A Study of Driver Behaviors at Unsignalized Intersections Using SHRP2 Naturalistic Driving Study Data and Field Observed Conflict Data

by

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Abstract

Unsignalized intersections on divided highways with wide medians (>30 ft) have the potential for severe crashes due to numerous conflict points and high speed. Drivers making minor road left turns have to make multiple judgments when crossing the intersection, exposing them to a higher risk environment. Therefore, the purpose of the study is to analyze the minor road left turn driver behaviors (e.g., driver visual workload, speed change behavior, stop and conflict behaviors) at unsignalized intersections with wide medians on high-speed divided highways in rural or suburban areas. The study also made suggestions on improving the intersection safety design based on the driver behaviors. collected a total of 440 left turn trips at six conventional unsignalized intersections, and 40 right-turn followed by U-turn trips at Restricted Crossing U-Turn (RCUT) intersections from the Second Strategic Highway Research Program (SHRP 2) Naturalistic Driving Study (NDS) database. Driver eye-glance data, speed change, brake pedal usage, stop condition and the roadway feature data were analyzed. Additionally, the study conducted conflict study between six pairs of unsignalized intersections in the state of Alabama to assess the safety effect of the two types of median opening access control treatments: (1) stop bars, stop signs, and double yellow line and (2) yield lines, yield signs and double yellow line.

The study first analyzed the NDS data of driver eye-glance, demographic information, and roadway features. The entropy rate of each trip was calculated as an indicator of the driver visual workload and was treated as the dependent variable for the statistical analysis. The higher the entropy rate the higher the workload. A comparative study between these two movements at

these two types of intersections was conducted. Results indicated that drivers at RCUT intersections have less random scanning and longer average fixation and spent more than 70% of time looking forward during the whole movement. Younger drivers at both types of intersections have higher entropy rates. Additionally, drivers at conventional intersections with higher AADT (≥ 30,000) have higher entropy rates.

The analysis of the driver speed change and stop behaviors were conducted for three different phases, including phase 1 - Deceleration, phase 2 - Intersection Entry, and phase 3 - Execute Turn. Study results show that 85th percentile of the left turn drivers tend to decelerate sharply when they are about 50 feet away from the minor road stop line; about half of the drivers did not make complete stops at the minor road; only 25% of the drivers stopped at the median opening; and 85th percentile of drivers used up to 650 ft to speed up to 45mph.

Additionally, a cross-sectional comparison was conducted between six pairs of unsignalized intersections (with access controls vs. without access controls at the median openings) in the state of Alabama. Video cameras were installed to monitor each intersection during a typical weekday. Two specific movements: minor road left-turn movement and major-road left-turn movement are significantly affected by the two median opening treatments. The study includes analyzing 16 hours of video for each location to record the number of traffic conflicts, near-crash situations, and left-turn driver behaviors (defined as understanding right-of-way, whether or not stopping at the median opening, and using two-stage left-turn movements). The results showed that the stop bars at the median opening can reduce the traffic conflict rate by 10% to 40% and help more drivers to stop or slow down at the wide median openings to make a better judgment of the safe gap. The stop and yield lines combined with a double yellow line can also help the left-turn drivers better understand the right-of-way and reduce the right-angle conflicts.

The study results will provide a better understanding of driver behaviors and the behaviors' safety implications at different types of unsignalized intersections. The corresponding suggestions for improving the roadway designs were also summarized at the end of the study.

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List of Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ALDOT	Alabama Department of Transportation
ANOVA	Analysis of Variance
AU	Auburn University
DRAC	Deceleration to avoid a crash
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
LTAPOD	Left Turn Across Path from Opposite Direction
MUTCD	Manual on Uniform Traffic Control Devices
MnDOT	Minnesota Department of Transportation
NCHRP	National Cooperative Highway Research Program
NCUTCD	National Committee on Uniform Traffic Control Devices
NDS	Naturalistic Driving Study
NHTSA	National Highway Traffic Safety Administration
PET	Post Encroachment Time
RCUT	Restricted Crossing U-turn
ROC	Risk of Collision
SHRP	Strategic Highway Research Program
SD	Sight Distance

TTC	Time to Collision
TCD	Traffic Control Devices
TWSC	Two-way Stop-controlled
VDOT	Virginia Department of Transportation
VTTI	Virginia Tech Transportation Institute

Chapter 1. Introduction

1.1 Research Background

A report from the National Cooperative Highway Research Program (NCHRP) on unsignalized intersection design shows approximately 30 to 40 percent of all crashes on rural divided highways were intersection-related (*Maze, et al. 2002*). More than 50 percent of the combined total of fatal and injury crashes occurred at or near intersections in the United States. Crashes in rural areas are usually more severe than in urban areas because of higher vehicle speeds and reduced enforcement of proper driver behaviors (*FDOT 2014*). **Figure 1.1** shows the intersection crashes by severity and speed environment in New Zealand based on the 2008 to 2012 data from High-risk Intersection Guide. While the study is not conducted in the U.S., to the author's knowledge, the similar data has never conducted in the U.S and we hypothesize that the similar trends will exist in the U.S. The data shows that the proportion of fatal and serious crashes increases with the speed limit. In urban environments the proportion of fatal and serious crashes of all injury crashes is 15% compared with 25% in rural areas.

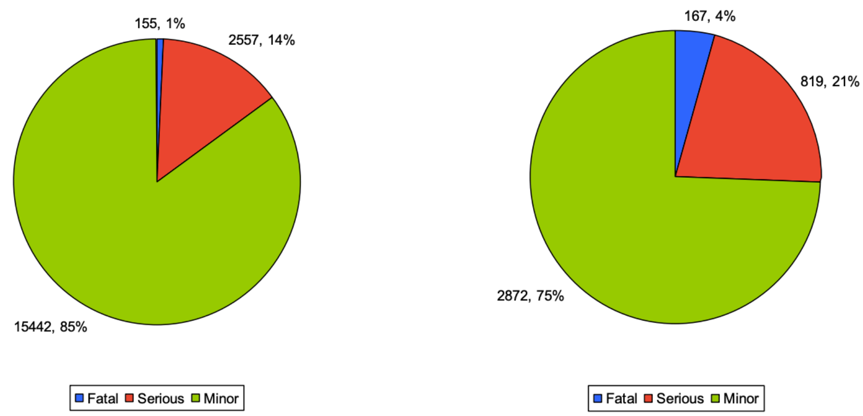

Figure 1.1 Intersection Crashes by Severity and Speed Environment, 2008-2012 (New Zealand Transport Agency, 2013)

In rural areas, more fatal and severe injury crashes occur at stop-controlled intersections than at signalized intersections (*FHWA 2009*). In 2018, 27 percent of crash deaths occurred at intersections, and 67 percent of intersection fatalities involved an unsignalized intersection (*NHTSA 2021*). At stop-controlled intersections, most crashes are caused by a failure to stop at a stop-controlled approach or an insufficient gap when entering the intersection (*Preston et al. 2004*). According to the crash data from the Critical Analysis Reporting Environment (CARE) database (see **Figure 1.2**), the crash numbers in Alabama rural areas steadily increased from 2015 to 2019. From 2018 to 2019, the total number of crashes in Alabama rural area decreased, but the percentage of the intersection related crashes increased, from 15.22% to 15.72%.

The high-speed rural divided highways with wide medians (≥ 30 ft) (see **Figure 1.3**) provide the safety benefits for a relatively large degree of separation of the opposing direction of traffic but leaves drivers from minor roads with more conflict points and higher risks when turning left compared to other movements. These drivers tend to complete the maneuver in two-stages: first crossing the near-side roadway, and subsequently pausing or waiting in the median before crossing or turning left onto the far-side roadway. The drivers have to make multiple judgments on sight distances, approach speeds of crossing traffic, and sufficient gaps in a high-risk and high-speed setting, which make these drivers exposure in higher risks than the direct one-stage left turn drivers.

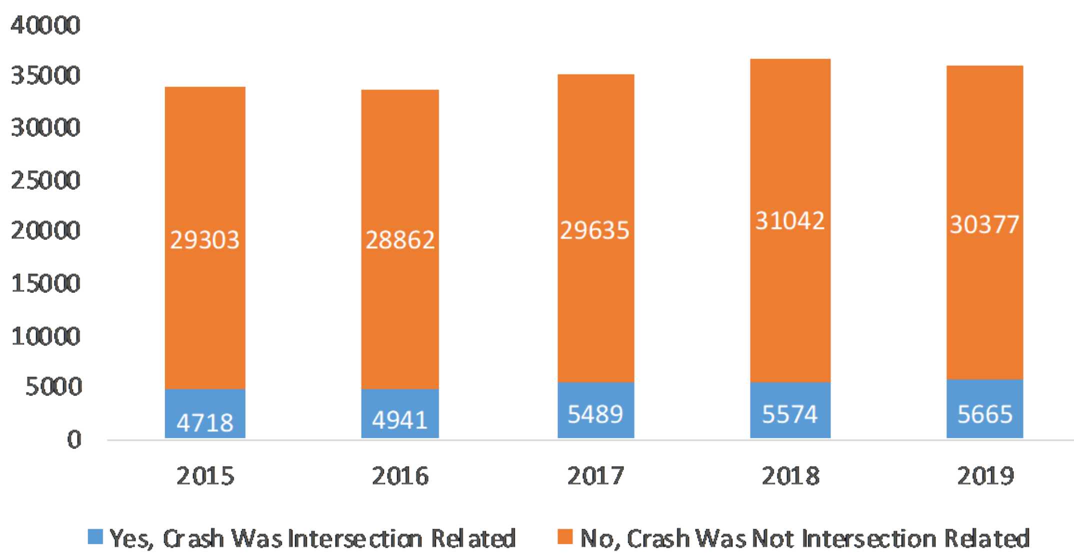

Figure 1.2 2015 – 2019 Crash numbers in Alabama Rural Areas (CARE Database)

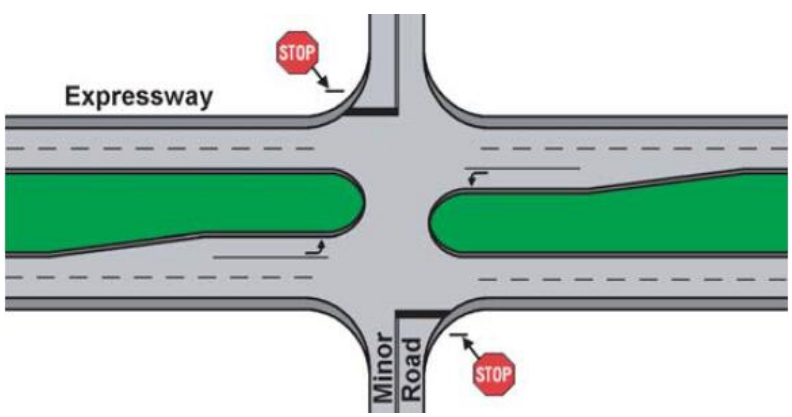

Figure 1.3 Typical Rural Two Way Stop Control (TWSC) Intersection with Wide Median (NCHRP Report 650, 2010)

This study examined the driver behaviors when making minor road left turn at unsignalized intersections by using the Second Strategic Highway Research Program (SHRP 2) Naturalistic Driving Study (NDS) database at the Virginia Tech Transportation Institute (VTTI). The driver behavior analysis including driver eye-glancing, driver speed change condition and the driver stop behaviors at the near-side roadway, far-side roadway, and median openings of this type of intersections by analyzing the collected SHRP 2 NDS data.

Conventional unsignalized intersection on a four-lane divided highway with wide median has 42 conflict points when considered at a lane-specific level (see **Figure 1.4)**, resulting in large amounts of interactive information and complex decision-making for drivers when crossing the wide median intersections (*Maze et al. 2002*). In recent years, many states have constructed Restricted Crossing U-turn (RCUT) intersections to replace conventional intersections (see **Figure 1.5**), which can reduce the conflict points at the intersection (*VDOT 2021*). In contrast to conventional designs, RCUT intersection prohibits the left-turn and through movements from side street approaches. The driver workload at RCUT intersections is still unknown. Therefore, this study compared the minor road left turn drivers' workload between the conventional intersections and the RCUT intersections by using the NDS data.

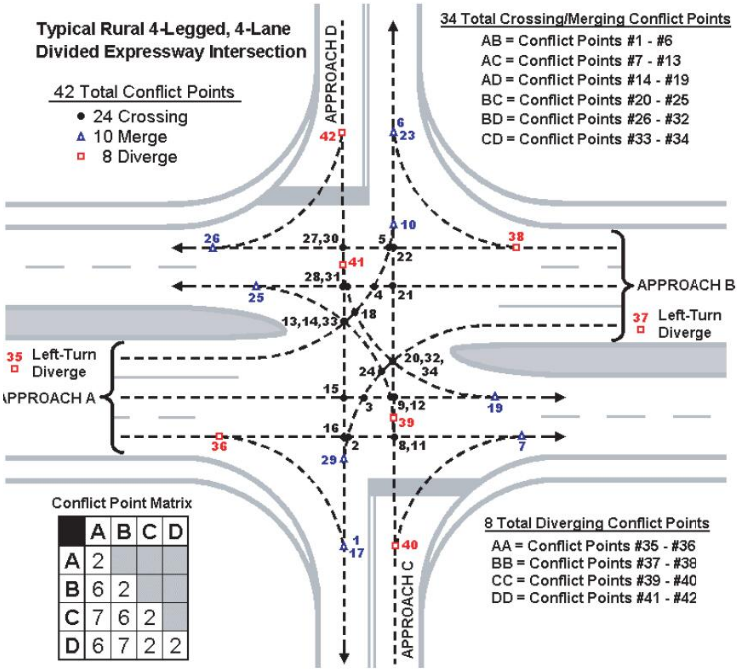

Figure 1.4 42 Conflict Points of the Divided Highway Unsignalized Intersections

(NCHRP Report 650, 2010)

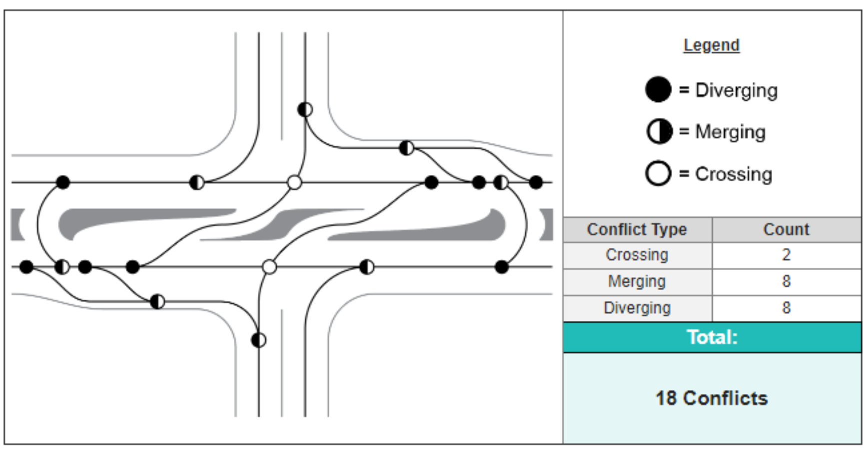

Figure 1.5 18 Conflict Points of the RCUT

(VDOT 2021)

Alternatively, ALDOT recently implemented two types of low-cost median opening treatments rather than build the expensive RCUT intersections: (1) stop line, stop sign and double yellow line (see **Figure 1.6)**; (2) yield lines and yield signs and double yellow line (see

Figure 1.7) to provide additional access control at the median openings. Both of the two treatments don't have crash modification factors (CMFs) from the CMF clearinghouse. Based on the literature review, there are no previous studies on the effectiveness of these two treatments.

Figure 1.6 Stop Lines, Stop Signs and Double Yellow Lines (Google Maps)

Figure 1.7 Yield Lines, Yield Signs and Double Yellow Line (Google Maps)

The Alabama Department of Transportation (ALDOT) funded two research projects: *Development of Guidance for Unsignalized Type Intersection Configuration on Rural Divided Highways (930-964)*, and *Application of the Naturalistic Driving Study Dataset to Improve Design Guides & Associated Practices (930-923)*. This dissertation is part of these two ongoing projects.

1.2 Study Objectives and Tasks

The objective of this dissertation is to understand different driver behaviors at unsignalized intersections by using the SHRP 2 NDS data, then develop the guidelines to improve intersection safety based on the driver behaviors. The study first analyzed the eye-glancing behavior and quantifies the visual workload for two types of traffic movements: direct left turns from the minor road at conventional intersections, and right-turn followed by U-turn movements at RCUT intersections by using NDS data. Other driver characteristics of the two-stage left turn are also studied, including driver speed change conditions and stop conditions. Due to the limited crash data, the safety and operational effectiveness of the stop/ yield signs and lines at the median of the intersections are studied by using conflict data and driving performance information. According to the data analysis results, a general guideline will be developed for ALDOT design, planning, and safety offices on how the data-driven research safety approach can be used to improve current practices for roadway design and traffic operations practices.

To achieve the study objective, below are the four specific tasks of the dissertation:

Task 1: Compare minor road left turn driver visual workload between conventional intersections and RCUT intersections.

Task 2: Study driver behaviors of minor road left turn movements, especially the two-stage left turn drivers, including the speed change conditions and brake use conditions.

Task 3: Evaluate safety effectiveness of the two types of median opening access control treatments through comparative studies using traffic conflict data (conflict rates and near crash rates), and driver performance data (e.g., whether stopping at the minor road, whether or not stopping at the median opening, and if the driver understands the right of way) collected in the field.

Task 4: Develop guidelines for safety countermeasures at unsignalized intersections on high-speed divided highways with wide medians in Alabama.

1.3 Dissertation Organization

This dissertation is consisted of six chapters. Chapter 1 provides the research background, objectives, and organization of the dissertation. A comprehensive literature review of existing research on driver behavior studies at intersections, unsignalized intersection conflict study and current design guidelines on wide median intersections is provided in Chapter 2. The data collection efforts are in Chapter 3, including the collection of SHRP2 NDS data and the conflict study data. Data Analysis methods are in Chapter 4, which includes detailed discussions on driver behavior analysis, such as analysis of entropy rate of driver visual workload, driver critical speed change points and the intersection conflict study. Chapter 5 presents the data analysis results of both the NDS data and the field conflict study data. Chapter 6 provides conclusions and recommendations of the study, the limitations of this study and the future work.

Chapter 2. Literature Review

2.1 Gaps in Previous Research and Proposed Work

There are few past studies used NDS data to study the driver behaviors, especially the driver visual workload at the unsignalized intersection on high-speed divided highways with wide medians since most past studies used the eye-glance data to do the driver distraction analysis. There are also few previous studies on the two-stage left turn driver behaviors at the intersections by analyzing the driver speed change trajectories. Furthermore, the safety effectiveness of the two types of median opening access control treatments (stop sign/ line and yield sign/ line) in Alabama is still unknow since there are limited crash data at those locations, and the literature shows that the conflict study can be a good alternative to evaluate the safety effectiveness of the treatments. The conflict study and driver behavior study results will be furtherly used by the author to develop the guidelines for the wide median intersection. Finally, providing guidelines for improve the unsignalized intersection designs to DOTs, traffic agencies, and policymakers is also in demand.

2.2 Driver Behavior Studies at Unsignalized Intersection

2.2.1 SHRP2 NDS-based Studies

A few studies of driver behaviors have recently been conducted based on NDS data. **Table 2.1** summarized the driver behavior studies at intersection using NDS database.

Oneyear et al. (2016) compared the driver braking behavior at the different rural stop-controlled intersections with different TCDs by using the SHRP 2 NDS data. They developed a linear regression model and found overhead flashing beacons and pavement marking increased the distance at which the driver began braking. Kim et al. (2018) compared different driver distraction at intersections in car following models based on driver's eye glance behavior from 100-car NDS database by using decision tree analysis. Dinakar et al. (2019) studied driver responses in left turn across path from opposite direction (LTAPOD) crash and near crash events at signalized intersections by comparing the driver brake behavior, second task, age, and perception-reaction time. LTAPOD scenario involves two vehicles initially traveling in opposite directions, and one of the vehicles turns left across the path of the other straight moving vehicle. The statistical test results showed that the drivers responded significantly faster when subjected to shorter time to contact events compared to longer ones. Other shorter reaction time at near crash events included when the turning vehicle did not stop before entering the intersection, or when the turning vehicle was visible for a short duration. But factors such as age, gender or secondary task engagement did not significantly influence response times. Lv et al. (2019) studied the influence of different factors such as road geometry, environmental factors, and traffic conditions on right-turn distracted driving behavior at intersections by using logistic model and random forest. They found that vehicle lane occupied, and traffic control are significantly correlated to distracted driving. They suggest that dedicated right-turn lane design, and TCDs (traffic signal, stop sign and yield sign) can reduce the probability of having right-turn distracted driving behaviors. Zafian et al. (2021) used NDS data to examine infrastructure and other factors contributing to older driver crashes during left turns at signalized intersections. Zafian et al. suggest that using only SHRP2 NDS data will not lead to definitive findings or recommendations for infrastructure changes to increase safety for older drivers at signalized intersections and during left turns since there was a small portion of crashes during left turns at signalized intersections in the database. Moreover, the findings of this study indicate the need to consider other data sources and data collection methods to address this critical literature gap in older driver safety.

Table 2.1 Summarized of the Driver Behavior Studies at Intersection Using NDS Database

Driver Behavior	Facility Type	Focus	Data	Methods	Authors & Year
Crash & near crash	Signalized intersections	Older driver left turn	Crash data, front video, driver demographic data	Video scoring & regression models	Zafian et al. 2021
Gap acceptance	Unsignalized intersections	Critical gap & factors affecting gap acceptance	Time series, front and rear-view video, driver demographic data	Logistic regression & decision tree	Li et al. 2021
Driver response & distracted driving	Signalized intersections	Factors affect the left turn across path from opposite direction	Time-series, secondary task	T-test, & ANOVA	Dinakar et al. 2019
Distracted driving	Intersections	Roadway geometry, & TCDs effects on right-turn drivers	Face video, driver demographic data	Logistic regression, & random forest	Lv et al. 2019
Distracted driving	Intersectiona	Car following models	100-car NDS	Total duration in a second	Kim et al. 2018
Speed change	6 signalized intersections	Right-turn driver	Time-series, forward video & face video	Factor influence index	Wu et al. 2017
Conflict, gap-acceptance & crash avoidance maneuvers	Signalized and TWSC intersections	Evaluation of left-turn lane offset	Front video	Logistic regression	Hutton et al. 2017
Stop & brake	Rural stop control intersections	Evaluation the relationship between driver and TCDs (e.g., flashing beacon, on-pavement sign)	Time-series forward video, & RID	Linear mixed effects model	Oneyear et al. 2016

2.2.2 Eye-glance Behavior Study

Traditional measurements of eye-glance features, such as duration and frequency, have been used by many studies as an indicator of drivers' visual workload (*Romoser et al. 2013; Shaaban et al. 2017; Bao 2009; Victor et al. 2005; Lansdown 2001; and Engström et al. 2005*). The quantitative metric of eye-glance behavior, entropy, was derived from the information theory. Entropy is a measure of the uncertainty of information associated with a random variable. It is commonly used in the flight area of analyzing pilot visual workload since the year of 1990 *(Boer 2000; Ellis 2009).*

Recently, several studies showed that the entropy rate can be a better approach to quantify visual workload in the driving domain when compared to mean glance duration (*Gilland 2008; Bao 2009; and Wang et al. 2014*). The entropy rate can provide measures on how drivers react to the visual locations. Wang et al. (2014) studied drivers' eye glance patterns during distracted driving, and entropy rate was calculated and used to assess the randomness associated with drivers' scanning patterns. Gilland (2008) suggested that the entropy metric proved to be more sensitive to attentional demands than all alternative visual metrics and it is useful for understanding the correlation between driver age and task–induced cognitive demands within the context of real-world driving.

No past studies were found to use the entropy rate to quantify the driver workload at conventional intersections and the alternative intersections (i.e., RCUT intersections).

2.2.3 Other Driver Behavior Studies at Intersections

The author started to study driver behavior at intersections before SHRP2 NDS data was collected. Some common driver behaviors were studied at the intersections, including eye-glance patterns (*Romoser 2008*); reaction times according to driver age and mental workload (*Makishita* *et al. 2008*); stopping behavior (*Muttart et al. 2011*); and abnormal trajectory (*Zhang 2017*). Romoser et al. (2008) studied the glance patterns of older and younger drivers while approaching and entering the intersection with no medians. They compared average amount of times spent in each region and found older adults are more likely to remain fixated on their intended path of travel and look less than younger drivers. Muttart et al. (2011) compared glancing and stopping behavior of motorcyclists and car drivers at intersections, and repeated-measure analysis of variance was utilized to test the effects of the two modes. They found motorcyclists were less likely to come to a complete stop and frequently failed to make proper glances. Zhang et al. (2017) studied the factors affecting the paths of left-turning vehicles from minor road approach at unsignalized intersections by observing vehicle trajectories. Six different trajectories were identified. The statistical analysis results implied that higher vehicle speed on major road and less minor road lanes can cause more abnormal trajectories for left turns from minor road. MnDOT (2020) evaluated the effectiveness of stop lines at stop-controlled intersections with a cross sectional safety study. The study found that both before and after line installations, drivers stopped 10 feet or more after the stop line or stop sign. The more space there was between the line or sign and the edge of the conflicting driving lane, the more drivers ignored the stop line. Some cases showed drivers stopping even closer to the conflicting lane than before. The study concluded that while the marking has some effect, most frequently it is not the predicted or desired effect.

2.3 Unsignalized Intersection Conflict Study

Crash data is reactive, safety evaluation takes place after crashes occur, while conflicts at specific locations are often early warning signs of crashes. Crash data analysis needs more than 5 years to achieve statistic significant, but conflicts occur more frequently and require short periods of observation to infrequent events of interest. Using crash surrogate events that properly reflect the data generating mechanism is critically important (*Tarko 2021*).

Glauz and Migletz (1980) first proposed the concept of safety-relevant event continuity, as shown in **Figure 2.1** . Safety-relevant events including the different level of conflicts and the crash. **Figure 2.2** shows the conceptual safety pyramids built by Hyden in 1987, which shows the relationship between the different level of crash and conflicts. Recently, Tarko (2021) summarized the past literatures on traffic conflicts and their connection with crashes.

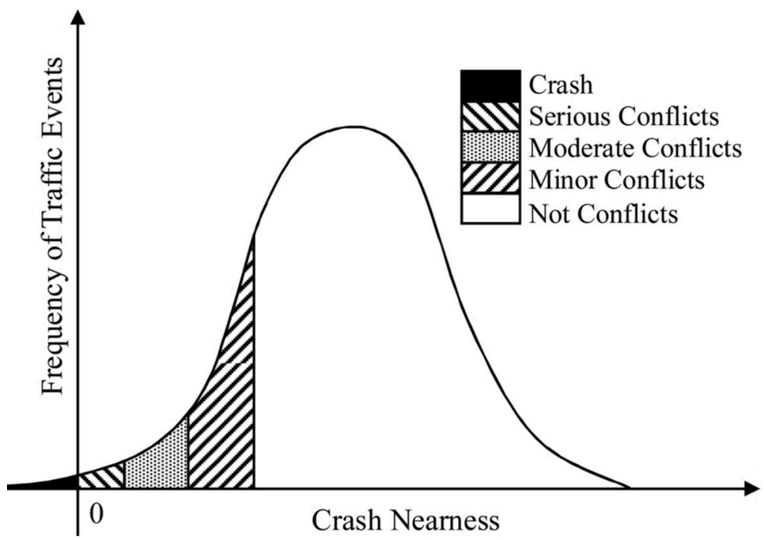

Figure 2.1 Concept of the Continuous Distribution of Crash Nearness as a Bridge Between Crashes, Near-crashes, and Other Safety-relevant Events (Glauz and Migletz, 1980)

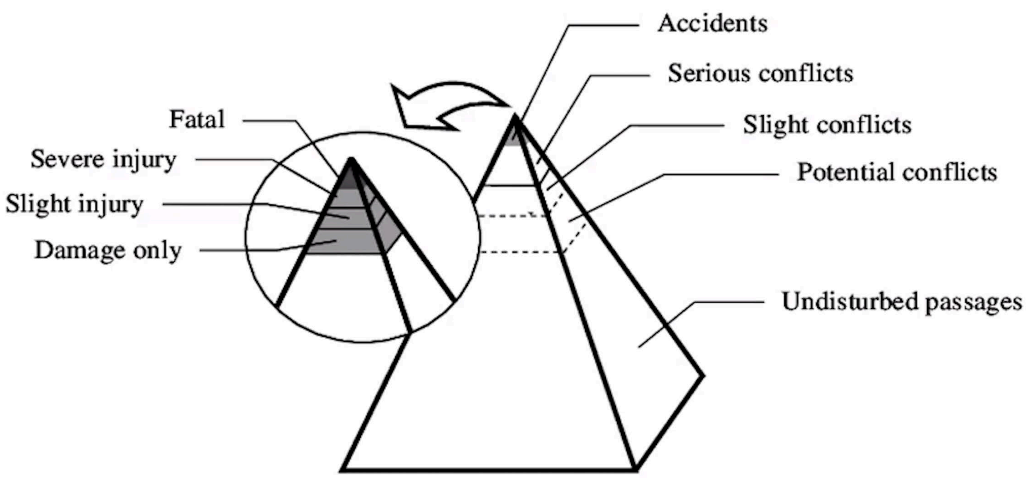

Figure 2.2 Conceptual Safety Pyramid (Hyden, 1987)

Zheng et al. (2019) summarized that the common conflict indicators at the intersection include: 1) post encroachment time (PET); 2) time to collision (TTC); 3) deceleration to avoid a crash (DRAC).

PET is the time difference between the moment an 'offending' vehicle passes out of the area of potential collision. Many studies (*Zhang et al. 2019; Pactrans 2020*) consider PET smaller than 3s as a conflict, and PET smaller than 2s as a critical speed, as shown in **Figure 2.3** below.

TTC is the time required for two vehicles to collide if they continue at their present speeds and on the same path. Studies usually use the indicator of the risk of collision (ROC): low, moderate, and high, based on the value of TTC, as shown in the **Table 2.2** below. Many studies consider TTC smaller than 1.5s as a conflict.

DRAC is the rate at which a following vehicle must decelerate to avoid the collision with the leading vehicle. Many studies consider vehicle DRAC larger than $3.35 m/s^2$ as a conflict.

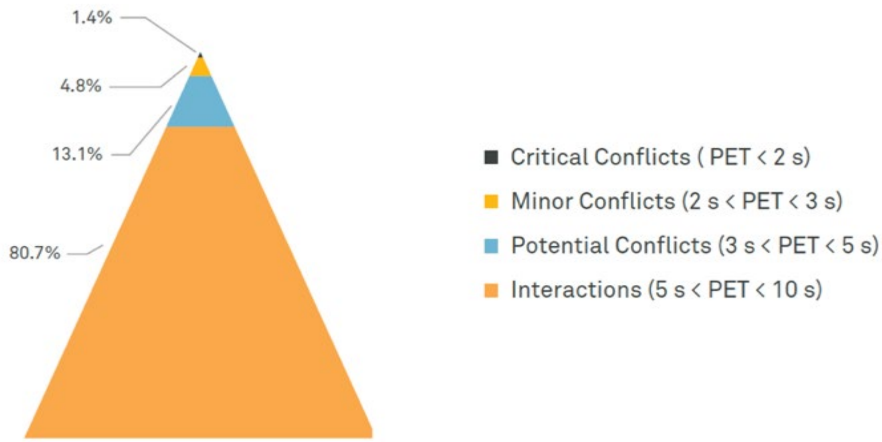

Figure 2.3 Frequency of Intersections with Different PET Volumes (ITE, 2020)

Table 2.2 TTC and ROC Scores

TTC and ROC Scores	TTC (s)	ROC
1	1.6-2.0	Low risk
2	1.0-1.5	Moderate risk
3	0.0-0.9	High risk

(Zheng et al. 2019)

2.4 Current Design Guidelines and Treatments on Wide Median Intersections

2.4.1 Current Design Guidelines

There have been many guidelines on the traffic design or access control at unsignalized intersections with wide median openings. The MUTCD (2009) provides the guidance **(Figure 2.2)** that where divided highways are separated by median widths at the median opening itself of 30 feet or more, median openings should be signed as two separate intersections. The ONE-WAY signs, double yellow line and the stop bars are suggested to be installed at the intersection. The national committee on uniform traffic control devices (NCUTCD) suggests divided highway crossings with median widths between 30 ft and 85 ft may function as either one or two intersections depending upon the interaction of the opposing left-turn vehicle paths and the available interior storage in the median for a crossing vehicle, as shown in **Figure 2.3.** For crossings treated as two intersections, it suggests removing the bullet-nose, install two stop lines at the median opening, and use a double yellow line at the middle to separate the traffic movements from opposite directions. The stop sign, yield sign, and one-way sign are also suggested.

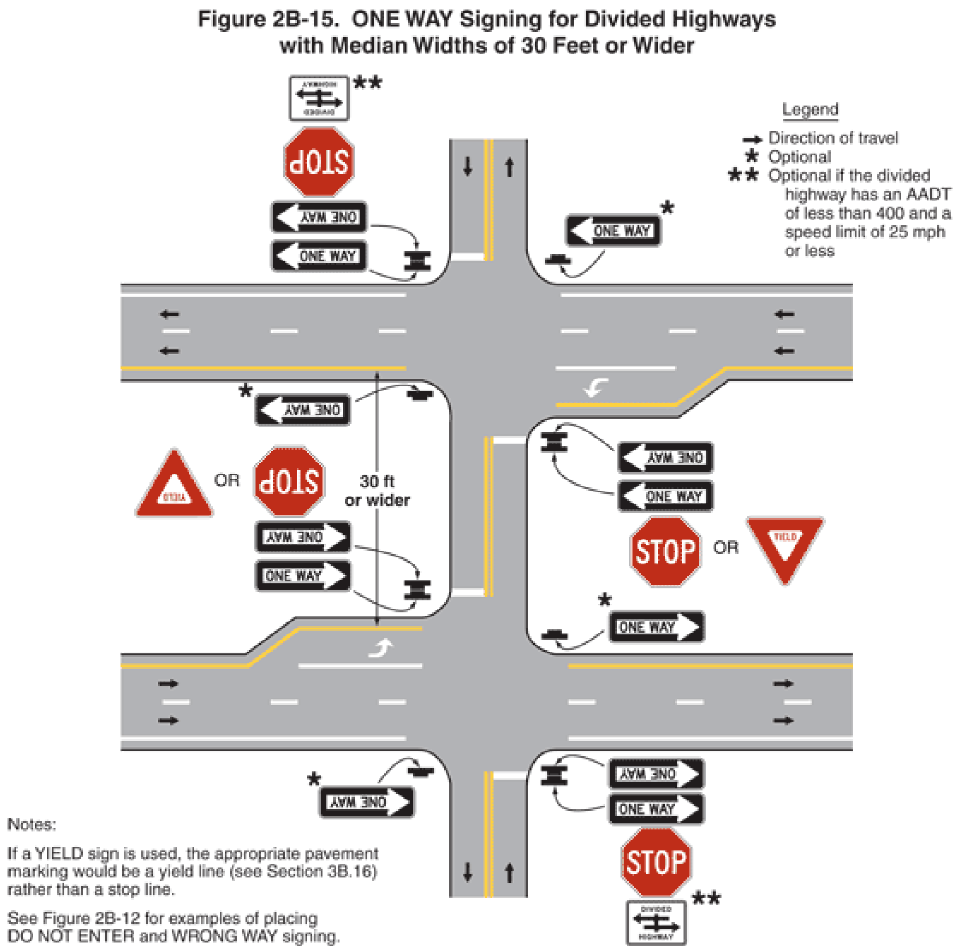

Figure 2.4 2009 Edition MUTCD Guidance on TCD Design of Divided Highways with Medians of 30 Feet or Wider

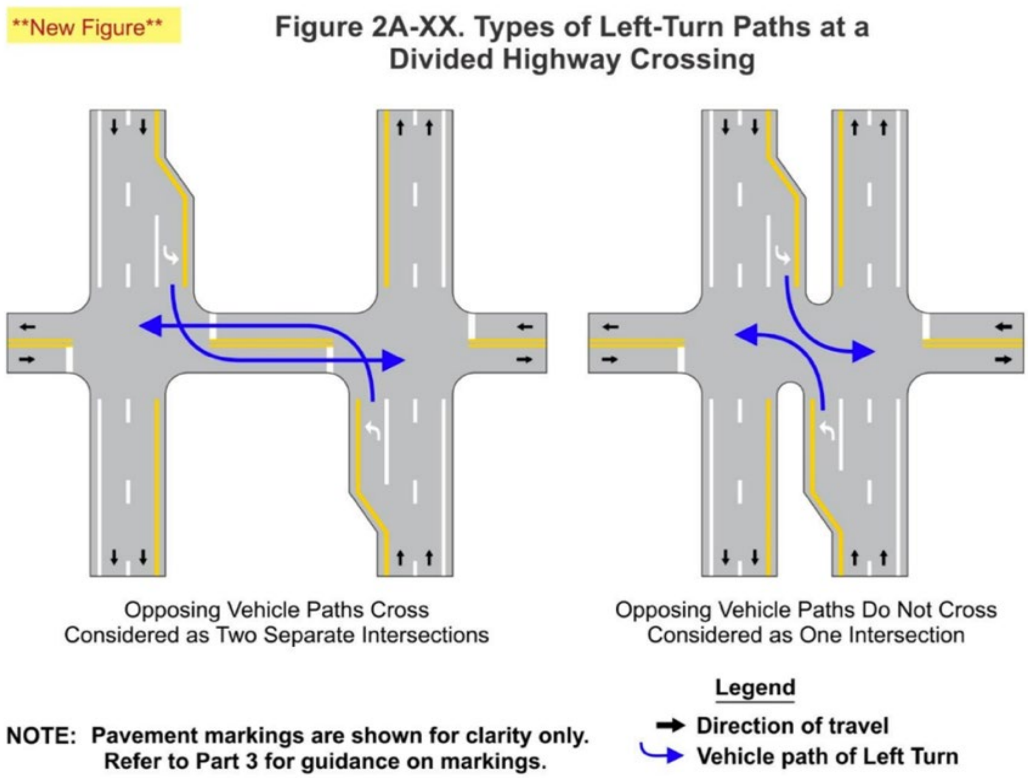

Figure 2.5 NCUTCD Recommended Treatments for Divided Highways with Wide Medians (NCUTCD)

Three NCHRP projects provided some guidelines on unsignalized intersection design. NCHRP Report 650 summarized the current related design guidance and recommended revision. **Figure 2.4** shows the recommended countermeasure matrices for two-way stop controlled (TWSC) rural expressway intersections. The report also provided some suggestions to improve the current design guide (*NCHRP Report 650, 2010*). NCHRP Report 500 suggested to provide a double yellow line at the median opening of a divided highway to avoid the side-by-side queuing and angle stopping within the median area (*NCHRP Report 500, 2003*). Recently, the national committee on uniform traffic control devices (NCUTCD) suggests divided highway crossings with median widths between 30 ft and 85 ft may function as either one or two intersections depending upon the interaction of the opposing left-turn vehicle paths and the available interior storage in the median for a crossing vehicle, as shown in the **Figure 2.5.** NCUTCD mentioned that other factors that could determine whether a divided highway crossing is operating as one or two intersections include: the geometric design of the divided highway crossing; the use of positive offset mainline left turn lanes; the length of the median opening (as measured parallel to the centerline of the divided highway); the geometric design of the median noses; other roadway geometric considerations such as a skewed side street approach or a variable median width; intersection sight distance; the physical characteristics of the design vehicle, and the observed prevailing driver behavior with regard to opposing left turn path interaction. NCHRP Report 375 suggested that opposing left-turn drivers leaving the expressway tend to turn in front of one another (i.e., simultaneous left-turns) when the median width is 50 feet or less, but tend to turn behind one another (i.e., interlocking left-turns) when the median width is greater than 50 ft**,** as shown in the **Figure 2.7 (***HARWOOD et al. 1995***).**

There are some other literatures related to median designs **(***Qi et al***.** *2012; Stamatiadis et al. 2009; and Dissanayake et al. 2003)***),** but they mainly focused on median openings on urban or suburban highways.

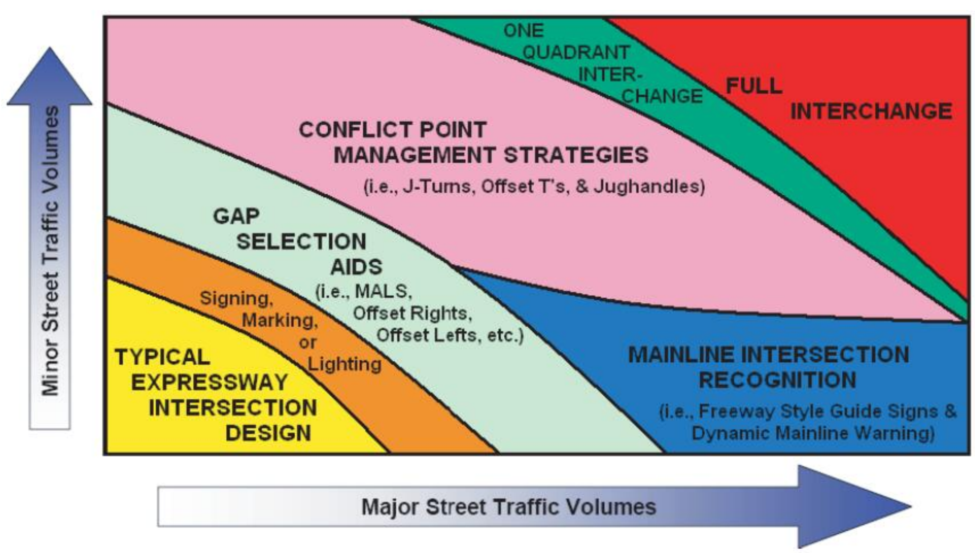

Figure 2.6 TWSC Rural Expressway Intersection Countermeasure Matrices (NCHRP Report 650, 2010)

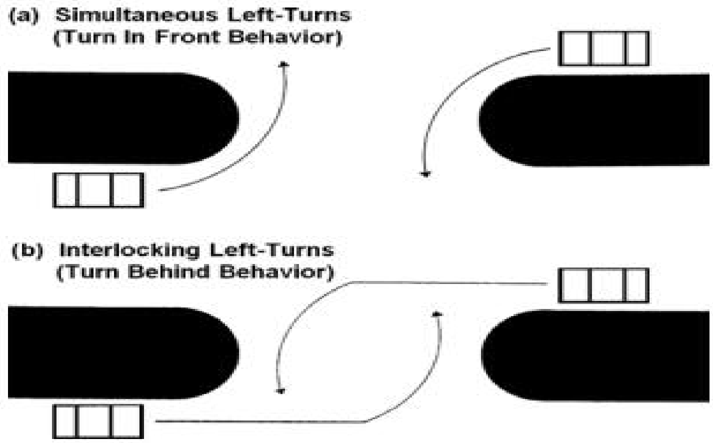

Figure 2.7 Opposing Left-Turn Leaving Driver Behavior (NCHRP Report 375, 1995)

State and federal transportation agencies have developed their own guidelines for median opening design. For instance, Florida Department of Transportation (FDOT) has a median design handbook that provides guidelines on safety improvements at unsignalized intersections (*FDOT 2008*). Besides the treatments for wide median openings based on MUTCD, the median handbook suggests using vehicle actuated flashing beacons for two-stage crossing, especially when an extraordinarily wide median results in an increased observance of accidents occurring at the far end of the intersection. Along with the continuous flashing beacons on the existing stop signs of the intersecting roadway, it is recommended that loop sensors can be placed within the median to activate flashing red beacons on the 2nd set of stop signs as well as flashing yellow beacons in advance of the intersection on the major roadway *(FDOT 2014).* Some other states, like Minnesota, developed design guidelines on rural intersection conflict warning systems, and design guide for roundabout and other alternative intersections, such as Restricted Crossing U-Turn (RCUT) Intersection *(MnDOT 2016).* Additionally, FHWA (2014) published a *Manual for*

Selecting Safety Improvements on High Risk Rural Roads. It includes 31 selected countermeasures for unsignalized intersection. Some of the countermeasures have the crash modification factors, performance ratings and costs. NCHRP Report 613 – Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections (2008) also gives guidance on selecting and installing the speed reduction treatments.

2.4.2 Summary of the Current Intersection Treatments

The study aims to find the effective treatments for wide median intersections; therefore, the author first reviewed all the treatments that are related to the intersection design. Treatments listed below are recommended for improving traffic safety at unsignalized intersections on rural high-speed divided highways with wide medians. The treatments include the different traffic control devices (signs, pavement markings, delineators) and the geometric design improvements. Three latest guidelines below were used as references to select the countermeasures.

- National Surface Transportation Safety Center for Excellence (NSTSCE). *Safety Countermeasures at Unsignalized Intersections – A Toolbox Approach.* VTTI. 2020.
- *Unsignalized Intersection Improvement Guide*. FHWA. 2015.
- *Innovative Operational Safety Improvements at Unsignalized Intersections*. FDOT. 2008.

Below is a list of the related countermeasures by different categories.

Traffic Control Devices - Signs

- Duplicate Stop Sign
- Oversized Stop Sign (R1-1)
- LED-Enhanced Stop Sign
- Retroreflective Panels on Sign Posts
- Signs with Red or Orange Flags

- Warning Signs with Perimeter Retroreflective Sheeting

Traffic Control Devices - Pavement Markings and Delineators

- Double-Yellow Centerline Within Median Opening
- Center Line Pavement Markings on the Minor Road Approach
- Dotted Line Pavement Markings
- Dotted Lines Through Full Median Openings
- Dotted Turn Path Markings
- Raised Pavement Markers at Intersection Approach
- Speed Reduction Pavement Markings (Peripheral Transverse Pavement Markings)
- Transverse Rumble Strips on Intersection Approach
- Wider Longitudinal Pavement Markings
- Post-Mounted Reflective Delineators at Intersection
- Install High-Friction Surface Treatment on Intersection Approaches

Traffic Control Devices - Traffic Signals

- Intersection Control Beacon
- Stop Beacon
- Advanced Stop Beacon

Geometric Improvements - Channelizing Islands and Devices

- Channelization to Limit Turning Movements
- Install Splitter Island on Minor Road Approaches
- Offset Left-Turn Lanes on Major Approaches
- Offset Right-Turn Lane on Major Approaches

Geometric Improvements-Intersection Realignment

- Convert to Restricted Crossing U-turn (RCUT) intersection
- Convert Between a Four-Legged Intersection and Two T-Intersections
- Install a Roundabout
- Modify Skewed Intersections
- Modify Horizontal/Vertical Alignment of Intersection Approach
- Modified T-Intersection

Geometric Improvements-Intersection Reconfiguration

- Close Median Opening
- Extend Left-Turn Lane
- Extend Right-Turn Lane
- Increase Intersection Curb Radius
- Install Left-Turn Lane on the Major Road
- Install Right-Turn Lane along the Major Road
- Install Left-Turn Acceleration Lane
- Install Right-Turn Acceleration Lane
- Lane Narrowing with Median Rumble Strips
- Reduce Width of Travel Lanes on Major Road Approaches (reduce speed)
- Restrict Driveway Access, Install Right-In-Right-Out (RIRO) Operations

Others

- Improve Intersection Sight Triangles Distance
- Eliminate Parking at or Near Intersection
- Install Intersection Lighting

Chapter 3. Data Collection and Reduction

Chapter 3 includes the data collection and reduction of SHRP2 NDS study, and the intersection conflict study in Alabama. For the SHRP2 NDS data collection, the introduction of the NDS database, the study location selection procedure, driver eye-glance data collection, speed change and brake use behavior data collection will be provided. For the intersection conflict study data collection in Alabama, the study intersection selection, and the study location information will be covered in this chapter.

3.1 SHRP2 NDS Data

3.1.1 Introduction of the SHRP2 NDS Data

According to the information from the SHRP2 NDS database, data were collected from more than 3, 500 volunteer passenger-vehicle drivers, ages 16 to 98, during a three-year period, with most drivers participating for one to two years. The study includes six states: Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington. The two predominantly rural sites, in Indiana and Pennsylvania, covered about 10 counties each; the other four urban or mixed sites covered one to three counties each. The total study area encompassed more than 21,000 square miles.

The NDS database contains about 35 million vehicle miles, 5.4 million trips, 2,705 near-crashes, 1,541 crashes, and more than 1 million hours of video. Data included 4 categories: vehicle, driver, trip, and event (see **Figure 3.1**). To be specific, vehicle speed, acceleration, and braking; vehicle controls, when available; lane position; forward radar; and video views forward and the rear, and on the driver's eye-glancing, face, hands, and demographic information are all included.

Figure 3.1 SHRP2 NDS Datasets (SHRP2 NDS Website)

Virginia Tech Transportation Institute (VTTI) developed the Data Acquisition System (DAS) to collect the data of all trips (*Campbell 2012*). The DAS system includes forward radar, four video cameras, accelerometers, vehicle network information, Geographic Positioning System (GPS), on-board computer vision lane tracking plus other computer vision algorithms, and data storage capability (*Dingus, et al. 2015*) as shown in **Figure 3.2.**

The goal of the SHRP2 Safety research program was to address the role of driver performance and behavior in traffic safety. This included developing an understanding of how the driver interacts with and adapts to the vehicle, traffic environment, roadway characteristics, traffic control devices, and the environment. It also included assessing the changes in collision risk associated with each of these factors and interactions

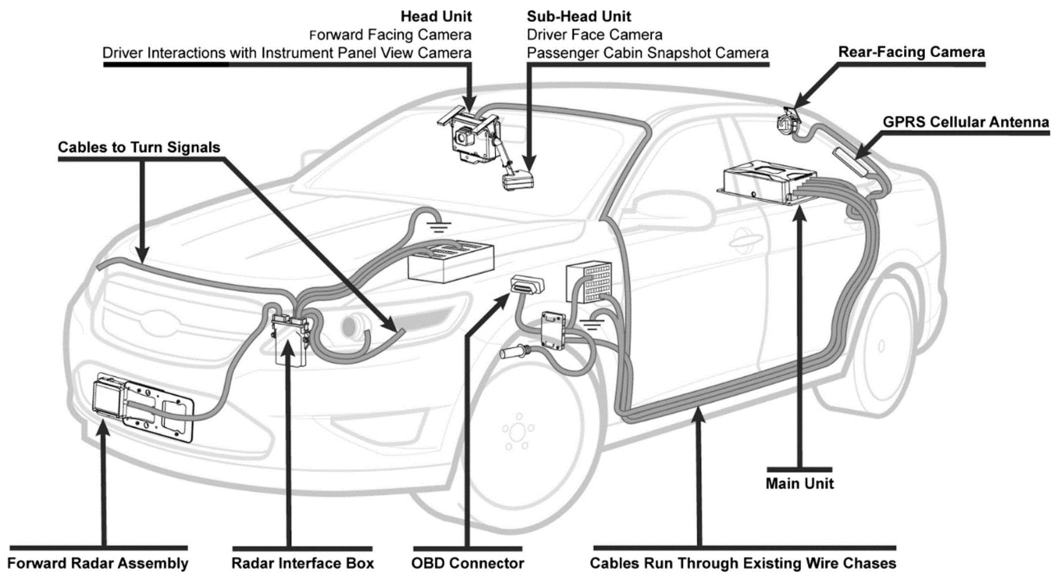

Figure 3.2 Side View Diagram of DAS Component (Antin, et al. 2019)

The following variables of the trips were requested from the SHRP2 NDS database for the study.

Driver Data

- Risk Perception Questionnaire
- Visual and Cognitive Tests
- Driver Demographics Questionnaire
- Eye glance data

Trip Summary Data

- Trip ID
- Driver ID
- Trip Start Month Local
- Trip End Local Hour of Day
- Trip Duration
- Is there a Crash or Near-Crash event during this trip?

Time Series Data

- Trip ID
- Speed
- Acceleration, x-axis, and y-axis
- Turn Rate (gyro_y)
- Pedal, Brake

Videos

- Front Videos
- Rear Videos

Figure 3.3 shows the screenshots of driver front videos at different timestamp. The timestamp of the trip is keep updating on the left bottom of the screen. The timestamps on the left bottom corner are the key references to connect the driver front view to the time series data (e.g., speed and pedal usage). Front videos with poor quality will not be included in the study, such as happened in raining days, or nighttime with poor light conditions.

The front videos show the driver time and the weather condition. All the nighttime trips and rainy-day trips will not be included in the study.

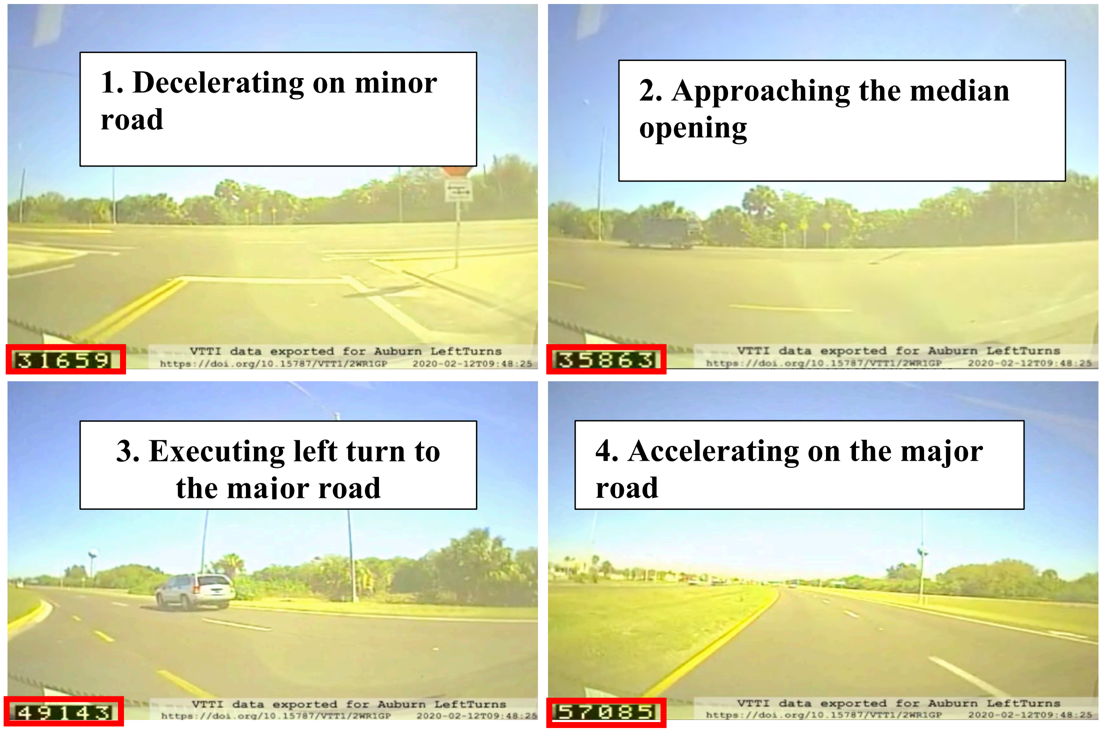

Figure 3.3 Screenshots of Driver Front Views at Different Timestamps

3.1.2 Study Location Selection

To select the study locations of the unsignalized intersections, the author first used Google Maps to identify the locations with the required geometric design features, and then check the traversal density map (**Figure 3.4)** from the SHRP 2 NDS database to select the intersections with minimum number of trips (>= 30 trips). **Figure 3.5** shows the two study scenarios, one at a conventional intersection and the other at a RCUT intersection. The study trips start when drivers begin to decelerate on the minor road and end when drivers approach a stable speed on the major road. The study facility types are four lane divided highways with wide median in rural or suburban areas. The major-road speed limit ranges from 45 to 55mph.

There are more trips at conventional intersections with wide median in NDS database than the RCUT intersections. The study found a total of 636 direct left turn trips at conventional intersections and 577 right-turn followed by U-turn trips at RCUT intersections based on the density maps at the beginning. After further reviewing the video clips, only 470 trips in total meet the study requirements, including 430 direct left turn trips and 40 right-turn followed by U-turn trips. All trips were in Florida or North Carolina.

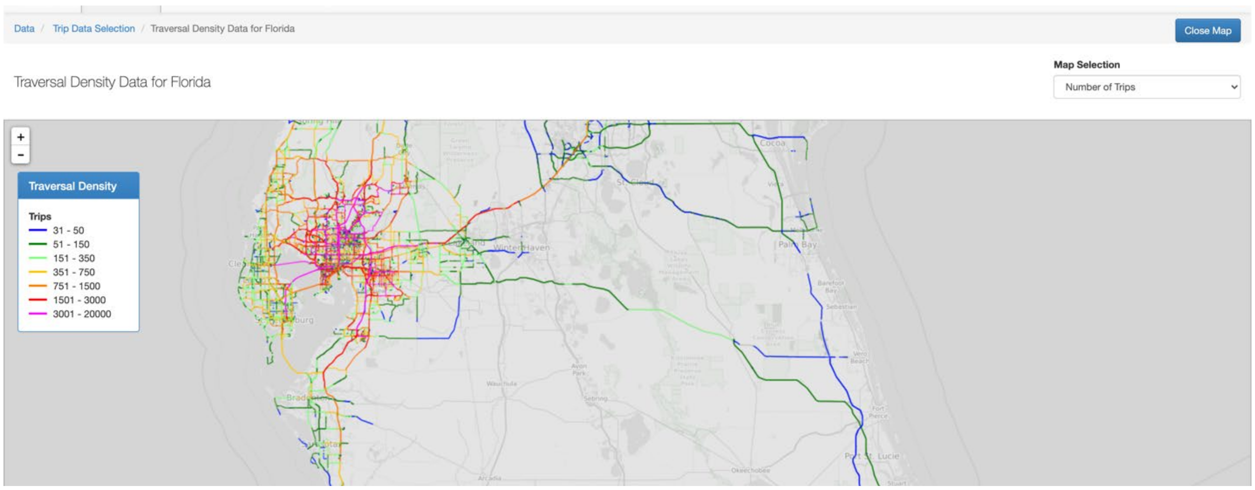

Figure 3.4 Example of Traversal Density Map from the SHRP2 NDS Database

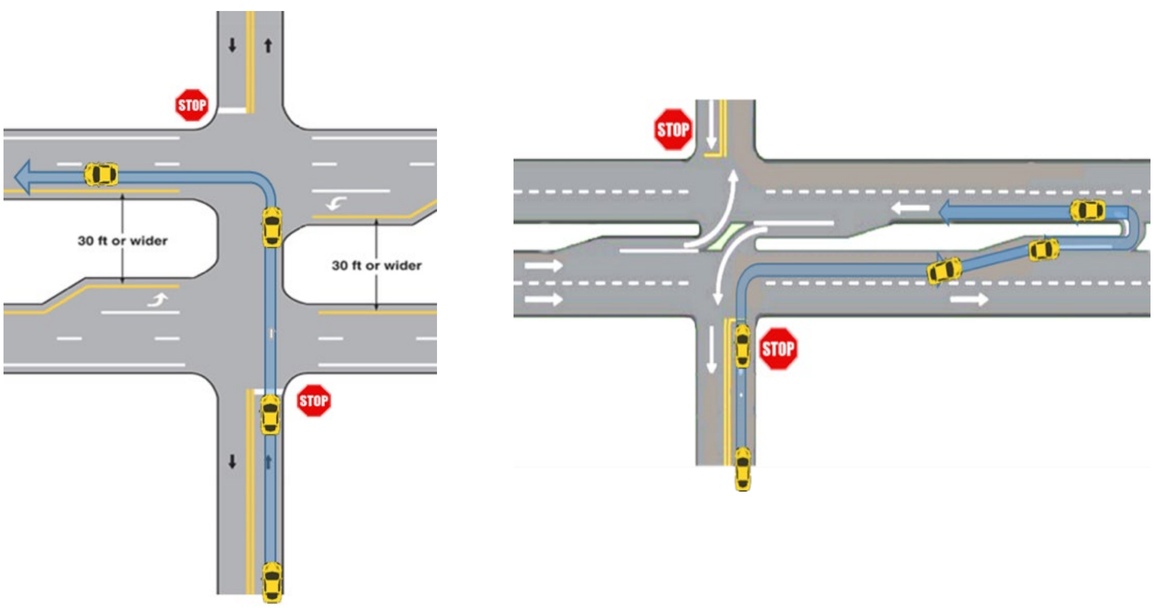

Figure 3.5 Study Scenario 1): Direct Left Turn at a Conventional Intersection (left); Study Scenario 2): Right-turn Followed by U-turn Movement at a RCUT Intersection (right)

Table 3.1 lists the information on RCUT trips at eight study sites. **Table 3.2** shows the information on the six selected conventional intersections in Florida, including location, median width, speed limit, number of trips and drivers.

Table 3.1 Information on the Selected RCUT Intersections in Florida and North Carolina

Loc	Major Rd	Minor Rd	Median Width (ft)	Major Rd Speed Limit (mph)	# of Trip	# of Drivers
FL RCUT1	E Fowler Ave	N 46 St	30	50	5	5
FL RCUT2	E Fowler Ave	N 52 St	25	50	4	4
NC RCUT1	New Bern Ave	Lord Ashley Rd	30	45	1	1
NC RCUT2	US 70	Cannon Blvd	35	55	7	5
NC RCUT3	NW Maynard Rd	Mall Access	25	45	13	3
NC RCUT4	US 441S	Webster Rd	30	40	6	5
NC RCUT5	Knightdale Blvd	Marks Creek Rd	35	45	1	1
FL RCUT6	Andrew Jackson Hwy	Walker Rd	20	55	3	3

Table 3.2 Information on the Selected Conventional Intersections in Florida

Location	Major Rd	Minor Rd	Median Width (ft)	Major Rd Speed Limit (mph)	# of Trips	# of Drivers	Intersection Type	Major Rd AADT	Channelization Island on Minor Rd
FL 1	U.S. 41	Flamingo Dr	40	55	96	21	3leg	16900	Yes
FL 2	U.S. 41	Miller Mac Rd	40	55	161	6	3leg	30000	Yes
FL 3	U.S. 41	Leisey Rd	40	55	29	10	3leg	30000	Yes
FL 4	FL 583	Gibson Ave	40	45	41	10	4leg	19200	No
FL 5	FL 583	E 127th Ave	40	45	44	6	4leg	19200	No
FL 6	E Fowler Ave	Williams Rd	44	45	66	20	4leg	16900	No

3.1.3 Driver Eye-glance Data

To collect driver eye-glance data, part of the research team requested the permission to watch the drivers' face videos in the VTTI Secure Data Enclave. Data were collected in VTTI in person. Before collecting the data, researchers watched several video clips together to make sure they all understand the definitions of the different driver eye-glance locations.

The driver eye-glance annotation tool **(Figure 3.6)** provided by VTTI was used to manually code the defined eye-glancing areas frame by frame. As listed in **Figure 3.6)**, there are a total of 12 eye-glancing areas defined by the author, such as the left or right side mirrors, the windshield, over the shoulder, passenger, cell phone, interior object, center stack, eyes are off-road, rearview mirror, etc. Only eight eye-glancing areas were used in studying workload of minor road left turns or right-turn followed by U-turn movements. The trip videos last from 40 to 120 seconds. Each second of the video contains about 14 frames.

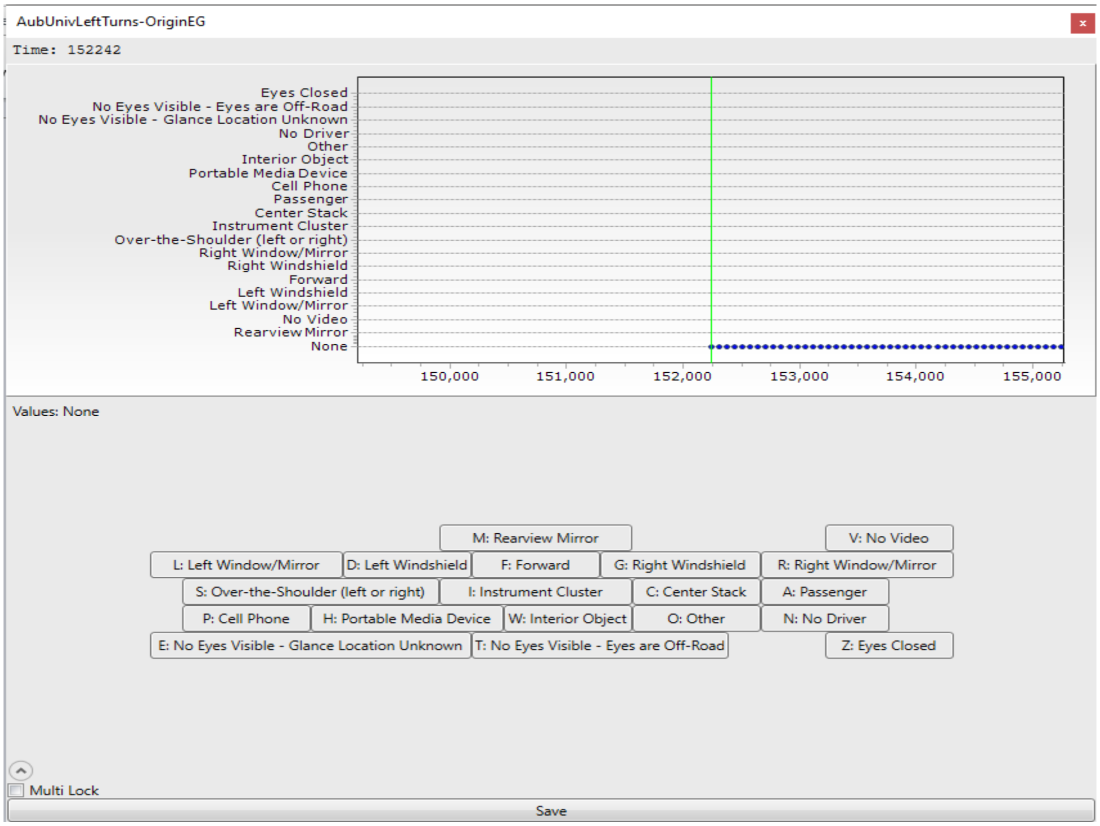

Figure 3.6 An Example of the Driver Eye-glance Annotation Tool Interface

Figure 3.7 shows sample images of driver face videos from NDS database. **Figure 3.8** shows the example of the final collected driver eye-glance data file. The column B: Event Id, column D: timestamp, and column E: location is important for the future data analysis.

Figure 3.7 Public Sample Images of Driver Face Videos from NDS Database

	A	B	C	D	E
1	**File ID**	**Event ID**	**User Name**	**Timestamp**	**Location**
2	548575	185543758	VTTI\beijiaz	2198	Forward
3	548575	185543758	VTTI\beijiaz	2264	Forward
4	548575	185543758	VTTI\beijiaz	2331	Forward
5	548575	185543758	VTTI\beijiaz	2398	Forward
6	548575	185543758	VTTI\beijiaz	2465	Forward
7	548575	185543758	VTTI\beijiaz	2531	Forward
8	548575	185543758	VTTI\beijiaz	2598	Forward
9	548575	185543758	VTTI\beijiaz	2665	Forward
10	548575	185543758	VTTI\beijiaz	2732	Forward
11	548575	185543758	VTTI\beijiaz	2798	Forward
12	548575	185543758	VTTI\beijiaz	2865	Forward
13	548575	185543758	VTTI\beijiaz	2932	Forward
14	548575	185543758	VTTI\beijiaz	2998	Forward
15	548575	185543758	VTTI\beijiaz	3064	Forward
16	548575	185543758	VTTI\beijiaz	3132	Forward
17	548575	185543758	VTTI\beijiaz	3199	Forward
18	548575	185543758	VTTI\beijiaz	3265	Forward
19	548575	185543758	VTTI\beijiaz	3332	Forward
20	548575	185543758	VTTI\beijiaz	3399	Forward
21	548575	185543758	VTTI\beijiaz	3466	Forward
22	548575	185543758	VTTI\beijiaz	3532	Forward
23	548575	185543758	VTTI\beijiaz	3599	Left Window/Mirror
24	548575	185543758	VTTI\beijiaz	3666	Left Window/Mirror
25	548575	185543758	VTTI\beijiaz	3733	Left Window/Mirror
26	548575	185543758	VTTI\beijiaz	3799	Left Window/Mirror
27	548575	185543758	VTTI\beijiaz	3866	Left Window/Mirror
28	548575	185543758	VTTI\beijiaz	3933	Left Window/Mirror
29	548575	185543758	VTTI\beijiaz	3999	Left Window/Mirror
30	548575	185543758	VTTI\beijiaz	4065	Left Window/Mirror
31	548575	185543758	VTTI\beijiaz	4133	Left Window/Mirror

Figure 3.8 The Example of the Final Collected Driver Eye-glance Data File

3.1.4 Speed Change and Brake Use Behavior Data

Figure 3.9 shows an example of time series data of one trip. Each file includes four key columns of this project: 1) Column A, video time frame; 2) Column C, vehicle accelerating speed; 3) column E, brake pedal use condition; 4) column G, vehicle speed; Based on these three columns we can know the driver speed and brake behavior of each time frame. Additionally, based on the driver front video (see Figure **3.3**) and the time frame in the video, we can locate the vehicle at any time. Therefore, we can also calculate the driving distance based on the speed of each time frame.

It has to mention that all the units of the original files are International System of Units, SI unit, the author transferred all the units to the U.S. unit for the study. Additionally, to build the driver speed-distance model, the author reviewed the speed data of each trip. For the vehicles which are in the car following mode (a lead vehicle in front of the study vehicle) will not be used to build the speed-distance model, since the speed change can be irregular for these vehicles.

vtti.timestamp	vtti.file_id	vtti.accel_x	vtti.gyro_y	vtti.pedal_brake_state	vtti.speed_gps	vtti.speed_network	vtti.video_frame
2200	548575	0.0203	0	0		0	5
2300	548575	0.0174	0.650391	0		0	6.5
2400	548575	0.0145	0.325195	0		0	8
2500	548575	0.0116	0.325195	0		0	9.5
2600	548575	0.0174	0.325195	0		0	11
2700	548575	0.0406	0.975586	0		0	12.5
2800	548575	0.0493	0.975586	0	0.981475	0	14
2900	548575	0.0551	0.650391	0		0	15.5
3000	548575	0.0667	0.975586	0		0	17
3100	548575	0.0899	1.30078	0		0.345	18.5
3200	548575	0.1102	1.30078	0		1.6475	20
3300	548575	0.1305	1.30078	0		2.035	21.5
3400	548575	0.1305	0.975586	0		2.5	23
3500	548575	0.1334	0.650391	0		3.0025	24.5
3600	548575	0.1392	1.30078	0		3.4675	26
3700	548575	0.1479	1.62598	0		3.9525	27.5
3800	548575	0.1508	1.30078	0	2.166653	4.42	29
3900	548575	0.145	1.95117	0		4.89	30.5
4000	548575	0.145	2.27637	0		5.325	32
4100	548575	0.1421	1.95117	0		5.78	33.5
4200	548575	0.1247	2.60156	0		6.265	35

FileId_548575_Index_185543758

Figure 3.9 Example of Time Series Data of One Trip

3.2 Intersection Safety Treatments Evaluations Data in Alabama

3.2.1 Study Intersection Selection

For the field conflict data collection, six pairs of study locations (in total 12 locations) were selected from Alabama for the comparative analysis. Each study location should meet the following criteria: unsignalized intersection on multilane divided highways, wide median (> 30 ft), major road with high-speed limit (> 45 mph). Most of these types of intersections are currently treated as one intersection with no traffic control in Alabama. ALDOT recently implemented two types of access control treatments at some locations as experiments. The author selected the locations with the traffic and access control treatments. Three of them had the stop lines/signs control and the other three had just yield lines/sign control. An additional six locations with no traffic controls devices were selected as comparison locations. The relative compared locations are normally close to each other and with the same major road. Cameras were installed on the roadside of the study locations, and 48-hour videos during a weekday of each location was collected for each location.

3.2.2 Study Intersection Detailed Information

Table 3.3 showing the detailed geometric design features and median treatments at the six pairs of study locations. **Figure 3.10** shows the Google Map Street View of the six pairs of the study locations. On the left side of the figure are all the six treated intersections, and on the right side are the untreated intersections for comparisons. All the study locations are on the four-lane divided highways with left-turn bays on the major roads. There are no sight distance issues at any of these ten locations. Geometric design features, major road traffic volumes and speeds are very similar within each pair of the study location. The study aims to see if this treatment is effective in reducing the traffic conflict rates and guiding the crossing drivers follow the right of way at the median openings

Table 3.3 Detailed Information of the Six Pairs of Study Locations

Pair #	Location #	Route	Median Width (ft)	Median Opening Width (ft)	Major Rd Speed Limit (mph)	Median Treatments
Pair #1	1.0	U.S. 80 & AL 25	42	72	65	Yield lines and yield signs; double yellow line; painted triangle islands.
	1.1	U.S. 80 & AL 97	43	62	65	-
Pair #2	2.0	U.S. 431 & AL 169	60	90	65	Yield lines and yield signs; double yellow line (faded)
	2.1	U.S.431 & Cutrin Dr	55	90	65	-
Pair #3	3.0	U.S. 280 & County Rd 21	45	85	65	Yield lines and yield signs; double yellow line
	3.1	U.S.280 & County Rd 87	55	90	65	-
Pair #4	4.0	U.S.280 & County Rd 40 AL	70	50	65	Stop lines and stop signs; double yellow line
	4.1	U.S.280 & County Rd 87	55	70	65	-
Pair #5	5.0	U.S. 84 & AL 51	70	40	65	Stop lines and stop signs; tapered on median opening two sides; double yellow line.
	5.1	U.S. 84 & AL 533	50	80	65	-
Pair #6	6.0	Atlanta Hwy & Somerset Dr	70	40	55	Stop lines and stop signs; double yellow line
	6.1	Atlanta Hwy & New Haven Blvd	40	60	55	-


Location 1.0

Location 1.1

Location 2.0

Location 2.1

Location 3.0

Location 3.1

Figure 3.10 Images of the Six Pairs of Study Locations (Google Maps)

Figure 3.11 shows an example of the screenshot of the recording of one study intersection. On the right bottom side of the figure shows the time and date of the recording and based on the time on the videos. The time on the recording is important for getting the PET time when doing the data collections.

Figure 3.11 Screenshot of the Recording of One Study Intersection

Chapter 4. Data Analysis Methods

Chapter 4 provides detailed information of data analysis methods for the eye-glance data, speed change and stop behavior data, and the methods for evaluating the intersection safety treatments in Alabama. For the eye-glance data analysis methods, the descriptive data analysis method and the entropy rate were introduced first. Different statistical methods also were included to analyze the relationship between the entropy rate and the different features (e.g., driver demographic features and the roadway geometric features). Speed change and stop behavior study defined the trip into three phases. The polynomial regression model and critical change point detection were also used for the speed change and stop behavior study. Intersection safety study methods including the introduction of different measurements, such as conflict rate, near crash rate, and other driver behaviors (e.g., stop behavior and understand right of way or not).

4.1 Eye-glance Data Analysis

4.1.1 Descriptive Data Analysis

The percentage of time spent on each eye glance location (T) was calculated for each trip. Average percentage of time spent on eye-glance locations of all the trips were calculated as follows:

$$T = \frac{Time\ spent\ on\ glancing\ at\ location\ X}{Total\ Trip\ Time} \times 100\% \quad (1)$$

Figure 4.1 illustrates the eight eye-glancing locations in the study, including the forward, left windshield, right windshield, rearview mirror, left window/mirror, right window/mirror, over the right shoulder and others (eyes closed, no eyes visible, etc.).

4.1.2 Entropy Rate

In information theory, entropy is a measure of the uncertainty of information associated with a random variable. Entropy rate in human information processing area usually refers to Shannon entropy. Shannon's theory defines a data communication system composed of three elements: a source of data, a communication channel, and a receiver (*Shannon, 1948)*. Entropy is a degree of uncertainty. For example, the entropy rate of a long string of repeating characters has an entropy rate of 0, since every character is predictable (i.e., no uncertainty).

Since the aim of this study is to propose an approach to measure the complexity of driver eye-glance locations, entropy rate was selected as the countermeasure. There are also some studies used entropy rate to typify complexity in heart rate variability *(Palazzolo et.al 1998, and Porta et.al 2001*) Indeed, entropy depends on whether there are some patterns (here, the eye-glance locations) more present than others, but it does not provide any information about the order or the dynamical relationship among patterns (i.e., the rule linking a pattern to the next one), while entropy rate evaluates whether there is a repetitive sequence of patterns, thus quantifying regularity of the index (*Pincus and Goldberger 1994, and Porta et.al 1998)*

Higher entropy indicates higher uncertainty and a more chaotic system. Data with full entropy is completely random and no meaningful patterns can be found. Low entropy data provides the ability or possibility to predict forthcoming generated values (*Edgar and Manz 2017*). This shows in the **Figure 4.1** below.

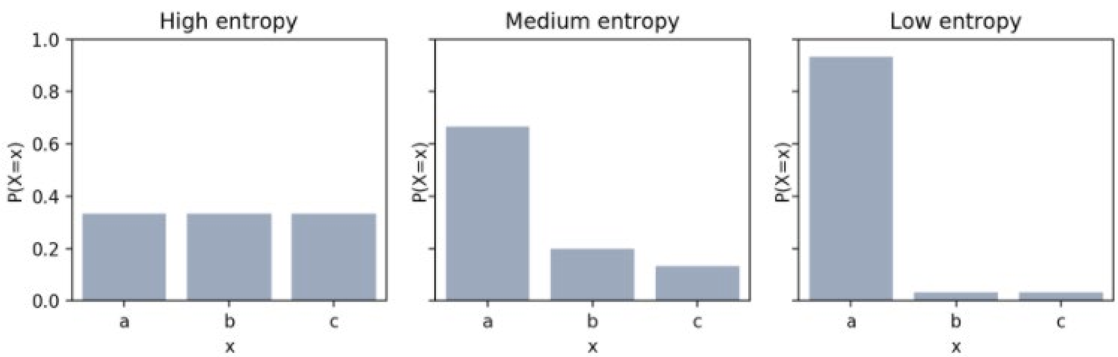

Figure 4.1 Examples of High, Medium and Low Entropy Visualization (Bernstein 2020)

Different studies hold different ideas on the relationship between complexity of glancing locations and workload. For example, Hilburn (2004) suggests that mental workload increase should increase the complexity of the glancing location, while the study of Di Nocera (2006) inferred that as workload increases, the observed glancing locations becomes less complex. For the case of pedestrians crossing the intersections, the more complex the glancing locations, the safer the pedestrians can find a suitable gap to cross the road. While for the case of the vehicle driver, the complicated glancing locations will add their mental workload because drivers have multiple tasks to handle, which reduce the safety level. Additionally, the question on "how much workload is too much" has received increased attention. In some traffic research, the workload redline could be considered as a useful concept as the consequences of too much workload in driving can be very serious (*Grier et.al 2008*). However, there are still other study questioned the correctness of putting the redline at the point at which performance is affected (*Waard 1996*). In this study, the observed glancing locations become more complicated was inferred as workload increases, leading to a higher entropy rate. Vice versa, as workload decreases, the observed glancing locations become less complicated, leading to a lower entropy rate, which is considered safer for drivers.

The calculation of the term in this study is normalized by the average duration of each glance. The entropy rate of each trip for the study was calculated using **Equation (2)**.

$$\text{Entropy Rate} = \sum_{i=1}^{D} \frac{\left(E/E_{max}\right)}{D \cdot T_{xi}}$$

(2)

D, number of variables in the visual scanning sequence

$$D = M * (M-1)^{N-1} \quad (3)$$

M, the defined visual scanning area of interests

N, the sequence length of interest

E, Shannon Entropy (*Shannon, 1948)*

$$E = \sum_{i=1}^{D} Px_i \log_2 \frac{I}{Px_i} \quad (4)$$

Px_i, probability of occurrence of x_i

$E_{max} = \log_2 D$

Tx_i, average fixation duration in the visual scanning sequence (per second)

In this study, each frame individual scan is of interest, so N=1, and the number of variables in the visual scanning sequence (D) is equal to the number of defined visual scanning area of interests (M). There are eight defined visual scanning area of interests for the study, as shown in **Figure 4.4.** When each eye-glancing location has the same probability of scanning, the E, Shannon Entropy, is the maximum value. So, here $E_{max} = \log_2 8$. Video was recorded at 14 frame per second, and the eye-glancing information was coded by each frame. Therefore, the duration for each frame is 1/14 second.

Figure 4.2 Eight Eye-Glancing Locations of the Study

4.1.3 Statistical Analysis Methods

Mann–whitney- -wilcoxon Test

The Mann-Whitney U test is used to compare whether there is a difference in the dependent variable for two independent groups. It is a non-parametric alternative to the unpaired two-samples t-test. It compares whether the distribution of the dependent variable is the same for the two groups and therefore from the same population without assuming them to follow the normal distribution (Wikipedia, 2021). In this study, Mann–whitney-wilcoxon test will be used to test if there is a significant difference of the entropy rate between conventional intersection and RCUT intersection. Here independent variables are the two intersection groups: the conventional intersection and RCUT intersection. The dependent variable is the entropy rate.

Welch T-test and Analysis of Variance (ANOVA)

The Welch t-test is an adaptation of Student's t-test. Unlike the classic Student's t-test, the Welch t-test formula involves the variance of each of the two study groups being compared.

In other words, it does not use the pooled variance. Therefore, it is used to compare the means of two groups of samples when the variances are different. In this study. The independent variable is the entropy rate, and the independent variables are the roadway features. Welch t-tests were applied for the alternative hypothesis below: 1) there is no significant difference of the mean entropy between 3-leg and 4-leg intersections; 2) there is no significant difference of the mean entropy between intersections with AADT ≤ 20,000 and AADT ≥ 30,000; 3) there is no significant difference of the mean entropy between intersections with speed limit of 45mph and speed limit of 55mph.

Analysis of variance (ANOVA) is a statistical technique that is used to check if the means of two or more groups are significantly different from each other. A two-way ANOVA was also conducted to analyze the driver entropy rate between different age and gender among drivers.

Pearson Correlation Analysis

Pearson correlation coefficient is a measure of the strength of a linear association between two variables and is denoted by r_{xy}. $r_{xy} is\ defined\ as$:

$$r_{xy} = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n} (y_i - \bar{y})^2}} \quad (5)$$

Where,

n, sample size

x_i, y_i, individual sample points indexed with i

$\bar{x}, \bar{y}$, the sample mean

r_{xy} can take a range of values from +1 to -1. A value greater than 0 indicates a positive association; that is, as the value of one variable increases, so does the value of the other variable. A value less than 0 indicates a negative association; that is, as the value of one variable increases, the value of the other variable decreases. Values obtained using an ordinal scale are not continuous, but their corresponding ranks are. Hence, Pearson's correlation coefficient on those ranks still can be used (*Wikipedia, 2021*).

The Pearson correlation coefficient was calculated in the study to see the correlation between the demographic features and the entropy rate (visual workload). Some variables are not continuous, but they can be ranked in order (e.g., education level, income level, and crash record). The correlation coefficient between the driver risk perception score and the entropy rate was also calculated. The author also tried to develop a multiple linear regression model to see which factors will affect the left turn drivers' workload at conventional intersections. Due to the limited number of participants, most of the factors were insignificant. All the analysis above were conducted in the software R.

The same participant may have more than one trips in the NDS database. It has to mention that for the statistical analysis here, all the tests are based on each trip rather than each participant with the repeated measures. The author considered the repeated measures for the participants at first, but the trip number of each participant is very different. Some driver has only one trip and the other drivers may have more than 15 trips, which will cause the error for the statistical analysis due the difference of the variance. For example, the measures ANOVA requires each group has same repeated numbers with close variance value. Therefore, the author did the analysis based on the data of each trip.

4.2 Speed Change and Stop Behavior Analysis

4.2.1 Study of Three Phases

The analysis of driver behavior was conducted for three different phases for making left turns: 1 – Deceleration; 2 - Intersection Entry; and 3 - Execute Turn. **Figure 4.3** shows the details of the study scenario for a typical left turn movement from a minor road stop control intersection. **Table 4.1** shows the driving tasks and speed characteristics corresponding to each of the three phases.

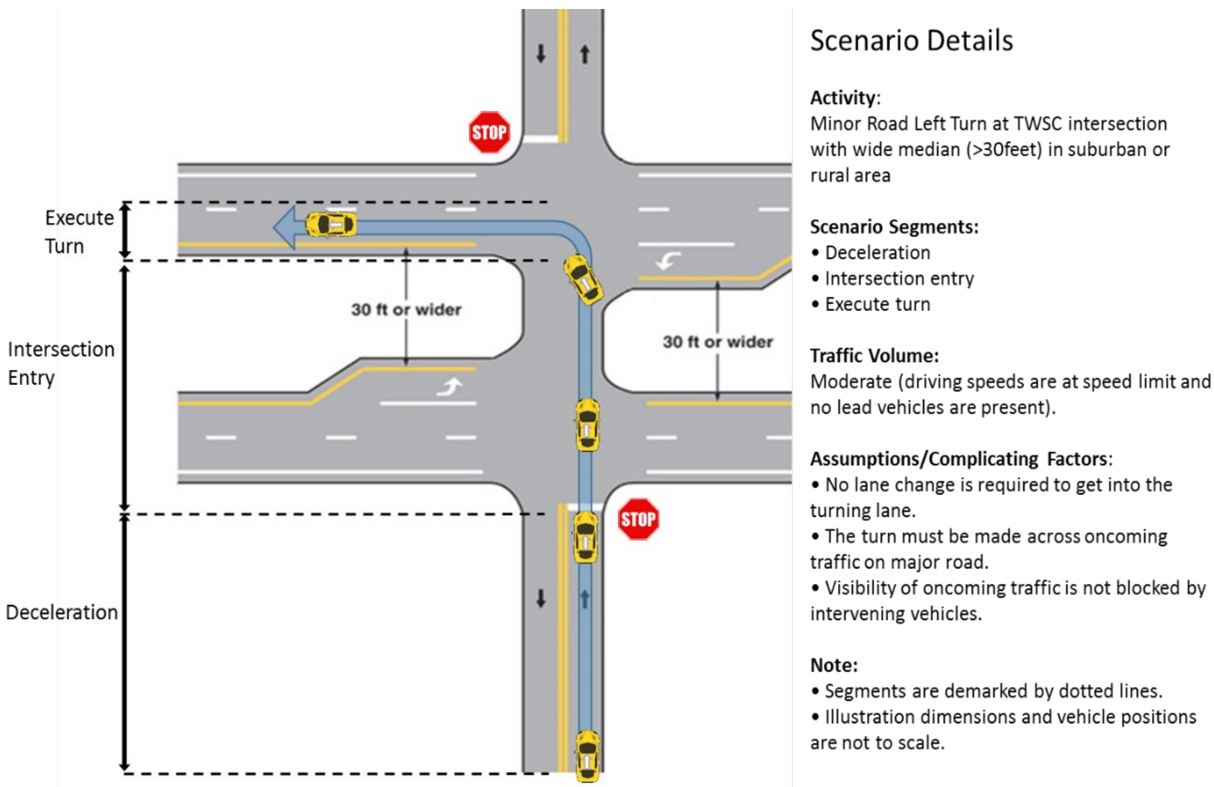

Figure 4.3 Scenario of Left Turn Movement Diagram at Minor Road Stop Control Intersection

Table 4.1 Driving Tasks and Speed Characteristics of the Three Phases

Phase	Driving Tasks	Speed Characteristics
Deceleration	Stop/ rolling stopped at the intersection, wait for a safe gap to enter the intersection	Start controlled decelerating until stopped/ rolling stopped
Intersection Entry	Get into position to turn, wait for a safe gap of major road oncoming traffic	Slowly advance into the median opening and stopped/ rolling stopped at the median opening
Execute Turn	Make the turn	Slowly move to the road edge, start to turn and accelerate up to the speed Limit

4.2.2 Polynomial Regression

A polynomial regression model was developed for 85th percentile speed during phase 1; vehicle deceleration on minor road. Models were also built for the 85th percentile speed for drivers of the different age groups. The polynomial regression method minimizes the sum-of-squared residuals between measured and simulated speeds. The least squares method is used to estimate unknown parameters. Equation (1) shows an example of a common polynomial regression model. The residual standard error was used as a measure of goodness-of fit to evaluate and determine the quality of the fitted model.

$$V = \beta_0 + \beta_1 * L + \beta_2 * L^2 + \beta_3 * L^3 + \ldots + \beta_n * L^n + \varepsilon \qquad (6)$$

where,

V = the speed of the vehicles

L = the distance (feet) of the vehicles to decelerate to stop at the minor road

βn = estimated parameters

ε = the error of the specification

4.2.3 Critical Speed Change Point Detection

Change point detection is an important part of time series analysis, as the presence of a change point indicates an abrupt and significant change in the data generating process. Detecting the critical speed change point can make the estimated location of the speed changepoint more efficient and accurate. By minimizing Equation (2), the critical speed change point can be detected.

$$\min_{\mathcal{T}} \sum_{i=1}^{n+1} \ell(\mathbf{y}_{\tau_{i-1}:\tau_i - 1}) + \lambda P(n) \tag{7}$$

Where, $\ell(\mathbf{y}_{\tau_{i-1}:\tau_i - 1})$ is a cost function for a segment (e.g., the negative maximum log-likelihood), $\lambda \geq 0$ a hyperparameter, and P(n) is a penalty on the number of change point (XX).

The package Rapture, a Python library for performing offline change point detection was used to detect the critical speed change point.

4.3 Evaluations of the Intersection Safety

4.3.1 Intersection Conflict Study

In this study, a comparative analysis has been conducted to understand the safety issues of a median opening designed as a single intersection compared to that designed as two separate intersections. In doing so, a conflict study was conducted by watching videos of traffic movement for 8-hours of two weekdays for each location. The 16-hours video for conflict observation consisted of 3-hours morning (AM) peak, 2-hours mid-day, and 3-hours afternoon (PM) peak to capture all possible heavy traffic conditions throughout the day.

The study mainly focused on observing conflicts with the following movement: Left-turning movements from minor road approaches. Consequently, the conflict study consisted of observing conflicts and other safety performance measures for the above-mentioned movements.

To evaluate the safety issues at median opening designed as a single intersection compared to that designed as two separate intersections, this study used the following performance measure:

Traffic Conflicts- Traffic conflict is defined as an observable situation in which two or more road users approach each other in time and space to such an extent that there is risk of collision if their movements remain unchanged (*Amundsen, 1977*). The total observed traffic conflicts are converted into the following two performance measures:

$$Conflict\ rate\ (per\ left-turning\ vehicles) = \frac{\#\ of\ conflicts}{Total\ left\text{-}turn\ volume} * 100\% \qquad (8)$$

Figure 4.4 below shows the six defined study conflict paths with directions. First is the minor road left turn driver interacting with major road left side through movement (MALT) drivers; the second conflict type is the minor road left turn driver interacting with major road right side through movement (MART) drivers; the third conflict type is the minor road left turn driver interacting with major road right side left turn movement (MALL) drivers; the fourth conflict type is the minor road left turn driver interacting with major road left side left turn movement (MARL) drivers; the fifth conflict type is the minor road left turn driver interacting with the opposite direction minor road through movement (MIT) drivers; the last conflict type is the minor road left turn driver interacting with the opposite direction minor road left movement (MIL) drivers.

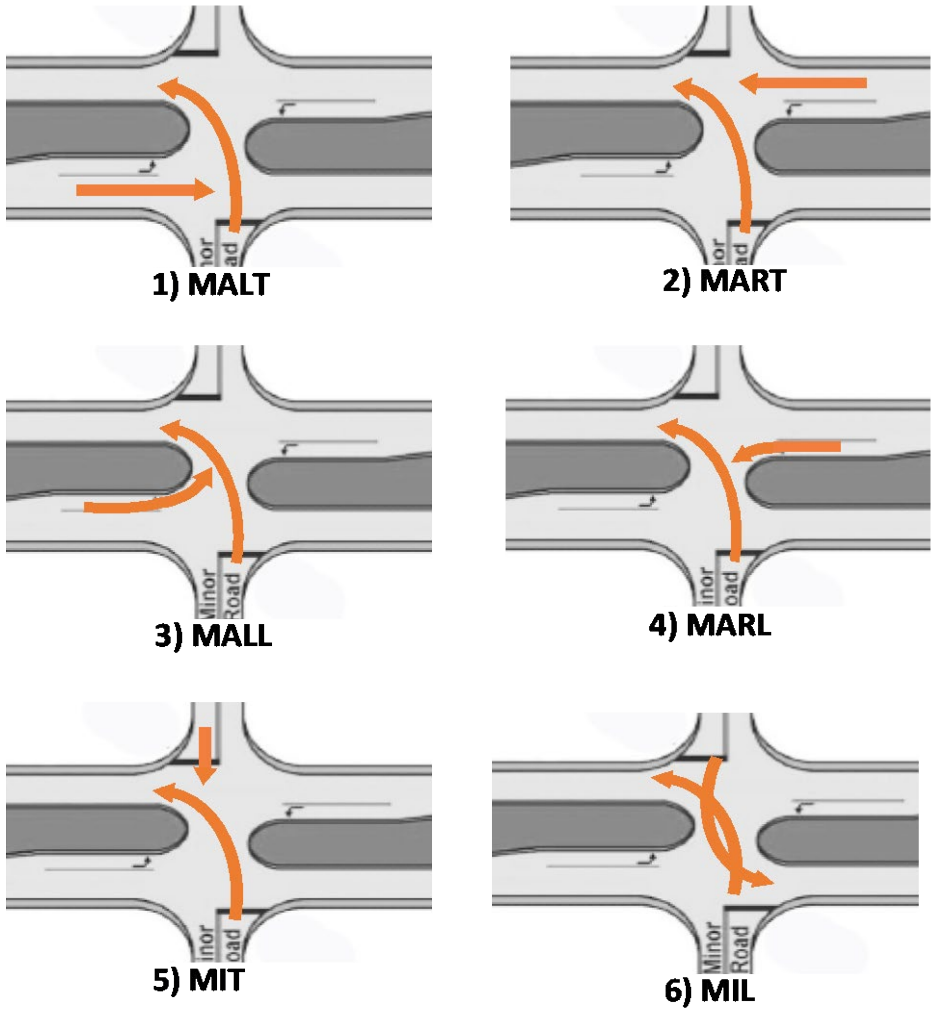

Figure 4.4 Six Defined Study Conflict Path with Directions. 1) MALT; 2) MART; 3) MALL; 4) MARL; 5) MIT; 6) MIL.

PET - The time difference between the moment an 'offending' vehicle passes out of the area of potential collision. PETs are sometimes used to measure the nearness of crash when two paths cross each other. In this study, the author considers PET smaller than 3s as a conflict, and PET smaller than 1.5s as a critical conflict (near crash). The timeline on the video screen was used to estimate the PET time.

Near Crash- An event is classified as a near-crash if an imminent crash is avoided due to a rapid evasive maneuver by the subject vehicle or any other vehicle that was required to avoid a crash. The total observed near-crash are converted into the following two performance measures:

$$Near\ crash\ rate\ (per\ left-turning\ vehicles) = \frac{\#\ of\ conflicts}{Total\ left{-}turn\ volume} * 100\% \quad (9)$$

4.3.2 Other Driver Behaviors for Safety Evaluations

Stopped/Slow down Behavior - This performance measure indicates if a vehicle stops, slow down or not stop at the median while at the minor road stop sign, and while crossing the median opening. As indicated earlier, stopping at the median is associated with less safety risk as the driver is more cautious and a better sight distance to the conflicting traffic is available to them.

Understanding of the Right-of-Way – This performance measure indicates if a vehicle used their correct right-of-way while crossing the median opening. Left turn trajectory types are categorized into three types, Type 1, Type 2, Type 3. They are defined in the figure below from left to right. The mainly difference part is the trajectory at the median openings. For Type 1, vehicles keep on the right side of the median opening to make the left turn; for Type 2, vehicles stayed on the middle of the median openings to make the left turn; for Type 3, vehicles driving toward the right side of the median openings to make the left turn. Among the six pairs of the study locations, since the median opening width are wide enough to store two vehicles aligned by each side, here consider the Type 1 trajectory as the "Understanding the Right of Way".

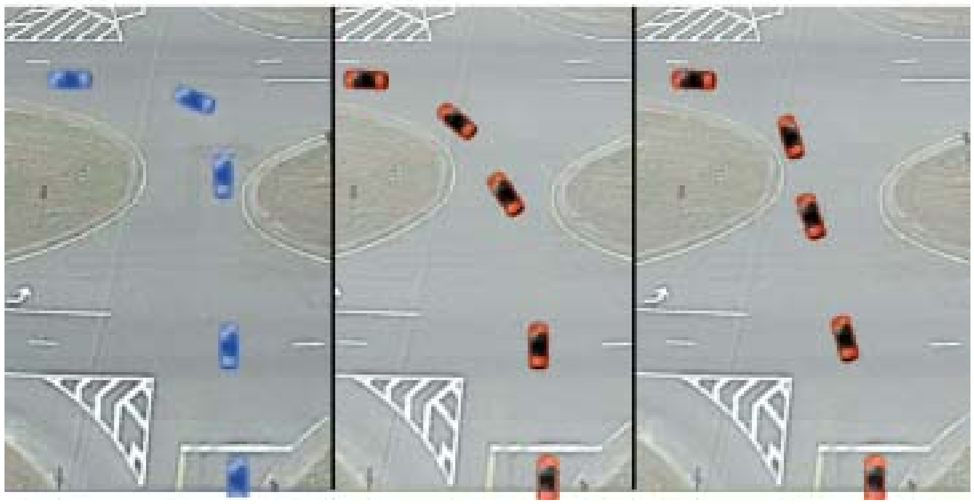

Figure 4.5 Three Types of Trajectories of Left Turn Vehicles

Chapter 5. Data Analysis Results

Chapter 5 contains the data analysis results of the driver visual workload study, driver speed change and brake behavior study, and the results of the intersection safety treatments evaluation study. For the driver visual workload study part, descriptive data analysis results, visual workload comparison between two types of intersections, and the visual workload analysis results at conventional were provided. Driver speed change and brake behavior study results were separated into three different phases. Then the evaluations of the safety treatments of the six pairs of the intersections in Alabama were explained.

5.1 Driver Visual Workload Analysis Results

5.1.1 Descriptive Data Analysis

Figure 5.1 shows the gender and age (younger, middle, and older drivers) distribution of the participants for all study trips at the two types of the intersections. Herein the younger drivers are those younger than 25-year-old; middle-aged drivers are among 25 to 65 years old; old drivers are older than 65 years old. The study consists of 78 participants with complete demographic information. The gender distributions among all the participants are comparatively even. The age distribution at conventional intersection is also even. However, at RCUT intersections, there were only four middle age drivers. Each driver may have more than one time of the trip of the same intersection in the database. For example, the participant #1 may drive through the same intersection for five times at the different days of a year.

Table 5.1 summarized the observed variables analyzed for the study, including the different categories of intersection type (conventional and RCUT), gender (female and male), education level (some graduate or professional school and advanced degree, college degree, High school diploma or G.E.D., Some education beyond high school but no degree, and some graduate or professional school, but no advanced degree), crash history (none, one, and two or more) over the past three years. Similarly, **Table 5.2** shows the summary of the observed variables of conventional intersection trips. **Table 5.3** shows the summary of the observed variables of RCUT intersection trips

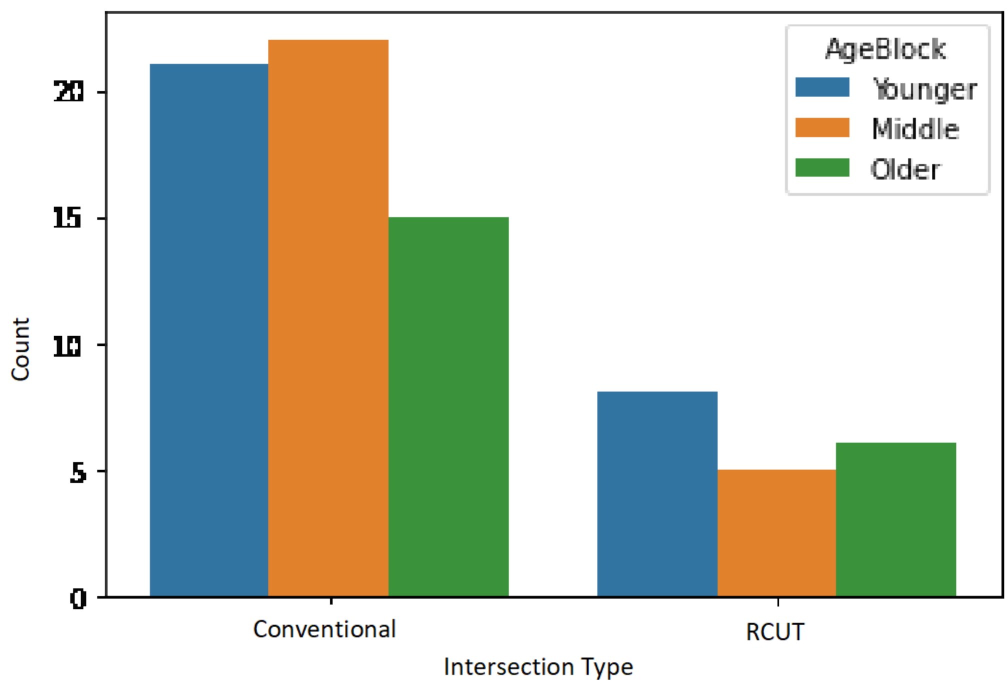

Figure 5.1 Gender and Age Distribution of the Participants

Table 5.1 Summary of the Observed Variables of All the Trips

Category	Variables	Percentage of All the Trips
Intersection	Conventional	91%
	RCUT	9%
Gender	Female	57%
	Male	43%
Age	Older	58%
	Middle	13%
	Younger	29%
Education level	High school diploma or G.E.D.	21%
	Some education beyond high school but no degree	30%
	College degree	17%
	Some graduate or professional school, but no advanced degree (e.g., J.D.S., M.S. or Ph.D.)	13%
	Some graduate or professional school and advanced degree	19%
Crash frequency in past years	None	59%
	One	31%
	Two or More	10%

Table 5.2 Summary of the Observed Variables of Conventional Intersection Trips

Category	Variables	Percentage of All the Trips
Gender	Female	49%
	Male	51%
Age	Older	25%
	Middle	38%
	Younger	38%
Education level	High school diploma or G.E.D.	0%
	Some education beyond high school but no degree	53%
	College degree	18%
	Some graduate or professional school, but no advanced degree (e.g., J.D.S., M.S. or Ph.D.)	6%
	Some graduate or professional school and advanced degree	24%
Crash frequency in past years	None	70%
	One	12%
	Two or More	18%

Table 5.3 Summary of the Observed Variables of RCUT Intersection Trips

Category	Variables	Percentage of All the Trips
Gender	Female	47%
	Male	53%
Age	Older	35%
	Middle	18%
	Younger	47%
Education level	High school diploma or G.E.D.	48%
	Some education beyond high school but no degree	16%
	College degree	20%
	Some graduate or professional school, but no advanced degree (e.g., J.D.S., M.S. or Ph.D.)	13%
	Some graduate or professional school and advanced degree	3%
Crash frequency in past years	None	38%
	One	27%
	Two or More	36%

Figure 5.2 shows the average driver risk perception score. Each volunteer driver enrolled in the program has to answer a risk perception questionnaire. In the questionnaire, they have to answer the question like "If you were to engage in the following actions, how do you think they would affect your risk of a crash". Thirty risk actions (Running Red Light, Driving Sleepy, Risks for Fun, Sudden Lane Changes, Running Stop Sign, Speeding for Thrill, Failure to Yield, Illegal Turns, Tailgating, Following Active Emergency Vehicles, In a Hurry, Bad Weather, Risk of Passing on Right, First off the Line, Yellow Light Acceleration, Driving after taking Drugs or Alcohol, Driving While taking Drugs or Alcohol, Road Rage, Driving to Reduce Tension, Secondary Tasks, Eyes off Road, Passenger Interaction, Racing, Checking Rearview Mirror, Speeding less than 20 MPH Over Limit, Speeding more than 20 MPH Over Limit, Not Yielding

to Pedestrians, Not Wearing Safety Belt, Not Signaling, Worn Tires, Visual Obstructions, Rolling Stop) are listed in the survey with risk level rank from 1 (Feel No Greater Risk) to 7 (Feel Much Greater Risk). For each driver, the average risk perception score was calculated as the average to all the questions.

It can be found that the older drivers tend to have higher risk perception score. Also, the female driver has much higher risk perception score compared with the male drivers. This is also in consistent with the previous analysis results that male driver are more aggressive and tend to have higher speed when close to the intersections.

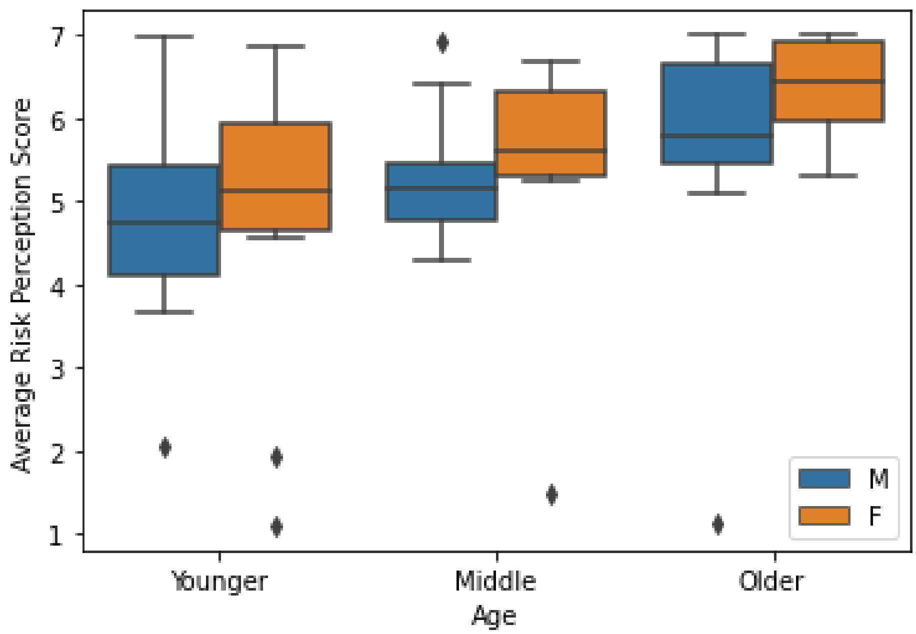

Figure 5.2 Average Driver Risk Perception Score

5.1.2 Average Percentage of Time Spent on Eye-glance Locations

Figure 5.3 showed the average percentage of time that left turn drivers spent on glancing at 430 conventional intersection trips and 40 RCUT intersection trips. For RCUT intersections, drivers spent the most proportion of time glancing forward (72%), followed by glancing the left window/ mirror (14%). For conventional intersection, beside looking forward (56%) and left window/mirror (17%), drivers also spent a large portion of time glancing the right window/ mirror (11%), and right windshield (5%). The results suggest that left turn drivers spent more time on looking left and right mirrors and less time looking forward. Additionally, the drivers at conventional intersections also spend more than 7% of time moving their body to look at the rearview mirror, and look backwards over the shoulder, which can bring more workload to the drivers while making the turning movements.

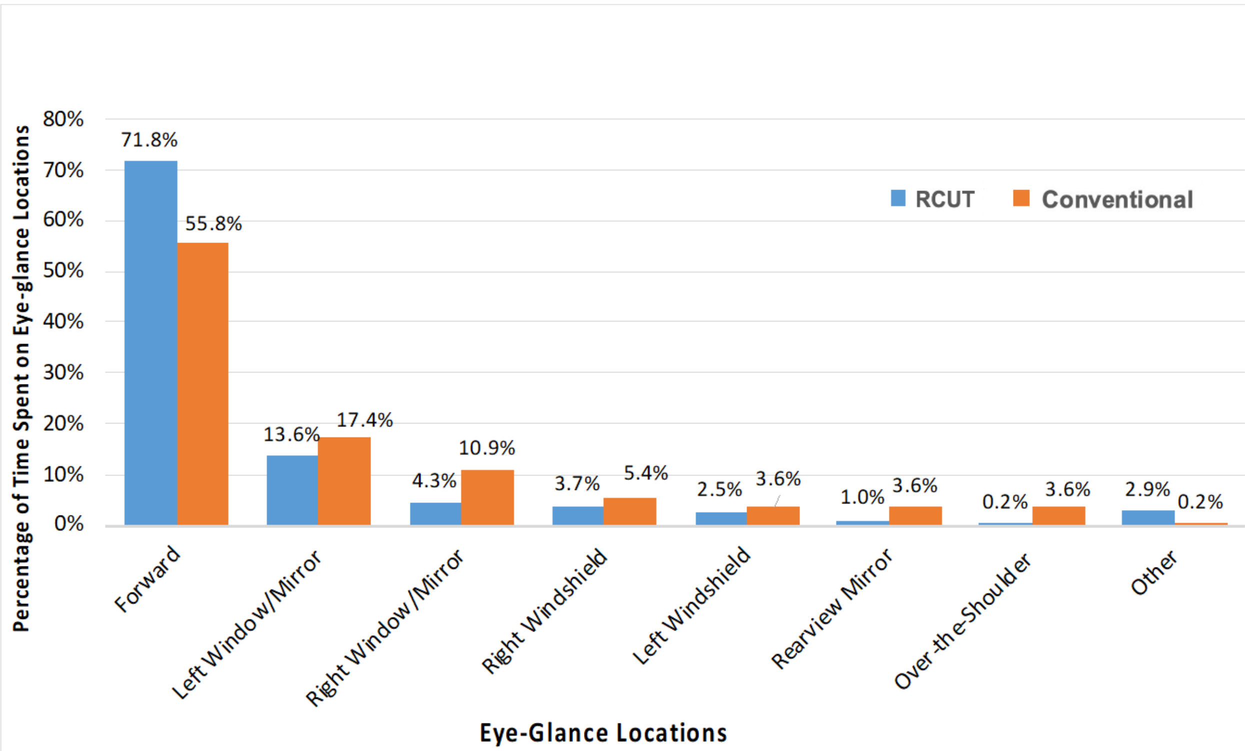

Figure 5.3 Average Percentage of Time Spent on Eye-glance Locations

5.1.3 Visual Workload Between Two Types of Intersections

Figure 5.4 showed the boxplots of entropy rates between conventional and RCUT intersections with Welch T-test results**.** The average entropy rate of drivers making left turns at conventional intersections (0.24) is more than twice higher than drivers making left turns at RCUT intersection (0.09). Similarly, the median value of entropy rate of drivers making left turns at conventional intersections s (0.22) is about four times higher than the drivers making left turns at RCUT intersections (0.06).

Mann-whitney-wilcoxon test was used to test the null hypothesis that the mean entropy rate of conventional intersection drivers is equal to the RCUT drivers. The test results show that the mean entropy rates of the two types of intersections differed significantly according to Mann-whitney-wilcoxon test, W= 14851, $p < .001$, implying a significant difference between the entropy rates of the two types of maneuvers. The results suggest that drivers making direct left turns at conventional intersections have a higher visual workload compared to drivers making diverted left turns at RCUT intersections.

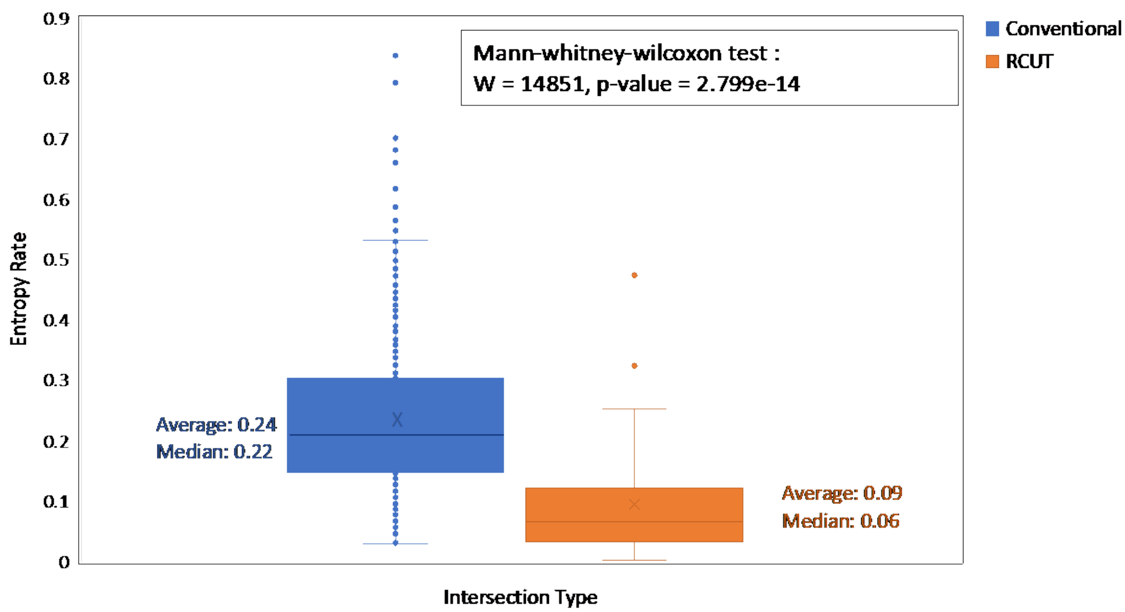

Figure 5.4 Boxplots of Entropy Rate Between Two Types of Intersections with Mann-whitney-wilcoxon Results

Figure 5.5 shows the boxplots of the entropy rates among drivers of different gender and age. Younger drivers did have a higher average entropy rate than middle-aged and older drivers for both intersections. The difference of entropy rates between male and female is not very obvious. The results suggest that younger drivers have higher visual workload, given the higher randomness in scanning patterns while crossing the intersections.

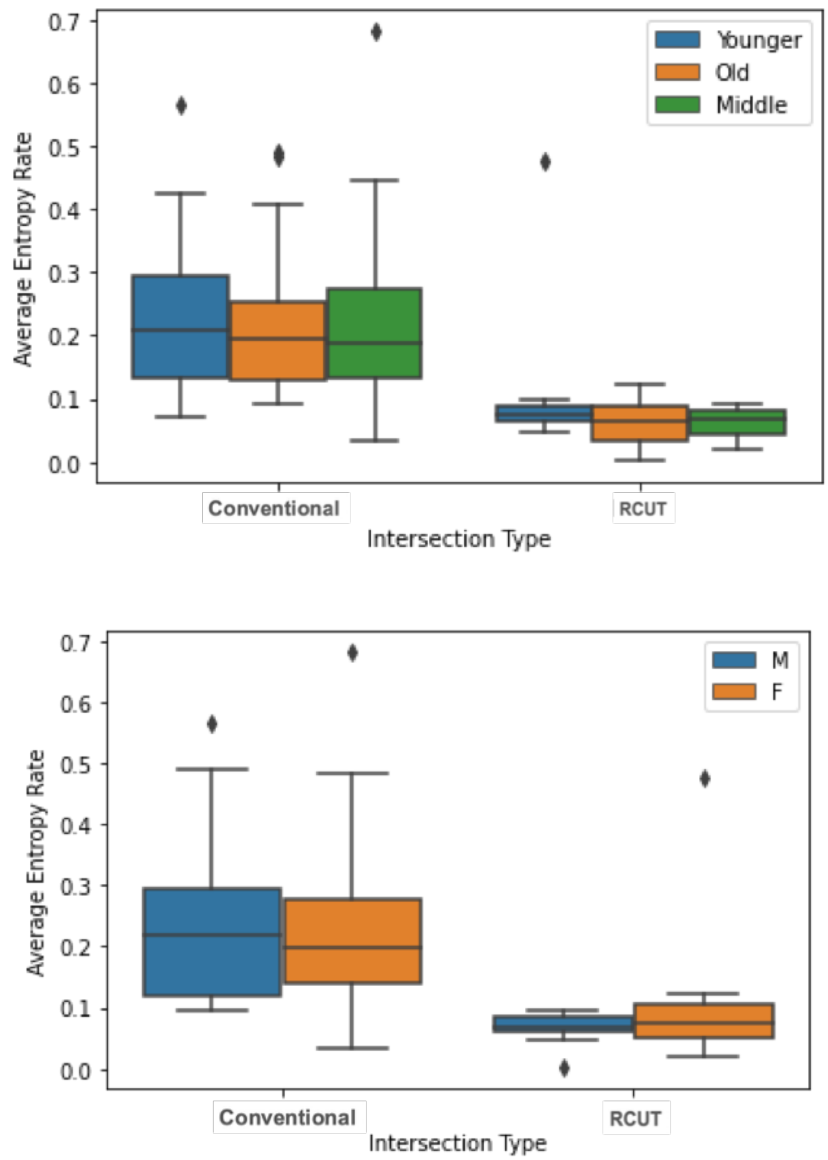

Figure 5.5 Boxplots of Entropy Rate among Drivers of Different Gender and Age

5.1.4 Visual Workload at Conventional Intersections

Further analysis was conducted to examinate the correlation between entropy rates and driver demographic characteristics and roadway design features at conventional intersection. Due to the limited participants and trip numbers, no statistical analysis for visual workload at RCUT intersections was conducted.

Driver Demographic Feature Analysis

A two-way ANOVA was used to analyze the effects of gender and age on entropy rate at conventional intersections **Table 5.4** shows the two-way ANOVA analysis results. All the p-values are larger than 0.05, indicating no observable differences in visual workload between drivers of different gender and age at conventional intersections.

Table 5.4 Two Way ANOVA Analysis of Entropy Rate at Conventional Intersections

	Df	Sum Sq	Mean Sq	F-value	P-value (>F)
Gender	1	0.0002	0.000175	0.017	0.898
Age	2	0.0077	0.00385	0.366	0.696
Gender: Age	2	0.046	0.022982	2.185	0.126
Residuals	40	0.4207	0.010517		

A Pearson correlation analysis was conducted to see if the socioeconomic and demographic features (income level, education level, driving years, crash numbers in the past 3 years) and the driver risk perception scores are correlated to entropy rate. **Table 5.5** lists the attributes of drivers' demographic features and risk score. They were categorized into different levels as continuous numbers for analysis purpose.

Table 5.5 Driver Demographic Information and the Average Risk Perception Scores

Features	Categories	Levels
Education	High school or G.E.D. (24%)	1
	Beyond high school or college degree (48%)	2
	Graduate or professional school or advanced degree (28%)	3
Income Level	<50,000 (41%)	1
	50,000 - 70,000 (15%)	2
	70,000 - 100,000 (33%)	3
	>100,000 (11%)	4
Driving Years	0-70	-
Crash Records in the past 3 years	0 crash (44%)	1
	1 crash (42%)	2
	≥ 2 crashes (14%)	3
Average Risk Perception Scores	0-7	-

The heatmap in **Figure 5.6** showed the Pearson correlation analysis results. The darker color indicates higher correlation. With the increase in education level, years of driving, crash numbers, and drivers risk perception scores, the average entropy rates decrease. The analysis results are significant at the 90% confidence interval.

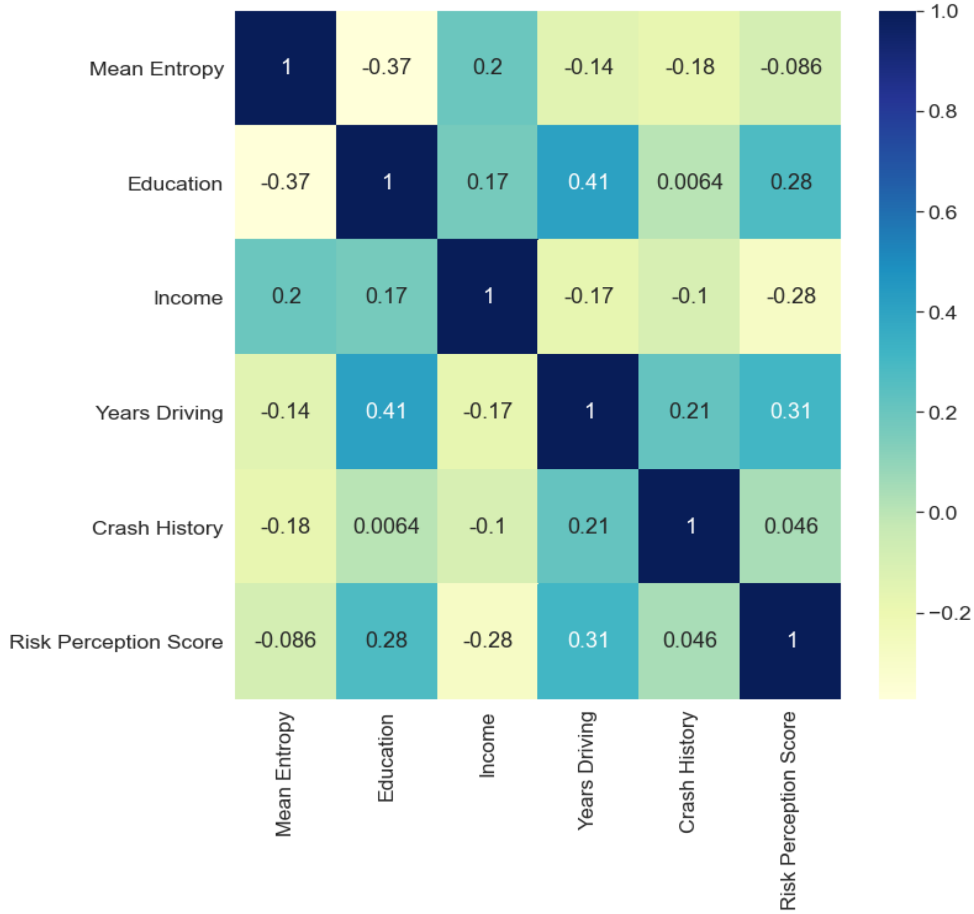

Figure 5.6 Pearson Correlation Between Driver Demographic Features

5.1.5 Roadway Feature Analysis

Impact of roadway features on entropy rates were also analyzed. The roadway features include channelization island at minor road; 3-leg or 4-leg intersection; major road AADT $\leq$ 20,000 or AADT $\geq$ 30,000; major road speed limit 45 mph or 55 mph. Welch t-tests were used to check whether or not these roadway features had a significant impact on driver visual workload. Table showed the Welch t-test results of impacts of different roadway features on entropy rates. Among the four features, only the p-value of AADT is smaller than 0.05, which means AADT has statistically significant impact on the visual workload. The results also show that driver visual workload at the intersections with major road AADT ≥ 30,000 is much higher than the intersections with AADT ≤ 20,000.

Table 5.6 Welch T-test Results of Entropy Rate Between Different Roadway Features

	95% Confidence Interval					
	Mean Difference	Lower	Upper	t	df	P-value
No Channelization (66.9%) vs. Channelization on Minor Road (33.1%)	-0.006	-0.035	0.023	-0.403	217.640	0.687
3_Intersection (75.8%) vs. 4-leg Intersection (24.2%)	0.015	-0.015	0.045	1.000	152.650	0.319
Major AADT≤20,000 (50.6%) vs. Major AADT≥30,000 (49.4%)	-0.069	0.045	0.092	5.677	407.860	<0.001***
45Mph (66.9%) vs. 55 Mph (33.1%)	0.006	-0.023	0.035	0.403	217.640	0.687

5.2 Driver Speed Change and Brake Behavior Analysis Results

Driver speed change behavior was analyzed for 430 direct left turn movements in three phases: deceleration, intersection entry, and executing turn.

Figure 5.8 shows the age and gender distribution of the drivers. Herein, the younger drivers are those younger than 25 years old; middle aged drivers are among 25 to 65 years old; old drivers are older than 65 years old. The gender and age distributions among the different types of intersections are comparatively even, only older female driver number is less than 10. The Each driver may take more than one times of the trips at the same locations.

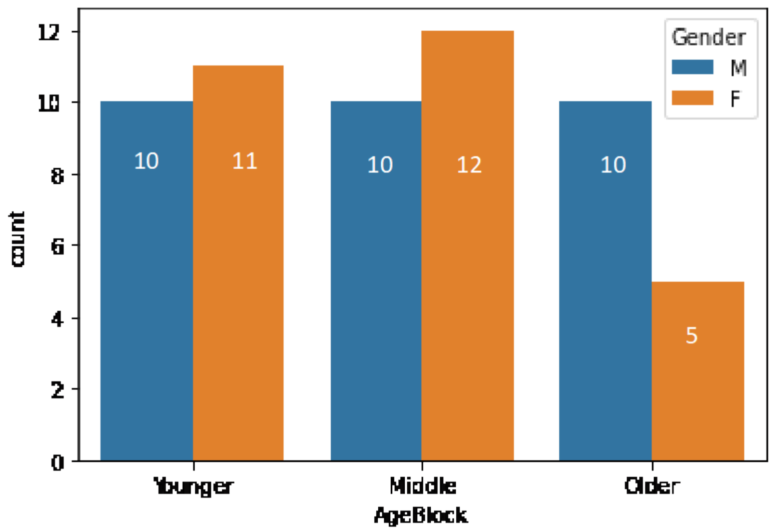

Figure 5.7 Age and Gender Distribution of the Studied Drivers

5.2.1 Phase 1 – Deceleration

Figure 5.8 shows the vehicle speed trajectory in phase one among the different age group drivers. Polynomial regression models were developed to predict 85th percentile speed for the different types of the drivers. The polynomial models are shown in the figure. R square of each model was calculated when developing the model, the model with the largest R square was finally selected. It was found that the 85th percentile speed of younger drivers is much higher than the middle age and order driver. **Table 5.7** shows the Tukey LSD test results of different age drivers of different distance at the confidence level of 95%, the results show that the speed of the younger driver is significant different with (p-value smaller than 0.05) the older and middle-aged drivers when the distance is smaller than 100ft.

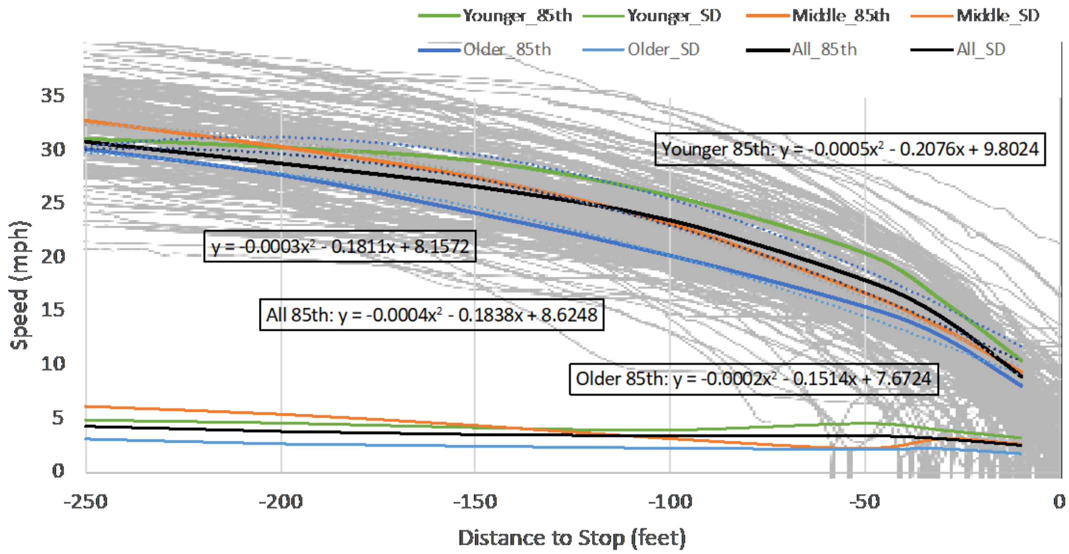

Figure 5.8 Vehicle Speed Trajectory on Minor Road by Different Age Drivers

Table 5.7 Tukey LSD Test Results of Different Age Drivers at Different Distance

Distance to stop (ft)	Tukey LSD Test Results				
		Diff	lower	upper	p-adj
-250	Old-Middle	1.054	-1.239	3.348	0.524
	Young-Middle	-0.291	-2.664	2.082	0.955
	Young-Old	-1.346	-2.838	0.147	0.087
-200	Old-Middle	0.103	-1.974	2.180	0.993
	Young-Middle	0.436	-1.713	2.585	0.881
	Young-Old	0.334	-1.018	1.685	0.830
-150	Old-Middle	-0.609	-2.462	1.245	0.719
	Young-Middle	1.572	-0.346	3.490	0.132
	Young-Old	2.181	0.974	3.387	< 0.05
-100	Old-Middle	-1.450	-3.126	0.227	0.105
	Young-Middle	1.836	0.102	3.571	< 0.05
	Young-Old	3.286	2.195	4.377	< 0.05
-50	Old-Middle	-0.755	-2.529	1.019	0.575
	Young-Middle	1.663	-0.173	3.499	< 0.05
	Young-Old	2.418	1.264	3.573	< 0.05

Figure 5.9 shows the critical change points of the 85th percentile speed of all trips. The critical change points suggest that most of the drivers tend to decelerate sharply when they are about 120 ft or 50 ft away from the minor road stop bar.

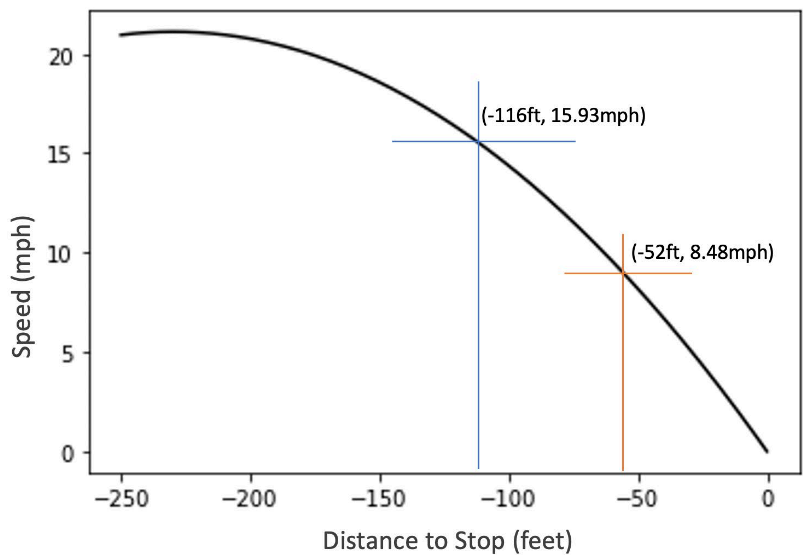

Figure 5.9 Critical Change Point of 85th Percentile Speed of All Trips on Minor Road

Figure 5.10 showed the brake pedal use condition in phase 1 of left turn movement on the minor road. At the first critical change point, when the vehicles were about 120 ft away from the stop line, about 35% of the vehicles used the brake pedal; and at the second critical change, when the vehicles were about 50 ft away from the stop line, about 50% of the vehicles used the brake pedal. The results are consistent with the speed trajectory analysis

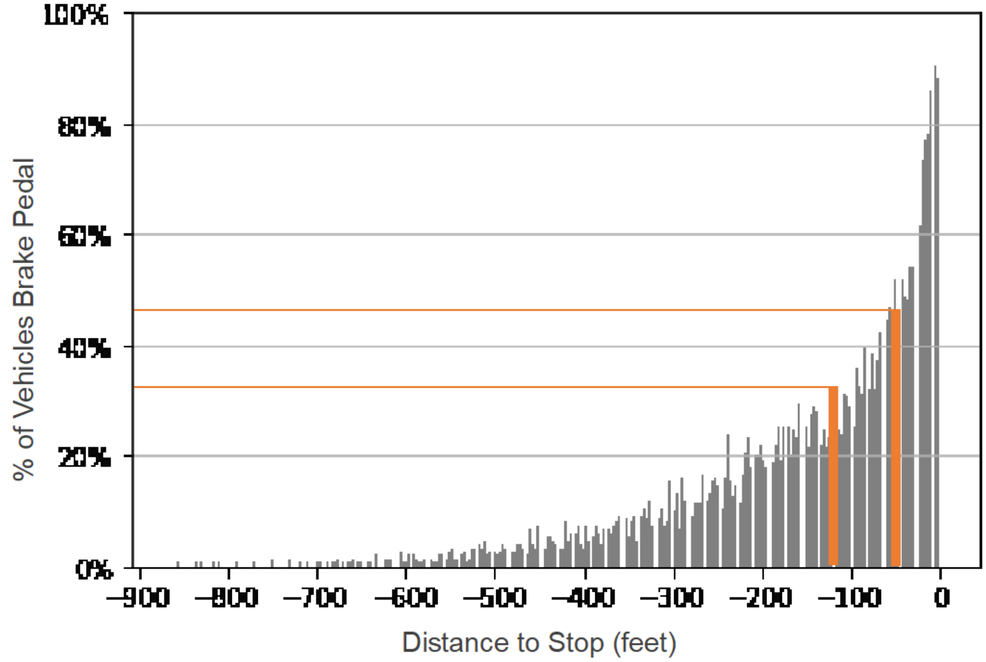

Figure 5.10 Brake Pedal Usage on Minor Road

The data analysis results suggest that advanced intersection warning sign should be located at least 120 ft+2.5 sec * Speed Limit (ft/sec) before the intersection assuming 2.5 seconds perception and reaction time.

Figure 5.11 shows the vehicle stop conditions at the median minor road. Here vehicle stopped are defined as the minimum speed is less than 3mph; slow down means the minimum speed is larger than 3mph but smaller than 10mph; none means the vehicle either stop or slow down at the median openings. The data shows that almost half of the driver (52.42%) didn't stop at the minor road, which is also consist with the **Figure 5.8**, and bout 25.12% of drivers slow down at the minor road. One of the reasons can be the driver sight distance (SD) at the stop line is not good, and there is still space between the line and the edge of the conflicting driving lane.

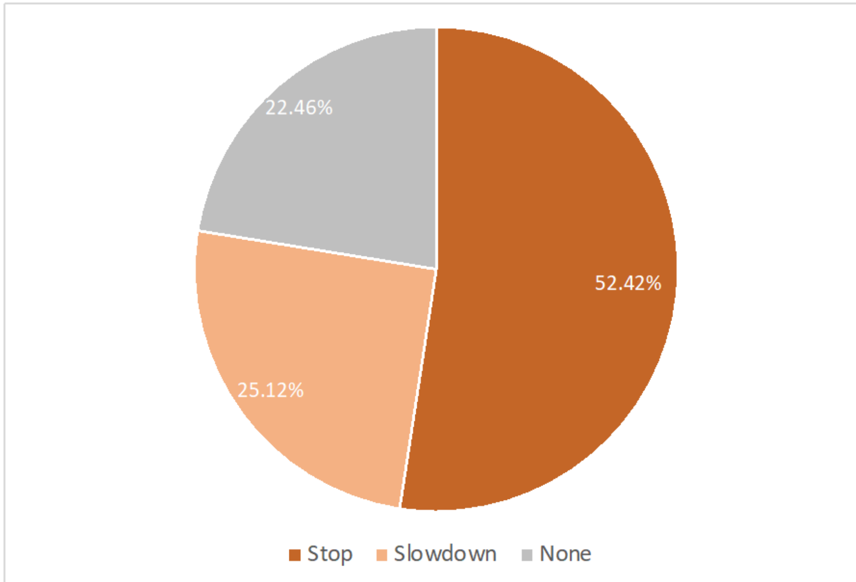

Figure 5.11 Vehicle Stop Condition at the Minor Road

5.2.2 Phase 2 Intersection Entry

Figure 5.12 showed the brake pedal use conditions during intersection entry phase. Approximately 70% of vehicles used brake pedal at the distance of 0 (near the minor road stop sign), while only 20% of the drivers braked at the median openings (distance between 80 to 100 ft).

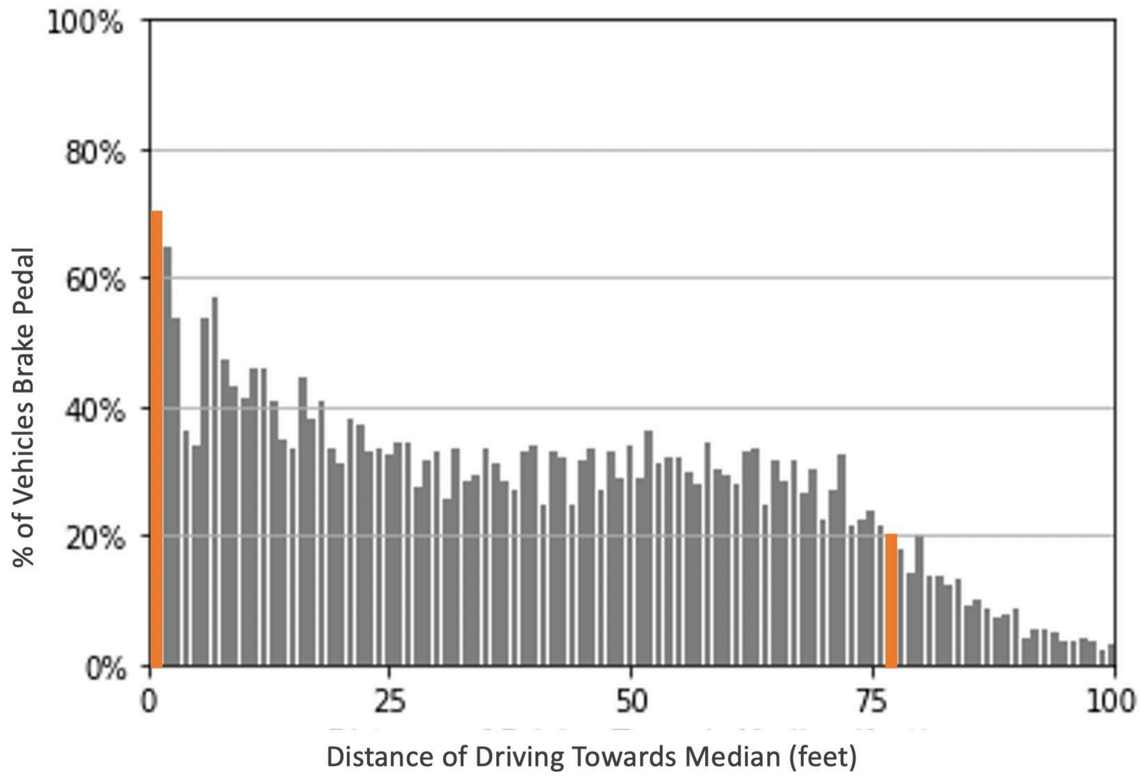

Figure 5.12 Brake Pedal Usage of Intersection Entry

Figure 5.13 shows the vehicle speed trajectory during the intersection entry. The trajectories show that part of the vehicles stop at the median (speed equals to 0 when the distance is around 80ft), and other parts of the vehicles didn't stop at the median, and their speed can be up to more than 20 mph while at the median openings.

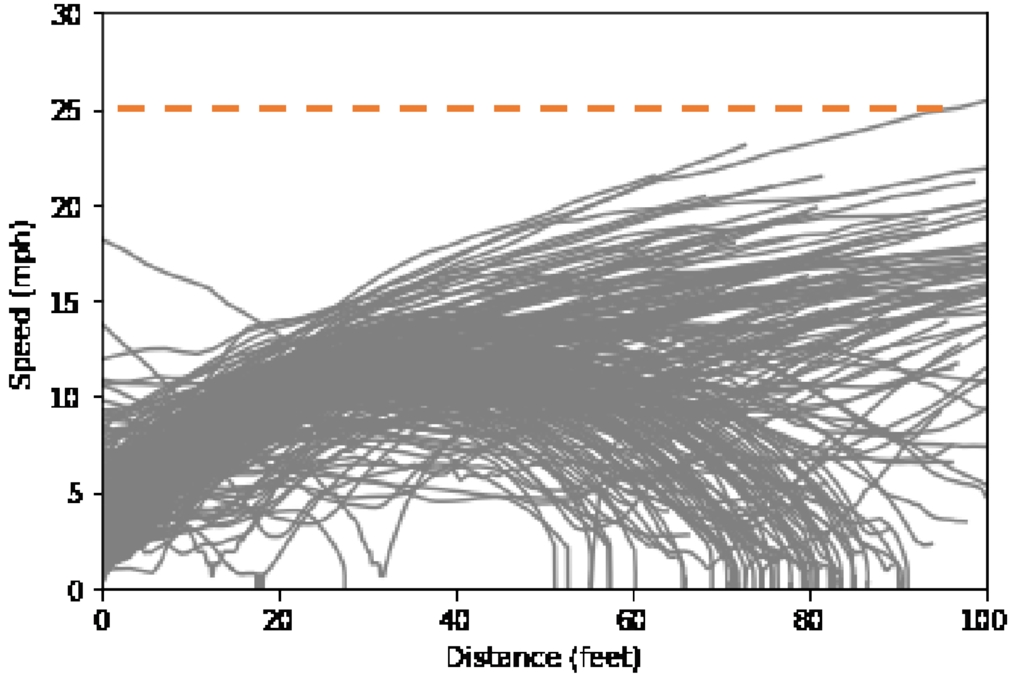

Figure 5.13 Vehicle Speed Trajectory During Intersection Entry

Figure 5.14 shows the vehicle stop conditions at the median openings. Here vehicle stopped are defined as the minimum speed is less than 3mph; slow down means the minimum speed is larger than 3mph but smaller than 10mph; none means the vehicle either stop or slow down at the median openings. The data shows that almost half of the driver didn't stop.

Figure 5.15 shows the vehicle speed trajectory of intersection entry of different age drivers who didn't stop or slow down at the median openings. Polynomial regression models were developed to predict 85th percentile speed for the different types of the drivers. It was found that the 85th percentile speed of younger drivers is much higher than the middle age and order driver.

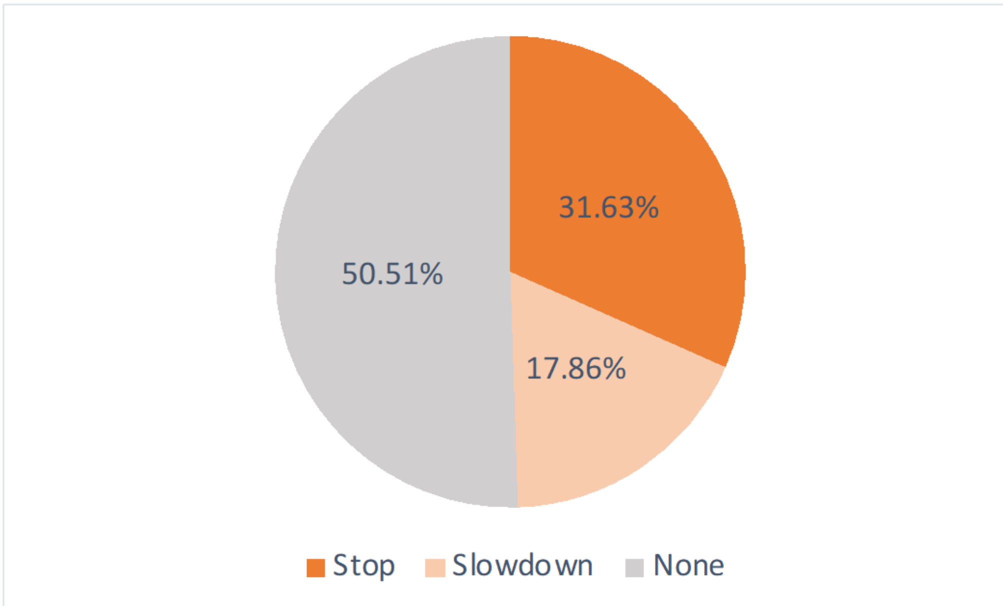

Figure 5.14 Vehicle Stop Condition at the Median Openings

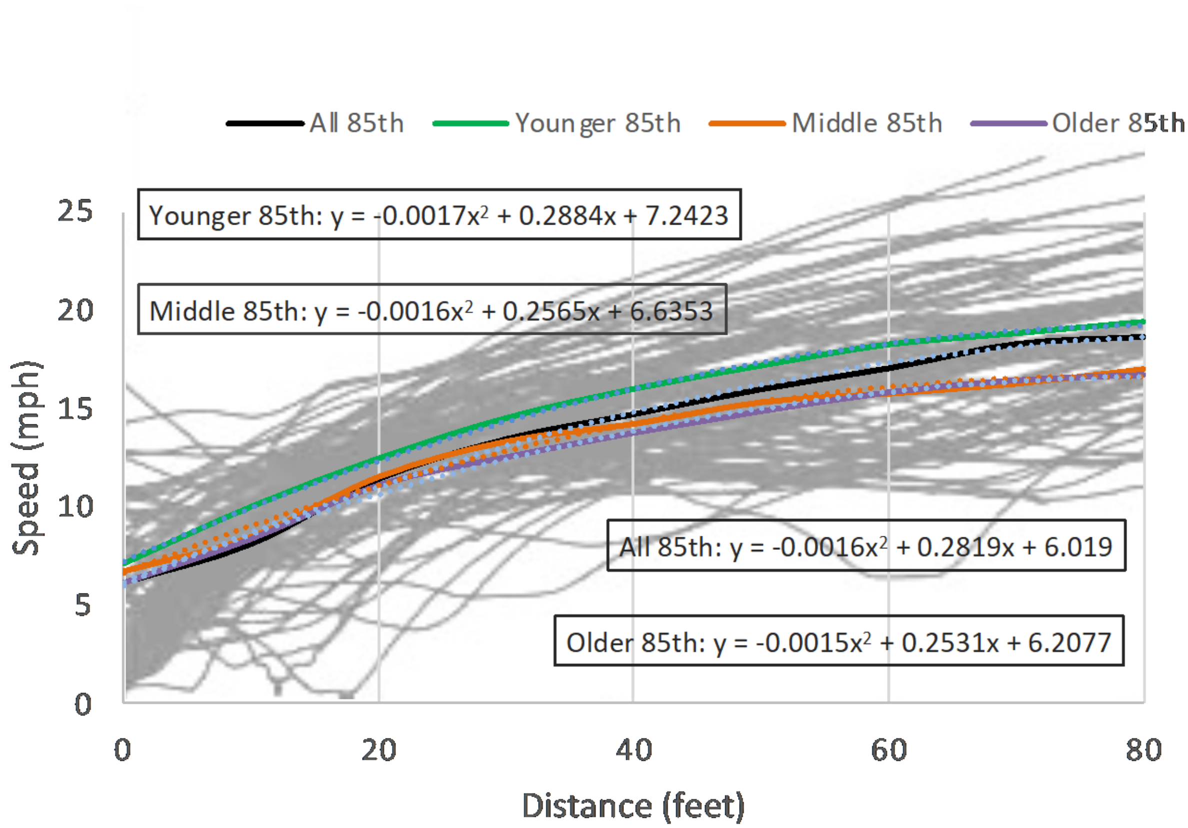

Figure 5.15 Vehicle Speed Trajectory of Intersection Entry of Different Age Drivers Who Didn't Stop or Slow down at the Median Openings

Table 5.8 shows the Tukey LSD test results of different age drivers (who didn't stop) of different distance at the confidence level of 90%, the results show that the speed of the younger driver is significant different (p-value smaller than 0.1) with the older and middle-aged drivers when the driving distance at the four study points (20ft, 40ft, 60ft and 80ft).

Table 5.8 Tukey LSD Test Results of Different Age Drivers (who didn't stop) at Different Distance of Phase 2

Distance to stop (ft)	Tukey LSD Test Results				
		Diff	lower	upper	p-adj
20	Old-Middle	-0.755	-2.529	1.019	0.575
	Young-Middle	1.663	-0.173	3.499	<0.1
	Young-Old	2.418	1.264	3.573	<0.001
40	Old-Middle	-0.755	-2.529	1.019	0.575
	Young-Middle	1.663	-0.173	3.499	<0.1
	Young-Old	2.418	1.264	3.573	<0.001
60	Old-Middle	-0.755	-2.529	1.019	0.575
	Young-Middle	1.663	-0.173	3.499	<0.1
	Young-Old	2.418	1.264	3.573	<0.001
80	Old-Middle	-0.755	-2.529	1.019	0.575
	Young-Middle	1.663	-0.173	3.499	<0.1
	Young-Old	2.418	1.264	3.573	<0.001

5.2.3 Phase 3 Execute Turn

Figure 5.16 shows the speed trajectory when drivers accelerating on the major road. To accelerate to the major road speed limit of 45 mph, 85th percentile of all the NDS drivers used less than 650 ft. The average distance of all the trips is 480ft for accelerating to the speed of 45 mph. Though the major road speed limit is 55mph at three study locations, less than half of the drivers accelerate to 55mph based on the speed data. The 85th percentile distance on major road with 55mph speed limit were not calculated**.**

Figure 5.17 shows the brake pedal use condition on major road. It suggests that about 16% of drivers in average used brake pedal to merge onto major road in the first 100 ft on major road. At the distance of around 100ft, there are almost no drivers brake the pedal.

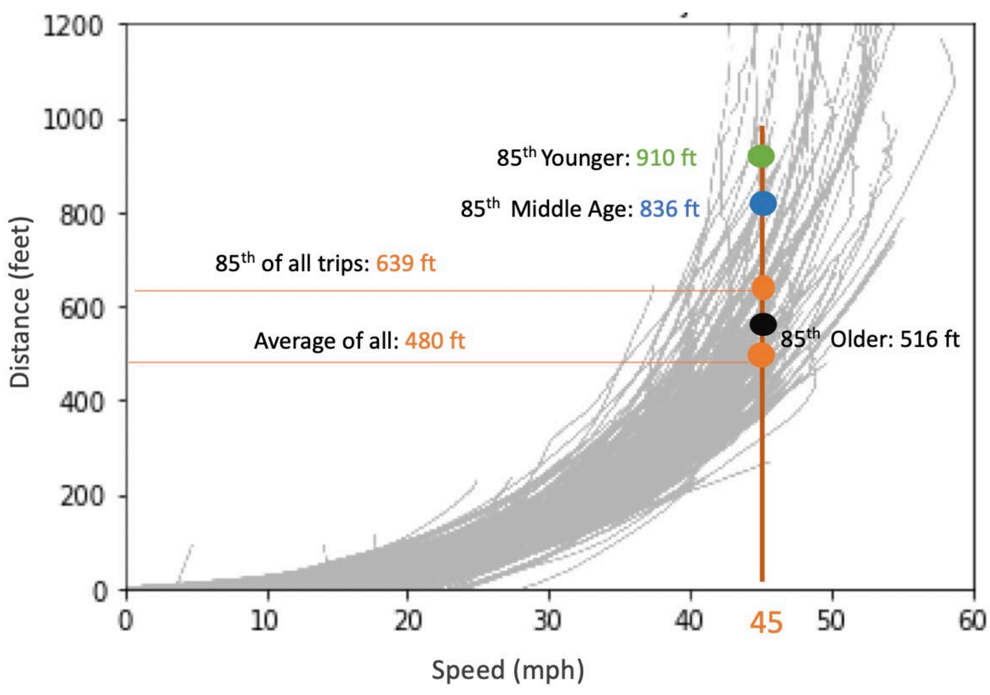

Figure 5.16 Vehicle Accelerating Trajectory on Major Road

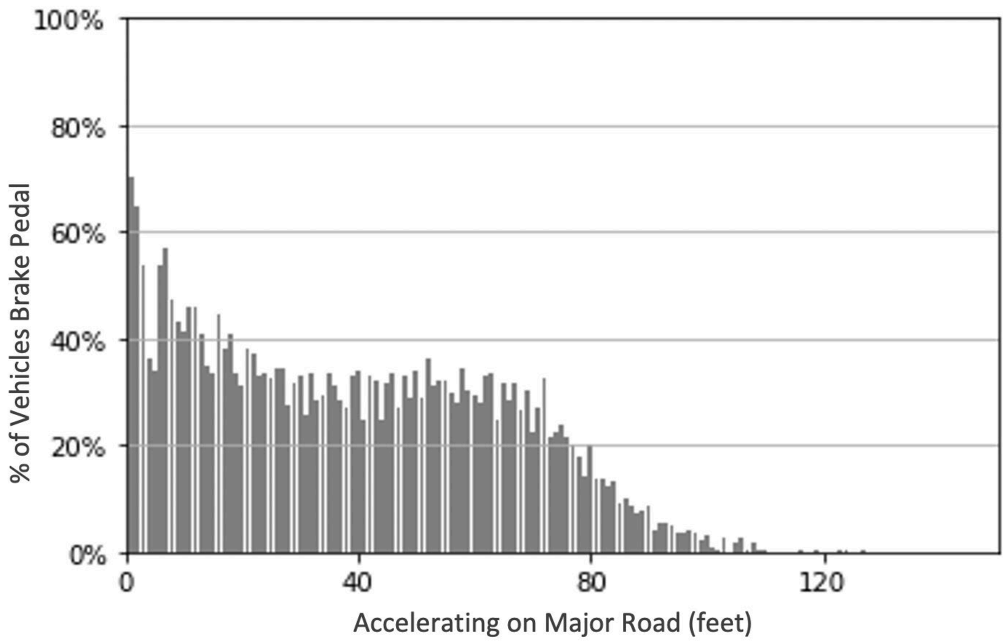

Figure 5.17 Brake Pedal Usage on Major Road

5.3 Intersection Safety Treatments Evaluations Results

Intersection safety treatments including yield sign and yield line at the roadway median, and the stop sign and lines at the roadway median were evaluated. The first three pairs of the study locations are used to evaluate the safety effectiveness of yield sign and yield line, and the last three pairs are for stop sign and stop line.

5.3.1 Summary of the Safety Evaluations of the Six Pairs of the Study Locations

Figure 5.18 shows the conflict rate among the six pairs of the study locations. The conflict here includes all types of left turn trajectory paths. As expected, treated locations have lower conflict rates than the untreated locations. Stop control can reduce more conflict compared with the yield control. The conflict rates can be reduced by 10% to 40% with stop sign and stop line. For Loc 6.0 stop sign at median openings, the conflict rate can be reduced by 40%.

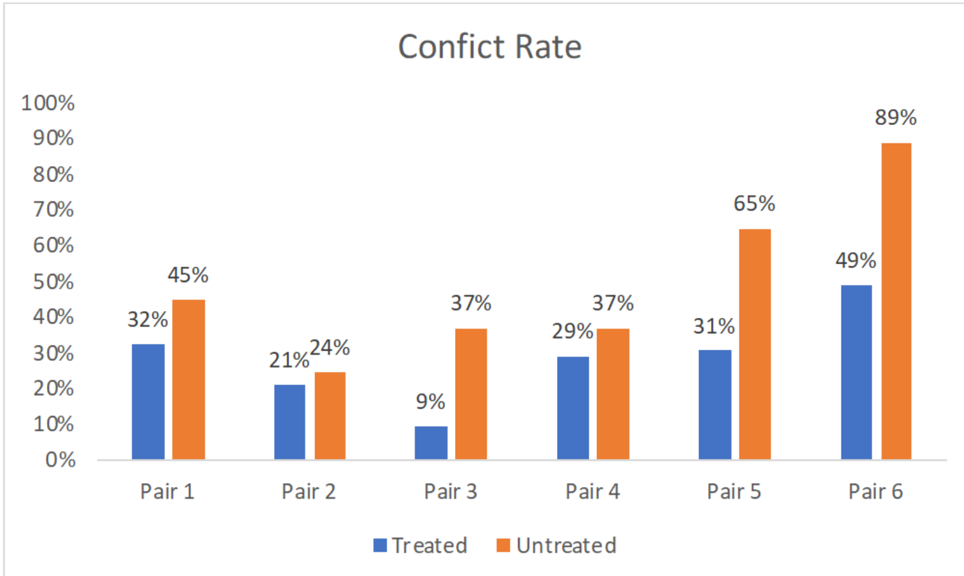

Figure 5.18 Conflict Rate Among the Six Pairs of the Study Locations

Figure 5.19 shows the near crash rate among the six pairs of the study locations. The near crash here includes all types of left turn trajectory paths. As expected, most of the treated locations have lower near crash rates than the untreated locations. The near crash rates can be reduced by 14% with the treatments. For Loc 4.0 with stop sign at median openings, the conflict rate was be reduced by 14%.

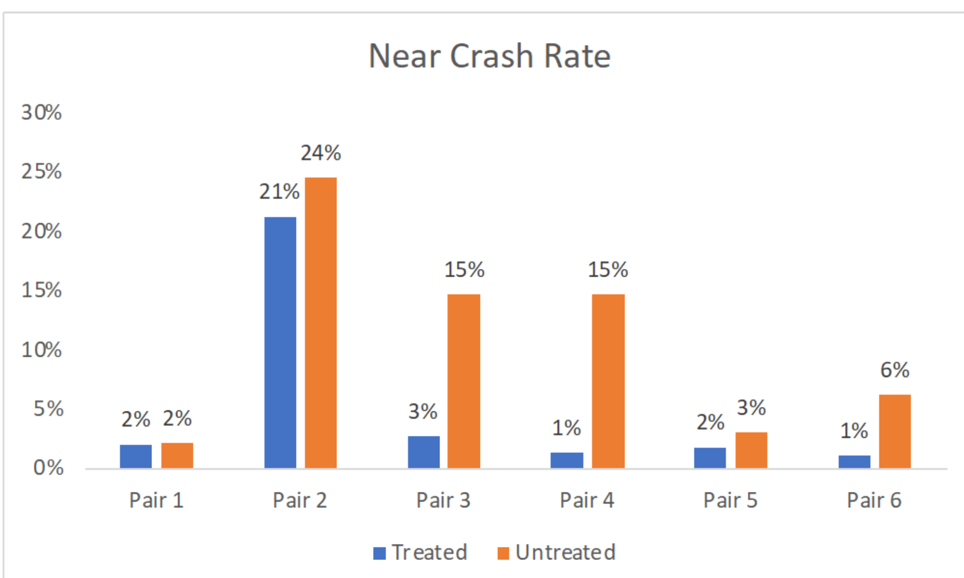

Figure 5.19 Near Crash Rate Among the Six Pairs of the Study Locations

Figure 5.20 shows the driver stop rate at the minor road among the six pairs of the study locations. Most of the treated locations have higher driver stop rates than the untreated locations. However, for most locations, the differences are less than 10%.

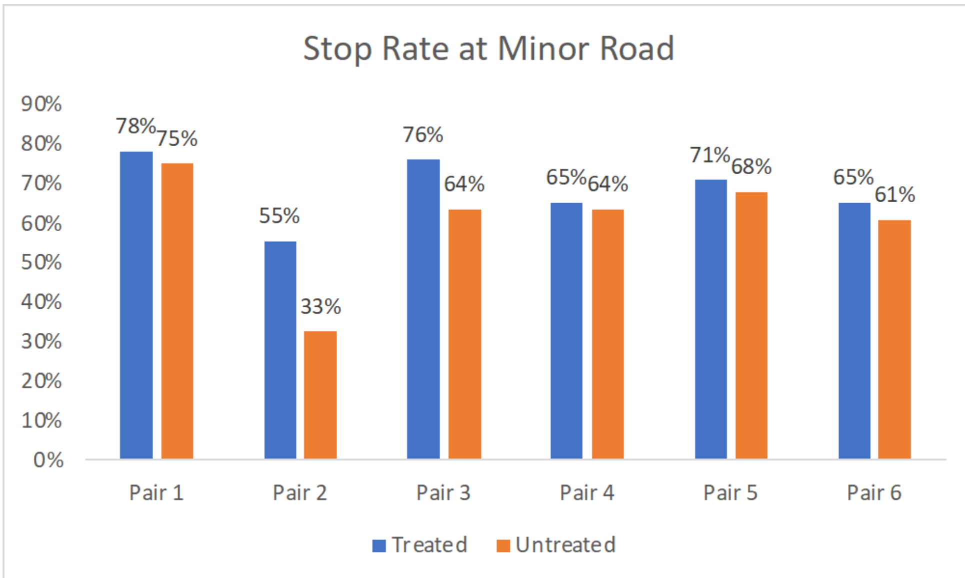

Figure 5.20 Stop Rate at Minor Road Among the Six Pairs of the Study Locations

Figure 5.21 shows the driver stop rate at the median openings among the six pairs of the study locations. Most of the treated locations have much higher driver stop rates than the untreated locations, especially for Loc 3.0, Loc 4.0, and Loc 6.0. The two intersections with stop sign and lines installed make more drivers stop at the median openings.

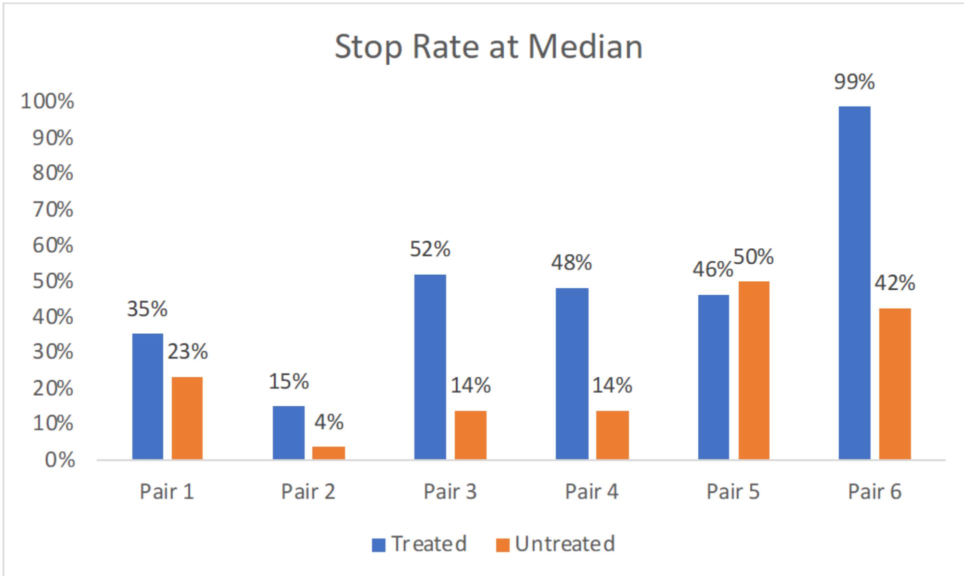

Figure 5.21 Stop Rate at Median Among the Six Pairs of the Study Locations

Figure 5.22 shows the rate of vehicle following the right of way among the six pairs of the study locations. As mentioned in the data analysis methods, the definition of the "following the right of the way" here is vehicle keep on the right side of the median opening while making the left turn. It shows that most of the treated locations have more drivers to following the right of the way. For the stop treatments intersections, the rate can be up to 99% and all the three locations have the rate higher than 50%.

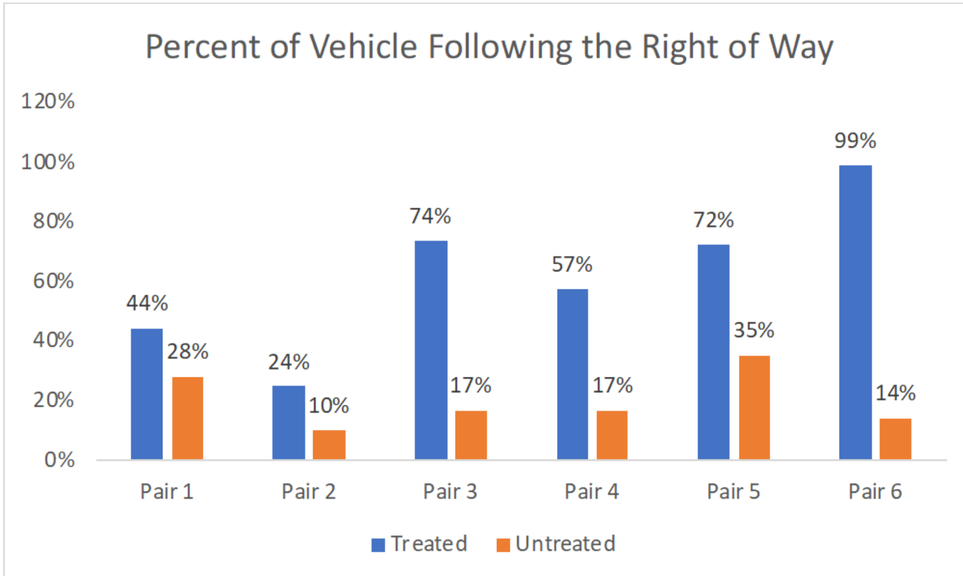

Figure 5.22 Percent of Vehicle Following the Right of Way Among the Six Pairs of the Study Locations

5.3.2 Details of the Safety Evaluations of the Six Pairs of the Study Locations

This part will discuss the details of the safety evaluations for the six pairs of the study locations. The authors will only show the analysis results of pair 1 and pair 4 here respectively as a representative of the two different types of the treatments. The detailed analysis results of the other pairs can be found in **Appendix A**.

Table 5.9 shows the detailed conflict study results of Loc 1.0 and Loc 1.1, including the information of the percentage of the conflict paths with directions, and the average PET time of each direction. It shows that most of the conflicts are between minor road left turn and the major road through movement vehicles, around 50% both before and after the treatments. There are not many conflicts with the minor road vehicles. One of the reasons may be the traffic volumes on the minor road is low at rural or suburban areas. The average PET time was also calculated for different types of the conflicts. It shows that the treated locations normally have longer PET time compared with untreated locations.

Table 5.9 Detailed Conflict Study Results of Loc 1.0 and Loc 1.1

Conflict Path with Directions	Percent of Conflicts		Ave. PET (s)	
	Treated	Untreated	Treated	Untreated
MALT	33.33%	20.73%	3.00	2.00
MART	31.25%	24.88%	3.00	2.00
MALL	10.42%	23.41%	2.60	2.45
MARL	25.00%	27.07%	2.55	3.00
MIT	0.00%	2.44%	-	2.30
MIL	0.00%	1.46%	-	3.00

Table 5.10 shows the detailed driver behavior study results of the Loc 1.0 and Loc 1.1. The table includes the left turn traffic volumes in 16 hours, the potential confit number of the left turn drivers in 16 hours, the near crash number, the driver stop condition (stop, slow down and not stop) at both minor road the median opening, and the vehicle left turn trajectories.

A simple descriptive analysis was included in the table. The percentage of the conflict rates reduced about 12%. There is no great difference of the near crash rate change. 3% more drivers stop at the minor road, and 12% more drivers stop at the median openings with the treatments. 16% more vehicles followed the right of way when making left turns.

The Pearson Chi-square test results were also included in the table. The confidence interval is 95% for the Chi-square test. The five hypothesis of the Chi-square tests are: 1) there is no significant difference of the potential conflicts between the treated and untreated intersections; 2) there is no significant difference of the near crash between the treated and untreated intersections; 3) there is no significant difference of the stop conditions at the minor road between the treated and untreated intersections; 4) there is no significant difference of the left turn trajectory types between the treated and untreated intersections; 5) there is no significant difference of the stop conditions at the median openings between the treated and untreated intersections.

The statistical analysis shows that the first four test results are not significant, and only the left turn trajectory between the treated and untreated are significantly different.

Table 5.10 Detailed Driver Behavior Study Results of Loc 1.0 and Loc 1.1

		Treated (Loc 1.0)		Untreated (Loc 1.1)					
		Number	%	Number	%	Difference After Treatments (%)	Chi-Square Test		
Left Turn Traffic Volumes (16hrs)		296		916			χ2	df	p-value
Potential Conflict (16hrs)		96	32.43%	410	44.76%	-12.33%	0.34	1	0.56
Near Crash (16hrs)		6	2.03%	20	2.18%	-0.16%	0.09	1	0.764
Stop Condition at Minor Road	Stop	231	78.04%	687	75.00%	3.04%	2.78	2	0.249
	Slow down	46	15.38%	119	12.99%	2.39%			
	None	19	6.42%	110	12.01%	-5.59%			
Stop Condition at Median	Stop	104	35.14%	211	23.03%	12.10%	4.56	2	0.102
	Slow down	27	9.12%	46	11.22%	-2.10%			
	None	165	55.74%	824	89.96%	-34.21%			
Left Turn Trajectory Type	1	131	44.26%	256	27.95%	16.31%	6.54	2	<0.05
	2	62	20.95%	348	37.99%	-17.05%			
	3	103	34.80%	312	34.06%	0.74%			

Table 5.11 shows the detailed conflict study results of Loc 4.0 and Loc 4.1, including the information of the percentage of the conflict paths with directions, and the average PET time of each direction. It shows that most of the conflicts are between minor road left turn and the major road through movement vehicles, around 60% both before and after the treatments. The conflicts

with the major road left turn movements are gently reduced after the treatments (about 2%). Similar as the study pair one, there are not many conflicts with the minor road vehicles.

The average PET time was also calculated for different types of the conflicts. It shows that the treated locations normally have longer PET time compared with untreated locations. The PET times for treated location are normally around 3s, and the PET times for the untreated locations are less than 3s.

Table 5.11 Detailed Conflict Study Results of Loc 4.0 and Loc 4.1

Conflict Path with Direction	Percent of Conflicts		Ave. PET (s)	
	Treated	Untreated	Treated	Untreated
MALT	34.62%	32.88%	3.00	2.50
MART	31.54%	30.14%	3.00	2.00
MALL	19.23%	19.18%	2.60	2.50
MARL	14.62%	16.44%	3.00	2.50
MIT	0.00%	1.37%	-	2.50
MIL	0.00%	0.00%	-	-

Table 5.12 shows the detailed driver behavior study results of the Loc 4.0 and Loc 4.1. The simple descriptive analysis shows that the percentage of the conflict rates reduced about 8%, and the near crash rates reduced about 13%. About 34% more drivers stop at the minor road, and 40% more drivers stop at the median openings with the treatments. 40% more vehicles followed the right of way when making the left turns.

The Pearson Chi-square tests show that all the test results are significant at the 95% confidence interval. It means the stop sign and stop line installed at the median openings can significantly change the driver behaviors, including the conflict rate, the near crash, the stop behaviors, and the left turn trajectories.

Table 5.12 Detailed Driver Behavior Study Results of Loc 4.0 and Loc 4.1

		Treated (Loc 4.0)		Untreated (Loc 4.1)					
		Number	%	Number	%	Diff. After Treatments (%)	Chi-Square Test Results		
Traffic Volume (16hrs)		446		198			χ2	df	p-value
Potential Conflict (16hrs)		130	29.15%	73	36.87%	-7.72%	99.30	1	< 0.001
Near Crash		6	1.35%	29	14.65%	-13.30%	20.10	1	< 0.001
Stop Condition at Minor Road	Stop	291	65.12%	126	63.64%	1.48%	11.34	2	0.003
	Slow down	112	25.12%	47	23.74%	1.38%			
	None	43	9.64%	25	12.63%	-2.99%			
Stop Condition at Median	Stop	214	47.98%	27	13.64%	34.35%	74.25	2	0.004
	Slow down	27	6.05%	34	17.17%	-11.12%			
	None	205	45.96%	137	69.19%	-23.23%			
Left Turn Trajectory Type	1	254	57.00%	33	16.67%	40.33%	81.14	2	<0.001
	2	49	10.99%	134	67.68%	-56.69%			
	3	143	32.01%	31	15.66%	16.36%			

The detailed analysis results of all the other pairs can be found in **Appendix A**. The analysis results can be summarized as:

1) The stop control at the median openings makes significant difference on the conflict and driver behaviors (stop behaviors at median and the left turn trajectories), compared with yield control.
2) Median openings using pavement markings and stop sign to treat as two intersections can reduce by 10% to 40% of conflict rates in total based on the field studies.
3) More than half of the drivers stopped at median opening with stop lines/ signs control at the median opening. More than 50% of the minor road left-turn vehicles made two-stage left turns onto the major road. This implies that the treatments can slow down the drivers and let them make a better judgment of the suitable gaps to cross the road.

4) Yield control can only get less than 40% drivers to stop or slow down at the median openings, and the statistic tests results are not significant of pair one and pair two locations.
5) For median openings with no access control, most of the locations, 30% of the minor road vehicles will stop at the median opening to make a two-stage left-turn.

Chapter 6. Conclusions and Recommendations

6.1 Conclusions

6.1.1 Driver Behavior Study Using NDS Data

For the study of driver behavior using NDS data, a driver visual workload study, and driver speed change and stop behavior study were conducted. For the analysis, the driver demographics (e.g., gender, age, income, education, driving years, crash records, and risk perception levels) and roadway/traffic features (e.g., channelization on minor road, leg numbers, major road speed limit, and AADT) were also analyzed to exam if they have an impact on the driver workload and behavior.

The key findings of these studies are as follows:

Driver Visual Workload Study

1) Descriptive data analysis indicates that drivers making left turns at conventional intersections spend more time looking at their left and right mirrors and less time looking forward, but at RCUT intersections, drivers are more focused on looking forward.
2) Overall entropy rates of left turn drivers at conventional intersections are statistically significantly higher than indirect left turn drivers at RCUT intersections. Drivers at conventional intersections have more random scanning and shorter average fixation duration during the movement. This is consistent with the descriptive data analysis results. It indicates that the entropy rate can be a proper measure for understanding the cognitive demands of real-world driving.

3) The results indicate that younger drivers at both types of the intersections have higher entropy rates than middle-aged and older drivers. More safety driving programs can be provided to younger drivers since they tend to have higher visual workload when crossing the intersections.
4) Correlation analysis results show that some demographic features, such as education level, driving years, crash numbers in the past 3 years, and the risk perception scores are negatively correlated with the entropy rate.
5) Statistical analysis results suggest that AADT has a significant impact on driver's visual workload. Higher AADT (≥30,000) on major road will increase drivers' visual workload compared with the AADT (≤ 20,000). Safety treatments should be considered at the intersections on high traffic volume roads.
6) The use of NDS data alone is not sufficient for specific roadway infrastructure design analyses since the participants of some specific study facilities (e.g., RCUT) are limited. Other surrogate analysis method can be integrated (e.g., conflict study).

Driver Speed Change and Stop Behavior Analysis

1) Based on phase 1 analysis, 85^{th} percentile of the left turn drivers tends to decelerate sharply when they are about 50 feet away from the minor road stop line, therefore advanced intersection warning sign should be located at least 115 ft+2.5 sec * Speed Limit (ft/sec) before the intersection giving 2.5 seconds perception and reaction time.
2) Based on phase 2 analysis, about half of the drivers did not make complete stops at the minor road, and only 25% drivers stopped at the median opening. Therefore, enhanced stop signs or pavement markings should be taken into consideration at the two-way stop control intersections.
    1) Based on phase 3 analysis, 85^{th} percentile of all the NDS drivers used less than 650 ft to accelerate to the 45 mph from median opening. It suggests that a 650 ft left turn

acceleration lane on major road can accommodate 85% of drivers on a road with the speed limit of 45 mph.

2) Most of the younger drivers tend to driver faster than middle-aged and older drivers. It was found that the 85th percentile speed of younger drivers is higher than the middle age and order driver when decelerating on minor road. Additionally, to accelerate to the major road speed limit of 45 mph, the distance of the 85th percentile of the younger drivers is 910 ft. Therefore, when the roadway design areas are near school or college, the use of speed control devices should be considered.

6.1.2 Unsignalized Intersection Safety Treatments Evaluations in Alabama

The study results of the safety effects of two types of median opening treatments based on a study of traffic conflict and driver behavior (understanding right-of-way, whether or not stopping at the median opening, and if or not making two-stage left-turn movements). The key findings are summarized below:

1) The stop control at the median openings makes significant difference on the conflict and driver behaviors (stop behaviors at median and the left turn trajectories), compared with yield control.
2) Median openings using pavement markings and stop sign to treat as two intersections can reduce by 10% to 40% of conflict rates in total based on the field studies.
3) More than half of the drivers stopped at median opening with stop lines/ signs control at the median opening. More than 50% of the minor road left-turn vehicles made two-stage left turns onto the major road. This implies that the treatments can slow down the drivers and let them make a better judgment of the suitable gaps to cross the road.
4) Yield control can only get less than 40% drivers to stop or slow down at the median openings, and the statistical test results are not significant between the pair one and pair two locations.

5) For median openings with no access control, most of the locations, 30% of the minor road vehicles will stop at the median opening to make a two-stage left-turn.

6.2 Recommendations

Figure 6.1 shows the suggested speed control devices installations at wide median intersections.

On the minor road, the advanced warning sign together with the in-lane rumble strips were suggested to be installed at least 120 ft +2.5 sec * speed limit (ft/sec) away from the intersection to let more drivers slow down. The advanced warning sign is optional. If the stop sign on minor road is not visible from the distance of 120 ft +2.5 sec * speed limit (ft/sec), there is a need to install advanced warning sign. The advanced warning sign should be visible from the distance of 120 ft +2.5 sec * speed limit (ft/sec). Since a large percent of drivers tend to stop after the stop line or stop sign of the minor road, a yield sign is suggested to be installed after the stop sign when the driver sight SD of the major road coming vehicles is limited (e.g., the major road installed separate right-turn lane, or there is a pedestrian line after the stop line) and there is still space between the line and the edge of the conflicting driving lane, which can reduce the vehicle conflicts with major road traffic.

At the median openings, stop sign and stop line or yield sign and yield line were suggested if the median opening is wide enough, which can force drivers to make the two-stage left turn and find a safer gap before merging.

On the major road, the left turn acceleration lane was suggested to install at least 650 ft when speed limit is 45 mph, which will reduce the conflict points for left turn drivers before they merge into the major road.

The author also summarized the design guidance of the safety control devices: advanced stop sign, transverse rumble strips, centerline pavement markings, left turn acceleration lane, and convert to RCUT intersections, which are listed in **Appendix B**. In the guideline, author also included the suggested application example in Alabama, and also picked the high-quality crash modification factors for the treatments.

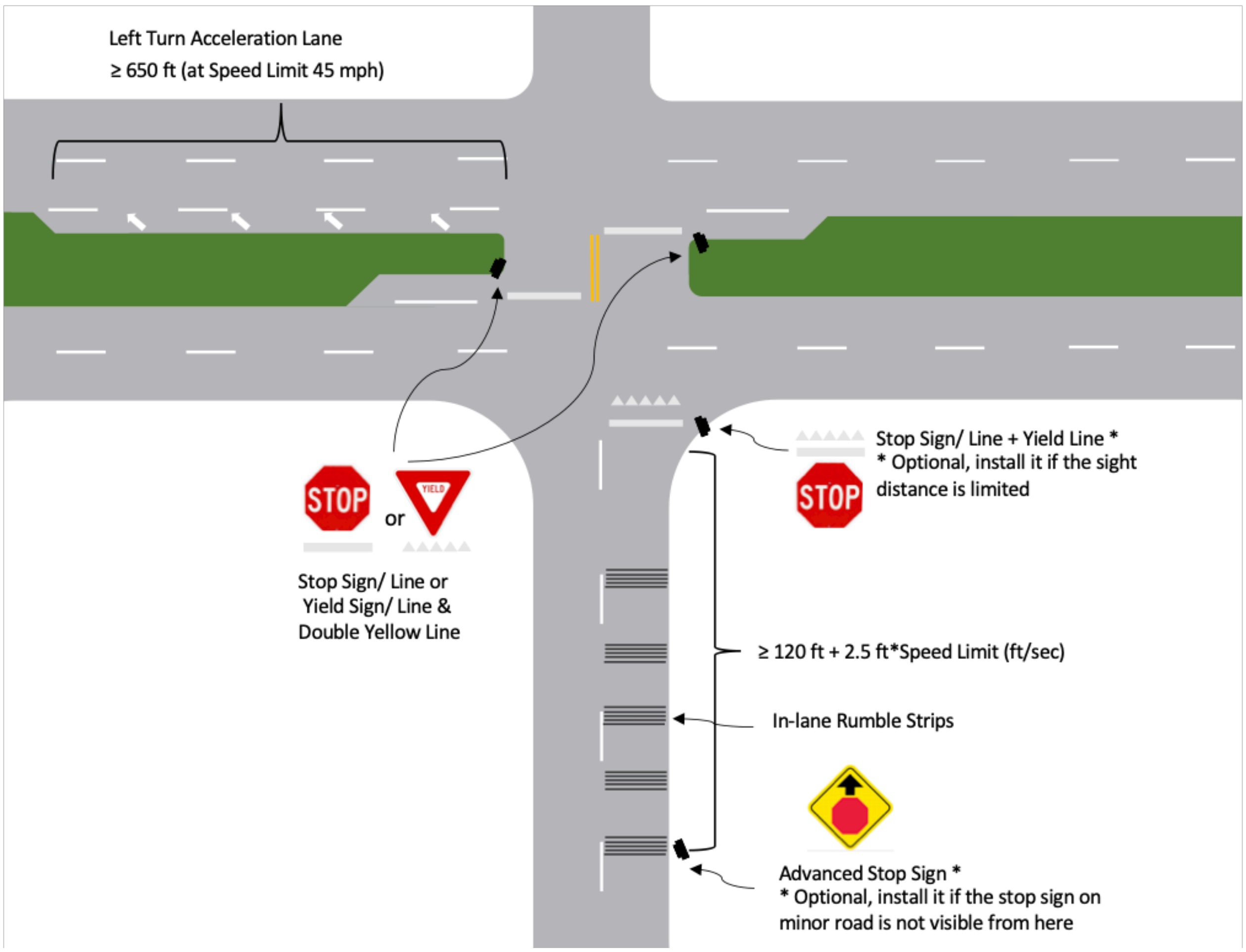

Figure 6.1 Suggested Speed Control Traffic Control Devices Installations at Unsignalized Intersections (not in scale)

6.3 Study Limitations and Future Work

For NDS study, participants that meet the study requirements are limited since most volunteers of the NDS database live in urban areas. Furthermore, sample size was further decreased due to the small amount of right-turn followed by U-turn trips at RCUT intersections.

For the driver visual workload study, the relationship between the entropy rate and the driver stop time, and the relationship between the entropy rate and the traffic volumes can be furtherly analyzed in the future. Additionally, with more data collected in the future, the repeated analysis for each participant can be conducted.

For the conflict study, if possible, the crash data of the study intersections can be achieved to evaluate the study results in the future.

Also, since the data of the conflict study were collected by observing, there are some human errors of the data. In the future, the video analytic method can be applied to get the conflict data and PET time automatically, therefore a more accurate PET time can be collected for the safety evaluations.

Appendix A Conflict and Driver Behavior Study Results

Table 1 Detailed Conflict Study Results of Loc 2.0 and Loc 2.1

Conflict Path with Directions	Percent of Conflits		Ave. PET (s)	
	Treated	Untreated	Treated	Untreated
MALT	33.90%	46.97%	2.83	2.92
MART	44.07%	43.94%	2.54	3.00
MALL	1.69%	3.03%	2.00	1.00
MARL	8.47%	6.06%	1.20	1.00
MIT	11.86%	0.00%	1.30	-
MIL	0.00%	0.00%	-	-

Table 2 Detailed Driver Behavior Study Results of Loc 2.0 and Loc 2.1

		Treated (Loc 2.0)		Untreated (Loc 2.1)					
		Number	%	Number	%	Difference after Treatments (%)	Chi-Square Test Results		
Traffic Volume (16hrs)		278		270			χ2	df	p-value
Potential Conflict (16hrs)		59	21.22%	66	24.44%	-3.22%	1.21	1	0.271
Near Crash		4	1.44%	11	4.07%	-2.64%	0.28	1	0.597
Stop Condition at Minor Road	Stop	154	55.40%	88	32.59%	22.80%	6.91	2	0.052
	Slow down	106	38.13%	144	53.33%	-15.20%			
	None	18	6.47%	38	14.07%	-7.60%			
Stop Condition at Median	Stop	42	15.11%	10	3.70%	11.40%	3.89	2	0.143
	Slow down	41	14.75%	14	5.19%	9.56%			
	None	195	70.14%	246	91.11%	-20.97%			
Left Turn Trajectory Type	1	68	24.46%	26	9.63%	14.83%	5.42	2	0.067
	2	146	52.52%	160	59.26%	-6.74%			
	3	64	23.02%	84	31.11%	-8.09%			

Table 3 Detailed Conflict Study Results of Loc 3.0 and Loc 3.1

Conflict Path with Directions	Percent of Conflicts		Ave. PET (s)	
	Treated	Untreated	Treated	Untreated
MALT	32.11%	43.12%	3.00	2.00
MART	41.12%	40.02%	2.50	2.00
MALL	2.12%	4.21%	2.60	2.45
MARL	12.41%	6.06%	3.00	3.00
MIT	10.12%	3.12%	-2.50	2.30
MIL	2.12%	3.47%	3.00	3.00

Table 4 Detailed Driver Behavior Study Results of Loc 3.0 and Loc 3.1

		Treated (Loc 3.0)		Untreated (Loc 3.1)					
		Number	%	Number	%	Difference After Treatments (%)	Chi-Square Test Results		
Traffic Volume (16hrs)		938		198			χ2	df	p-value
Potential Conflict (16hrs)		88	9.38%	73	36.87%	-27.49%	60.12	1	< 0.01
Near Crash		25	2.67%	29	14.65%	-11.98%	18.01	1	< 0.01
Stop Condition at Minor Road	Stop	713	76.01%	126	63.64%	12.38%	3.90	2	0.142
	Slow down	163	17.38%	47	23.74%	-6.36%			
	None	61	6.50%	25	12.63%	-6.12%			
Stop Condition at Median	Stop	485	51.71%	27	13.64%	38.07%	7.54	2	<0.01
	Slow down	211	22.49%	34	17.17%	5.32%			
	None	242	25.80%	137	69.19%	-43.39%			
Left Turn Trajectory Type	1	690	73.56%	33	16.67%	56.89%	81.14	2	<0.01
	2	225	23.99%	134	67.68%	-43.69%			
	3	23	2.45%	31	15.66%	-13.20%			

Table 5 Detailed Conflict Study Results of Loc 5.0 and Loc 5.1

Conflict Path with Direction	Percent of Conflicts		Ave. PET (s)	
	Treated	Untreated	Treated	Untreated
MALT	46.67%	41.84%	2.50	2.50
MART	42.86%	43.95%	2.50	2.00
MALL	10.48%	9.21%	3.00	3.00
MARL	0.00%	3.68%	0.00	2.60
MIT	0.00%	0.79%	-	2.50
MIL	0.00%	0.53%	-	3.00

Table 6 Detailed Driver Behavior Study Results of Loc 5.0 and Loc 5.1

		Treated (Loc 5.0)		Untreated (Loc 5.1)					
		Number	%	Number	%	Diff. After Treatments (%)	Chi-Square Test Results		
Traffic Volume (16hrs)		684		588			$\chi 2$	df	p-value
Potential Conflict (16hrs)		210	30.70%	380	64.63%	-33.92%	70.23	1	< 0.05
Near Crash		12	1.75%	18	3.06%	-1.31%	0.12	1	0.72
Stop Condition at Minor Road	Stop	486	71.05%	399	67.86%	3.20%	3.12	2	0.077
	Slow down	179	26.17%	167	28.40%	-2.23%			
	None	19	2.78%	22	3.74%	-0.96%			
Stop Condition at Median	Stop	3566	52.05%	150	21.93%	30.12%	71.30	2	< 0.01
	Slow down	253	36.99%	237	34.65%	2.34%			
	None	75	10.96%	201	29.39%	-18.42%			
Left Turn Trajectory Type	1	492	72.00%	206	35.00%	37.00%	69.08	2	<0.01
	2	82	12.00%	241	40.99%	-28.99%			
	3	109	16.00%	141	24.01%	-8.01%			

Table 7 Detailed Conflict Study Results of Loc 6.0 and Loc 6.1

Conflict Path with Direction	Percent of Conflicts		Ave. PET (s)	
	Treated	Untreated	Treated	Untreated
MALT	45.69%	36.91%	2.50	2.00
MART	47.37%	43.38%	3.00	2.00
MALL	4.07%	8.68%	3.00	2.50
MARL	2.87%	9.62%	3.00	2.50
MIT	0.00%	0.47%	-	2.50
MIL	0.00%	0.95%	-	2.50

Table 8 Detailed Driver Behavior Study Results of Loc 6.0 and Loc 6.1

		Treated (Loc 6.0)		Untreated (Loc 6.1)					
		Number	%	Number	%	Diff. After Treatments (%)	Chi-Square Test Results		
Traffic Volume (16hrs)		856		714			χ2	df	p-value
Potential Conflict (16hrs)		418	48.83%	634	88.80%	-39.96%	100.12	1	< 0.01
Near Crash		10	1.17%	44	6.16%	-4.99%	1.22	1	0.203
Stop Condition at Minor Road	Stop	558	65.19%	435	60.92%	4.26%	3.52	2	0.172
	Slow down	215	25.12%	193	27.00%	-1.88%			
	None	83	9.70%	86	12.04%	-2.35%			
Stop Condition at Median	Stop	847	98.95%	303	42.44%	56.51%	80.43	2	< 0.01
	Slow down	2	0.23%	200	28.01%	-27.78%			
	None	7	0.82%	211	29.55%	-28.73%			
Left Turn Trajectory Type	1	847	98.95%	100	14.01%	84.94%	90.22	2	<0.01
	2	5	0.58%	89	12.46%	-11.88%			
	3	4	0.47%	525	73.53%	-73.06%			

Transverse Rumble Strips on Stop Control Approaches

To alert approaching drivers of the upcoming intersection. Can be particularly beneficial at intersections where users do not expect Stop signs, or roads with high-speed limit.

Target Crash Type	Rear-end crash		**Target Problem**	Speeding
				Low Stop sign compliance
Selected CMFs	ID	9046	9049	
	CMF	0.71	0.75	
	Severity	KABCO	KABCO	
	Quality	4 Star	4 Star	
	Unadjusted SE	0.08	0.1	
	Crash Type	All	Angle	
	Intersection Geometry	4-leg		
Example	US 431 @ AL 169, AL			
Other Resources	● MUTCD: Section 3J.02: Transverse Rumble Strip Markings			
	● NCHRP Report 613: Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections			
	● Safety Evaluation of Transverse Rumble Strips on Approaches to Stop-Controlled Intersections in Rural Areas			

Minor road speed limit: 55 mph; Grade change between minor road and the intersection. The start point of the rumble strip is 900ft away from the intersection.

Advanced Stop Beacon

The beacon indications supplement STOP (R1-1) signs and face the minor road. It can be used to increase the conspicuity of the Stop sign; used at locations or conditions where users do not expect Stop signs, such as poor nighttime visibility.

Target Crash Type	Right-angle	**Target Problem**	Inadequate visibility of the intersection
	Rear-end crash		
	Opposing left turn		Low Stop sign compliance

Selected CMFs					
	ID	446	447	448	449
	CMF	0.95	0.9	0.92	0.87
	Severity	All	ABC	All	All
	Quality	4 Star	4 Star	4 Star	4 Star
	Unadjusted SE	0.04	0.05	0.09	0.05
	Crash Type	All	All	Rear end	Angle
	Intersection Geometry	4-leg			

Example AL 25 @ U.S. 80, AL

An isolated intersection in rural area, with poor nighttime visibility. Minor road speed limit: 40mph.

Other Resources

- MUTCD Section 4L.02: Flashing Beacons
- Safety Evaluation of Flashing Beacons at STOP-Controlled Intersections, FHWA

<table>
<tr><th colspan="4">Left turn (Median) Acceleration Lane</th></tr>
<tr><td colspan="4">An auxiliary lane that allows left-turning vehicles from the minor road to accelerate along the major road before merging into the through lane.</td></tr>
<tr><td rowspan="3">Target Crash Type</td><td>Right-angle</td><td rowspan="3">Target Problem</td><td>High left-turn volume onto high-speed or high-volume major road</td></tr>
<tr><td>Rear-end (major road)</td><td>High volume of trucks or RV turn left</td></tr>
<tr><td>Sideswipe, same direction</td><td>Misjudgment of gaps</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td colspan="4">No Recommended CMFs.</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td>Example</td><td colspan="3">St. & Tom Mann Rd., Newport, NC</td></tr>
<tr><td colspan="3">

</td><td>It's a T-intersection with a physical channelization. Picture shows the major road left-turn acceleration lane with the pavement arrow.</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td>Other Resources</td><td colspan="3">• AASHTO Green Book Section 9.7: Auxiliary Lanes</td></tr>
</table>

Center Line Pavement Markings in a Median Crossing

Application of double yellow line to delineate the center of a median crossing can be used to serve vehicles in both directions, and to promotes two-stage crossing.

Target Crash Type	Right-angle	**Target Problem**	Interlocking left turns on the major road
	Opposing left turn		Side-by-side left-turn queuing in median
	Sideswipe, same direction		Observed conflicts in median
	Head-on		

No Recommended CMFs

Example Co Rd 21 & U.S. 280, AL

The median opening is wide (85ft). The double yellow line helps to separate the crossing vehicles queueing in median.

Other Resources

- MUTCD, Installation of Pavement Markings

Convert to RCUT

Conversion of minor road left turns and through movements to right turns and U-turns, usually on divided highways with wide median and multiple lanes in each direction.

Target Crash Type	Right-angle	**Target Problem**	Insufficient gaps for minor road crossing vehicles
	Opposing left turn		
	Rear-end (major road)		
	Pedestrian		

Selected CMFs	ID	10382	10383	
	CMF	0.8	0.8	
	Severity	All	All	
	Quality	4 Star	4 Star	
	Unadjusted SE	0.0683	0.073	
	Crash Type	All	All	

Example AL219 & US82, Centreville, AL

Unsignalized RCUT intersections are installed with flashing beacons to reduce the minor road left turn crashes

Other Resources

- Restricted Crossing U-Turn Intersections, FHWA
- MUTCD, Section 2B.18: Movement Prohibition Signs
- GDOT, RCUT

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