DETERMINATION OF THE OFFSET DISTANCE BETWEEN DRIVEWAY EXITS AND DOWNSTREAM U-TURN LOCATIONS FOR VEHICLES MAKING RIGHT TURNS FOLLOWED BY U-TURNS

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16. Abstract

This study evaluated the impacts of the offset distance between driveway exits and downstream median opening or signalized intersection on the safety and operational performance of vehicles making right-turns followed by U-turns. This study evaluated the impacts of offset distance under 4 different roadway conditions including: 4-lane divided roadways accommodating U-turns at median openings; 4-lane divided roadways accommodating U-turns at signalized intersections; 6 or more-lane divided roadways accommodating U-turns at median openings; and 6 or more-lane divided roadways accommodating U-turns at signalized intersections. Three basic approaches were applied including crash data analysis, conflict analysis, and operations analysis. Field measurements were conducted at 68 selected sites in the Tampa Bay area in Florida. Crash history of 192 roadway segments was investigated. Statistical models were developed based on the collected field data to quantitatively evaluate the safety and operational performance of vehicles making RTUT at various offset distances. It was found that the crash rate and conflict rate at weaving sections decrease with the increase of the offset distance between driveway and downstream U-turn location. The cumulative curves were plotted for the crash rates and conflict rates of all sample sites. The 50th percentile value of crash rate and conflict rate was used to determine the critical value of offset distance. The critical offset distance for vehicles making RTUT under different scenarios were determined by applying the 50th percentile value of crash rate and conflict rate into the regression models developed in this study. The research results obtained from this research could be used to estimate the minimum offset distance between driveway exits and the U-turn locations to facilitate vehicles making RTUT without causing significant safety problems at weaving sections.

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DETERMINATION OF THE OFFSET DISTANCE BETWEEN DRIVEWAY EXITS AND DOWNSTREAM U-TURN LOCATIONS FOR VEHICLES MAKING RIGHT TURNS FOLLOWED BY U-TURNS

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ABSTRACT

Florida increasingly uses restrictive medians and directional median openings on multi-lane highways to manage left turn egress maneuvers from driveways or side streets. By installing non-traversable medians and replacing full median openings with directional median openings at various locations, Florida prohibits direct left-turn exits onto some major arterials; hence, **Direct Left-Turn** (**DLT**) egress maneuvers from driveways or side streets would be replaced by making a **Right Turn Followed By A U-Turn** (**RTUT**) at downstream median openings or signalized intersections.

Though several studies have been conducted to evaluate the safety and operational effects of using U-turns as alternatives to direct left-turns, these studies have not focused on the impacts of the offset distance between driveways and downstream U-turn location. Very short offset distance may lead to operational and safety characteristics somewhat similar to direct left turns and may discourage drivers to make right-turns followed by U-turns. Too long offset distance, on the other hand, may result in long travel time and, sometimes, tend to discourage drivers' willingness to make right turns followed by U-turns. Therefore, the safety and operational performance of vehicles making RTUT are highly correlated with the offset distance between subject driveway and downstream median opening or signalized intersection.

This study evaluated the impacts of the offset distance between driveway exits and downstream median opening or signalized intersection on the safety and operational performance of vehicles making right-turns followed by U-turns. The focus of this research was on urban or suburban multilane divided arterials. This study evaluated the impacts of offset distance under 4 different roadway conditions including: 4-lane divided roadways accommodating U-turns at median openings; 4-lane divided roadways accommodating U-turns at signalized intersections; 6 or more-lane divided roadways

accommodating U-turns at median openings; and 6 or more-lane divided roadways accommodating U-turns at signalized intersections. Three basic approaches were applied including crash data analysis, conflict analysis, and operations analysis. Field measurements were conducted at 68 selected sites in the Tampa Bay area in Florida. Crash history of 192 roadway segments was investigated. Statistical models were developed based on the collected field data to quantitatively evaluate the safety and operational performance of vehicles making RTUT at various offset distances. It was found that the crash rate and conflict rate at weaving sections decrease with the increase of the offset distance between driveway and downstream U-turn location. The cumulative curves were plotted for the crash rates and conflict rates of all sample sites. The 50^{th} percentile value of crash rate and conflict rate was used to determine the critical value of offset distance. The critical offset distance for vehicles making RTUT under different roadway conditions were determined by applying the 50^{th} percentile value of crash rate and conflict rate into the regression models developed in this study. The research results obtained from this research could be used to estimate the minimum offset distance between driveway exits and the U-turn locations to facilitate vehicles making RTUT without causing significant safety problems at weaving sections.

Keywords *- Access Management, U-turn, offset distance, Weaving, Crash Rate, Conflict*

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1. INTRODUCTION

1.1 Background

Florida increasingly uses restrictive medians and directional median openings on multi-lane highways to manage left turn egress maneuvers from driveways or side streets. By installing non-traversable medians and replacing full median openings with directional median openings at various locations, Florida prohibits direct left-turn exits onto some major arterials; hence, **Direct Left-Turn** (**DLT**) egress maneuvers from driveways or side streets would be replaced by making a **Right Turn Followed By A U-Turn** (**RTUT**) at downstream median openings or signalized intersections.

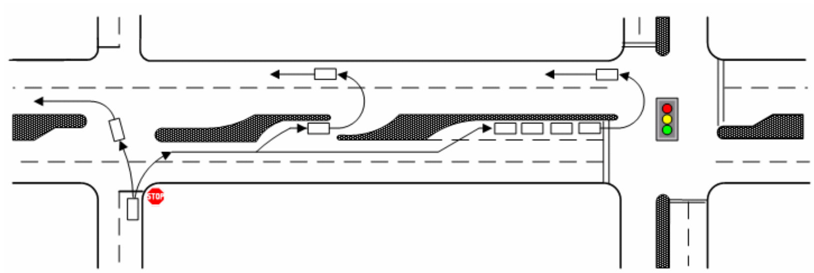


Figure 1-1 Three Different Driveway Left-turn Alternatives in Florida

The purpose of using U-turns as alternatives to direct left-turns is to reduce conflicts and improve safety along multilane roadways. Replacing a full median opening with a directional median opening will reduce conflict points from 32 to 8. It will simplify driving tasks and could significantly reduce crash rate. In practice, however, the median modification projects, including installing non-traversable medians, closing existing full median openings, or replacing full median openings with directional median openings, could be controversial and sometimes difficult to handle. Some business owners believe that the loss of direct left-turn access would have some adverse impacts on their business. In addition, arguments have been advanced by some opponents of median modification projects that the increased number of U-turns may cause safety and operational problems to the major road. .

From 2001 to 2004, a series of research projects concerning the safety and operational effects of U-turns were conducted by the University of South Florida (1, 2, 3, 4, 5, 6 and 7). These research studies took three basic approaches in evaluating a widely used access management treatment – right turns followed by U-turns as alternatives to direct left-turns from driveways or side streets, including crash data analysis, conflict analysis, and operations analysis. Comprehensive field studies were conducted on 34 selected roadway segments in central Florida. Video cameras and Hi-star portable traffic analyzers were used to collect traffic data in the field. Over 1000 hours of traffic data were recorded. Statistical analysis was conducted based on field data to quantitatively evaluate the safety and operational performance of U-turns and left-turns. The USF studies proved that under high through traffic volume and driveway volume conditions, direct left-turns resulted in higher traffic conflicts, crash rate and, sometimes, longer stop delay and total travel time as compared with right-turns followed by U-turns if the length of the offset distance between driveway and downstream median opening or the signalized intersection was sufficiently long.

One of the important considerations on the choice between making right-turns followed by U-turns and direct left-turns lies with the offset distance between subject driveways and downstream median opening or signalized intersection. In practice, vehicles wishing to make a RTUT would first turn right onto the major road, accelerate to the operating speed of through traffic, weave to the inside lane, and then stop at the median opening or signalized intersection to perform a U-turn maneuver. Very short offset distance between driveway and U-turn location may lead to operational and safety characteristics somewhat similar to direct left turns and may discourage drivers to make right-turns followed by U-turns. Too long offset distance, on the other hand, may result in long travel time and, sometimes, tend to discourage driver willingness to make right turns followed by U-turns. Therefore, the safety and operational performance of vehicles making RTUT are highly correlated with the offset distance between subject driveway and downstream median opening or signalized intersection. There might be an optimum offset distance range for a given combination of major street and driveway volumes. However, previous studies, including the USF studies, have not specifically focused on these issues, and as a result, the impacts of offset distance on traffic operational and safety performance for vehicles making right-turns followed by U-turns are still not clear.

1.2 Research Approach

In this study, the offset distance was defined as the separation distance between driveway exit and downstream median opening or signalized intersection, as shown in Figure 1-2 and Figure 1-3.

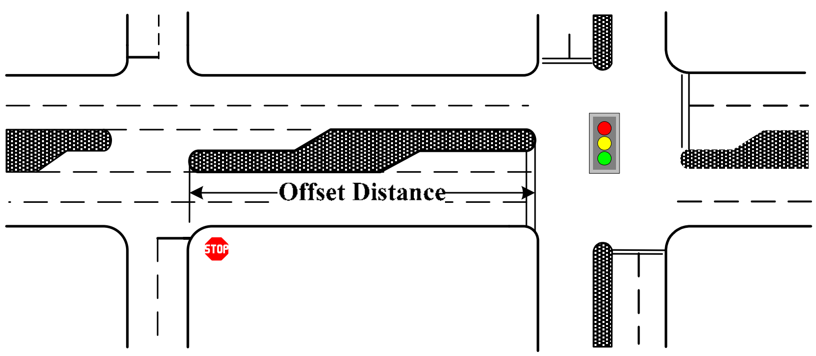


Figure 1-2 Offset Distance for Vehicles Making RTUT at Signalized Intersections

This study evaluated the impacts of the offset distance between driveway exit and downstream U-turn location on the safety and operational performance of vehicles making right-turns followed by U-turns. The focus of this research was on urban or suburban multilane divided arterials. This study evaluated the impacts of offset distance under 4 different roadway conditions, including: 4-lane divided roadways accommodating U-turns at median openings; 4-lane divided roadways accommodating U-turns at signalized intersections; 6 or more-lane divided roadways accommodating U-turns at median openings; and 6 or more-lane divided roadways accommodating U-turns at signalized intersections. Three approaches were applied including crash data analysis, conflict analysis, and operations analysis. Field measurements were conducted at 68 selected sites in the Tampa Bay area in Florida. Crash history of 192 roadway segments was investigated. Statistical models were developed based on the collected field data to quantitatively evaluate the safety and operational performance of vehicles making RTUT at various offset distances. The research results obtained from this study could be used to estimate the minimum and optimal offset distance between driveways and downstream U-turn locations required by drivers to perform the RTUT movements safely and efficiently.

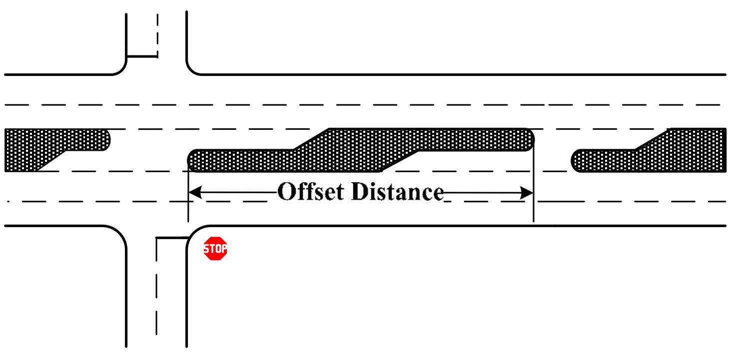


Figure 1-3 Offset Distance for Vehicles Making RTUT at Median Openings

1.3 Research Objectives

The main objective of this research was to evaluate the impacts of the offset distance between a driveway and downstream median opening or signalized intersection on traffic operational and safety performance. With such results, the optimum offset distance can be determined so that drivers have better access to make right-turns followed by U-turns.

Results from this research can be used to develop guidelines for determining optimum offset distance under different combinations of given traffic conditions.

To reach this main objective, the research project focused on two major parts: traffic operational performance and safety performance. The traffic operational performance part was based on the evaluation of vehicles travel time at various offset distances and the safety performance part was based on the evaluation of traffic conflicts and crash data. For the both performance evaluations, roadway sections with different offset distances between driveways and downstream U-turn locations were selected. Traffic data and conflict data on these sections were collected with the use of video cameras and other traffic data measuring systems. The relationships between offset distances and traffic performance and traffic conflicts were developed based on field data.

1.4 Outline of the Report

This report consists of six chapters. Chapter 1 provides a brief introduction of the research. Chapter 2 describes a summary of past studies in this area. Chapter 3 explains the methodology employed in achieving the research objectives. Chapter 4 focuses on the data collection and the data reduction procedure. Analysis results and research findings are presented in Chapter 5. Finally, Chapter 6 provides summary, conclusions and recommendations of this research.

2. LITERATURE REVIEW

2.1. U-turns as Alternatives to Direct Left-turns

Increasingly, U-turns are used as alternatives to direct left-turns. Since 1993, Florida Department of Transportation (FDOT) has mandated that all new or reconstructed multi-lane arterials with design speeds over 40 mph be designed with restrictive medians. The purpose of using U-turns as alternatives to direct left-turns is to reduce conflicts and improve safety along multilane roadways. Replacing a full median opening with a directional median opening will reduce conflict points from 32 to 8; therefore it will simplify driving tasks and could significantly reduce crash rate. In practice, however, the median modification projects, including installing non-traversable medians, closing existing full median openings, or replacing full median openings with directional median openings, could be controversial and sometimes difficult to handle. Some business owners believe that the loss of direct left-turn access would have some adverse impacts on their business. In addition, arguments have been advanced by some opponents of median modification projects that the increased number of U-turns may cause safety and operational problems. Recently, these issues were hotly discussed. Numerous studies have been conducted. The focus of these studies includes:

(1) The economic impacts of installing non-traversable medians (8, 9, 10, 11);

(2) Safety effects of U-turns at median openings and signalized intersections (12, 13, 14, 15, 16, 17); and

(3) The effects of U-turns on the capacity of signalized intersections or median openings (18, 19, 20).

Previous studies have demonstrated that the use of non-traversable medians and directional median openings have little or no overall adverse impacts on business activities; and the increased U-turn volumes at unsignalized median openings and signalized intersections will not cause major safety concern. For example, a recent NCHRP research (16) analyzed crash data at 481 conventional full median openings and 187 directional median openings and found that accidents related to U-turn and left-turn maneuvers at median openings occur very infrequently. In urban arterial corridors, median openings experienced an average of 0.41 U-turn plus left-turn accidents per median openings per year. In rural arterial corridors, unsignalized median openings experienced an average of 0.20 U-turn plus left-turn accidents per median opening per year. Based on these limited accident frequencies, the researchers of that study concluded that U-turns at median openings do not constitute a major safety concern. Carter and Hummer (17) examined U-turn collision history of 78 signalized intersections and found that 65 of the 78 sites did not have any collisions involving U-turns in the three year study period. U-turn collisions at the remaining 13 sites ranged from 0.33 to 3.0 collisions per year. Researchers of that study concluded that U-turns do not have a large negative safety effect at signalized intersections. There have been several studies conducted concerning the operational effects of U-turns (17, 18, 19, and 20). The focus of these studies was on the effects of U-turns on the capacity of signalized intersections or median openings.

From 2001 to 2004, a series of research projects concerning the safety and operational effects of U-turns were conducted by the University of South Florida (1, 2, 3, 4, 5, 6 and 7). These research studies took three basic approaches in evaluating a widely used access management treatment – right turns followed by U-turns as alternatives to direct left-turns from driveways or side streets, including crash data analysis, conflict analysis, and operations analysis. Comprehensive field measurements were conducted on 34 selected roadway segments in central Florida. Video cameras and Hi-star portable traffic analyzers were used to collect traffic data in the field. Over 1000 hours of traffic data were recorded. Statistical analysis was conducted based on field data to quantitatively evaluate the safety and operational performance of U-turns and left-turns. The USF studies proved that under high through traffic volume and driveway volume conditions, direct left-turns resulted in higher traffic conflicts, crash rate and, sometimes, longer stop delay and total travel time as compared with right-turns followed by U-turns if the length of the weaving section between the driveway and the median opening or the signalized intersection was sufficiently long.

2.2. Weaving Issues Related to RTUT

As mentioned before, the safety and operational performance of vehicles making RTUT highly depends on the length of offset distance between driveway and downstream U-turn location. However, previous studies concerning the safety and operational effects of U-turns have not specifically focused on the impacts of different offset distances.

The NCHRP 420 contains some guidelines about the weaving patterns for vehicles making RTUT under various separation distances between driveway exits and the downstream U-turn channels (15). There are three different types of weaving patterns for RTUT as shown in Figure 2-1:

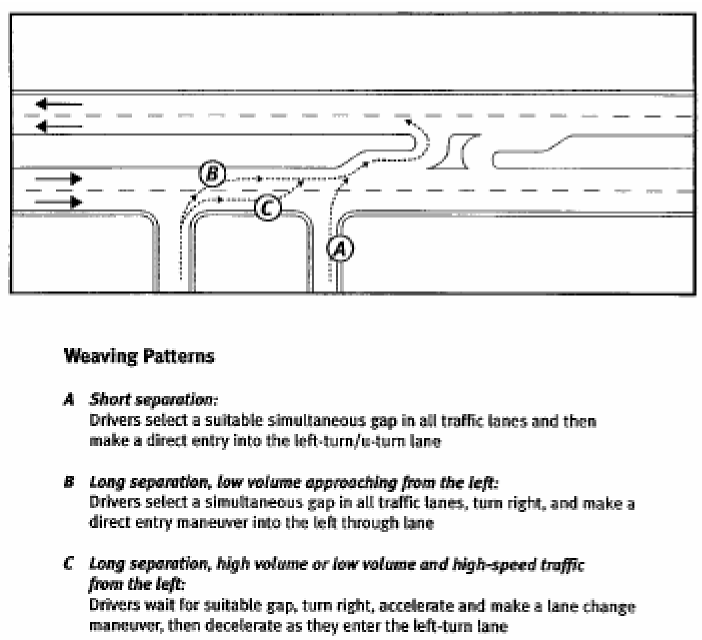


Figure 2-1 Weaving Patterns for RTUT

(Source: NCHRP 4-20)

Zhou and Hsu developed a working model to decide the optimal location of mid-block U-turn median openings on multilane divided roadways where the signalized intersections are coordinated (21). A case study of that study showed that the average delay of U-turns will significantly decrease and the capacity of U-turns will increase if the U-turn median opening is located at an optimal location downstream of driveway.

Zhou's study focused on determining an optimal distance between driveway and downstream mid-block median opening such that the waiting delay of vehicles making RTUT could be minimized. The findings of that study provided very useful insights on traffic operations and safety of right turn plus U-turns design. However, that study did not look specifically at the crash data and traffic conflicts occurred at weaving sections. Further work need to be conducted to evaluate the impacts of various weaving lengths on traffic safety performance.

Though several methods have been established to analyze weaving on freeways; most of these methods are not directly applicable to analyze weaving that occurs in the non-freeway environment. The Highway Capacity Manual (2000) presents a methodology for prediction of weaving speed and non-weaving speed in freeway weaving sections (22). The procedure is sometimes applied to at-grade arterials, although it has been recognized that weaving speed and non-weaving speed are not the best measures of traffic operations of at-grade weaving sections.

2.3. Interchange Spacing

Adequate spacing and design of access to crossroads in the vicinity of freeway ramps avoids traffic backups onto the mainline and preserves safe and efficient traffic operation in the vicinity of the ramp terminals with the crossroad (23). Several research studies have been conducted to determine the optimal distance from a freeway ramp terminal to the first median opening. As presented by the Florida Median Handbook (24), drivers tend to make erratic maneuvers when there is a limited separation distance between the gore area of the off-ramp and the median opening. Desirable conditions would permit a driver to accelerate, merge into the outside traffic lane, select an acceptable gap in order to merge into the inside lane and then move laterally into the left-turn lane and then come to a stop as illustrated in Figure 2-2. Similar driving behaviors were observed when vehicles make a right turn followed by a U-turn.

The NCHRP report 420 contains some guidelines for interchange area spacing (15). The desired access separation distances for free-flowing right turns from exit ramps should include the following components:

(1)Perception-reaction distance (100–150 ft);

(2)Lane transition (150–250 ft);

(3)Left-turn storage (50 ft per left-turn per cycle);

(4)Weaving distance (800 ft, 2-lane arterials; 1200 ft, 4-lane arterials; 1600 ft, 6-lane arterials); and

(5)Distance to centerline of cross street (40–50 ft).

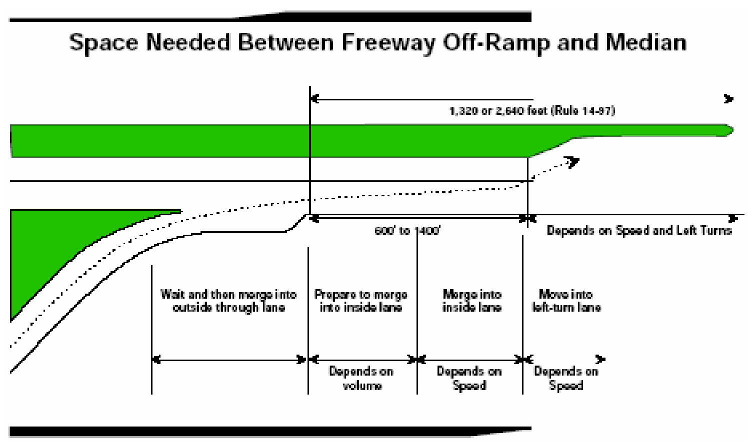


Figure 2-2 Space Needed Between Freeway Off-Ramp and Median

The Florida Median Handbook set up a procedure to determine the minimum weaving distance from a freeway ramp terminal to the first median opening through a technique developed by Jack Leisch in Procedure for Analysis and Design of Weaving Sections (FHWA Project - 1982). Based on the methodology, At speeds and volumes normally encountered in urban and suburban areas, weaving distances of 700 to 800 ft will be adequate for most conditions along 2-lane roads. Along multilane roads, weaving distances of 1,200 to 1,600 ft will usually be adequate.

Jacobson and Nowlin investigated weaving on frontage roads *(25).* The study focused on developing the guideline of the minimum distance for vehicles weave from freeway exit ramp to the first driveway based on results of the safety and operations studies; and desirable weaving distance based on a combination of the distance of weaving requirements and the level of service on the frontage road. It was found by the author that the majority of drivers use between 60 and 120 meters to weave from an exit ramp to the right-most lane on a frontage road; however, a few drivers use as much as 150 meters. The study examined crash data in the vicinity of exit ramp at several sites. A linear regression model was built to identify which of the factors had a significant effect on the total accident rate. The research team of that study collected traffic data in the field to determine the distance that drivers used to weave between an exit ramp and a driveway along a frontage road. The minimum weaving lengths suggested by the author are shown in Figure 2-3.

Number of Lanes in Weaving Section	Minimum Weaving Distance (m) [1]
2	80
3	110
4	140

[1] Based on 50th percentile weaving and decelerating distances from field observation.

Figure 2-3 Minimum Required Distance to Weave From Exit-Ramp to First Driveway (Source: Jacobson and Nowlin Study)

2.4. Corner Clearance

Corner clearance represents the distance that is provided between an intersection and the nearest driveway. Inadequate corner clearances can result in traffic-operation, safety, and capacity problems. These problems can be caused by blocked driveway ingress and egress, conflicting and confusing turns at intersections, in-sufficient weaving distances, and backups from a downstream driveway into an intersection (23). When the corner clearance is too short, vehicles making a RTUT at signalized intersection may constitute a safety concern due to the limited weaving length.

The upstream functional distance establishes the minimum upstream corner clearance for the major roadway. As presented by Florida Median Handbook, this distance consists of three components: the distance traveled during vehicles' perception–reaction time (d_1); the maneuver distance (d_2) and the queue storage length (d_3) at signalized intersections, as shown in Figure 2-4.

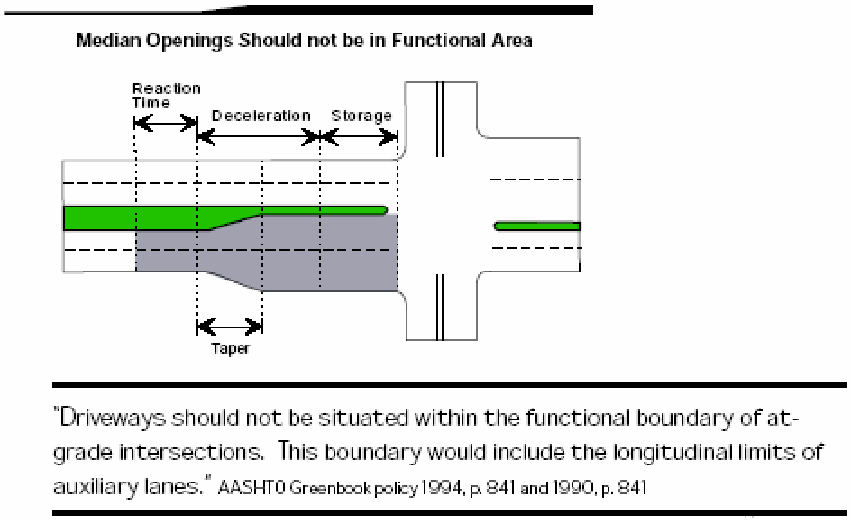


Figure 2-4 Upstream Functional Area at Signalized Intersection

The NCHRP report 420 summarized the corner clearance criteria of different agencies (15). The minimum upstream corner clearance varies from 16 ft (Iowa DOT) to 325 ft (Colorado DOT), as shown in Figure 2-5.

2.5. Conflict Studies

Traffic conflicts have been surrogate measures for traffic crashes and have been used since the 1970's for safety assessment purposes. Parker and Zeeger defined the conflicts as a traffic event involving the interaction of two or more road users usually motor vehicles, where one or both drivers take evasive action such as braking or swerving to avoid a collision (26,27). The traffic conflict technique is a methodology for field observers to identify conflict events at intersections by watching for strong braking and evasive maneuvers. The traffic conflict technique has a long history of development, including research on (28):

(1)Data collection methods;

(2)Data collection standards;

(3)Definitions of various types of conflicts;

(4)Severity measures Relationship between conflicts and crashes; and

(5)Conflicts that are related to specific crash types.

Government Unit	Criteria
Collier County, FL	With Median: 75 to 115 ft. upstream, 100 to 230 ft. downstream Without Median: 100 to 230 ft. upstream, 100 to 230 ft. downstream.
Colorado DOT	325 feet from intersection for 40 mph.
Florida DOT	75 to 115 ft. upstream, 100 to 230 ft. downstream.
Ingham County, MI	125 feet from intersection.
Iowa DOT	16 feet from intersection in urban area.
Maine DOT	Suggested spacing in urban areas: Signalized intersections - 115 to 230 feet Unsignalized intersections - 85 to 115 feet Suggested spacing in rural area is double the above
New York DOT	Approximately 35 to 75 feet from the intersection.
North Dakota DOT	Signalized intersections: Local - 50 ft., Collector-85 to 175 ft., Arterial 115 to 230 ft. Unsignalized intersections: Local - 50 ft., Collector - 75 to 85 ft., Arterial 85 to 115 ft.
New Jersey	50 ft. unsignalized/100 ft. signalized.
Oshtemo Township, MI	75 to 250 feet from intersection.
Palm Beach, FL	75 to 125 feet from intersection.
Pennsylvania DOT	"follows AASHTO criteria."
Texas DOT	"AASHTO green book for corner clearances without medians."
Virginia DOT	50 desirable, 25 feet minimum from intersections.
Washington DOT	Varies depending on classification of road.

Figure 2-5 Summary of Corner Clearance Criteria
(Source: NCHRP 4-20)

Traffic conflicts were used for other purposes other than being safety measures for a location. An ITE study found that 33 percent of the reporting agencies used a left-turn conflict rate of four conflicts per 100 left-turn vehicles as a warrant for implementing left turn phase in signal phasing. The operational quality of service has an affect on number of the conflicts. The result of the study that intended to comprehend the relationship between traffic operations and safety at signalized intersections found that average stopped delay significantly affects the vehicle and lane change conflicts. Also, those types of conflicts decreases as the average total delay increases (29, 30).

Sayed (31) described the application of the traffic conflict technique for the estimation of safety at an unsignalized intersection. In this study, a computer simulation was used to simulate critical traffic events. Data was collected from 30 different surveys to establish the traffic conflict frequency and the severity standards. The standards established by this study allow the relative comparison of the conflict risk at different intersections (31).

Another research by Sayed established frequency and severity standards for signalized intersections acquiring data from 94 conflict surveys. The study developed an intersection conflict index to compare the conflict risk at signalized intersections (32).

Weerasuriya and Pietrzyk (33) used traffic conflicts to analyze intersection and develop expected conflict value tables for future studies where intersections do not have a history of crashes. Various types of intersections with varying lane number and volumes were analyzed in that research. The tables resulted from this study, provided mean, variance, and 90th and 95th percentile conflict rates. It was proposed that those tables could be used to estimate the safety problem at different intersections.

The relationship between traffic volumes and conflicts has been another subject for researchers to investigate. Salman and Almaita (34) had a research on three leg intersections. The summation of all volumes entering the intersection and the square root of the product of the volumes that generated the conflicts were used to correlate conflicts and volumes. It was found that the correlation between conflicts and the square root of the product of volumes was higher than that of summation of volumes. Migletz. et al. (35) defined the traffic volumes depending on the conflict types, which were through cross traffic conflicts, opposing left turn conflicts and same direction conflicts. For opposing left-turn conflicts the volume was defined as the square root of the product of the left turn volume and opposing through volume summed over two approaches at unsignalized intersections. Through cross-traffic conflicts were related to the through cross traffic volume, which was defined as the square root of the product of through cross traffic from right (or left) volume with the through volume summed over the four approaches at both signalized and unsignalized intersections. Same direction conflicts were related to the same direction volume, which was defined as sum of the volumes of all the approaches. Katamine (36) worked on 15 four leg unsignalized intersections to define the relationship between traffic volumes and the conflicts. Eleven types of conflicts were related to thirteen different volume definitions. The study found that the total volume entering the intersection was significantly correlated to most conflict types but using the total volume cannot explain the different conflicts' occurrence at the intersections.

2.6. Conflicts vs. Crashes

The main purpose of the traffic studies is to enhance the safety of traffic locations or the movements at those locations. As it was mentioned in the previous chapter, reducing the number of crashes will reduce the injuries and fatalities related to them. Since the main purpose is to reduce the number of crashes, researchers have been using crashes to assess safety problems. However, problems have been documented with crashes. Firstly, the number of crashes at a specific site is usually too small to do any kind of analysis. Many years are required to obtain a required crash data from a specific site. Secondly, some property damage crashes have never been reported to the police. Also, the crash data may include human errors or may be missing. Thirdly, a reduction in the number of crashes may be the result of a successful counter measure, or to the fact that the period before the measure had randomly high number of crashes (26, 27, 37, 38, and 39).

On the other hand, traffic conflicts have some advantages when compared to traffic crashes: First, a researcher can collect the conflict data required for a site in a short period of time so it is not necessary to wait several years to make any improvements to a location (26, 27, 39). Second, the data collected can be used as supplementary data to crash data for analysis purposes (26, 27). Third, the effectiveness of a countermeasure can be evaluated in a short time and can be changed in a short time with traffic conflicts (26, 27). Fourth, traffic conflict provides information about volumes, frequency of different kinds of conflicts and severity of conflicts while the crash data can only give information on property damage and injury severity (40). Fifth, conflict data includes human factors because the conflict data collection requires observation of the drivers at the field (41).

Though researchers have intensely studied the correlation between crashes and conflicts, they have shown minute success in distinguishing their relationship to each other. Migletz et al (42) found 10% correlation between crashes and conflict. Engel (43) found that the relationship between the total crashes and the conflicts was not significant, but if different types of crashes and conflicts were studied the relationship would have been significant. Glauz et al (44) stated that the conflicts can be used to estimate the number of crashes in a particular year but it will not predict actual number. Therefore, traffic conflict can be used as a replacement of the crashes.

3. METHODOLOGY

This chapter presents a detailed description of the methodology used to achieve the research objective of this study. This research took three basic research approaches to evaluate the impacts of the offset distance between driveway exit and downstream U-turn location on the traffic operational and safety performance including: operational analysis, crash data analysis and conflict analysis.

3.1 Phase One -- Operational Analysis

As shown in Figure 3-1, vehicles making a RTUT at downstream median opening or signalized basically usually require four steps:

Step 1: Stopping at the driveway, and making a right turn onto the major road when there is a suitable gap from left-side through-traffic.

Step 2: Accelerating to the operating speed of through-traffic, weaving to the inside lane, and decelerating to a stop at the U-turn median opening or signalized intersection.

Step 3: Waiting for a suitable gap in the through-traffic to perform a U-turn maneuver; and

Step 4: Accelerating to the operating speed of through-traffic.

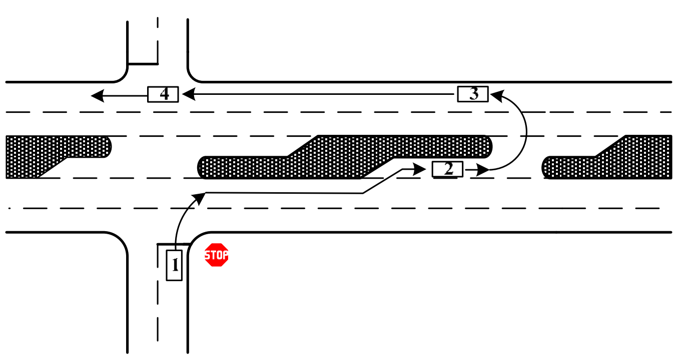


Figure 3-1 The Procedure for Vehicles Making RTUT

The average running time for vehicles making RTUT was highly correlated with the offset distance between driveway and downstream median opening or signalized intersection. If the distance is too long, drivers may not prefer to make a RTUT due to the perception that this procedure may result in longer travel time and consume more gas as compared with a DLT. The average running time for vehicles making RTUT consisted of the following parts, as shown in Figure 3-2:

(1) The running time from vehicle leaves driveway until it stops at the exclusive left-turn bay of downstream signalized intersection or median opening; and

(2) The running time from vehicle starts making a U-turn until it finishes traversing the offset distance from U-turn location to subject driveway at the speed of through traffic.

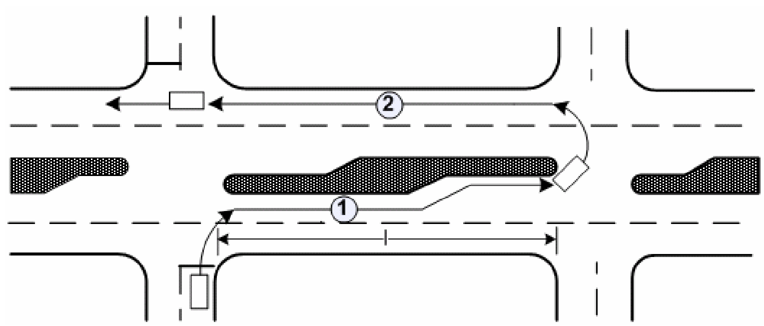


Figure 3-2 Average Running Time for Vehicles Making RTUT

3.2 Weaving Issues Related to RTUT

The Highway Capacity Manual (2000) provides a procedure to estimate the average weaving and non-weaving speed in the freeway weaving areas. A total of three types of freeway weaving areas were identified in the HCM 1996. The type C (b) weaving area illustrated in Figure 3-3 is the one that closely compares to the weaving maneuver of a right-turn followed by a U-turn.

The definition of type C weaving by HCM 2000 is that weaving vehicles in one direction may complete a weaving maneuver without making a lane change, whereas other vehicles in the weaving segment must make two or more lane changes to successfully complete a weaving maneuver. Similar maneuvers happen in the right-turn followed by a U-turn weaving sections. The RTUT maneuver has to make two to three lane changes from entering the roadway to stopping at the median opening or signalized intersection on a divided multilane roadway. Major-road through-traffic does not have to make a lane change unless it has to avoid conflicts with the slow weaving vehicles in the weaving section. The difference is that, in the freeway weaving section, there are always acceleration and deceleration ramp lanes so that the weaving vehicles have appropriate entering speed and exiting speed. In the at-grade weaving section, however, weaving vehicles enter the through traffic stream from a stop, have to accelerate to a certain speed, and then weave into the left-turn deceleration lane. On the urban and suburban arterials, traffic flow is interrupted by the upstream signals. Thus, drivers making a RTUT can execute the right-turn in an acceptable gap between the platoons and then decelerate into the median opening. This has no impact on the major-road traffic platoons. Only the random arrivals or stragglers on the major arterial may be impacted by the weaving maneuver of a RTUT in the weaving segment.

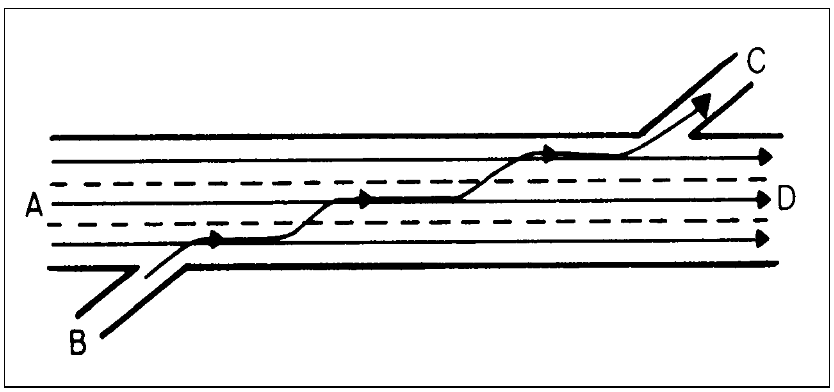


Figure 3-3 The Type C (b) Weaving Area in HCM 1994

It was observed in the field that, the weaving patterns for RTUT are highly dependent on the offset distance between driveway exits and downstream U-turn locations. In general, there are three different types of weaving patterns of a RTUT as illustrated in Figure 3-4:

(1)When the offset distance is short, which is less than the left turn deceleration lane on the major road, many drivers will select a suitable simultaneous gap in all three through lanes and then make a direct entry into the left turn deceleration lane (Type A Weaving);

(2)When the offset distance is medium, which is not long enough for a RTUT maneuver make a comfortable lane change, many drivers will select a suitable simultaneous gap in all three through lanes and then make a direct entry into the most inside lane (Type B Weaving); and

(3)When the offset distance is sufficiently long, drivers will select a suitable gap, turn into the right-side lane, accelerate to appropriate speed, and then make a lane change into the left through lane (Type C Weaving).

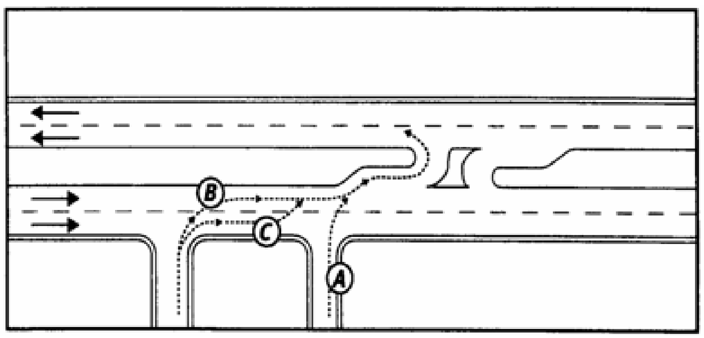


Figure 3-4 Weaving Patterns (Source: NCHRP 4-20)

In the field, it was found that more than 80 percent of drivers making a RTUT would select the weaving type "B" if they knew the location of the downstream U-turn median opening or that U-turn median opening is located within the drivers' sight distance. However, some drivers would make a sudden lane change to reach the left turn deceleration lane when they were not familiar with the area and suddenly find the U-turn median opening. To avoid these undesirable maneuvers, the sign indicated U-turn median openings may be installed at the driveway where left turns were prohibited.

3.3 Phase Two -- Conflict Analysis

3.3.1 Types of Conflicts Studied

In this study, a weaving vehicle is defined as a vehicle turning right from driveway and reaching the exclusive left turn lane of either a signalized intersection or a median opening. The conflicts between main road vehicles and weaving vehicles are considered as weaving conflicts. Three different types of conflicts were considered as weaving conflicts which are described as follows and illustrated in Figures 3-5 through Figure 3-7:

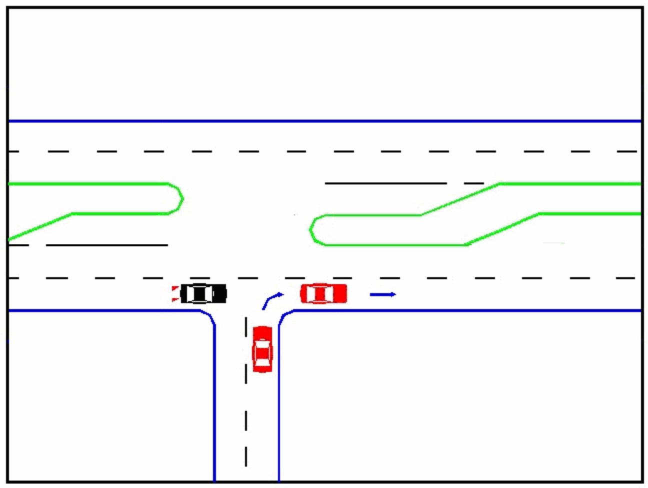


Figure 3-5 Right-Turn Out of the Driveway

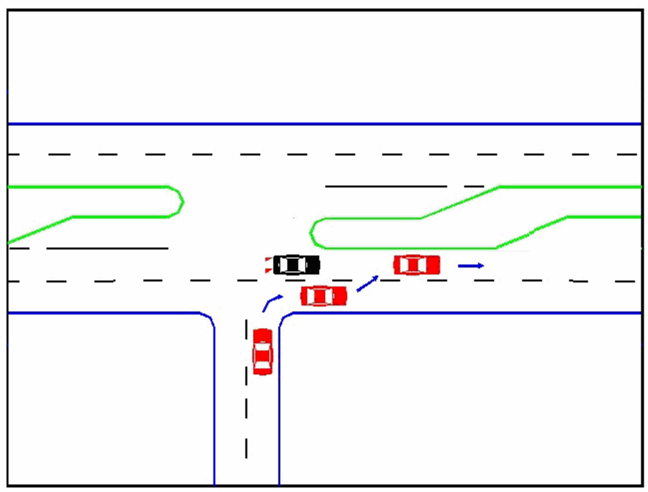


Figure 3-6 Slow-Vehicle, Same-Direction Conflict

Right-Turn Out of the Driveway, occurs when a vehicle waiting at a driveway, turns to the right and gets onto the major road, placing another vehicle (conflicting vehicle) on the major-road with increased potential of a rear-end or sideswipe collision.

Slow-Vehicle, Same-Direction Conflict, occurs when a right turning vehicle is already on the major road and begins to accelerate while on the path of a major road vehicle, thus, the major road vehicle is encountered with increased potential of a rear-end collision.

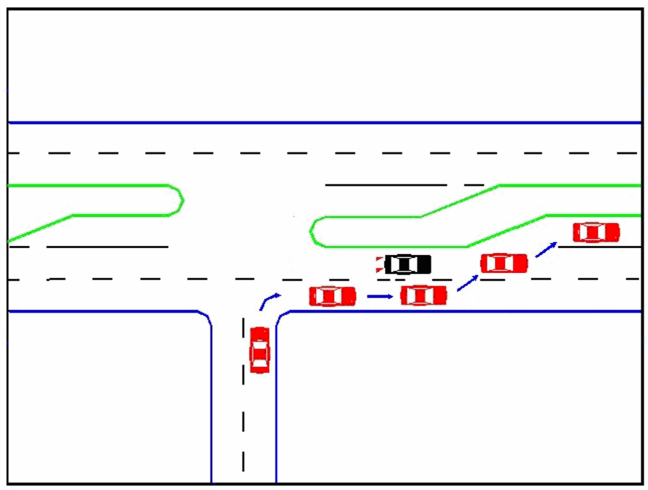


Figure 3-7 Lane Change Conflict

Lane Change Conflict, occurs when a vehicle from a driveway that turned to the right changes from one lane to another (weaving) until it reaches the U-turn bay. This maneuver may place through-traffic vehicles with increased potential of rear-end and sideswipe collisions.

3.3.2 Identification of Conflicts

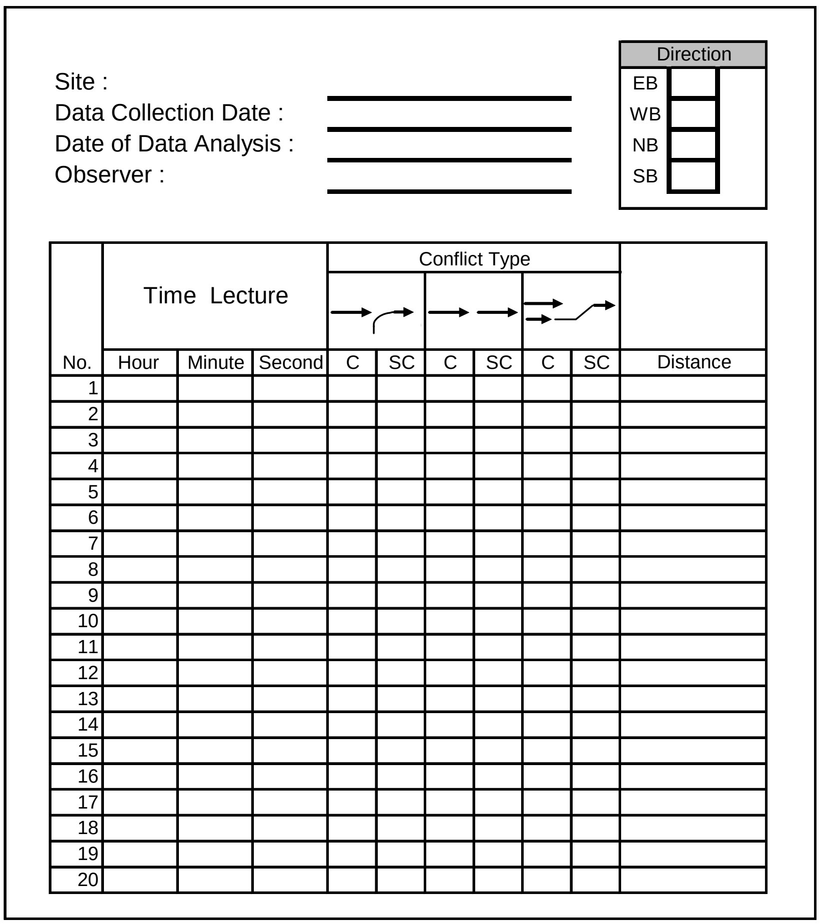
Conflicts, unlike accidents, do not have consequences after they occur. The observer has to identify the conflict during the indication of the conflict being observed. The traffic does not stop and the vehicles continue to flow after the conflict. Conflicts are defined as evasive maneuvers to avoid collision. Indicators of conflicts are applying brakes, swerving and noticeable deceleration of vehicles.

Brake applications are frequently used to identify conflicts. Observers should not only be aware of vehicles' brake lights, but also the speed of the vehicles and conditions to identify a conflict. Hence, there are some situations where drivers may apply brakes for several different reasons other than a conflict situation. Especially, at signalized intersection sites of this study, following the downstream of driveways, signalized traffic intersections are present. The vehicles, which travel on major roadways, apply brakes to slow down as they approach to the signalized intersection. This precautionary brake application may be interpreted as a traffic conflict; although, a conflict did not occur between the vehicles. Another condition is that drivers may apply brakes cautiously even when a conflict is not present in a situation.

Swerving is another indicator of a traffic conflict. Drivers may change the direction of the vehicle or the lane they traveled instead of applying brakes to avoid collision. Swerving does not occur as frequent as brake applications because the drivers might put their selves into another conflict situation by swerving. The driver has to decide an evasive maneuver in an instant of time. Brake application is usually safer than swerving because of the fact that the driver does not have the time to check the side lanes to change the lane in case of a conflict. The observer, in identifying a conflict by swerving, has to be careful not only to check if the vehicle swerves but also if the driver avoids collision by swerving.

Noticeable deceleration is more of a subjective indicator and it is rarely used in the cases of a vehicle's brake lights having a mechanical failure, when the brake lights are obstructed or not able to be seen from the angle of a video camera. Both swerving and noticeable deceleration is more subjective and harder to identify compared to applying brakes. Traditionally, conflict studies are conducted at the field. Trained observers are required to conduct the studies. Conflicts have to be identified and recorded in very short periods of time. In this study, by recording the data to the video tapes, the time pressure could be reduced for the observers, therefore a conflict could be watched more than once and the problems mentioned above about the indicators of conflicts can be reduced in exchange of the time spent on data reduction.

Identifying the conflicts is a time consuming process. A systematic and efficient procedure was developed in previous studies performed by the University of South Florida. For this procedure an algorithm shown in Figure 3-8 was used to identify the conflicts. Once the conflict was identified it had to be recorded, Traffic Conflict Technique: Observer's Guide includes a standard form for conflict studies. The conflicts in this study were slightly different from the conflicts explained in that guide. Some modifications were made to the conflict forms so that they could be used in this study. The conflict form which was used for all types of sites were illustrated in Figure 3-8



Site :
Data Collection Date :
Date of Data Analysis :
Observer :

Direction	
EB	
WB	
NB	
SB	

	Time Lecture			Conflict Type						
No.	Hour	Minute	Second	C	SC	C	SC	C	SC	Distance
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										
16										
17										
18										
19										
20										

Figure 3-8 Conflict Record Form

3.3.3 Sample Sizes

Sample size, as in all engineering studies related to statistics, was required to be calculated prior to data collection. The procedure to calculate the sample size depends on the conflict rates to be analyzed. Engineers use two types of conflict rates for conflict studies: conflicts per unit time and conflicts per vehicle observed. There are two procedures to calculate the sample size based on the conflict rates.

The first procedure is based on the conflict per unit time as presented in Equation 3-1. The outcome for this procedure is the minimum number of hours that the data will be collected in the field. This procedure requires error of the mean and variance from the past studies, which used the same methodology and geometric conditions. Also, level of significance and level of error are required to perform the procedure.

$$n = \left(100 \times \frac{t}{p}\right) \times \frac{\sigma_e^2}{Y^2} \qquad \text{3-1}$$

where,

n = number of hours of observation needed;

t = statistic from the normal distribution related to the selected level of significance;

p = error of the hourly mean;

σ^2 = hourly variance of conflicts estimated from previous studies; and

Y = hourly mean number of conflicts of a specific type.

The second procedure based on the conflict per vehicles observed is shown in Equation 3-2. Sample size, which is calculated by this procedure, is the minimum number of vehicles to be observed. This procedure requires conflicting rate, level of significance and level of error.

$$n = p \times (1 - p) \times \left(\frac{z}{D}\right)^2 \qquad \text{3-2}$$

where,

n = number of vehicles to be counted;

p = expected proportion of vehicles observed that are involved in a conflict;

z = statistic that is based on the level of significance desired;

D = permitted level of absolute error of sample size.

In this study both conflict rates mentioned previously were considered. For the first procedure, mean and variance values were unknown from the past studies because there were no past studies available that used the same methodology and geometric conditions. Although, Parker and Zeeger established the tables that included the mean and variance values for signalized and non-signalized intersections (26), these values may not be used for the movement studied in this project. For the second procedure, conflicting rate is not known but could be conservatively assumed based on the calculation of 384 vehicles. After the data collection, sample size can be verified by Equation 3-2.

$$n = 0.50 \times (1 - 0.50 \times \sqrt{\frac{1.96}{0.50}} = 384 \quad \text{Approach vehicles}$$

3.3.4 Conflict Rates

The purpose of this study was to estimate the minimum and optimum offset distance between driveway and downstream U-turn location. The conflict data by itself would not take the traffic conditions into consideration. Especially, the geometric conditions of the sites have also affects on traffic conflicts. To identify the influence of the geometric conditions on conflicts, these geometric conditions are studied separately. In addition, traffic volumes on subject driveways and main arterials have direct affects on the conflicts occurred. Traffic conflict rates, that will take the influence of traffic volumes on traffic conflicts, were employed.

In previous studies, conflict rates which take traffic volumes into consideration showed some differences for the use of traffic volumes as variable of traffic conflicts. For this study, the conflict rates presented in Equation 3.4 and 3.5 are employed and results were obtained. The results showed that these conflicts rates cannot sufficiently reflect the effects of driveway volumes. The driveways, selected in this study had volume variation of 25 vehicles per hour -100 vehicles per hour while the variation of volumes on main arterials did not vary to a large extent. Another issue was the big difference between the driveway volumes and main road volumes. Because of the big difference in two volumes, both conflict rates presented below could not explain the affect of driveway volume on conflict rate.

$$CR = \frac{Number \cdot of \ \cdot conflicts}{\sqrt{(V_1) \times (V_2)}} \times 1000 \qquad 3\text{-}3$$

$$CR = \frac{Number \cdot of \ \cdot conflicts}{V_1 + V_2} \times 1000 \qquad 3\text{-}4$$

where,

CR = conflict rate;

CR_2 = conflict rate 2;

V_1 = traffic volume on arterial; and

V_2 = volume of weaving vehicles from driveway.

The issues explained below could be solved by defining a conflict rate that can take both driveway volume and arterial volume into consideration directly. This problem is solved by the conflict rate presented in Equation 3-4. Result obtained by using this conflict rates was found to reflect the effect of driveways volumes accurately and also showed that the results were consistent with other studies.

3.4 Phase Three -- Crash Data Analysis

3.4.1 Types of Crashes Studied

Table 3-1 listed all the different crash types maintained in the FDOT mainframe database. Among these crashes, the most common types include rear end crashes, angle crashes, sideswipe crashes and head on crashes. A rear-end crash usually occurs when one vehicle is stopped and another vehicle collides with the first vehicle in the ‘rear end’ of the vehicle. The severity of these crashes can range from minor to severe depending on the speed of the vehicle that hits the first vehicle. Rarely do these crashes end in a fatality.

Angle crashes are also common where one vehicle tries to cross the path perpendicular to the other vehicle. Depending on the speeds of the vehicles involved, the severity of these crashes can range from minor to severe. This type of crash does tend to be more severe than the rear end type of crash. Usually an angle collision will have at least one injury and it is more common for this type of crash to have fatalities. Left turn and right turn crashes are similar to the angle crashes except it is known that one vehicle was making a turn of some sort when they crossed the path of the other vehicle. The severity of these crashes is the same as that of the angle type of crash.

Table 3-1 Crash Types in FDOT Crash Database

Crash Code Number	Crash Type
1	Rear End
2	Head On
3	Angle
4	Left Turn
5	Right Turn
6	Sideswipe
7	Backed Into
8	Parked Car
9	W/Other Motor Vehicle on Road
10	Pedestrian
11	Bike
12	Bike in Bike Lane
13	Moped
14	Train
15	Animal
16	Sign/Sign Post
17	Utility/Light Pole
18	Guardrail
19	Fence
20	Concrete Barrier Wall
21	Bridge Abutment/Pier
22	Tree/Shrub
23	Construction Barricade/Sign
24	Traffic Gate
25	Crash Attenuators
26	Fixed Object Above Road
27	Other Fixed Object
28	Moveable Object on Road
29	Ran Into Ditch/Culvert
30	Ran Off Road Into Water
31	Overturned
32	Occupant Fell From Vehicle
33	Tractor Trailer Jack-knifed
34	Fire
35	Explosion
77	All Other

A sideswipe crash usually occurs when a vehicle collides with another one on its side when it attempts to change lanes. Compared with the other types, this type of crash has a broader range of severity. However, unless a sideswipe happens at an extremely high speed, these crashes do not usually end in fatalities or major injuries.

A head on collision is where two vehicles running in opposite directions collide in front of each other. This type of crash usually happens on undivided roadways with narrow lane width and has the highest potential to end in a fatality.

In practice, when a median opening is closed or replaced with a directional median opening, drivers wishing to make a DLT would first turn right onto the major road, accelerate to the operating speed of through-traffic, weave to the inside lane, and then stop at the median opening or signalized intersection to perform a U-turn maneuver. The accidents that may occur during this procedure include:

(1)*Angle Crash/Right Turn Crash*: occurs when a vehicle wishing to leave the driveway, make a right turn onto the major road. When the offset distance between driveway exit and downstream U-turn location is too short, drivers do not have enough space to accelerate to the operating speed of through-traffic and then perform a weaving maneuver. In this condition, drivers sometimes could accept too small a gap in the major road through-traffic, make a direct entry into the left-turn deceleration lane, placing another vehicle on the major road with increased potential of an angle crash. Sometimes this kind of crash could also be recorded as a right turn crash;

(2)*Sideswipe Crash*: occurs when a vehicle from the outside lane of the major road weaves to the inside lane and stop at the median opening or signalized intersection. If the offset distance is not long enough, vehicles do not have enough space to accelerate to the operating speed of through-traffic, placing through-traffic vehicles with increased potential of sideswipe collisions; and

(3)*Rear-end Crash*: occurs when a right turning vehicle is already on the major road and begins to accelerate. If the offset distance between driveway and downstream

U-turn location is not long enough, vehicles do not have enough space to accelerate to the operating speed of through-traffic, thus, the major road vehicle is encountered with increased potential of a rear-end collision. In this study, the rear-end crashes occurred in the weaving section were incorporated into the database for analysis. The rear-end crashed happened at driveways or signalized intersections were not taken into consideration due to the fact that this kind of accidents usually occur when vehicles decelerate to enter driveways or stop at signalized intersections; and therefore, are not directly related with the length of the weaving section.

Table 3-2 shows the crash types selected for analysis. All other crash types listed in Table 3-1 were not considered when analyzing crash data due to the fact that they may not be directly associated with vehicles making right turns followed by U-turns, and therefore, cannot successfully reflect the impacts of weaving length on the safety performance of vehicles making RTUT.

Table 3-2 Types of Crashes Selected for Analysis

Crash Code Number	**Crash Type**
1	Rear End
3	Angle
5	Right Turn
6	Sideswipe

3.4.2 Crash Rate

In this study, crash rate was calculated at each selected roadway segment. The main reason for using crash rate instead of using crash frequency was reduce the influence of traffic volume on the results. Therefore, using crash rate as the measure of effectiveness could better reflect the impacts of weaving length on safety performance as compared with the method using crash frequency.

Traffic volume, or average daily traffic volume (ADT), is a variable that has previously been suggested as possibly being able to affect crash rates although its exact effect on crash rate is not yet well understood. It is believed that the crash frequency tends to increase as the through way traffic volume (or ADT) goes up. In this study, the corresponding ADT for each site was used according to the date of the crash. In other words, the time period for the volume data matches the time period of the crash data being analyzed.

In this study, the definitions of the crash the crash rate for each site were based upon the Institute of Transportation Engineers' (ITE) *Manual of Transportation Engineering Studies*.9. The crash rate for a selected roadway segment was defined as crashes per million vehicle miles traveled (crash/MVM), as shown in the following equation:

$$Crash \cdot rate = \frac{1{,}000{,}000 \times A}{365 \times T \times V \times L} \qquad \text{3-5}$$

where

A = the number of reported crashes;

T = the time frame of the analysis (years);

V= the average ADT volume of the segment at three years time period; and

L = the length of the selected roadway segment (miles).

3.4.3 Crash Severity

The coding scheme for the extent of injuries in FDOT database includes the following categories:

(1)No Injury;

(2)Possible Injury: The person complained of pain or momentary loss of consciousness due to an injury during the crash, but no visible sign of injury is evident to the investigators;

(3)Non-Incapacitating Injury: The person experienced a visible but not serious or incapacitating injury during the crash;

(4)Incapacitating Injury: The person experienced serious, incapacitating, nonfatal injuries during the crash. Broken bones, massive losses of blood, or more serious injuries are rated in this category;

(5)Fatality: The person died within 90 days of the crash as a direct result of injuries received during the crash; and

(6)Non-Traffic Fatality.

As mentioned before, if the offset distance between driveway exit and downstream U-turn location is too short, for example, less than the left turn deceleration lane on the major road, many drivers will select a suitable simultaneous gap in all three through lanes and then make a direct entry into the inside lane and then stop at the left turn deceleration lane. This maneuver may place another vehicle on the major road with increased potential of an angle crash if the drivers accept too small a gap in the major road through-traffic. Sometimes this kind of crash could also be recorded as a right turn crash. An angle collision will usually have at least one injury, and it is also more common to have fatalities.

4. DATA COLLECTION

The main objective of this research was to evaluate the impacts of the offset distance between a driveway and the downstream median opening or signalized intersection on traffic operational and safety performance. With such results, the optimum offset distance between driveway exits and downstream U-turn locations could be determined so that drivers have better access to make right-turns followed by U-turns. The research team took 3 different research approaches to achieve this objective including: operational analysis, crash data analysis and conflict analysis. Extensive field measurements were conducted in Tampa Bay area in Florida. This chapter presents the detailed efforts of data collection work.

4.1. Average Running Time for Vehicles Making RTUT

The average running for each vehicle making a right turn followed by a U-turn at various offset distances was measured in twenty nine selected street segments in central Florida. The criteria for selecting study sites include:

(1) The selected roadway should be a multilane arterial designed with non-traversable medians;

(2) The selected roadway segment should be located in urban or suburban area;

(3) Speed limit on the arterial should be 40 mph or higher; and

(4) Driveway volumes should be high so that there are a considerable number of RTUT vehicles.

Among these selected study sites, 13 sites were located on 4-lane divided roadways with 2 lanes in each direction, while 16 sites were located on 6 or more-lane divided roadways with at least 3 lanes in each direction. The reason for considering the 4-lane and 6 or more-lane conditions separately lies in the fact that, on a 4-lane roadways, vehicles making RTUT need to make one lane change before they stop at the exclusive left-turn lane; on 6 or more-lane roadways, however, vehicles making RTUT need to make at least two lane changes before they can stop at the exclusive left-turn lane. Therefore, vehicles making RTUT on 6 or more-lane divided roadways may require longer running time as compared with the condition on 4-lane divided roadways. The selected sites were classified into 4 categories based on different U-turn locations and the number of lanes of the selected roadways, as shown in Table 4-1.

Table 4-1 Summary of Selected Sites for Operations Study

	U-turn Locations	
	Unsignalized Median Opening	Signalized Intersection
4-lane Roadways	6	7
6 or more-lane Roadways	8	8

A video camera was set up in the field to record traffic data. The video camera was set up on scaffoldings to achieve adequate viewing height, as shown in Figure 4-1. A least 30 hours traffic data were recorded in each site. Data were not collected during inclement weather or under unusual traffic conditions on the road. The offset distance was measured in the field using a measuring wheel. Over 1300 vehicles making RTUT were observed at 29 selected sites. From videotapes, each vehicle coming from the driveway making a RTUT was tracked. The average running time for each vehicle making a RTUT was recorded since a vehicle left the driveway until it finished traversing the offset distance from U-turn location to subject driveway, as shown in Figure 4-2. The average running time for vehicles making RTUT do not include vehicles waiting delay at driveway or intersection.

Figure 4-1 Video Cameras Set Up On Scaffolding

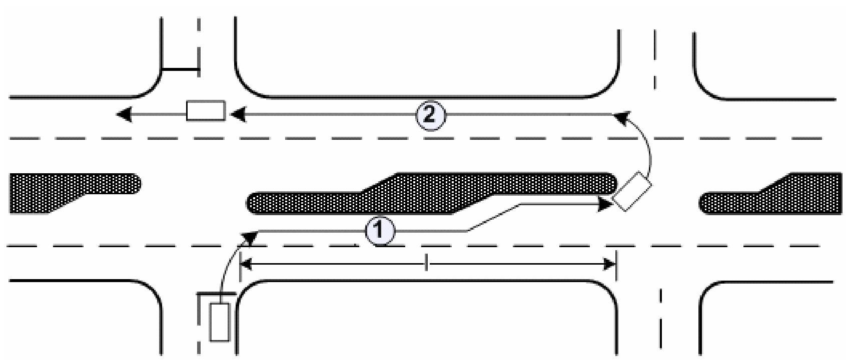


Figure 4-2 Average Running Time for Vehicles Making RTUT

4.2. Conflict Data Collection

4.2.1. Site Selection

City of Tampa, City of Saint Petersburg and City of Plant City were selected for data collection because of these cities being close to the project center where data reduction was conducted and also equipment and materials were stored. Prior to selection of study sites, a preliminary list of sites were created by selection of the sites that would fit the geometric criteria. After preparing the list, traffic volumes on driveways and arterials of the preliminary sites were measured. Especially, vehicles making the studied movement were counted by observers so the required sample size could be reached and the study could be completed in an efficient way. In this study, four different geometric conditions were taken into consideration. These geometric conditions resulted in four different types of sites for data collection. These sites were named and described as following:

(1)*6 or more-lane signalized intersection sites*: Driveways are on a arterial with at least 3 lanes in each direction, after the right turn from driveway driver reaches the exclusive left lane of the signalized intersection;

(2)*6 or more-lane median opening sites*: Driveways are on a arterial with at least three lanes in each direction, after the right turn from driveway driver reaches the exclusive left lane of median opening;

(3)*4-lane signalized intersection sites*: Driveways are on a 4-lane arterial, after the right turn from driveway driver reaches the exclusive left lane of the signalized intersection; and

(4)*4-lane median opening sites*: Driveways are on a 4-lane arterial, after the right turn from driveway driver reaches the exclusive left lane of median opening.

The criteria for selecting research sites for conflict analysis were listed as following:

(1)The arterial or major road must have two lanes in each direction at 4-lane sites and at least three lanes at 6 or more-lane sites;

(2)Traffic volume on the driveway should be relatively high so that the adequate turning vehicles could be studied;

(3)The minimum distance between the driveway and upstream signal should be at least 200 ft, which is the median value of the distance traveled during driver perception-reaction time and the impact distance due to a right turning vehicle;

(4)The downstream signal should be located at an appropriate distance away from the driveway in order to avoid the effects of possible spillbacks; and

(5)Posted speed on the major road is equal to or greater than 40 MPH.

During the selection of sites geometric components of the sites have been taken into consideration. These geometric components were median openings, upstream and downstream signalized intersections, and offset distance. Figure 4-3 illustrates the location of traffic signals and direction of traffic streams at signalized intersection sites. Also, Figure 4-4 illustrates the location of traffic signals and direction of traffic streams at median opening sites.

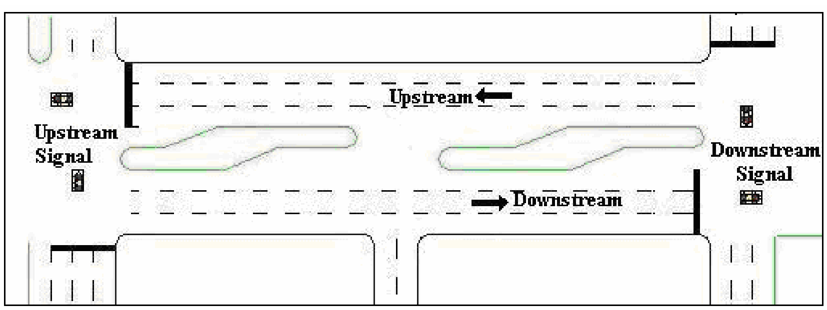


Figure 4-3 4-lane and 6 or more-lane Signalized Intersection Sites Components

Study locations were selected according to the criteria mentioned previously. All of the driveways are from either commercial centers or high density residential areas. The study locations are explained in the following subtitles as they were divided by geometric criteria.

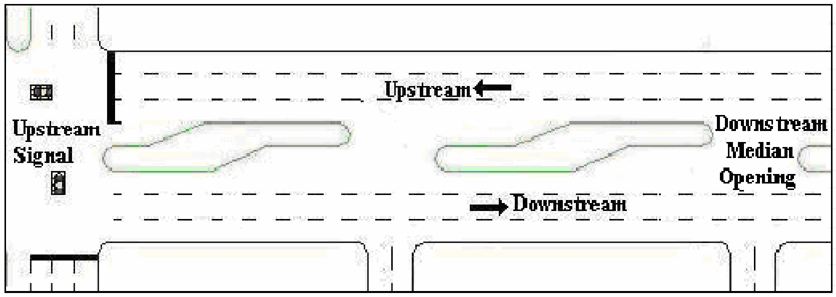


Figure 4-4   4-lane and 6 or more-lane Median Opening Sites Components

(1)*4-lane Median Opening Sites*: Seventeen sites were selected for this geometric condition. Twelve sites are in the city of Tampa, four sites are in the city of Brandon, and one site is in the city Plant City. The offset distances at selected sited varied from 275 feet to 1150 feet. Table 4-2 presents the location and the geometric properties of 4-lane median opening sites;

(2)*4-lane Signalized Intersection Sites*: Thirteen sites were selected in Tampa Bay Area for this geometric condition. Nine of the selected sites were in the City of Tampa, while three sites were in the City of Plant City and one site is in the City of Brandon. The offset distance variation was from 285 feet to 985 feet for the selected sites. Table 4-3 presents the location and the geometric properties of 4-lane signalized intersection sites;

(3)*6 or more-lane Median Opening Sites*: Nineteen sites were selected in Tampa Bay Area for this geometric condition. Nine of the selected sites were in the City of Tampa, while three sites were in the City of Plant City and one site is in the City of Brandon. The offset distance variation was from 190 feet to 970 feet for the selected sites. Table 4-4 presents the location and the geometric properties of 6-lane median opening sites; and

(4) *6 or more-lane Signalized Intersection Sites*: Nineteen sites were selected in Tampa Bay Area for this geometric condition. Fifteen of the selected sites were in the City of Tampa, while the rest of the sites were in the City of St. Petersburg. The offset distance variation was from 260 feet to 1430 feet for the selected sites for this geometric condition. Table 4-5 presents the location and the geometric properties of 6-lane signalized intersection sites.

Table 4-2 Location and Offset Distance for 4-lane Median Opening Sites

4-Lane Median Opening Sites			
No	**Arterial**	**City**	**OD(ft.)**
1	Bears Ave.	Tampa	350
2	Fletcher Ave. Ave.	Tampa	675
3	Fletcher Ave. Ave.	Tampa	450
4	J L Redman Pkwy.	Plant City	410
5	Bruce B. Downs Blvd.	Tampa	835
6	US 301	Brandon	730
7	US 301	Brandon	710
8	US 301	Brandon	655
9	US 301	Brandon	610
10	Bears Ave	Tampa	1150
11	Bears Ave	Tampa	650
12	Gunn Hwy.	Tampa	605
13	Gunn Hwy.	Tampa	605
14	Gunn Hwy.	Tampa	570
15	Gunn Hwy.	Tampa	275
16	Gunn Hwy.	Tampa	880
17	Gunn Hwy.	Tampa	200

Table 4-3 Location and Offset Distance for 4-lane Signalized Intersection Sites

Four-lane Signalized Intersection Sites			
No	**Arterial**	**City**	**OD(ft.)**
1	Bruce B. Downs Blvd	Tampa	900
2	Bruce B. Downs Blvd	Tampa	910
3	Bears Ave.	Tampa	510
4	Fletcher Ave.	Tampa	985
5	Fletcher Ave.	Tampa	385
6	J L Redman Pkwy.	Plant City	750
7	J L Redman Pkwy.	Plant City	285
8	J L Redman Pkwy.	Plant City	270
9	Bruce B. Downs Blvd.	Tampa	675
10	US 301	Brandon	860
11	Gunn Hwy.	Tampa	810
12	56th Street	Tampa	355
13	56th Street	Tampa	280

4.2.2. Field Procedure

Data were collected under normal traffic conditions (good weather, daylight and dry pavement). During the time of congested traffic conditions, either data collection was stopped, or the collected data were not used for the analysis. Conflict studies consider a day of data collection, as eleven hours from 7:00 AM to 6:00 PM. Sites studied in this project were the driveways from shopping plazas and activity centers, which had few traffic movements' egress of the driveways during early hours. Traffic volumes from driveways would reach the desired values around noon peak hours. Data collection started usually prior to noontime and continued until the end of the data collection day. Another reason to start the data collection at those times was that the set up of the data collection equipment took two to three hours of time.

Table 4-4 Location and Offset Distance for 6 or more-lane Median Opening Sites

6 or more-lane Median Opening Sites			
No	**Arterial**	**City**	**OD (ft.)**
1	Fowler Ave.	Tampa	575
2	Fowler Ave.	Tampa	240
3	Fowler Ave.	Tampa	840
4	Fowler Ave.	Tampa	590
5	Fowler Ave.	Tampa	266
6	Fowler Ave.	Tampa	480
7	Fowler Ave.	Tampa	720
8	Fowler Ave.	Tampa	620
9	Hillsborough Ave.	Tampa	330
10	Bruce B. Downs Blvd.	Tampa	190
11	Bruce B. Downs Blvd.	Tampa	675
12	56^{th} S.	St. Petersburg	290
13	56^{th} S.	St. Petersburg	490
14	56^{th} S.	St. Petersburg	350
15	US 19	Clearwater	570
16	Bruce B. Downs Blvd.	Tampa	970
17	Hillsborough Ave.	Tampa	300
18	US 19	Tarpon Springs	550
19	US 19	Tarpon Springs	600

A typical data collection day starts with the set up of equipment. At a typical site, the scaffolding was used. Before setting up any necessary electronic equipment, scaffolding was assembled and placed at suitable location. The reason for starting with the scaffolding is that the procedure requires all the manpower available before assigning any of the staff to any camera locations. After the setup of scaffolding, all the equipment was set up and made ready for the start of the data collection day. Placement of the video cameras requires experienced personnel because if the data needed were not collected (correct image), it would be a waste of resources and reliability so the data collected would dramatically be reduced. Another issue is synchronization of the video camera times, which is implemented before the placement of the cameras. After synchronization and placement of the video cameras, data collection started with all the cameras at the same time. Assigned staff stayed with the video cameras and all the equipment was to be checked frequently so that recording was continued to avoid any loss of data.

Table 4-5 Location and Offset Distance for 6 or more-lane Signalized Intersection Sites

6 or more-lane Signalized Intersection Sites			
No	**Arterial**	**City**	**OD (ft.)**
1	Fowler Ave.	Tampa	530
2	Fowler Ave.	Tampa	880
3	Fowler Ave.	Tampa	1180
4	Fowler Ave.	Tampa	1430
5	Fowler Ave.	Tampa	695
6	Fowler Ave.	Tampa	915
7	Fowler Ave.	Tampa	1080
8	Fowler Ave. & 22nd St.	Tampa	1380
9	Hillsborough Ave.	Tampa	505
10	Hillsborough Ave.	Tampa	330
11	Dale Mabry Hwy.	Tampa	550
12	Bruce B. Downs Blvd.	Tampa	405
13	Bruce B. Downs Blvd.	Tampa	905
14	Bruce B. Downs Blvd.	Tampa	1050
15	56th S.	St. Petersburg	590
16	56th S.	St. Petersburg	340
17	56th S.	St. Petersburg	260
18	56th S.	St. Petersburg	425
19	Dale Mabry Hwy.	Tampa	560

Traffic volumes were also needed for analysis purposes. During the data collection periods, Hi-Star devices, an automatic volume and speed recorder, were installed on the pavement to collect the speed and volumes of the vehicles on major roadways. Other minor volume requirements were obtained from videos by manual counts.

4.2.3. Data Reduction Procedure

Data reduction had to be done in a systematic way to increase the time efficiency. The data collected for conflict data analysis were initially checked for accuracy and quality purposes at the end of every data collection day. The tapes that covered the entire study locations were watched and all the vehicles egress of the driveways was observed. All of the times are required to be in second's accuracy for the reason that those times were used for different purposes with different tapes. After the initial reduction of data, these movements were carefully observed for indicators of conflicts. In case a conflict related to the studied movement was observed, its time of the occurrence was recorded. When all of the vehicles were studied for conflicts and recorded, conflict data was checked for accuracy and errors.

Usually, conflict studies are considered eleven hours in one day, starting at 7:00 AM and ending at 6:00 PM. Traffic Conflict Technique for safety and Operation's - Engineer's Guide recommends adjusting the data for the periods which data were not collected. Equation 4-1 is used to calculate the number of conflicts for the non-observed periods.

$$ANOC = \frac{C_1 + C_2}{2} \times \frac{TTNOP}{RP} \qquad \text{4-1}$$

where,

ANOC = adjusted non-observed period conflicts;

C_1 = number of conflicts occurred before the non-observed period;

C_2 = number of conflicts occurred after the non-observed period;

TTNOP = total time of non-observed period;

RP= duration of recording period.

After calculating adjusted non-observed period conflicts, the daily numbers of conflicts were obtained by adding all observed and non-observed conflicts.

Figure 4-5   Equipment Used for Data Collection

4.3. Crash Data Collection

4.3.1. Site Selection

In this study, crash history at 192 roadway segments was investigated. The roadway segment was defined as an urban or suburban arterial segment that was designed with non-traversable medians. The roadway segments begin at a driveway/side street and continue downstream toward a median opening or signalized intersection which accommodating U-turns, as shown Figure 4-6. The driveway/side streets selected are those active access points that have high ingress and egress volumes. To avoid interference between driveways, conditions of one U-turn bay shared by several active driveways along the arterial were not studied.

The major purpose of site selection is to find compatible site with high RTUT volume. The following criteria were applied when selecting sites:

(1)The selected roadway should be a multilane arterial designed with non-traversable medians;

(2)The selected roadway segment should be located in urban or suburban area;

(3)Speed limit on the arterial should be 40 mph or higher, because FDOT mandates that all new or reconstructed multi-lane arterials with design speeds over 40 mph be designed with restrictive medians; and

(4)The driveway volumes should be high and direct left-turn access at subject driveway was not permitted so that there were a considerable number of RTUT vehicles.

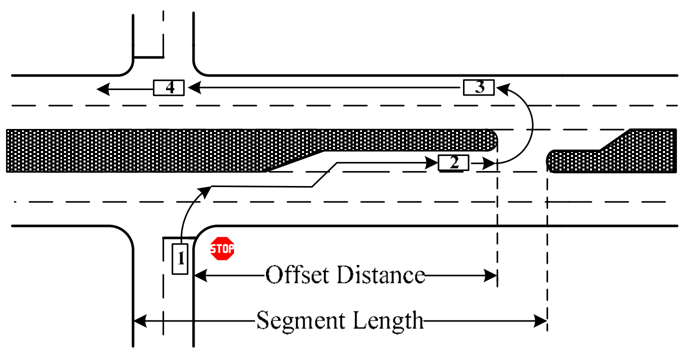


Figure 4-6 Definition of a Roadway Segment for Study

A total of 192 sites were randomly selected in the Tampa Bay area in Florida. The selected sites were located on urban or suburban multilane state highways. All of these sites were considered to have similar operational or design characteristics. The selected sites can be divided into four groups based on the number of through traffic lanes and U-turn locations including: research sites located on 4-lane arterials accommodating U-turns at median openings; research sites located on 4-lane arterials accommodating U-turns at signalized intersections; research sites located on 6 or more-lane arterials accommodating U-turns at median openings; and research sites located on 6 or more-lane arterials accommodating U-turns at signalized intersections. Table 4-6 presents a summary of the selected sample sites. Most of the traffic and geometric information such as posted speed; signal installation and length of weaving section were determined from field observations. The other necessary site information was obtained from various documents, video logs, straight-line diagrams and aerial photographs provided by FDOT and/or county governments. The aerial photographs of two sample sites were shown in Figures 4-7 and 4-8.

Table 4-6   Summary of Selected Sites for Crash Data Analysis

	U-turn Locations	
	Unsignalized Median Opening	Signalized Intersection
4-lane Roadways	39	27
6 or more-lane Roadways	80	46

4.3.2. Setup of Crash Database

This section provides the general information about the creation of the crash database for analysis. The crash data used in this study were collected from the accident and roadway files of Florida Department of Transportation's crash database. FDOT maintains a very large crash database generated by merging crash data from the Department of Highway Safety and Motor Vehicles (DHSMV) with roadway information from FDOT. This database is updated yearly. All reported crashes with a fatality, an injury, and high property damage occurred on state roads are included in this database. The state roads and the accident locations in FDOT crash database are recorded by using FDOT section number and milepost. Every state road in Florida has been given an eight-digit code by

FDOT. This code is called “section” number, which uniquely defines that roadway. Milepost is used to describe those interacting points on the roadway, such as intersections, crossing interstates, driveways, key commercial developments, etc.

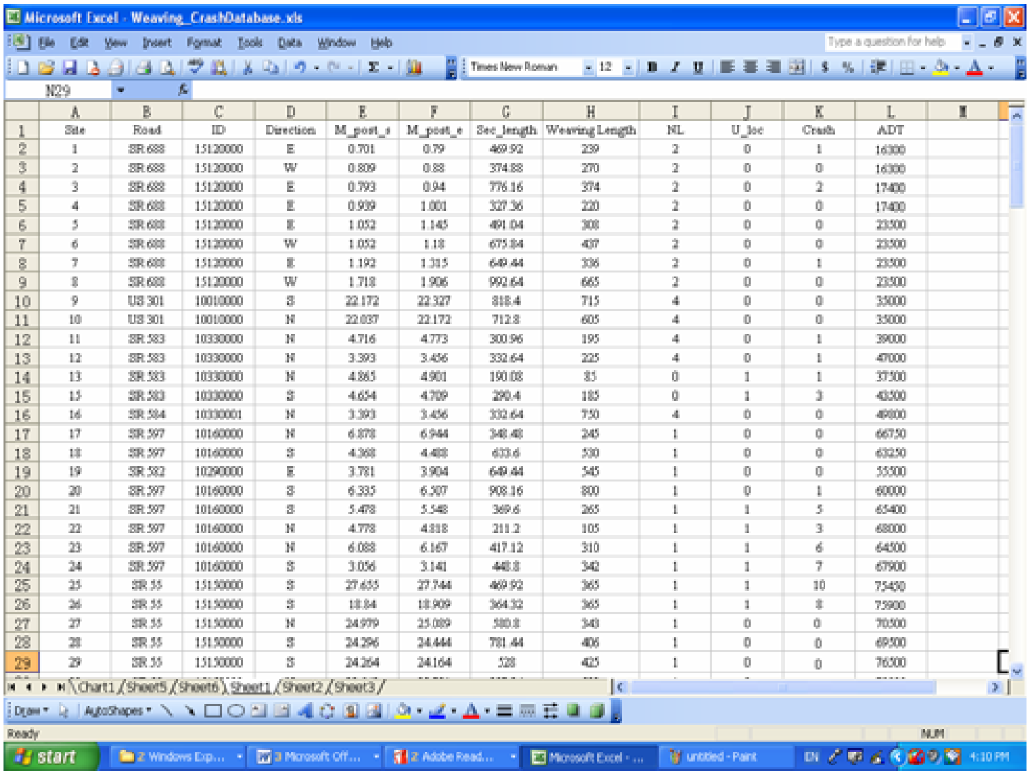
Figure 4-7 Aerial Photograph of a Sample Site Which Accommodates U-turns at a Median Opening

In this study, a SAS (Statistical Analysis System) program was written to extract crash data from the FDOT crash database. It is commonly believed that three years would usually provide a sufficient number of accidents for analysis while reducing the possibility of extraneous factors influencing the accident data. In this study, therefore, crash data of three consecutive years, from 2001 through 2003, were used for the analysis process. The Transportation Improvement Program provided by the Metropolitan Planning Organization of each county was reviewed. The purpose of this step was to confirm that no significant construction had taken place on the selected sites during those years that crashes were counted and analyzed in this project. The Straight-Line Diagram was obtained from FDOT district seven. The information obtained from the Straight-Line

Diagram includes the section and subsection number of the major road where the selected site locates on, the milepost of the subject driveway and the milepost of the downstream median opening or signalized intersection where U-turns are accommodated.

Figure 4-8 Aerial Photograph of a Sample Site Which Accommodates U-turns at a Signalized Intersection

A crash database was created to perform the crash data analysis. The information contained in the crash database include: number of crashes happened in the selected roadway segments during three-year time period, the length of weaving section for each site, the Annual Daily Traffic Volume (ADT) for each site, the number of lanes for each selected roadway segment, and the location of U-turns (median opening or signalized intersection) at each site. Figure 4-9 shows the sample database for crash data analysis.



Site	Road	ID	Direction	M_post_s	M_post_e	Sec_length	Weaving Length	NL	U_loc	Crash	ADT
1	SR 688	15120000	E	0.701	0.79	469.92	239	2	0	1	16300
2	SR 688	15120000	W	0.809	0.88	374.88	270	2	0	0	16300
3	SR 688	15120000	E	0.793	0.94	776.16	374	2	0	2	17400
4	SR 688	15120000	E	0.939	1.001	327.36	220	2	0	0	17400
5	SR 688	15120000	E	1.052	1.145	491.04	308	2	0	0	23500
6	SR 688	15120000	W	1.052	1.18	675.84	437	2	0	0	23500
7	SR 688	15120000	E	1.192	1.315	649.44	336	2	0	1	23500
8	SR 688	15120000	W	1.718	1.906	992.64	665	2	0	0	23500
9	US 301	10010000	S	22.172	22.327	818.4	715	4	0	0	35000
10	US 301	10010000	N	22.037	22.172	712.8	605	4	0	0	35000
11	SR 583	10330000	N	4.716	4.773	300.96	195	4	0	1	39000
12	SR 583	10330000	N	3.393	3.456	332.64	225	4	0	1	47000
13	SR 583	10330000	N	4.865	4.901	190.08	85	0	1	1	37500
15	SR 583	10330000	S	4.654	4.709	290.4	185	0	1	3	43500
16	SR 584	10330001	N	3.393	3.456	332.64	750	4	0	0	49800
17	SR 597	10160000	N	6.878	6.944	348.48	245	1	0	0	66750
18	SR 597	10160000	S	4.368	4.488	633.6	530	1	0	0	63250
19	SR 582	10290000	E	3.781	3.904	649.44	545	1	0	0	55500
20	SR 597	10160000	S	6.335	6.507	908.16	800	1	0	1	60000
21	SR 597	10160000	S	5.478	5.548	369.6	265	1	1	5	65400
22	SR 597	10160000	N	4.778	4.818	211.2	105	1	1	3	68000
23	SR 597	10160000	N	6.088	6.167	417.12	310	1	1	6	64500
24	SR 597	10160000	S	3.056	3.141	448.8	342	1	1	7	67900
25	SR 55	15150000	S	27.655	27.744	469.92	365	1	1	10	75450
26	SR 55	15150000	S	18.84	18.909	364.32	365	1	1	8	75900
27	SR 55	15150000	N	24.979	25.089	580.8	343	1	0	0	70500
28	SR 55	15150000	S	24.296	24.444	781.44	406	1	0	0	69500
29	SR 55	15150000	S	24.264	24.164	528	425	1	0	0	76500

Figure 4-9 Sample Database for Crash Data Analysis

5. DATA ANALYSIS

5.1. Average Running Time for Vehicles Making RTUT

The average running time for vehicles making RTUT was highly dependent on the offset distance between driveway exits and downstream median openings or signalized intersections. If the offset distance is too long, additional travel distance and travel time for diverted left turn drivers will increase.

In this study, a linear regression model was developed to determine the relationship between the average running time for vehicles making RTUT and possible explanatory variables. Data collected from 29 sites were used to build this model. The selected sites were found to have significant number of vehicles making RTUT. The dependent variable was the average running time for each vehicle making a RTUT at a selected site.

The stepwise regression method was applied to determine explanatory variables that should be included into the regression model. A pre-selected F_{OUT} critical value of 0.1 was selected as the criteria for selecting explanatory variables. The selected explanatory variables include the number of lanes of major road, U-turn locations (signalized intersection or median opening), speed limit of major road, and the offset distance between driveway exits and downstream U-turn locations. Descriptive statistics for selected explanatory variables and regression results were given in Table 5-1. The regression model has fairly high R^2 value (0.912) and adjusted R^2 value (0.901). T-statistics indicated that the selected explanatory variables were statistically significant at a 95% level of confidence. The regression residuals were plotted against the fitted value. It was found that the residuals were randomly distributed around the *y=0* axle, indicating the fact that the model was correctly specified and the homogeneous assumption about the error term was not violated. According to these parameter estimates, the final developed regression equation was shown as follows:

$$T = 22.0 + 0.032l - 3.701NL + 2.838U\_loc - 0.296V \qquad 5\text{-}1$$

where,

T = average running time for each vehicle making a RTUT (sec./veh);

l = offset distance between driveway exits and downstream U-turn locations (ft);

NL = dummy variable (NL=1 when the study site located on 4-lane roadways with 2 lanes in each direction; NL = 0 when the selected site located on 6 or more-lane roadways with at least 3 traffic lanes in each direction);

U_loc = dummy variable (U_loc=1 when U-turns are located at signalized intersection; U_loc=0 when U-turns are located at median opening); and

V = speed limit on the major road (mph).

Table 5-1 **Average Running Time for Vehicles Making RTUT**

	N	**Min**	**Max**	**Mean**	**Std. Deviation**	**t**	**Sig.**
Intercept	N/A	N/A	N/A	N/A	N/A	3.17	0.0042
l	29	285	1150	608.97	216.66	16.33	0.0000
V	29	40	55	46.55	3.56	-2.22	0.0363
NL	29	0	1	0.41	0.50	-4.30	0.0002
U_loc	29	0	1	0.55	0.51	3.15	0.0043
$\mathbf{R^2}$ = 0.927, $\mathbf{R^2_{adj}}$ = 0.914							

From Equation 5-1, it is clear that the average running time for vehicles making RTUT increases with the offset distance between driveway exits and downstream U-turn locations and decreases with the increases of the speed limit of major road. Vehicles making RTUT on 6 or more-lane roadways require around 4 seconds of extra travel time as compared with those on 4-lane roadways. Vehicles making RTUT at downstream signalized intersection require around 3 seconds of extra travel time than those making U-turns at median openings. The estimated coefficients are reasonable due to the fact that drivers usually slow down the approaching speed to signalized intersection when the signal turns red, and it is easier for vehicles to weave to the inside lane on 4-lane roadways than on 6 or more-lane roadways.

The regression model (Equation 5-1) could be used to estimate the average running time for vehicles making RTUT at various offset distances between driveways and downstream U-turn locations. For example, based on the model, vehicles making RTUT at downstream median opening on a 6 or more-lane roadway require 47 seconds running time when the offset distance between driveway and downstream median opening is 1200 ft and the speed limit of major road is 45 mph.

5.2. Crash Data Analysis

5.2.1. Summary

In this study, crash history at 192 roadway segments was investigated. It was found that crashes at multilane divided roadway weaving segments occurred relatively infrequently, as compared with the crash history at driveways or intersections. Out of the 192 sites investigated, 52 sites do not have any crashes during 3 years time period. The crashes identified at the selected roadway sections vary from 0 to 18 with an average of 2.9 crashes within 3 years. A total of 557 crashes were identified at the selected roadway segments during three years time period. Out of these crashes, about 49% crashes are rear end crashes; about 29% crashes are angle crashes (including right turn crashes); and about 22% crashes are side swipe crashes. The distribution of the crashes identified in selected weaving segments is shown in Table 5-2 and Figure 5-1.

For each selected roadway segment, a crash rate was calculated. The definition of crash rate was explained in Chapter 3. Regression model was used to identify which of the factors had a significant impact on the crash rate. The stepwise regression method was applied. A pre-selected F_{OUT} critical value of 0.1 was selected as the criteria for selecting explanatory variables. It was found that the offset distance, the number of lanes of major road, and the U-turn locations (signalized intersection or median opening) significantly impact the crash rate at selected roadway segments. The major-road through traffic volume and the major-road speed limit were not found to be significant at a 90% level of confidence; and therefore, were not included into the regression model.

The offset distance of selected roadway segments varies from 73 ft to 1150 ft with an average of 418 ft. The crash rate for each selected sites varies from 0 to 2.27 with an average of 0.36 crashes per million involved vehicles per mile. The regression results are presented in Table 5-3. T-statistics indicated that the selected explanatory variables were statistically significant at a 95% level of confidence. The regression equation was shown as follows:

$$CR = 0.472 - 0.001l + 0.094NL + 0{,}114U\_loc \qquad 5\text{-}2$$

Where,

CR = crash rate at selected roadway segment (crashes/MVM);

l = offset distance between driveway exits and downstream U-turn locations (ft);

NL = dummy variable (NL=1 when the site located on 4-lane roadways with 2 lanes in each direction; NL =0 when the site located on 6-lane roadways with 3 lanes in each direction); and

U_loc = dummy variable (U_loc=1 when U-turns are located at signalized intersection; U_loc=0 when U-turns are located at median opening).

Table 5-2 Distribution of Crash Types

Crash Type	Frequency	Percent (%)
Rear End	274	49.19
Angle	149	26.75
Right Turn	13	2.33
Side Swipe	121	21.72
Total	**557**	**100.00**

From the regression analysis, it is clear that, the offset distance significantly affects the crash rate at selected roadway segments, and the crash rate decreases with the increases of the offset distance. The coefficient for the variable of NL is positive indicating the fact that the crash rate on 6-lane divided roadways is higher than the crash rate on 4-lane divided roadways. This result follows from the fact that vehicles making RTUT on 6 or more-lane divided roadways need to traverse at least 3 lanes before they stop at the U-turn bay. On 4-lane divided roadways, vehicles making RTUT only need to weave 2 lanes, therefore, may have less chance to be involved in an accident. The coefficient of U_loc is positive implying the fact that if U-turns are accommodated at signalized intersection, vehicles making RTUT may have greater chance to be involved in an accident in the weaving section as compared with the condition where U-turns are accommodated at a median opening.

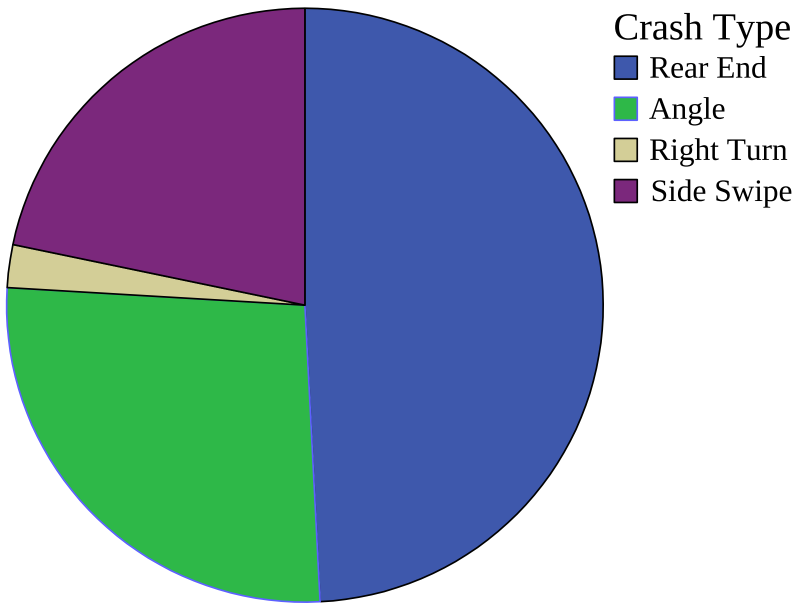


Figure 5-1 Distribution of Crash Types

Table 5-3 Regression Results for Crash Rate Model

	Coefficient	t	Sig.
Intercept	0.472	7.452	<0.001
l	-0.001	-4.897	<0.001
NL	0.094	2.159	0.325
U_loc	0.113	2.579	0.109
$\mathbf{R}^2 = 0.231$, $\mathbf{R}^2_{adj} = 0.215$			

5.2.2. Analysis of Crash Rate Under Different Conditions

In this study, the selected research sites were divided into scenarios based on the number of through traffic lanes and U-turn locations, including: research sites located on 4-lane arterials where U-turns are accommodated at median openings; research sites located on 4-lane arterials where U-turns are accommodated at signalized intersections; research sites located on 6 or more-lane arterials where U-turns are accommodated at median openings; and research sites located on 6 or more-lane arterials where U-turns are accommodated at signalized intersections. In each scenario, the crash rate was analyzed separately; and regression models were built to quantitatively evaluate the relationship between crash rate and weaving length.

U-turns at Median Opening on 4-lane Divided Roadways

Crash history at 39 roadway segments was investigated. Crash rate at each site was calculated. Regression model was built to quantitatively evaluate the relationship between the crash rate and offset distance. The dependent variable is the crash rate at each roadway segment. The independent variable is the offset distance between driveway and downstream median opening. The collected crash rate varies from 0 to 1.56 with an average of 0.28 crashes per million involved vehicles per mile. The offset distance measured in the field varies from 73 ft to 750 ft with an average of 361 ft.

Several regression models were tried, it was found that the linear regression model with a logarithmic form has the best goodness of fit to field data. The R^2 value of the model is 0.15. The independent variables (including the intercept) were found to be statistically significant at a 95% level of confidence. The regression results were shown in Table 5-4. The collected crash rates were plotted against the offset distances, as shown in Figure 5-2. The regression model was shown as follows:

$$CR = -0.27\ln(l) + 1.84 \qquad \text{5-3}$$

where,

CR = crash rate at selected roadway segments (crashes/MVM); and

l = the offset distance between driveway and downstream U-turn location (ft).

Table 5-4 Regression Results for Crash Rate Model

(4-lane Median Opening)

	Coefficient	**t**	**Sig.**
Intercept	1.841	2.977	0.005
l	-0.27	-2.534	0.016
$\mathbf{R^2}$ = 0.15, $\mathbf{R^2_{adj}}$ = 0.13			

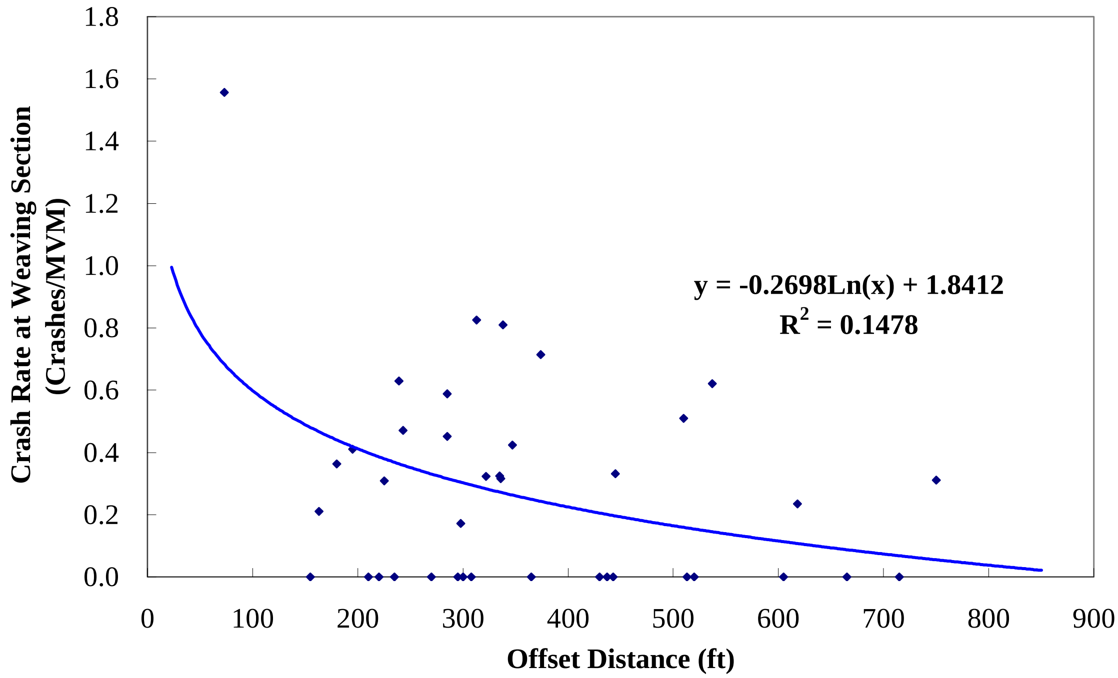


Figure 5-2   Crash Rate at Selected Roadway Segments vs. Offset Distance (4-lane Median Opening)

U-turns at Signalized Intersection on 4-lane Divided Roadways

Crash history at 27 roadway segments was investigated. Crash rate at each site was calculated. Regression model was built to quantitatively evaluate the relationship between the crash rate and offset distance. The dependent variable is the crash rate at each roadway segment. The independent variable is the offset distance between driveway and downstream signalized intersection. The collected crash rate varies from 0 to 1.10 with an average of 0.41 crashes per million involved vehicles per mile. The offset distance measured in the field varies from 85 ft to 650 ft with an average of 335 ft.

Several regression models were tried, it was found that the linear regression model with a logarithmic form has the best goodness of fit to field data. The R^2 value of the model is 0.21. The independent variables (including the intercept) were found to be statistically significant at a 95% level of confidence. The regression results were shown in Table 5-5.The collected crash rates were plotted against the offset distances measured in the field, as shown in Figure 5-3. The regression model was shown as follows:

$$CR = -0.27\ln(l) + 1.96 \quad \text{5-4}$$

where,

CR = crash rate at selected roadway segments (crashes/MVM); and

l = the offset distance between driveway and downstream U-turn location (ft).

Table 5-5 Regression Results for Crash Rate Model
(4-lane Signalized Intersection)

	Coefficient	t	Sig.
Intercept	1.956	3.215	0.004
l	-0.271	-2.550	0.017
R^2 = 0.21, R^2_{adj} = 0.18			

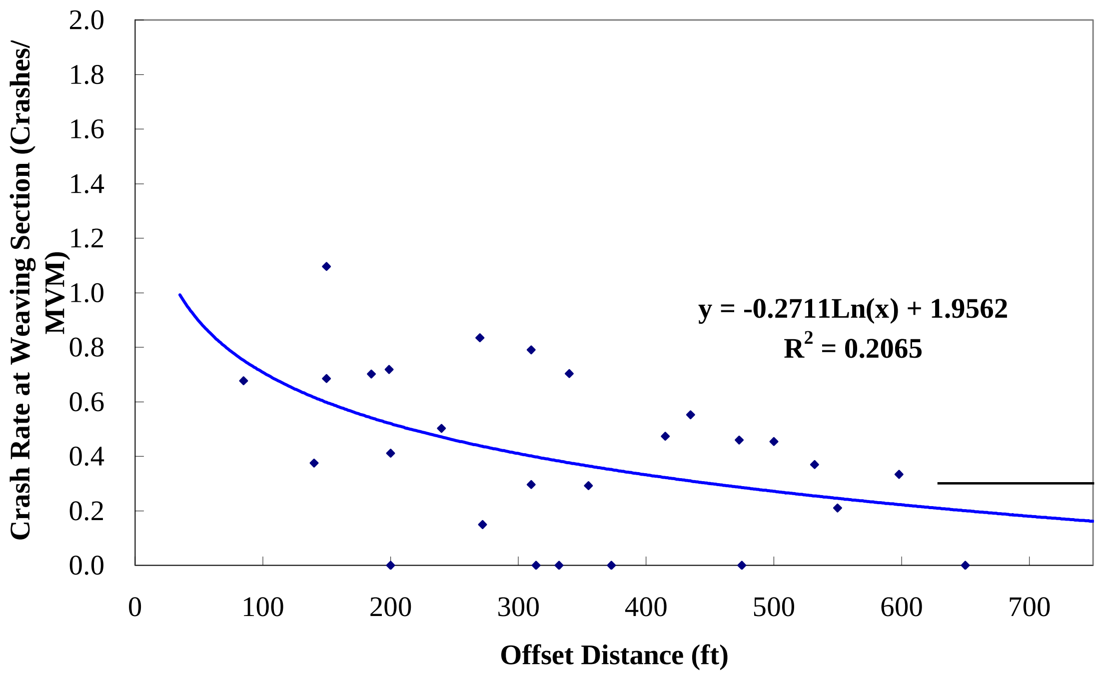


Figure 5-3 Crash Rate at Selected Roadway Segment vs. Offset Distance
(4-lane Signalized Intersection)

U-turns at Median Opening on 6 or more-lane Divided Roadway

Crash history at 80 roadway segments was investigated. Crash rate at each site was calculated. Regression model was built to quantitatively evaluate the relationship between the crash rate and offset distance. The dependent variable is the crash rate at each roadway segment. The independent variable is the length of offset distance between driveway and downstream median opening. The collected crash rate varies from 0 to 2.27 with an average of 0.30 crashes per million involved vehicles per mile. The offset distance measured in the field varies from 97 ft to 930 ft with an average of 473 ft.

Several regression models were tried, it was found that the linear regression model with a logarithmic form has the best goodness of fit to field data. The R^2 value of the model is 0.22. The independent variables (including the intercept) were found to be statistically significant at a 95% level of confidence. The regression results were shown in Table 5-6. The collected crash rates were plotted against the offset distances, as shown in Figure 5-4. The regression model was shown as follows:

$$CR = -0.385\ln(l) + 2.64 \qquad \text{5-5}$$

where,

CR = crash rate at selected roadway segments (crashes/MVM); and

l = the offset distance between driveway and downstream U-turn location (ft).

Table 5-6 Regression Results for Crash Rate Model (6-lane Median Opening)

	Coefficient	**t**	**Sig.**
Intercept	2.64	5.237	<0.001
l	-0.385	-4.652	<0.001
$\mathbf{R^2}$ = 0.21, $\mathbf{R^2_{adj}}$ = 0.21			

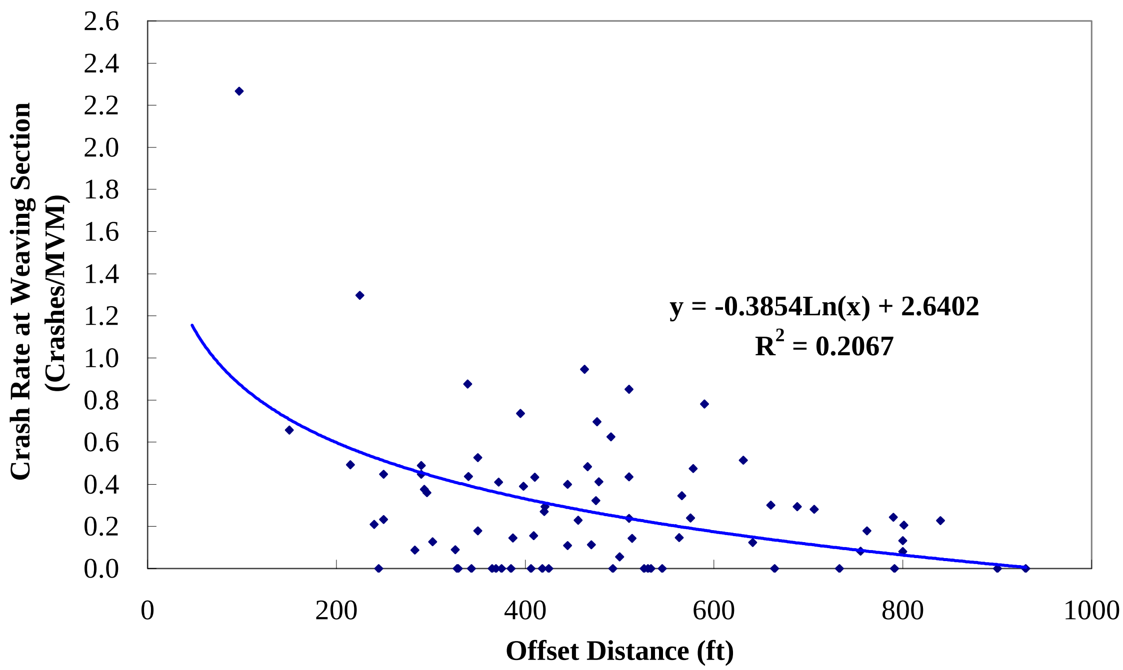


Figure 5-4 Crash Rate at Selected Roadway Segments vs. Offset Distance (6-lane Median Opening)

U-turns at Signalized Intersection on 6 or more-lane Divided Roadway

Crash history for 46 roadway segments was investigated. Crash rate at each site was calculated. Regression model was built to quantitatively evaluate the relationship between the crash rate and offset distance. The dependent variable is the crash rate at each selected roadway segment. The independent variable is the offset distance between driveway and downstream signalized intersection. The collected crash rate varies from 0 to 1.67 with an average of 0.50 crashes per million involved vehicles per mile. The offset distance varies from 105 ft to 1150 ft with an average of 420 ft.

Several regression models were tried, it was found that the linear regression model with a logarithmic form has the best goodness of fit to field data. The R^2 value of the model is 0.12. The independent variables (including the intercept) were found to be statistically significant at a 95% level of confidence. The regression results were shown in Table 5-7. The collected crash rates were plotted against the offset distances measured in the field, as shown in Figure 5-5. The regression model was shown as follows:

$$CR = -0.28\ln(l) + 2.15 \qquad 5\text{-}6$$

where,

CR = crash rate at selected roadway segments (crashes/MVM); and

l = the offset distance between driveway and downstream U-turn location (ft).

Table 5-7 Regression Results for Crash Rate Model
(6-lane Signalized Intersection)

	Coefficient	t	Sig.
Intercept	2.147	3.198	0.003
l	-0.281	-2.441	0.019
$\mathbf{R^2}$ = 0.12, $\mathbf{R^2_{adj}}$ = 0.10			

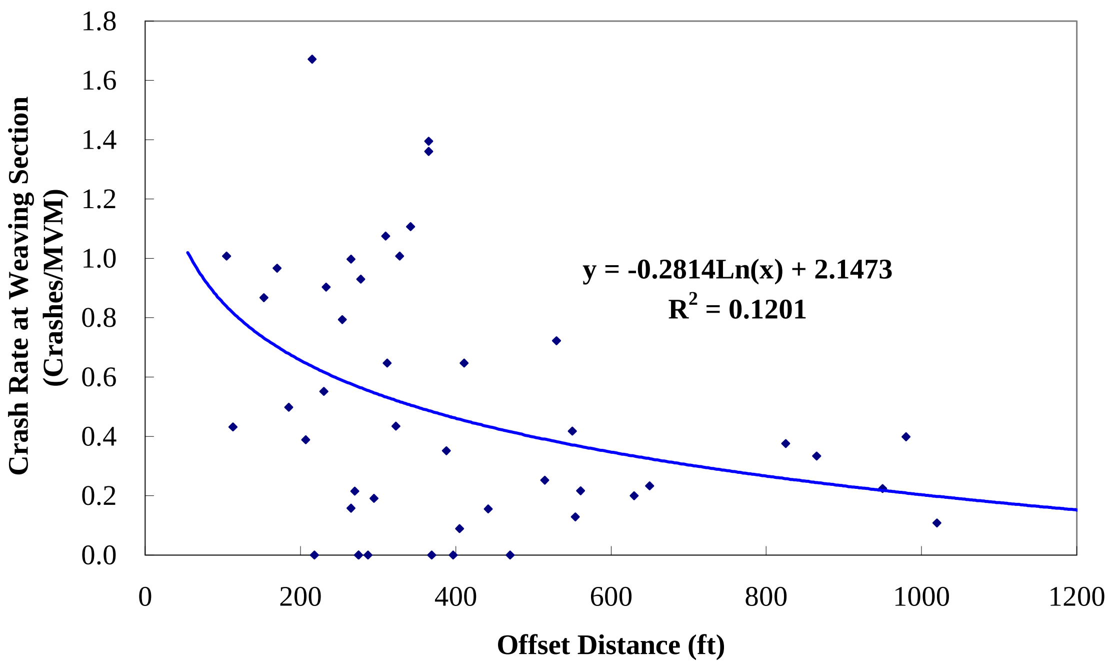


Figure 5-5 Crash Rate at Selected Roadway Segments vs. Offset Distance
(6-lane Signalized Intersection)

5.2.3. Determination of Minimum Offset Distance for RTUT

The cumulative curves were plotted for the crash rates of all sample sites. Each data point on the cumulative curve represents the percentage of those sites with a crash rate no larger than a certain value. The 50th and the 85th percentile values were marked on the cumulative curve, as shown in Figure 5-6. For each movement, the 50th percentile value is the median crash rate, and the 85th percentile value represents the point where 85 percent of all the sites have crash rates no larger than this point's X-coordinate value. These two percentiles are the most commonly used in engineering analysis. As shown in Figure 5-6, the 50th percentile value of crash rate is 0.29 crash/MVM and the 85th percentile value is 0.71 crash/MVM.

The 50th percentile value of crash rate was used to determine the critical value of offset distance. The critical offset distance for vehicles making RTUT under different roadway conditions were determined by applying the 50th percentile value of crash rate into the regression models developed in the previous section. The thinking behind this methodology is that the roadway segment with offset distance less than the critical value will have a crash rate greater than the average level. The critical offset distance could be considered as the minimum offset distance for vehicles making a RTUT without cause significant safety problems at weaving section. The procedures to obtain the critical values of offset distance under different roadway conditions were presented through Figures 5-7 to 5-10.

5.3. Conflict Data Analysis

5.3.1. 4-lane Median Opening Sites

The relationship between conflict rate and offset distance is defined by a model that would explain the influence of offset distance on conflict rate. Several models were employed in this research. The results showed that the logarithmic model had the best goodness of fit for the conflict data. The R^2 value of the model is 0.25. The independent variables were found to be statistically significant at a 95% level of confidence. The collected crash rates were plotted against the offset distances measured in the field, as shown in Figure 5-11.

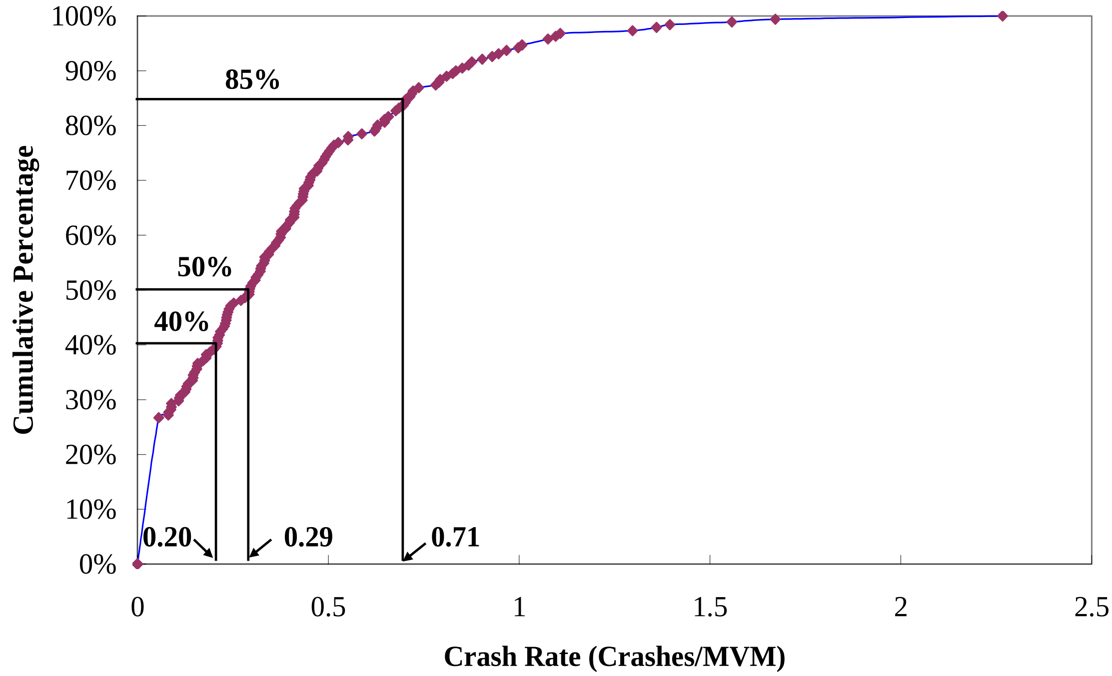


Figure 5-6 50th and 85th Percentile Values of Crash Rate

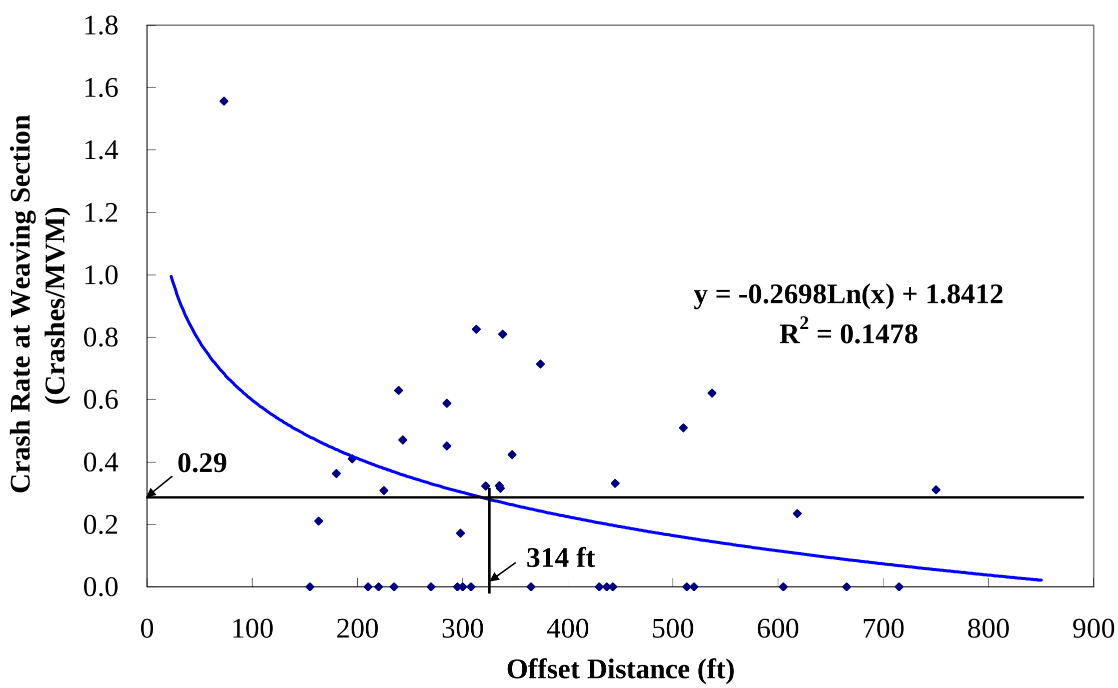


Figure 5-7 The Minimum Offset Distance According to 50th Percentile Value (4-lane Median Opening)

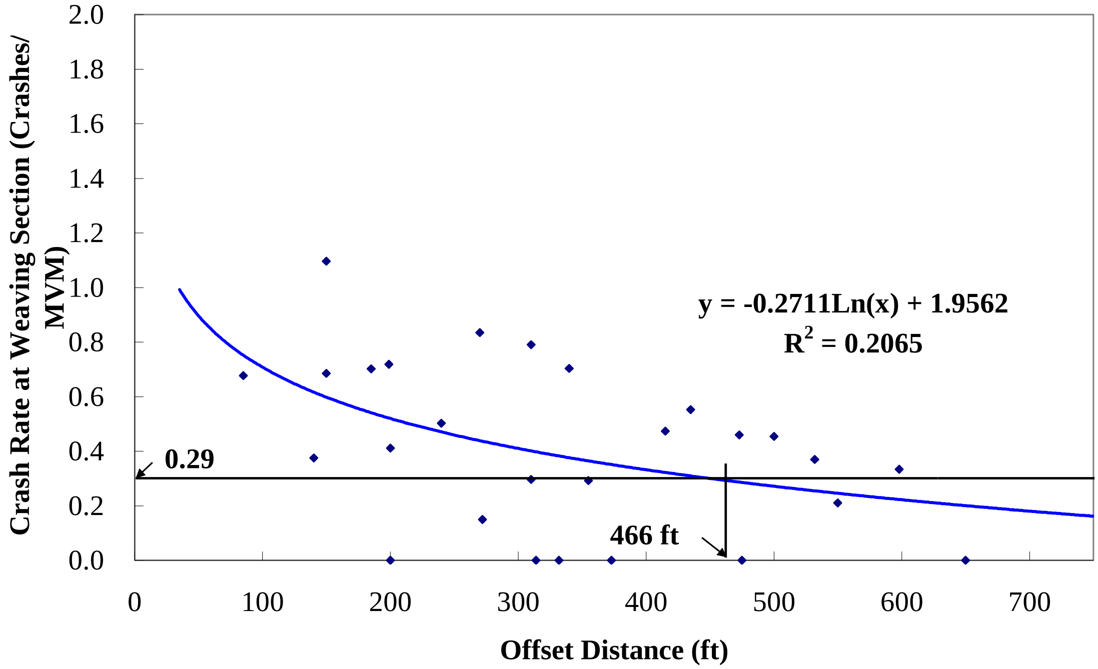


Figure 5-8 The Minimum Offset Distance According to 50th Percentile Value (4-lane Signalized Intersection)

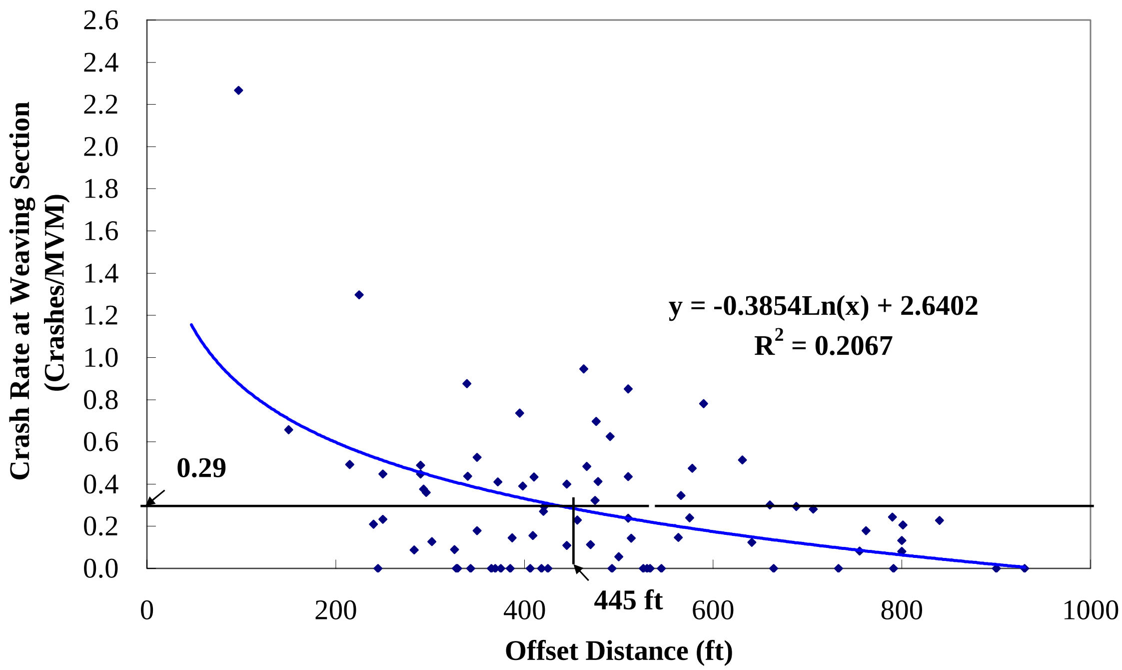


Figure 5-9 The Minimum Offset Distance According to 50th Percentile Value (6 or more-lane Median Opening)

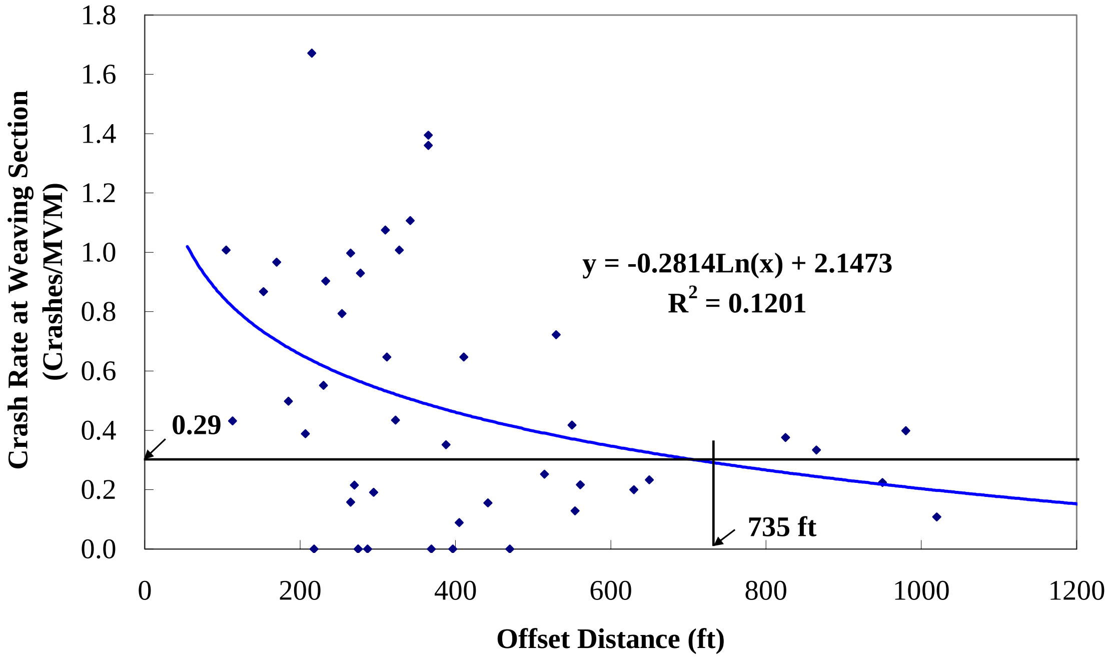


Figure 5-10 The Minimum Offset Distance According to 50th Percentile Value (6 or more-lane Signalized Intersection)

The estimation of minimum offset distance was based on the 50th percentile value of conflict rate observed at the 4-lane median opening sites. The cumulative curve and the 50th percentile value were shown in Figure 5-12. The critical offset distances for vehicles making RTUT at median openings on 4-lane roadways were determined by applying the 50th percentile value of conflict rate into the regression models developed in this study.

5.3.2. 4-lane Signalized Intersection Sites

The relationship between the conflict rate and offset distance was defined by a model that would explain the influence of offset distance on conflict rate. Several models were employed. The results showed that the logarithmic model had the best goodness of fit for the conflict data. The R^2 value of the model is 0.35. The independent variables (including the intercept) were found to be statistically significant at a 95% level of confidence. The observed conflict rates were plotted against the offset distances measured in the field, as shown in Figure 5-13.

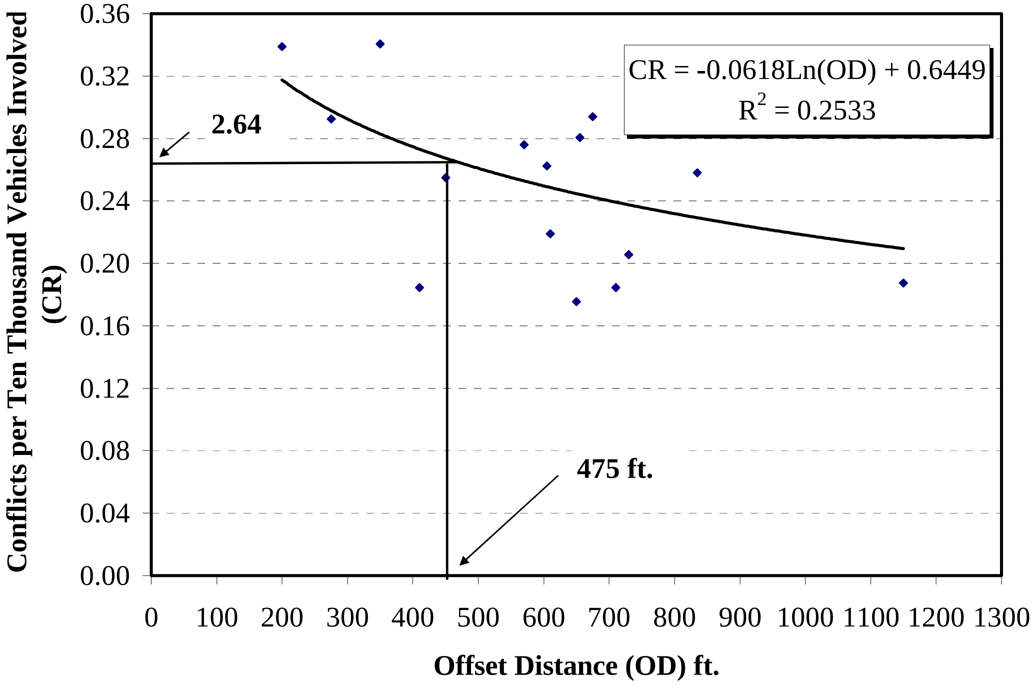


Figure 5-11 Conflict Rate at Selected Roadway Segments vs. Offset Distance (4-lane Median Opening Sites)

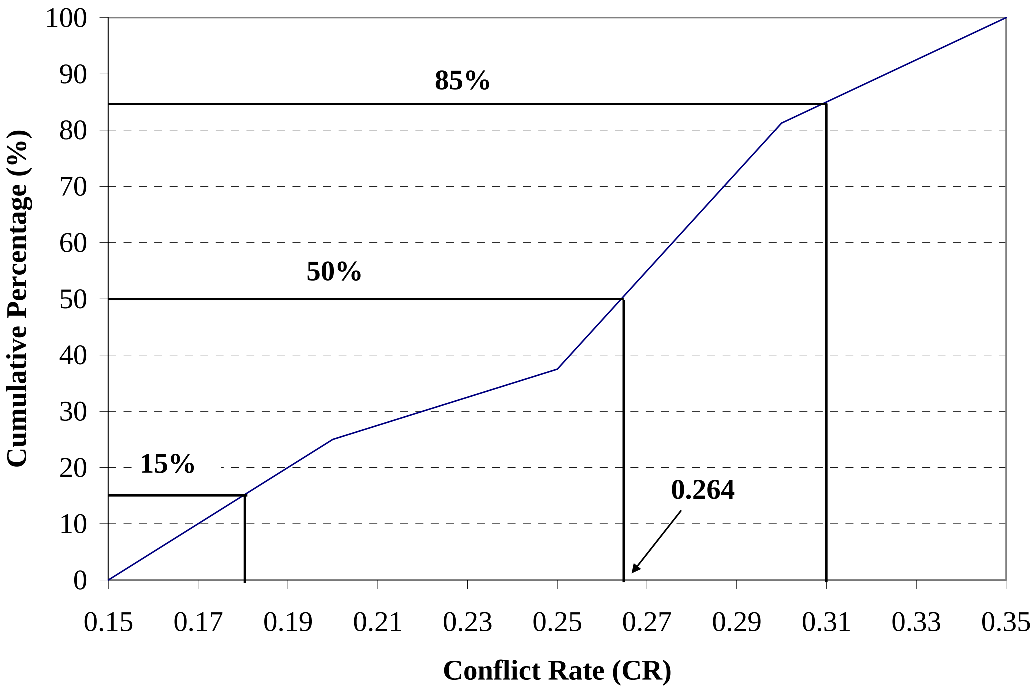


Figure 5-12 50th and 85th Percentile Values of Conflict Rate (4-lane Median Opening Sites)

The estimation of minimum offset distance was based on the 50th percentile value of conflict rate observed at the 4-lane signalized intersection sites. The cumulative curve and the 50th percentile value were shown in Figure 5-14. The critical offset distance for vehicles making RTUT at signalized intersections on 4-lane roadways were determined by applying the 50th percentile value of conflict rate into the regression models developed in this study.

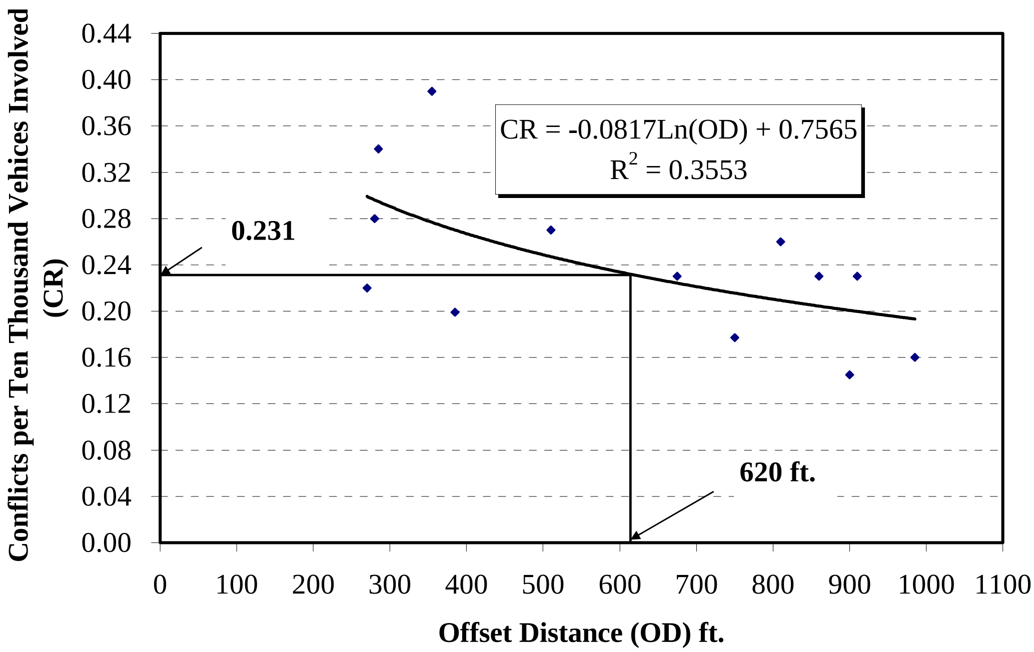


Figure 5-13 Conflict Rate at Selected Roadway Segments vs. Offset Distance (4-lane Signalized Intersection Sites)

5.3.3. 6 or more-lane Median Opening Sites

The relationship between the conflict rate and offset distance was defined by a model that would explain the influence of offset distance on conflict rate. Several models were employed. The results showed that the logarithmic model had the best goodness of fit for the conflict data. The R^2 value of the model is 0.20. The independent variables (including the intercept) were found to be statistically significant at a 95% level of confidence. The observed conflict rates were plotted against the offset distances measured in the field, as shown in Figure 5-15.

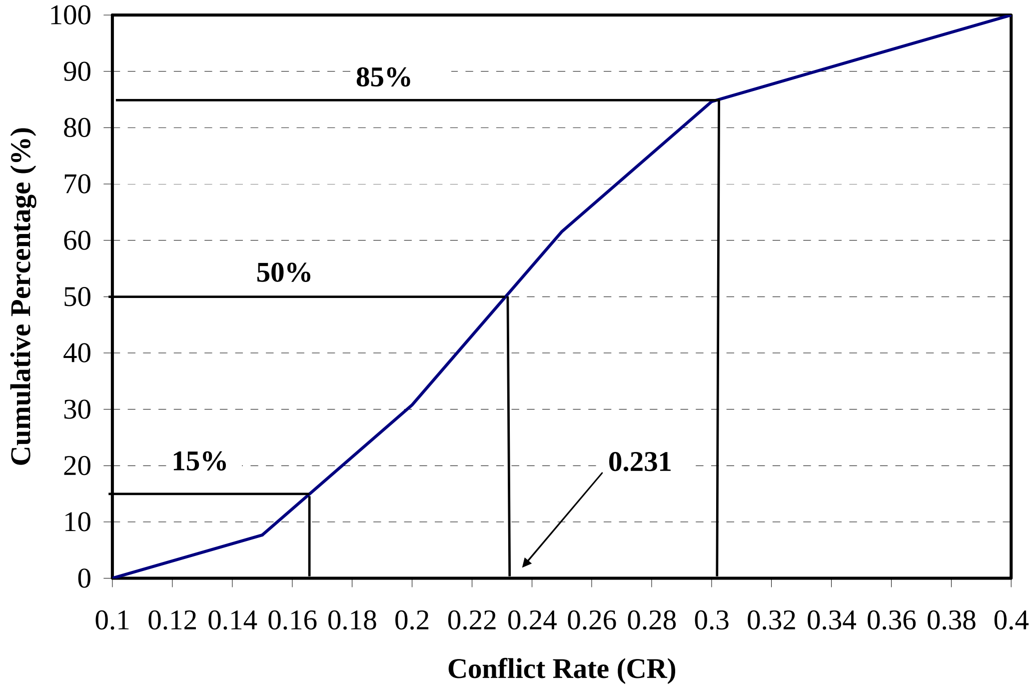


Figure 5-14 50th and 85th Percentile Values of Conflict Rate
(4-lane Signalized Intersection Sites)

The estimation of minimum offset distance was based on the 50th percentile value of conflict rate observed at the 6 or more-lane median opening sites. The cumulative curve and the 50th percentile value were shown in Figure 5-16. The critical offset distances for vehicles making RTUT at median openings on 6 or more-lane roadways were determined by applying the 50th percentile value of conflict rate into the regression models developed in this study.

5.3.4. 6 or more-lane Signalized Intersection Sites

The relationship between the conflict rate and the offset distance between driveways and downstream U-turn locations was determined by a regression model. The regression model was based on data collected from 6 or more-lane signalized intersection sites. The dependent variable is the average conflict rate at selected roadway segments, and the independent variable is the offset distance. Several models formats were employed. It was found that the regression with a logarithmic form have best goodness of fit to collected field data. The R^2 value of the model is 0.35. The independent variables (including the intercept) were found to be statistically significant at a 95% level of confidence. The collected conflict rates were plotted against the offset distances measured in the field, as shown in Figure 5-17.

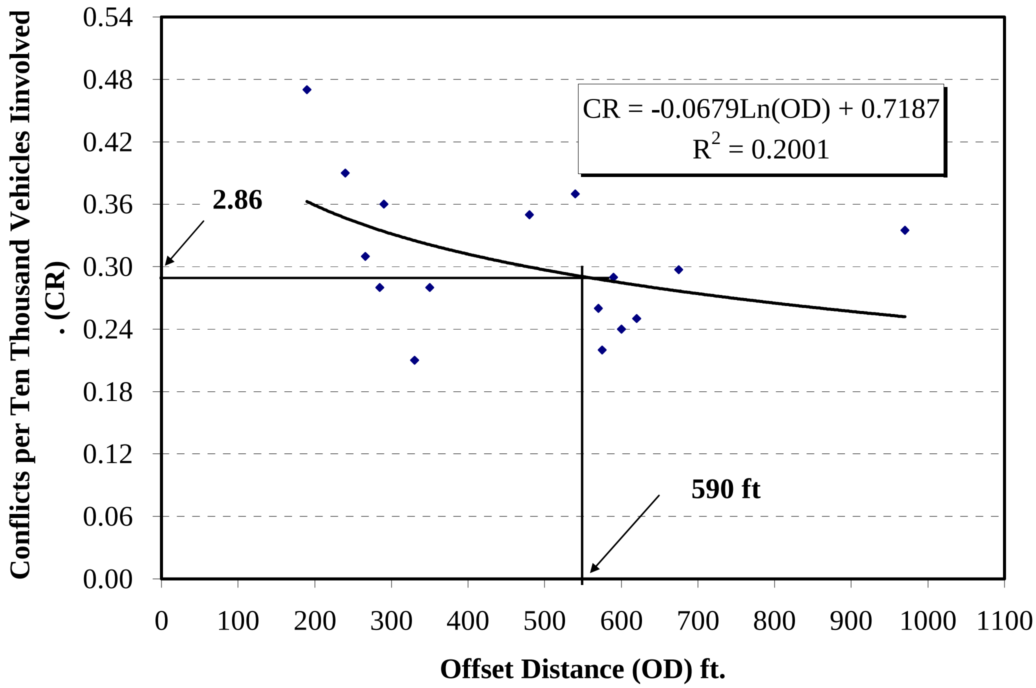


Figure 5-15 Conflict Rate at Selected Roadway Segments vs. Offset Distance (6 or more-lane Median Opening Sites)

The estimation of minimum offset distance was based on the 50th percentile value of conflict rate observed at the 6 or more-lane signalized intersection sites. The cumulative curve and the 50th percentile value were shown in Figure 5-18. The critical offset distance for vehicles making RTUT at signalized intersections on 6-lane roadways were determined by applying the 50th percentile value of conflict rate into the regression models developed in this study.

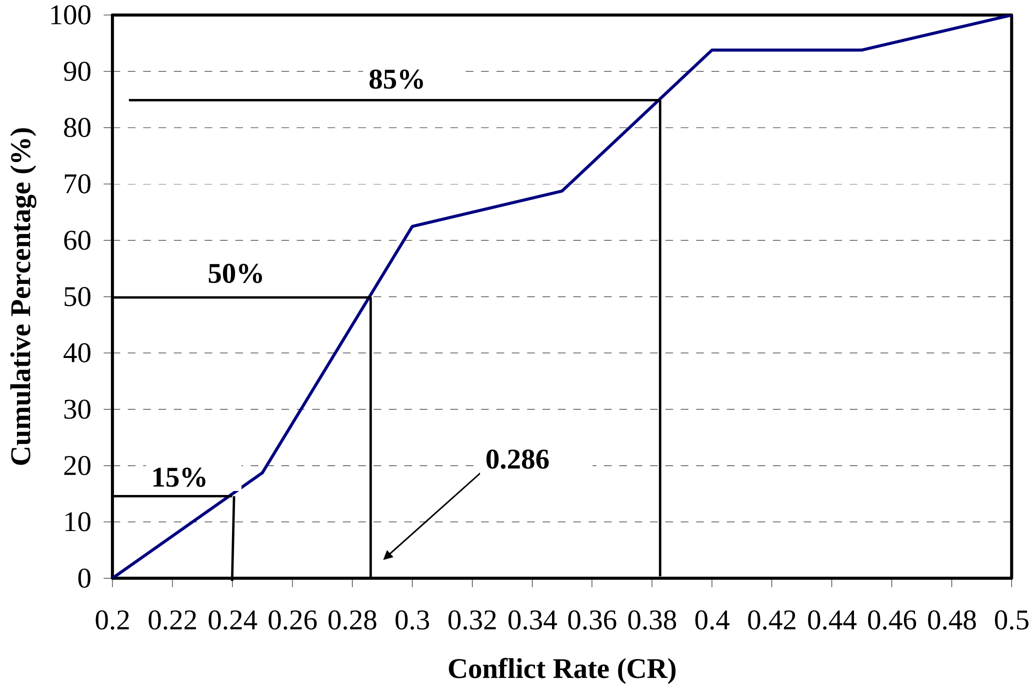


Figure 5-16 50th and 85th Percentile Values of Conflict Rate
(6 or more-lane Median Opening Sites)

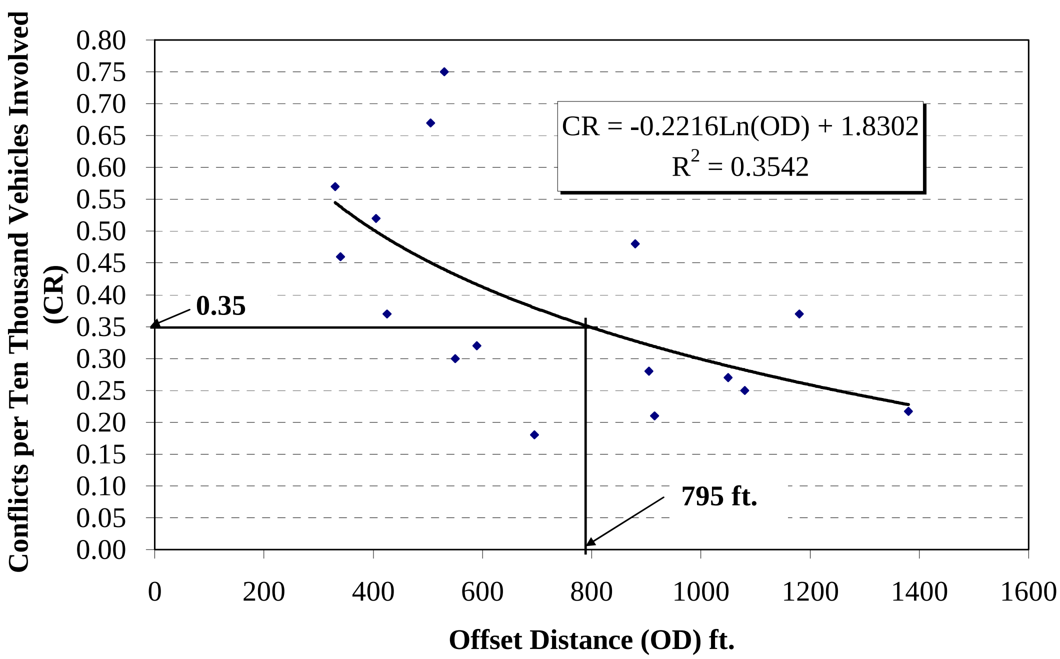


Figure 5-17 Conflict Rate at Selected Roadway Segments vs. Offset Distance
(6 or more-lane Signalized Intersection Sites)

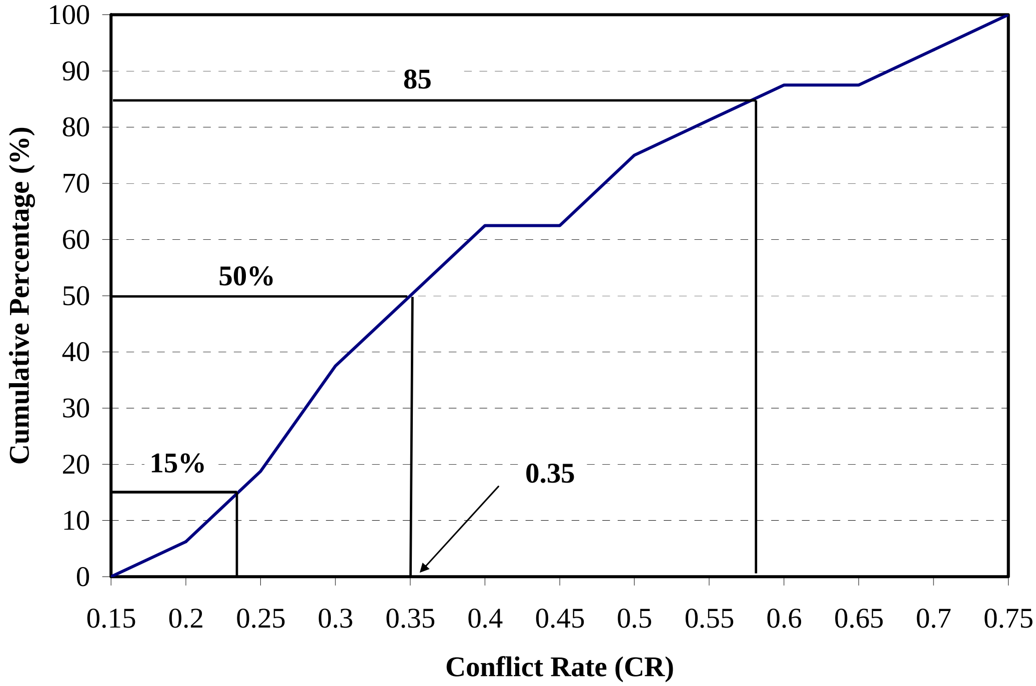


Figure 5-18 50th and 85th Percentile Values of Conflict Rate
(6 or more-lane Signalized Intersection Sites)

5.4. The Minimum Offset Distance for RTUT

In previous two sections, the procedures for determining the minimum offset distance for vehicles making RTUT were presented. Two research approaches were applied when estimating the minimum offset distance including crash data analysis and conflict data analysis. The minimum offset distances obtained from these two research approaches were shown through Figures 5-11 to 5-18. It was found that, the minimum offset distances obtained from crash data analysis are always less than the results obtained from conflict data analysis. This result follows from the fact that traffic conflicts do not always result in crashes. Therefore, the offset distance required by drivers to perform a RTUT without causing a conflict should be longer than the distance required by drivers to perform a RTUT without causing a crash.

In this section, the minimum offset distances obtained from crash data analysis and conflict data analyses were combined. The minimum offset distance guidelines are based on the results of the crash data analysis and conflict data analysis. The mean value of the minimum offset distances determined through two different research approaches was selected as the recommended minimum offset distances. The recommended minimum offset distances can be calculated by Equation 5-9. The recommended minimum offset distances under different roadway geometric conditions were shown in Table 5-8.

$$l_R = \frac{l_{Crash} + l_{Con}}{2} \qquad 5\text{-}9$$

where,

l_R = recommended minimum offset distance (ft);

l_{Crash} = minimum offset distance determined by crash data analysis (ft); and

l_{Con} = minimum offset distance determined by conflict data analysis (ft).

Table 5-8 Recommended Minimum Offset Distance for RTUT

U-turn Location	Number of Lanes	l_{Crash} (ft.)	l_{Con} (ft.)	l_R (ft.)
Median Opening	4	314	475	400
	6 or more	445	590	500
Signalized Intersection	4	466	620	550
	6 or more	735	795	750

It is important to note that, the offset distance defined in this study represents the separation distance between driveway exits and downstream U-turn locations. Thus, this includes the length of weaving sections, the transition length and the length of storage bay. This study not only looked at crash data occurred in weaving section, but also the crash data at transition length and storage length. This methodology follows the fact that drivers could use transition length and storage length to perform the weaving maneuver, as observed in the field. Therefore, the minimum offset distances recommended by this study are based on this driver behavior observed in the field. From safety perspective, **it is not desirable** to perform a weaving maneuver at transition length and storage bay. Due to this reason, it was recommended by the author that a transition length and a storage length be added to the minimum offset distance.

6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1. Summary

Florida increasingly uses restrictive medians and directional median openings on multi-lane highways to manage left turn egress maneuvers from driveways or side streets. By installing non-traversable medians and replacing full median openings with directional median openings at various locations, Florida prohibits direct left-turn exits onto some major arterials; hence, direct left-turn egress maneuvers from driveways or side streets would be replaced by making a right turn followed by a U-turn at downstream median openings or signalized intersections.

Though several studies have been conducted to evaluate the safety and operational effects of using U-turns as alternatives to direct left-turns, these studies have not focused on the impacts of the offset distance between driveways and downstream U-turn location. Very short offset distance may lead to operational and safety characteristics somewhat similar to direct left turns and may discourage drivers to make right-turns followed by U-turns. Too long offset distance, on the other hand, may result in long travel time and, sometimes, tend to discourage drivers' willingness to make right turns followed by U-turns. Therefore, the safety and operational performance of vehicles making RTUT are highly correlated with the offset distance between subject driveway and downstream median opening or signalized intersection.

This study evaluated the impacts of the offset distance between driveway exits and downstream median opening or signalized intersection on the safety and operational performance of vehicles making right-turns followed by U-turns. The focus of this research was on urban or suburban multilane divided arterials. This study evaluated the impacts of offset distance under 4 different scenarios including: 4-lane divided roadways accommodating U-turns at median openings; 4-lane divided roadways accommodating

U-turns at signalized intersections; 6 or more-lane divided roadways accommodating U-turns at median openings; and 6 or more-lane divided roadways accommodating U-turns at signalized intersections. Three basic approaches were applied including crash data analysis, conflict analysis, and operations analysis. Field measurements were conducted at 68 selected sites in the Tampa Bay area in Florida. Crash history of 192 roadway segments was investigated. Statistical models were developed based on the collected field data to quantitatively evaluate the safety and operational performance of vehicles making RTUT at various offset distances. It was found that the crash rate and conflict rate at weaving sections decrease with the increase of the offset distance between driveway and downstream U-turn location. The cumulative curves were plotted for the crash rates and conflict rates of all sample sites. The 50^{th} percentile value of crash rate and conflict rate was used to determine the critical value of offset distance. The critical offset distance for vehicles making RTUT under different roadway conditions were determined by applying the 50^{th} percentile value of crash rate and conflict rate into the regression models developed in this study. The research results obtained from this research could be used to estimate the minimum offset distance between driveway exits and the U-turn locations to facilitate vehicles making RTUT without causing significant safety problems at weaving sections.

6.2. Conclusions and Recommendations

Through this study, conclusions can be made as follows:

(1) The length of the offset distance between driveway exits and downstream U-turn locations significantly impact the safety performance of vehicles making right turns followed by U-turns;

(2) The crash rate at weaving sections decreases with the increases of the offset distance between driveway exits and downstream U-turn locations;

(3)The conflict rate at weaving sections decreases with the increases of the offset distance between driveway exits and downstream U-turn locations;

(4)The average running time for vehicles making RTUT increases with the offset distance between driveway exits and downstream U-turn locations. A linear regression model was developed to estimate relationship between the average running time of RTUT and explanatory variables.

One of the major objectives of this study was to determine the minimum offset distance between driveway exits and downstream U-turn locations for a right turn followed by a U-turn maneuver. The minimum offset distance was determined based on the results of the crash data analysis and conflict data analysis. The minimum offset distance recommended by this study was shown in Table 6-1.

Table 6-1 Minimum Offset Distance

U-turn Location	Number of Lanes	Offset Distance (ft.)
Median Opening	4	400
	6 or more	500
Signalized Intersection	4	550
	6 or more	750

It is important to note that, the offset distance defined in this study represents the separation distance between driveway exits and downstream U-turn locations. Thus, this includes the length of weaving sections, the transition length and the length of storage bay. This study not only looked at crash data occurred in weaving section, but also the crash data at transition length and storage length. This methodology follows the fact that drivers could use transition length and storage length to perform the weaving maneuver, as observed in the field. Therefore, the minimum offset distances recommended by this study are based on this driver behavior observed in the field. From safety perspective, **it**

is not desirable to perform a weaving maneuver at transition length and storage bay. Due to this reason, it was recommended by the author that a transition length and a storage length be added to the minimum offset distance. An optimal offset distance for RTUT should include the minimum offset distance recommended by this study, the transition length and the length for a storage bay.

As mentioned before, the crash rate and conflict rate for RTUT decrease with the increases of the offset distance. However, too long offset distance may result in long travel time and, sometimes, tend to discourage drivers' willingness to make right turns followed by U-turns. In this condition, drivers are facing a tradeoff between the increased travel time and a safer driving environment. This study developed a statistical model to quantitatively evaluate the relationship between the average running time of RTUT and explanatory variables. The regression model (Equation 5-1) could be used to estimate the average running time for vehicles making RTUT at various offset distances between driveway exits and downstream U-turn locations. For example, based on the model, vehicles making RTUT at downstream median opening on a 6-lane roadway require 47 seconds running time when the offset distance between driveway and downstream median opening is 1200 ft and the speed limit of major road is 45 mph. An extra travel time of 47 seconds usually do not constitute a major operational concern. Therefore, it was recommended by the author that, the average running time of vehicles making RTUT should not be used as a major criterion to determine the offset distance for RTUT.

This study has not focused on the safety performance of heavy vehicles. It can be estimated that the offset distance required by heavy vehicles to perform a RTUT should be longer than that required by normal passenger cars. In addition, when estimating the minimum offset distance, this study did not consider the effects of some other factors such as land use. Future studies could focus on these areas.

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