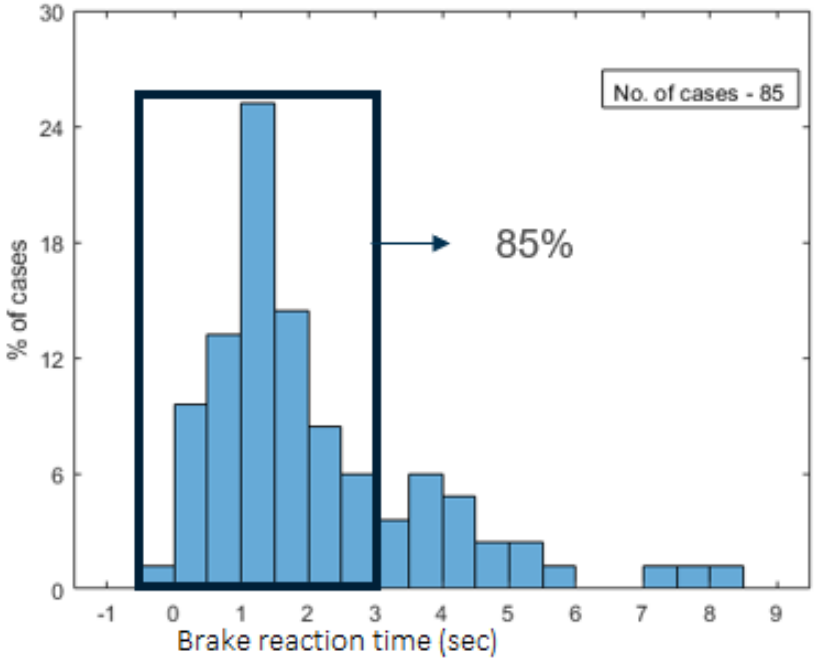

Figure 4.11: Histogram of Brake reaction time ($T_0 - T_b$)

The figure 4.12 shows a plot of time duration from T_0-T_1 vs BRT (T_0). In almost all the cases, the SV start to brake after the POV makes the first lateral movement (T_0). However, in one case, the SV starts to brake before the first lateral movement, possibly due to blinking. The Pearson correlation coefficient between the time duration from T_0-T_1 and the brake reaction time is 0.567. The number of cases used to calculate the correlation is 83. This is a reduction from 89 cases as seen in the 4.4, due to presence of NaN values in the data set. The NaN values were the cases where either time duration from T_0-T_1 or the brake reaction time was unavailable. The correlation between the two variables seems to indicate that the faster the POV moves towards the lane boundary - which is a surrogate measurement of the lateral speed - the faster the SV driver brakes. However, the lateral speed of the POV may not be the only factor influencing the braking of the SV. For this reason, the correlation between the SV drivers' brake reaction time and other variables - such as blinking, time to collision (TTC), overshadowing - were also investigated.

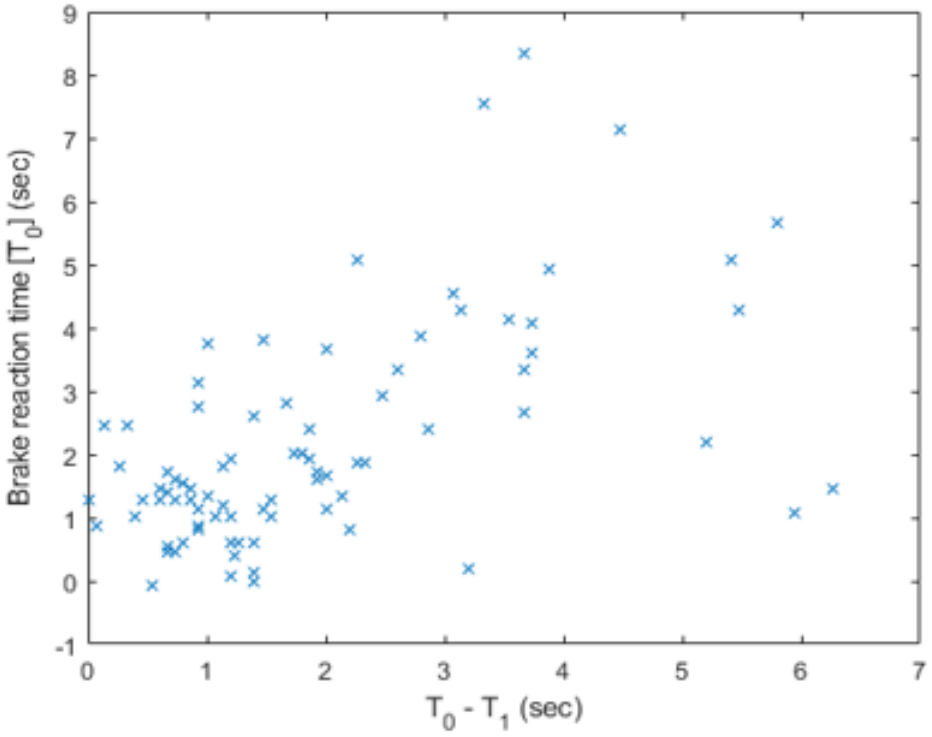

Figure 4.12: Plot of $T_0 - T_1$ Vs BRT

To assess the effect of blinking of the POV on the braking behaviour of SV, only the cases where the POV blinked before the lateral movement (T_0) were considered. Figure 4.13 shows a plot of the time duration from T_0 to T_1 against the BRT of the SV for the cases when the POV blinked before the lateral movement (T_0) and did not overshadow. The correlation coefficient between the two variables was 0.625, showing a marginal increase compared to the correlation reported for Figure 4.12 and the number of cases was 28.

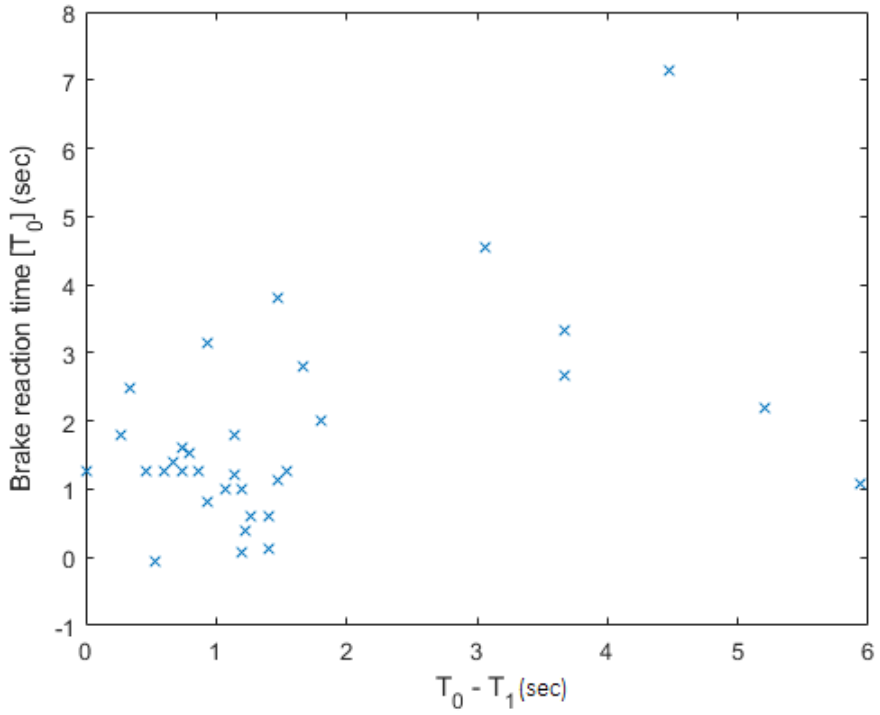

Figure 4.13: Plot of $T_0 - T_1$ Vs BRT when the POV blinked before the lateral movement (T_0)

Figure 4.13 aimed to assess the correlation between the SV drivers' brake reaction time and the lateral speed, when the POV drivers blinked before the first lateral movement (T_0). On the other hand, figure 4.14 shows the same correlation for cases in which the POV made the lateral movement before blinking and without overshadowing. A note to be made is that these cases include blinking after lateral movement and no blinking as similar events as the lateral movement happens first. The correlation coefficient between the duration from T_0-T_1 and brake reaction time (T_0) is 0.71 and the number of cases is 38. The correlation coefficient increases to 0.71 compared to the original value (0.567) and, therefore, the lateral speed of the POV appears to be a good candidate to explain the brake reaction time of the SV.

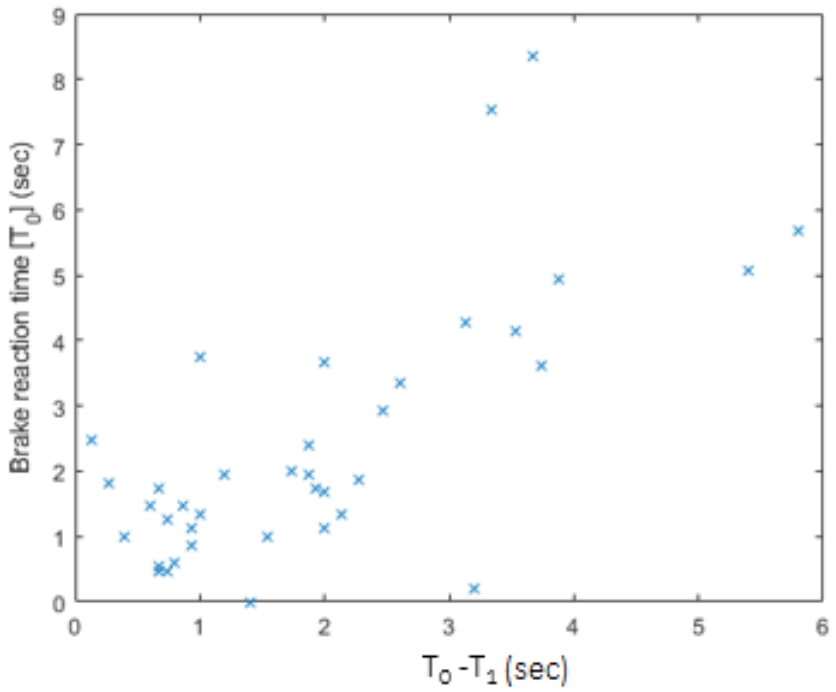

Figure 4.14: Plot of $T_0 - T_1$ Vs BRT when the POV made the lateral movement first

Investigating further for the cases when the POV blinked before making the lateral movement (T_0), surrogate TTC was introduced to explain the behaviour of the SV drivers. The data points in figure 4.13 were re-plotted using different colours for a range of surrogate TTC values. The idea behind this was to see if the data points with the same range of surrogate TTC would be in the same area in the plot. However, the data points were scattered and did not help in explaining the braking behaviour of the SV drivers. The same was performed for the cases when the POV made the lateral movement first and the surrogate TTC did not explain the braking behaviour of the SV drivers. Similarly, the longitudinal distance between the POV and SV when the POV made the first lateral movement (T_0) was used to explain the braking behaviour of the SV. Like the surrogate TTC, the longitudinal distance failed to explain the braking behaviour of SV drivers.

From Figure 4.12 and the correlation coefficient between T_0-T_1 and brake reaction time (T_0), the lateral movement (T_0-T_1) was identified as the major factor that triggered the SV drivers to brake. As shown in Figures 4.13 and 4.14, it was observed that the blinking of the POV also had an effect on the braking of the SV. It was also seen that the variables like the surrogate TTC and longitudinal distance between the SV and POV failed to explain the braking behaviour of the SV drivers and were not considered. Next, a generalized linear mixed effect model describing the brake reaction time of the SV as a function of several independent variables was formulated. Using the lateral movement of the POV (T_0-T_1) and the blinking of the POV as the two main factors, a model to estimate the brake reaction time was developed.

The Equation 4.1 below is the description of the model which represents the brake reaction time of the SV driver. In the equation below 'T_0-T_1' is the time duration that the POV takes to move from T_0 to T_1, 'blinking' is a logical variables which is '1' when the blinkers are activated by the POV before the lateral movement and '0' in all other scenarios. All other scenarios include cases when the POV does not blink and also the cases when the blinkers are activated after the first lateral movement. 'α_1' and 'α_2' are the coefficients of the variables 'T_0-T_1 and 'blinking' respectively. On the other hand, 'α_0' is the intercept, which accounts for the time required for the human driver to respond to an external stimulus.

$$BRT = \alpha_0 \ + \ \alpha_1(T_0 - T_1) \ + \ \alpha_2(blinking) \tag{4.1}$$

Akaike information criterion (AIC) value is one of the statistics used to assess the goodness of fit of the model. A lower AIC is associated to a better model, when comparing two models. The AIC for this model was 299. The results of the model also indicates the coefficient values (α_1 and α_2) of each variable, the t-statistic for a hypothesis test that variables is equal to 0 and a p-value that correspond to the t-statistic. A variable is considered significant if it has p-value less then 0.05.

The α_1 and α_2 values were 0.64 and -0.32 respectively. The negative value indicates that the blinking of POV before the lateral movement reduces the SV' brake reaction time. The p-values for the variables 'T_0-T_1' and 'blinking' are $4.47 * 10^{-8}$ and 0.3. Since the p-value of the variable 'blinking' was greater than 0.05, the variable not significant. Due to the higher p-value, the variable 'blinking' was not be included in the model. But the correlation coefficient had indicated that the blinking had an effect on the braking behaviour of the SV. Therefore, to investigate further, the interaction between blinking and the time duration required for the POV to move from T_0 to T_1 was considered and used as a variable in Equation 4.2.

$$BRT = \alpha_0 \ + \ \alpha_1(T_0 - T_1) \ + \ \alpha_2(T_0 - T_1)(blinking) \tag{4.2}$$

The p-value for the interaction between blinking and the time duration required for the POV to move from T_0 to T_1 was 0.07 making the variable marginally significant. The AIC for this modified model was reduced to 297 compared to the earlier value of 299 and the α_2 value was -0.22.

Next, a variable which accounted for the speed difference of SV between T_0 ($V_{sv_{T_0}}$) and T_b ($V_{sv_{T_b}}$) was considered. This variable would be crucial in understanding the SV driver's behaviour from the time POV makes the lateral movement T_0 till the SV starts to brake T_b. The variable would be positive if the SV accelerated after T_0 which would increase the BRT. Contrarily, if the variable was negative, then it meant SV would have shorter BRT.

$$BRT = \alpha_0 \ + \ \alpha_1(T_0 - T_1) \ + \ \alpha_2(T_0 - T_1)(blinking) \ + \ \alpha_3(V_{sv_{T_0}} - V_{sv_{T_b}}) \tag{4.3}$$

The AIC value for the model was 293 and the p-values for the variables 'T_0-T_1', '(T_0-T_1)*blinking' and $V_{SV_{T_0}}$ - $V_{SV_{T_b}}$ were $1.47 * 10^{-9}$, 0.03 and 0.01 respectively. α_1, α_2 and α_3 values were 0.72, -0.29 and 0.20. The equation can be written in mathematical form as below,

$$y = 0.95 + 0.72x_1 - 0.29x_2 + 0.20x_3 \tag{4.4}$$

where, y = brake reaction time
x_1 = time duration, (T_0-T_1)
x_2 = (time duration, (T_0-T_1))*blinking
and x_3 = speed difference of the SV between T_0-T_b, ($V_{sv_{T_0}}$ - $V_{sv_{T_b}}$)

5
Discussion

An automated truck performing a lane change should account for the gap and the state of the vehicles around it, before initiating a lane change. In this context of automated lane change maneuvers, this thesis anchors its aims to study the lane change maneuvers usually performed by drivers of heavy vehicles and also analyse the factors that triggered a response from the following SV driver. Data is an essential component of any research and, for this thesis, a naturalistic driving dataset (SHRP2) collected in the US was used. After suitable data reduction, a total of 89 lane change cases were extracted and annotated manually from the video feed. After this iterative process of analysing and annotating videos, a data matrix consisting of all the lane changes and their associated variables was generated and exported to MATLAB. This data was then carefully analyzed in order to understand what factors triggered a response from the SV driver. This section mainly deals with interpretations of the results from the characterization of the lane change performed by the POV and how it relates to the objectives of the thesis.

The initial analysis was conducted on the nature of the lane change (direction, motivation) performed by the POV. Out of the 89 relevant cases that were investigated, 70% of the lane changes were right to left in direction. Among these right to left lane changes, it was noticed that one motivating factor for the truck to perform a lane change was in order to overtake a slow leading vehicle. On the other hand, most of the lane changes from left to right were in order to enable taking a ramp exit. Another scenario where truck drivers performed a left to right lane change was at a toll booth: in order to take the desired exit at the toll booth (most often the rightmost lane), some truck drivers performed either single or multiple lane changes close to the toll booths. Besides these, some other motivations for trucks to perform a left to right lane change was in order to complete an overtaking maneuver by moving to the slower lane, or in case of POV's lane closure.

According to a report by the NHTSA on the examination of lane change crashes [33], 75% of all lane change crashes occur due to a recognition failure by the driver. Hence, it is essential for the vehicle performing the lane change to show intention to the following SV. One of the most widely used and standard method of showing such an intention is the use of blinkers before initiating a lane change. Activation of blinkers well before the start of lane change gives the following vehicle the buffer to maintain a safe distance to the vehicle ahead or to perform an evasive maneuver. In the analysis performed, only 65% of the drivers activated the blinkers. Among these, in terms of direction, 44 cases were right to left lane changes and 14 cases were

left to right. One possible explanation for this disproportionate use of blinkers in terms of direction is the fact that the drivers are most often interacting with a fast approaching vehicle in the faster lane when performing a right to left lane change. On the other hand, the lane changes performed from left to right are in order for the truck to either take a ramp exit or sudden maneuvers at toll booths, and show more urgency than its counterpart. According to a study from China [51], 65% of drivers blinked before or while changing lanes on highways. This result is similar to the findings from this thesis which used data collected in the US.

Previous studies [52] suggests that the attention of the drivers is caught by the visual looming associated to the braking of the vehicles ahead. Similarly, the driver of the SV also responds to any change in the position of the POV by performing an evasive maneuver in order to avoid a collision. It was observed that this evasive maneuver was dependent on the direction of lane change as well. Among the right to left lane changes, in 60% of cases (36 out of the 60 cases), the SV drivers braked as an evasive response to the POV's lateral movement. In most cases the SV was travelling in the leftmost lane and didn't have additional lane to steer away from the POV. However, in left to right lane change only 40% of SV drivers braked and 60% of drivers braked and steered. The increase in the number of brake & steer cases was due to the fact that in many cases, SV was travelling in the centre or right lane when the POV made the lane change. The SV had free lane on the right or used the shoulder to steer away from POV. An automated truck while changing lanes should consider the direction in which it is changing lane along with the speed of the following vehicle, so as to provide to the SV enough time and space to perform a safe evasive maneuver. Additionally, these results can be related to the study by Brännström et al [53], which suggests that when a vehicle performs a lane change, it should also be accounted for the possibility to perform an evasive maneuver even after it has reached its destination lane.

Lane change duration is the time from when the POV makes the first lateral movement (T_0) till the time when the POV is comfortably in the SV's lane (T_c). The range of time duration of the lane change maneuver for two axle (four and six tire) and three axle trucks was 3-3.5 seconds while five and more axle trucks and buses took over 6 seconds. The shorter time duration for two and three axle wheels can be attributed to the relatively shorter length of the vehicles. Five and six axle trucks were comparatively longer and therefore need longer duration to complete the lane change. The longer time duration to complete the lane change for buses was because of the lower speed at the start of lane change: for example, in as many as 8 cases, the buses that performed lane change were departing from standstill position. Also, in terms of how fast the lane change was performed, it was also observed that many left to right lane changes were quicker than the right to left lane change.

In this thesis, the entire lane change maneuver of the POV was divided into different stages.

- first lateral movement to the front wheels touching the lane boundary (T_0-T_1)
- front wheel touching lane boundary to first rear wheel touching same lane

boundary (T_1-T_2).
- first rear wheel touching the lane boundary to the last rear wheel touching the lane boundary (T_2-T_3)

The average time duration from the start of a lateral movement (T_0) of the POV to the time when the first front wheel of the POV touches the lane boundary (T_1) was 1.5 seconds. The average time duration from when the first front wheel of the POV touches the lane boundary (T_1) till the first rear wheel of the last axle touches the lane boundary (T_2) was 0.52 seconds. The duration for the POV to move from T_1 to T_2 is a factor of the length of the truck and also the speed during the lane change. Therefore, the longer trucks took longer time to complete this stage. During the next stage of the lane change, i.e., from T_2 to T_3, the trucks took an average of 2.8 seconds. It was observed that the the long duration of the stage from T_2 to T_3 was due to the countersteering of drivers to center the vehicle in the destination lane. Average times for the different stages of lane change shows that T_1-T_2 is the fastest stage of the entire lane change maneuver.

From the histogram of brake reaction times of the SV (see Figure 4.11), we see that the average braking time for all types of vehicles is 1.75 seconds after the POV makes the first lateral movement (T_0). According to Green, the average brake response time for cases when an object suddenly moves onto the driver's path, is 1.5 seconds [50], which is in accordance with the brake times observed in this thesis as a measure of the time from when the POV initiates a lateral movement (T_0) in the direction of the SV's lane. As shown in Figure 4.12, it is observed that the longer the POV took to perform the lateral movement (that is the time duration between T_0 and T_1), the later the start of braking occurred. Also, the Pearson correlation coefficient between the lateral movement time duration (T_0-T_1) and the brake reaction time is 0.567. This is indicative that the lateral movement of the POV is a major contributing factor for the SV driver to start braking. However, there are cases, when the braking and the lateral movement begins simultaneously. This indicates that there are additional factors like blinking of the POV which could be responsible for the SV to brake.

The correlation coefficient between the lateral movement time duration (T_0-T_1) and the brake reaction time was 0.71 for the cases when the POV made the lateral movement first and did not overshadow. However, the correlation coefficient between the lateral movement time duration (T_0-T_1) and the brake reaction time was only 0.62 for the cases when the POV blinked before the lateral movement and did not overshadow. It can be assumed that the higher correlation for the cases when the POV made the lateral movement first was because of the absence of factors like blinking and overshadowing, which might imply that the blinking of the POV is a motivating factor for the SV drivers to brake.

A generalized linear mixed effect model describing the brake reaction time of the SV as a function of several independent variables like the lateral movement and blinking of the POV was formulated. Blinking of the POV as an independent variable was not significant, due to the low p-values. Therefore, a new variable describing the

interaction between the lateral movement and blinking of the POV was included in the model which had favourable p-values. An additional variable which accounted for the difference in the SV speed between T_0 ($V_{sv_{T_0}}$) and T_b ($V_{sv_{T_b}}$) was included in the model. The brake reaction time would increase if the SV accelerated after the POV made the first lateral movement (T_0) making the speed difference variable in the model positive. On the other hand, the brake reaction time would decrease if the SV braked or did not accelerate after the POV made the first lateral movement (T_0) making the speed difference variable in the model negative. The model can be written in mathematical form as below,

$$y = 0.95 + 0.72x_1 - 0.29x_2 + 0.20x_3$$

where, y = brake reaction time
x_1 = time duration T_0-T_1
x_2 = time duration T_0-T_1*blinking
and x_3 = speed difference of the SV between T_0-T_b ($V_{sv_{T_0}}$ - $V_{sv_{T_b}}$)
and 0.95 accounts for the time required for the human driver to respond to an external stimuli.

Limitations

This study does not account for the real time kinematics of the POV since the data is collected from an instrumented SV. The values of POV speed and relative distances are manually annotated from the videos and there is possibly a parallax error during the annotation process. For the manual annotation process, changes in accelerations of the POV and the SV during the stages of the lane change were not considered; rather the average speeds of the SV and POV were used. Besides, the video quality of the data was often poor and the time stamp of different parameters like speed, acceleration, yaw rate etc. and the video feed were not in synchronisation. The videos in the SHRP2 database are trimmed for a time period of 30s. Due to this, for some cases the video abruptly ends before the completion of lane change. This gives rise to inability to analyse the time for lane change completion. During the study, it was observed that a factor that affected the responses of the SV was the time duration from the POV first lateral movement to the left or right lane. Such a variable can be considered a surrogate measurement of the lateral speed of the POV during the initial stage of the lane change. Nevertheless, this study does not directly measure this variable. The generalized linear mixed effect model describing the brake reaction time of the SV is valid for critical situations (near crashes) but not for regular driving (non-conflict) situations.
Finally, this study is based on the data collected in the US by SHRP2 and also only from 7 data collection sites. Hence, from a driver behaviour perspective this study also restricts itself to the behaviour of truck drivers in the US. Therefore, the results might not be completely valid for truck drivers in a different country.

Future Work

In the current study, it was found that the lateral movement of the POV, the blinking of the POV and the difference in the SV speed between the T_0 and T_b are significant

factors triggering an avoidance maneuver from the SV driver, during critical lane change maneuvers. The future part of the study could involve investigating the roles of other variables which was not possible to be measure in this study. The study could can also be expanded to include the modelling SV driver's behaviour for the same scenario in a non safety-critical situation.

Data Source

The data was analyzed under the the data license agreement SHRP2-DUL-A-2-18-354.
The findings and conclusions of this paper are those of the author(s) and do not necessarily represent the views of VTTI, the Transportation Research Board, or the National Academies.

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A

Appendix 1

Table A.1: Categories of event nature as listed by VTTI [44]

Event Nature
Conflict with a lead vehicle
Conflict with a following vehicle
Conflict with oncoming traffic
Conflict with vehicle in adjacent lane
Conflict with merging vehicle
Conflict with vehicle turning across another vehicle path (same direction)
Conflict with vehicle turning across another vehicle path (opposite direction)
Conflict with vehicle turning into another vehicle path (same direction)
Conflict with vehicle turning into another vehicle path (opposite direction)
Conflict with vehicle moving across another vehicle path (through intersection)
Conflict with parked vehicle
Conflict with pedestrian
Conflict with pedestrian entering/exiting vehicle
Conflict with pedal cyclist
Conflict with animal
Conflict with obstacle/object in roadway
Conflict with out of control vehicle in roadway
Single vehicle conflict
Others
None

Table A.2: Categories of Precipitating event as listed by VTTI [44]

Precipitating event	
This vehicle lost control - blow-out or flat tire	Subject lane change - right, other
This vehicle lost control - stalled engine	Subject vehicle making a U-turn
This vehicle lost control - disabling vehicle failure	Subject vehicle backing
This vehicle lost control - minor vehicle failure	Subject vehicle ahead - decelerating
This vehicle lost control - poor road conditions	Subject vehicle ahead - at a slower constant speed
This vehicle lost control - excessive speed	Subject vehicle, other
This vehicle lost control - other cause	Other vehicle ahead - stopped on roadway more than 2 seconds
This vehicle lost control - unknown cause	Other vehicle ahead - at a slower constant speed
Subject over left lane line	Other vehicle ahead - decelerating
Subject over right lane line	Other vehicle ahead - accelerating
Subject over left edge of road	Other vehicle - traveling in opposite direction
Subject over right edge of road	Other vehicle - in crossover
Subject vehicle - end departure	Other vehicle - making U-turn
Subject in intersection - turning left	Other vehicle - backing
Subject in intersection - turning right	Other vehicle lane change - left in front of subject
Subject in intersection - passing through	Other vehicle lane change - right in front of subject
Subject vehicle ahead - stopped on roadway more than 2 seconds	Other vehicle lane change - left behind subject
Subject vehicle ahead - slowed and stopped 2 seconds or less	Other vehicle lane change - right behind subject
Subject lane change - left behind vehicle	Other vehicle lane change - left, sideswipe threat
Subject lane change - right behind vehicle	Other vehicle lane change - right, sideswipe threat
Subject lane change - left in front of vehicle	Other vehicle lane change - left other
Subject lane change - right in front of vehicle	Other vehicle lane change - right other
Subject lane change - left, sideswipe threat	Other vehicle oncoming - over left line

Table A.3: Categories of Pre-incident maneuver as listed by VTTI [44]

Pre-incident maneuver	
Going straight, constant speed	Turning right
Going straight, accelerating	Turning left
Going straight, but with unintentional "drifting" within lane or across lanes	Making U-turn
Decelerating in traffic lane	Negotiating a curve
Starting in traffic lane	Changing lanes
Stopped in traffic lane	Merging
Passing or overtaking another vehicle	Maneuvering to avoid an animal
Disabled or parked in travel lane	Maneuvering to avoid a pedestrian/pedalcyclist
Leaving a parking position	Maneuvering to avoid an object
Entering a parking position	Maneuvering to avoid a vehicle
Backing up (other than for parking purposes)	Others

Table A.4: Categories of Motorist/Non-motorist/Animal/Object 2 as listed by VTTI [44]

Motorist/Non-motorist/Animal/Object 2	
Automobile	Tractor only
Sport Utility Vehicle	Tractor-trailer: Enclosed box
Van (minivan or standard van)	Tractor-trailer: Flatbed
Pickup truck	Tractor-trailer: Tank
Light Vehicle pulling trailer	Tractor-trailer: Car carrier
School bus	Tractor-trailer: Livestock
Transit bus	Tractor-trailer: Lowboy trailer
Motor Coach bus	Tractor-trailer: Dump trailer
Single-unit straight truck: Multistop/Step van	Tractor-trailer: Multiple box
Single-unit straight truck: Box	Tractor-trailer: Multiple grain
Single-unit straight truck: Dump	Tractor-trailer, other
Single-unit straight truck: Garbage/Recycling	Other large construction equipment
Single-unit straight truck: Concrete mixer	Motorcycle or moped
Single-unit straight truck: Flatbed	Ambulance
Single-unit straight truck: Tow truck	Fire truck/car
Single-unit straight truck, other	Police
Single-unit straight truck + trailer	Other vehicle type
Pedestrian	Cyclist
Other non-motorist	Animal
Object	Unknown

Table A.5: Table showing the categories of Traffic Density that was annotated by SHRP2

Level of Service	Short Description
A1	LOS A1 represents a free flow traffic situation when the subject vehicle has no leading traffic in any lane (following traffic may or may not be present).
A2	LOS A2 represents a free flow traffic with a leading vehicle present in at least one lane. However, individual drivers are still virtually unaffected by the presence of others in the traffic stream. Freedom to select desired speeds and to maneuver within the traffic stream is extremely high.
B	LOS B is still in the range of stable flow, but the presence of other users in the traffic stream begins to be noticeable. Freedom to select desired speeds is relatively unaffected, but there is a slight decline in the freedom to maneuver within the traffic stream from LOS A.
C	LOS C is still in the range of stable flow, but marks the beginning of the range of flow in which the operation of individual users becomes significantly affected by interactions with others in the traffic stream. The selection of speed is now affected by the presence of others, and maneuvering within the traffic stream requires substantial vigilance on the part of the driver. The general level of comfort and convenience declines noticeably at this level.
D	LOS D represents a high-density, but stable flow. Speed and freedom to maneuver are severely restricted, and the driver or pedestrian experiences a generally poor level of comfort and convenience. Small increases in traffic flow will generally cause operational problems at this level.
E	LOS E represents operating conditions at or near the capacity level. All speeds are reduced to a low, but relatively uniform value. Freedom to maneuver within the traffic stream is extremely difficult, and it is generally accomplished by forcing a vehicle or pedestrian to "give way" to accommodate such maneuvers. Comfort and convenience levels are extremely poor, and driver or pedestrian frustration is generally high. Operations at this level are usually unstable, because small increases in flow or minor perturbations within the traffic stream will cause breakdowns.
F	LOS F represents forced or breakdown flow. This condition exists wherever the amount of traffic approaching a point exceeds the amount which can traverse the point. Queues form behind such locations. Operations within the queue are characterized by stop-and-go waves, and they are extremely unstable. Vehicles may progress at reasonable speeds for several hundred feet or more, then be required to stop in a cyclic fashion.

Table A.6: Table shows the categories of Incident Type that was annotated by SHRP2 [44]

Incident Type	Short Description
Lane deviation (left or right) (Truck Only)	Any tire on the subject vehicle leaves the intended travel lane and moves into a shoulder or adjacent lane, but does not leave the roadway, and has no interaction with any other motorist, non-motorist, or object
Road departure (left or right)	Any tire on the subject vehicle leaves the roadway, beyond the shoulder or onto median, on the left or right side of the roadway. Includes interaction with roadside barriers and curbs.
Road departure (end)	Any tire on the subject vehicle leaves the end of the roadway
Ground impact - low speed (MC ONLY)	Two-wheeled vehicle falls coincident with low or no speed (even if in gear), due to issue not defined in other Incident Type categories. The rider allows the bike to lean while it is being stopped, just beginning to move from a stop, or making a turn at low speed. Vehicle upright stability is lost due to lack of input by the rider to counteract the effect of gravity.
Rear-end, striking	Subject vehicle (V1) makes contact or nearly makes contact with any portion of the back of the vehicle in front (V2). Point of impact is or would have been the back plane of the lead vehicle (V2).
Rear-end, struck	Vehicle behind (V2) makes contact or nearly makes contact with any portion of the back of the Subject vehicle (V1). Point of impact is or would have been the back plane of the Subject vehicle (V1).
Sideswipe, same direction (left or right)	Subject vehicle (V1) is struck or nearly struck by another vehicle (V2) or strikes or nearly strikes another vehicle (V2) on either the driver or passenger side of the vehicle (V1 or V2) when the vehicles were traveling in the same direction. Point of impact is or would have been the side plane of either vehicle.
Opposite direction (head-on or sideswipe)	Subject vehicle (V1) and other vehicle (V2) make or nearly make contact when the vehicles were traveling in opposite directions. Point of impact is/would have been front plane of both vehicles
Straight crossing path	Vehicle (Subject or V2) crosses another vehicle path perpendicularly. Both vehicles intending to proceed straight across each other's paths.
Turn across path	Vehicle (Subject or V2) crosses in front of the path of another vehicle. Vehicles were initially on the same roadway, either in the same or opposite directions. Vehicle turning across path intends to turn right or left onto another trafficway and drove in front of the other vehicle.
Pedal cyclist-related	Interaction with a person on any type of self-propelled pedaled cycle, as either the driver or the passenger, which is on a trafficway or on a sidewalk or path contiguous with a trafficway including bicycles, tricycles, and unicycles. Also include pedal cyclists who hold onto a motor vehicle in motion.