DRIVER BEHAVIOR DURING LANE CHANGE FROM THE 100-CAR NATURALISTIC DRIVING STUDY

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ABSTRACT

Lane changes with the intention to overtake the vehicle in front are especially challenging scenarios for forward collision warning (FCW) designs. These overtaking maneuvers can occur at high relative vehicle speeds and often involve no brake and/or turn signal application. Therefore, overtaking presents the potential of erroneously triggering the FCW. A better understanding of lane change events can improve designs of human-machine interface and increase driver acceptance of FCW. The objective of this study was to characterize driver behavior during lane change events using naturalistic driving data.

The analysis was based on data from the 100-Car naturalistic driving study, collected by the Virginia Tech Transportation Institute. The 100-Car study contains approximately 1.2 million vehicle miles of driving and 43,000 hours of data collected from 108 primary drivers. In order to identify overtaking maneuvers from a large sample of driving data, our study developed and validated an algorithm to automatically identify overtaking events. The lead vehicle and minimum time to collision (TTC) at the start of lane change events was identified using radar processing techniques developed in a previous study. The lane change identification algorithm was validated against video analysis which manually identified 1,425 lane change events from approximately 126 full trips.

Forty-five (45) drivers with valid time series data was selected from the 100-Car study. From the sample of drivers, our algorithm identified 326,238 lane change events. Lane change events were evenly distributed between left side and right side lane change. The characterization of lane change frequency and minimum TTC was divided into 10 mph speed bins for vehicle travel speeds between 10 mph to 90 mph. A total of 90,639 lane change events were found to involve a closing lead vehicle. For all lane change events with a closing lead vehicle, the results showed that drivers change lanes most frequently in the 50-60 mph speed range. Minimum TTC was found to increase with travel speed, and the variability in minimum TTC between drivers also increased with travel speed.

INTRODUCTION

One of the most frequent crash modes on the roadway is rear end collisions. The National Highway Traffic Safety Administration (NHTSA) reported 1.8 million rear end crashes occurred in the United States in 2012 [1]. Forward collision warning (FCW) systems have great potential to reduce rear end collisions on the roadway. Studies have estimated that FCW can reduce the number of fatally injured drivers by as much as 29% [2]. However, driver acceptance of the systems is paramount to the effectiveness of a FCW system. If a system delivers the warning too early the driver may be annoyed and turn off the system.

Lane changes with the intention to pass the vehicle in front are especially challenging scenarios for FCW designs because these overtaking maneuvers can occur at high relative vehicle speeds and often involve no brake and/or turn signal application. Therefore, overtaking presents the potential of prematurely triggering the FCW. A better understanding of lane change events can increase driver acceptance of FCW and improve the effectiveness of FCW systems. The objective of this study is to characterize driver behavior during lane change events using the 100-Car Naturalistic Driving Study.

METHOD

The 100-Car Naturalistic Driving Study

The 100-Car study was a landmark large-scale Naturalistic Driving Study (NDS) conducted by the Virginia Tech Transportation Institute (VTTI) from 2001 to 2004. The study contains approximately 1.2 million vehicle miles of driving and 43,000 hours of data collected from 108 primary drivers and 299 secondary drivers [3]. Drivers were recruited from the Washington D.C. metropolitan area. No restrictions were used to select subjects, e.g. excluding those with traffic violations. Younger drivers, i.e. under 25 years, and self-reported high mileage drivers were, however, sought and oversampled [4].

Vehicles were instrumented with cameras and inertial measurement devices and equipped with a PC-based computer to collect and store the data. The data collection box housed a yaw rate sensor, dual axis accelerometers, and a GPS navigation unit. In addition, radar sensors were mounted on the front and rear of the vehicle that were able to track other vehicles. The data collection box was usually installed on the roof of the trunk of the vehicle in order to be unobtrusive. All data were sampled at a rate of 10 samples per second. Some of the sensors had lower sample rates. These data were still sampled at 10 samples per second but would have multiple samples with equal magnitude.

There were five (5) cameras that offered continuous views in and around the vehicle. An exemplar view is shown in Figure 1. The upper left frame shows a view of the driver's face and upper body, blurred to protect the identity of the driver in Figure 1. The lower left pane is an over-the-shoulder view of the driver, the upper right pane is a forward view out the front of the vehicle, and the lower right pane is split between a view out the passenger side of the vehicles and out the rear of the vehicle. The video was useful in the study in interpreting vehicle instrumentation data.

Figure 1. Combined Video Views from the 100-Car Naturalistic Study [4]**.**

Overall Study Approach

Our approach for the current study was broken down into three subtasks, as shown in Figure 2. The first subtask of the study was to find the lane change maneuvers and determine the start and finish of the lane change events. Since not all lane change events involve braking and/or turn signal use, we have developed an algorithm which used the lane tracking instrumentation data to identify lane change events. The second subtask of the study was to identify whether a lead vehicle was present during lane change events. Lastly, minimum Time to Collision (TTC) was computed for each lane change maneuver.

Figure 2. Overall Project Approach

Automated Search Algorithm Development

The identification of lane change events was based on the lane change signal recorded by the on-board lane tracking system. The lane change signal was triggered when the vehicle center line met the lane edge as the vehicle moved across the lane. In addition to the distance of vehicle centerline relative to the lane boundary, the lane tracking system also records the confidence level, from 0 to 100%, that the lane tracking system was providing correct distance evaluation. The following conditions must have been met in order to be accepted as a valid lane change: the duration of the lane change maneuver was greater than 0.3 seconds, no aborted lane change signals, vehicle speed above 10 mph, and average lane tracking confidence greater than 30% during the duration of lane change.

Figure 3 shows the definition of lane change duration used in this study. The start of lane change was defined as the time when the vehicle leading edge met the lane edge, and the end of lane change event was defined as the time when the vehicle was completely within the boundaries of the adjacent lane.

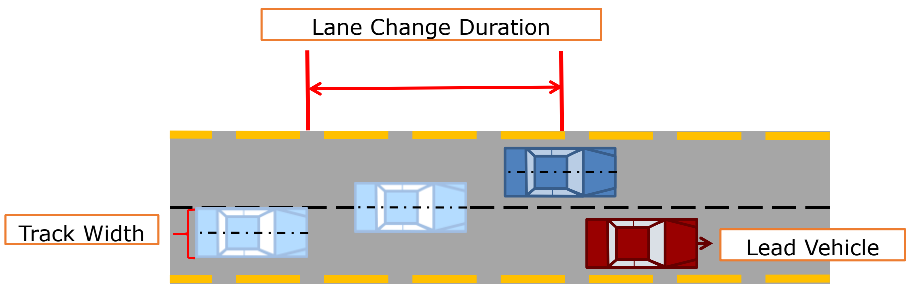

Figure 3 Definition of Lane Change Duration.

The lead vehicle identification algorithm developed in this study was based on a previously methodology [5]. The lead vehicle detection algorithm utilizes the on-board instrumentation, such as radar, vehicle speed, vehicle azimuth, and vehicle acceleration, to identify the correct lead vehicle at the start of a lane change event.

For each lane change with a lead vehicle present, the TTC was calculated as the range divided by range rate at the start of the lane change event, as shown in Equation (1).

$$TTC = \frac{x}{\dot{x}} \tag{1}$$

Algorithm Validation

Both the lane change identification and lead vehicle detection algorithm were validated against a sample of 1,425 manually identified lane change events. The sample of validation lane change events was examined from inspection of 126 trips, containing nearly 50 hours of video footage.

Table 1 shows the distribution of lane change maneuvers and the presence of lead vehicles in the validation sample. Merging lane change maneuvers include entering and exiting the highway. Lane changes involving drivers changing lanes to pass a lead vehicle were considered overtaking events. All other events were labeled “Lane

Change – Other”. Examples of “Lane Change – Other” include events when drivers change lanes but do not overtake any vehicle. As shown by Table 1, 94% of the passing lane change events included the presences of a lead vehicle, as identified by reviewer. However, only 42% of merging events and 37% of lane change events had lead vehicle presence. By our definition, overtaking events should always have a lead vehicle. However, during the validation process, if the reviewer could identify a lead vehicle in the video but the on-board radar did not identify a lead vehicle, the particular lane change event was marked as not having a lead vehicle. Based on the large percentage of merging events and the low incidence of lead vehicle presence during merging events, this sample of validation data suggest that in most lane change event there will not be a lead vehicle present.

Table 1.
Lane Change Maneuver and Presence of Lead Vehicle

Maneuver	Total Number of Lane Changes	Lead Vehicle Present (Count)	Lead Vehicle Present (% of Lane Changes)
Merging	439	184	42%
Overtaking	420	395	94%
Lane Change - Other	566	209	37%
Total	1425	788	55%

RESULTS

Algorithm Validation

The performance of the lane change detection algorithm was evaluated based on contingency matrix shown in Figure 4. The sensitivity (% of correctly detected true positives) and specificity (% of correctly detected true negatives) of the algorithm was calculated as the ratio of true positive and true negative to the corresponding lane change maneuver.

Table 2 summarizes the comparison of the video and lane tracking indicated lane change events. For all valid lane changes with sufficient lane tracking information (i.e. lane tracking confidence > 30%, vehicle speed > 10 mph, and headway < 3 s). The lane change detection algorithm performed very well. The sensitivity of the algorithm was 0.87 and the specificity of the algorithm was 0.98.

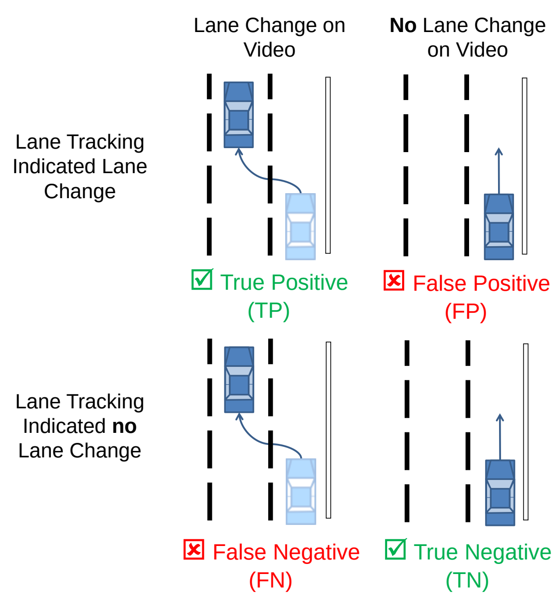

Figure 4: True Positive and False Negative Matrix

Table 2.
Comparison Results of Video and Lane Tracking Indicated Lane Changes

Lane changes with sufficient lane tracking information	645
$Sensitivity = \frac{TP}{TP+FN}$	0.87
$Specificity = \frac{TN}{TN+FP}$	0.98

The lead vehicle detection algorithm correctly identified the car following situation in 84% of the lane changes in the validation sample. Figure 5 shows the lead vehicle identification algorithm performance in five different car following scenarios. Scenario a) is the correct identification of a lead vehicle when there is lead vehicle present, b) is the correct determination of no lead vehicle, c) is the identification of a lead vehicle when no lead vehicle is present, d) is no lead vehicle is identified when a lead vehicle is present, and e) is identifying the wrong vehicle as the lead vehicle.

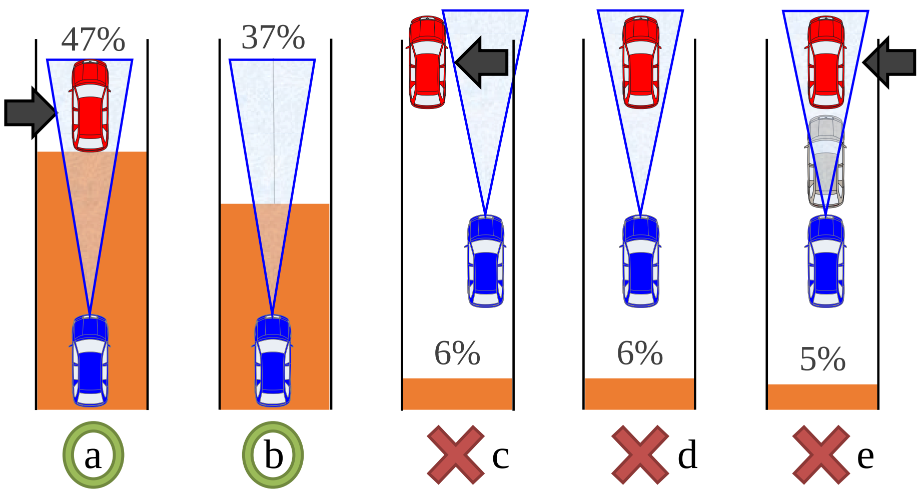

Figure 5: Lead Vehicle Detection Scenarios

Driver Selection

A total of 108 primary drivers and 299 secondary drivers were included in the 100-Car study period in which all driving in an instrumented vehicle was recorded [3]. Primary drivers were the primary owners or leasers of the instrumented vehicles. Secondary drivers occasionally drove the vehicles. Primary drivers accounted for 89% of all miles driven during the study period. The entire 100-Car database contains approximately 1.2 million miles of driving, 1,119,202 miles of which were driven by primary drivers in 139,367 trips [3]. Some primary drivers drove in multiple vehicles. For the current study only trips where a primary driver was driving in the vehicle that he or she most frequently drove during the study, i.e. their primary vehicle, were selected.

Prior to the analysis, the status of all time-series data was inspected. Instrumentation data, including front facing radar, vehicle speed, brake switch status, yaw rate signals, and lane tracking, were checked for missing or invalid data. The current study only included vehicle which had valid data in at least 60% of all trips and 60% of all distance traveled. Table 3 summarizes the sample of trips with valid sensor data. A total of 46,250 trips from 45 drivers were used in this study.

Table 3.
Driver Selection with Valid Sensor Data

Number of Drivers	45
Number of Trips	46,250
Total Miles Driven	406,606.7
Median Trip Distance (miles)	4.6
Median Trip Duration (minutes)	11.4

Population Distribution of TTC at Lane Change

Table 4 shows the result of the lane change detection algorithm for all drivers with valid sensor data, organized by lane change scenarios. A total of 326,238 lane changes were found in the 46,250 trips. The distribution of left side and right side lane changes was essentially even. A total of 90,639 lane changes involved a closing lead vehicle. Closing lead vehicles was defined to be lane change events where the driver was moving closer to the lead vehicle. As shown in the table, lane changes with closing lead vehicle accounted for approximately 28% of all lane change events. Similar to the distribution of all lane change events, left side lane change accounted for approximately 52% of all lane changes with closing lead vehicle, and right side lane changes was approximately 48% of all lane changes with closing lead vehicle.

Table 4.
Lane Change Scenario Distribution

	All Lane Changes (% of All Lane Changes)	**Lane Change with Closing Lead Vehicle (% of Lane Change with Closing Lead Vehicle)**
Left Side Lane Change	171,519 (52.6%)	47,420 (52.3%)
Right Side Lane Change	154,719 (47.4%)	43,219 (47.7%)
Total Lane Change	326,238 (100%)	90,639 (100%)

Table 5 summarizes the distribution of lane change frequency. The zero 10^{th} percentile values in each of the measurements in the table resulted from the fact that no lane changes were detected in approximately 35% of the trips.

Table 5.
Lane Change Frequency Distributions

Measurement	**10^{th} Percentile**	**Median**	**90^{th} Percentile**
Lane change per trip	0	3	19
Lane change per mile	0	0.8	2.3
Lane change per hour	0	19.7	58.4

Figure 6 shows the distribution of total number of lane changes with a closing lead vehicle within each speed bin. The label above the figure shows the number of driver who made lane changes within the speed bin, e.g. n = 45 drivers in the 10-20 mph speed bin. Not all drivers made lane changes within each speed bins, therefore not all speed bins had 45 drivers. The figure shows a skewed left distribution, suggesting that lane change events with closing lead vehicles are more likely to occur at higher travel speeds, such as suburban roads with speed limits ranging from 35-45 mph, and highways with speed limits ranging from 55-65 mph. As shown in the figure, the speed bin with the most number of lane changes is the 60-70 mph range. This speed range corresponds to the highest highway speed limit surrounding the Washington D.C. metropolitan area, and could be the result of frequent driver movement through traffic gaps in congested area. However, this total is skewed by one outlier driver, who had more than 4,000 lane changes in the 60-70 mph speed range.

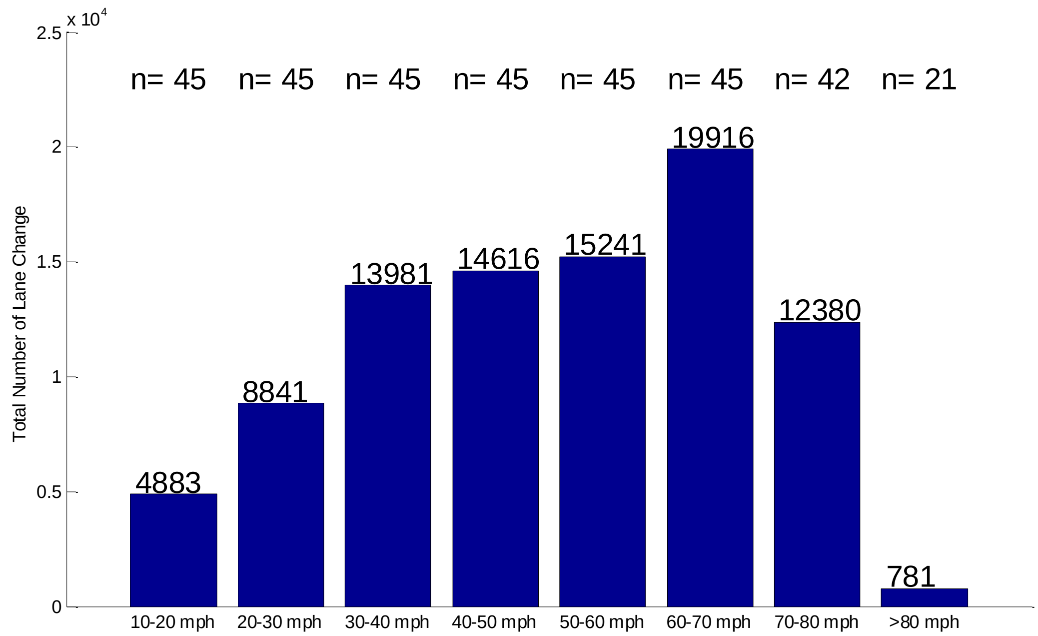

Figure 6: Distribution of Lane Change with Closing Lead Vehicle and TTC (90,639 total lane changes)

Figure 7 shows the distribution of minimum TTC by driver in each speed bin. Each driver has one point in each 10 mph speed bin. The cumulative distribution of minimum TTC for each driver are plotted below for each speed bin. In Figure 7, TTC was computed as the TTC at the start of lane change, and minimum TTC for each driver refers to the lowest (closest to zero) TTC for trips within each speed bin.

In general, the minimum TTC increases with travel speed. The variability in minimum TTC between drivers also increases with travel speed. The plot shows the number of drivers who made lane changes with a closing lead vehicle in each speed bin (ex. N = 45 in the 60-70 mph bin). Due to the relatively low percent of lane change at high speeds, not all drivers had lane changes with a closing lead vehicle in the >80 mph speed range.

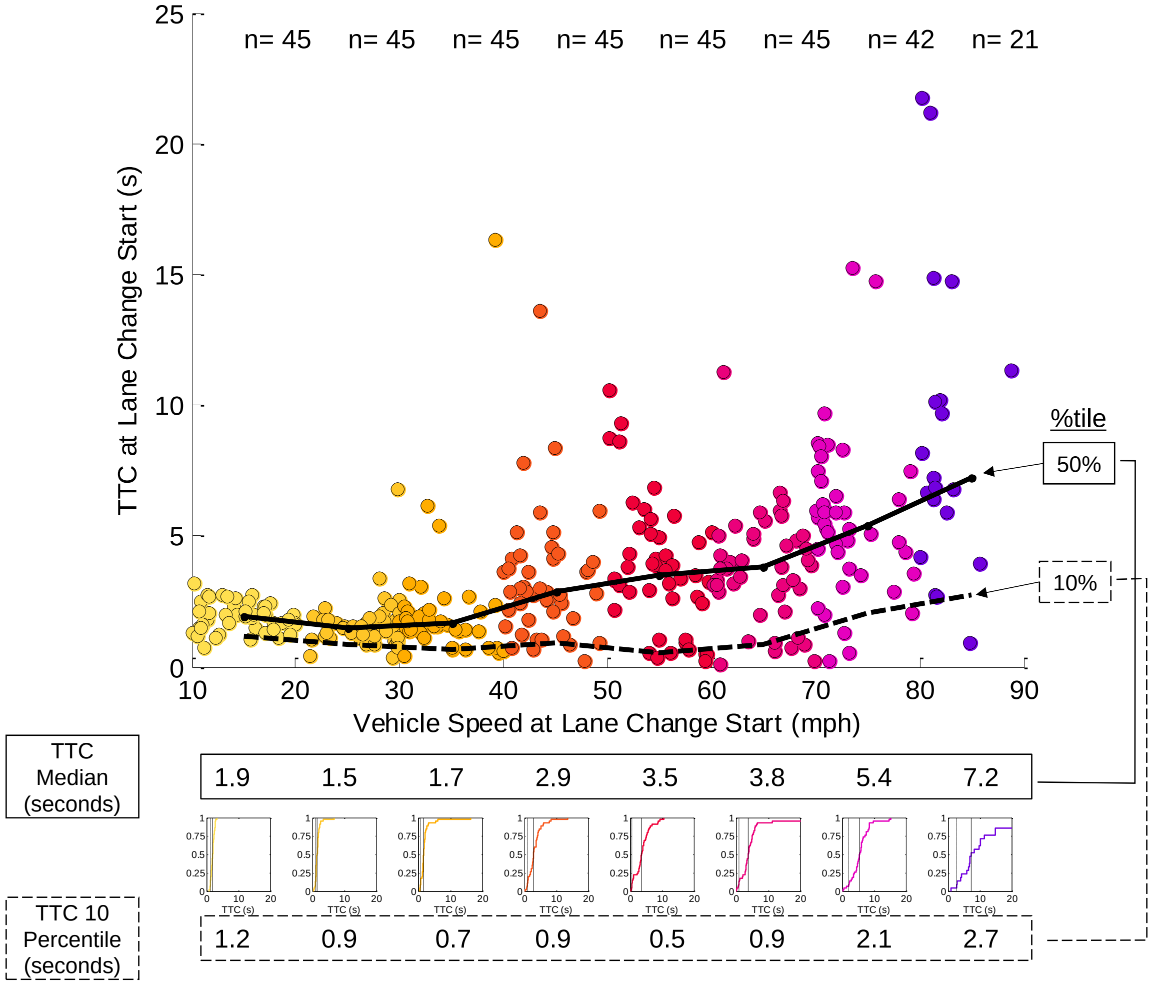

Figure 7: Minimum TTC for Each Driver by Travel Speed Bin (n =90,639 lane changes)

CONCLUSIONS

The objective of this study was to characterize driver behavior during lane change events. This study presented a methodology to detect lane change events and a methodology to identify lead vehicle in lane change events in the 100-Car NDS. The performance of these two algorithms was validated against 126 trips, in which the researchers manually examined the video footage to determine the time frame of lane change and lead vehicle presence. Finally these algorithms were applied to the 100-Car NDS dataset to obtain the distribution of TTC at lane change with a lead vehicle in front of the subject car.

In 126 randomly selected validation trips, the researcher manually reviewed the trip video and identified 1,425 lane change events. 420 events were found to be overtaking event, in which the video shows a driver passing a lead vehicle. A total of 439 merging lane change was found in the sample, in which a closing lead vehicle was present in about 42% of the merging events. For lane change events other than overtaking and merging (566 events), a closing lead vehicle was present in 37% of these events. Overall, the lane change detection algorithm performed very well. For lane changes with sufficient lane tracking information, the validation process showed that the automated lane change algorithm had a sensitivity of 0.87 and a specificity of 0.983. The lead vehicle identification algorithm also performed reasonably well, and correctly identified the car following situation in 84% of the validation sample of lane change events. Our lane change detection algorithm is highly dependent on the presence of lane markings, therefore our analysis was restricted to marked roadways. It is currently uncertain how our results will be generalized to roads with poor lane markings.

A total of 326,238 lane change events were identified by the algorithm in 46,250 trips, totaling over 400,000 miles of driving. In addition, the breakdown of lane change frequency by speed bin also shows that drivers are more likely to change lanes in travel speeds ranging from 30-60 mph. The lower lane change frequency in the lower speed range bins can potentially be due to several reasons. First, it is likely that lane changes events in lower speed ranges (i.e. lower than 30 mph) were on roads with lower speed limit and were 2-lane roads with no adjacent lanes to change into. We also hypothesize that when drivers initiate lane change maneuvers in lower speed ranges, they were more likely to speed up and thus are grouped into higher speed bin ranges. An example scenario would be during congested traffic conditions in the Washington D.C. area, the instrumented vehicle are in a lane with slow moving traffic but speeds up to change into the adjacent lane in order to move ahead of traffic.

The distribution of TTC showed that minimum TTC, as well as variability of TTC between drivers, generally increased with travel speed. The increase in TTC can be attributed to drivers generally becoming more cautious and increase following distance as travel speed increases. As driver begins to increase following distance, lead vehicles are more likely to be outside of the range of the front radar. Although our study was highly dependent on the radar to detect lead vehicle, therefore biased towards what the radar can “see”, the results are still relevant in improving the effectiveness of a FCW system in a crash imminent situation.

The characterization of lane change events presented in the current study will provide active safety system designers further understanding of driver action in overtaking maneuvers and can improve designs of FCW systems. Specifically, the results of this study show that the frequency and TTC in lane change events vary by vehicle speed. The large variability in minimum TTC between drivers shows the need for FCW systems to implement several different warning thresholds depending on different driving style.

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