OPERATIONAL EVALUATION OF RIGHT TURNS FOLLOWED BY U-TURNS (4-LANE ARTERIALS) AS AN ALTERNATIVE TO DIRECT LEFT TURNS

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16. Abstract

Florida uses restrictive medians and directional median openings to manage left turns and crossing movements on multilane highways. Left turn egress movements from driveways or side streets would be replaced by turning right onto the major road and then making U-turns at downstream median openings or signalized intersections. One of the public concerns regarding this treatment is that drivers making a right-turn followed by a U-turn (RTUT) could experience much longer delay and travel time than those who would otherwise make a direct left turn (DLT). This study analyzed the operational effects of a widely used access management treatment: Right turns followed by U-turns an alternative to direct left turns. The focus of this research was on the operational effects of U-turns at 4-lane arterials. Data were collected on sixteen selected street segments in the Tampa Bay area in Florida. A total of more than 600 hours of traffic data were collected. Empirical models were developed based on the collected field data to quantitatively evaluate the operational impacts. Delay and travel time models provided a tool to help address public concerns related to the operational impacts of U-turns and would be particularly helpful in identifying the circumstances in which the RTUT takes less time than the DLT. Additionally, in order to determine the minimum turning radius required by U-turning vehicles, from the operations point of view, an empirical model was developed to estimate the relationship between the turning radius and the average turning time required by each U-turning vehicle. This model can be directly used in estimating the average turning time required by U-turning vehicles under restricted geometric conditions. The findings of this study are helpful in providing local and state transportation agencies with recommendations for the design and selection of median treatments in six to eight lanes urban or suburban arterial roads.

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OPERATIONAL EVALUATION OF RIGHT TURNS FOLLOWED BY U-TURNS (4-LANE ARTERIALS) AS AN ALTERNATIVE TO DIRECT LEFT TURNS

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ABSTRACT

Florida uses restrictive medians and directional median openings in the State Highway System to manage left turn egress movements from driveways and side streets. By installing raised curb medians and replacing full median openings with directional median openings in some places, direct left turn movements are substituted by making a right-turn followed by a U-turn at downstream median opening or signalized intersection.

This report is one of the reports that summarize the research reports that evaluate the safety and operational effects of a widely used access management treatment: right turn followed by a U-turn (RTUT) as an alternative to direct left turn (DLT). The focus of this report is on the operational effects of U-turns on four-lane urban or suburban arterials. The primary objectives of this study were to explore methodologies for evaluating the operational effects of U-turns as alternatives to direct left turns on four-lane arterials; and to provide information on the potential operational impacts of these alternatives under various conditions.

To achieve these objectives, field studies were conducted at sixteen selected sites in the Tampa Bay area in Florida. Over 600 hours of traffic data were collected using video cameras. While reviewing videotapes, each vehicle coming from the driveway making DLT or RTUT was tracked. Delay and travel time for each vehicle making DLT or RTUT were recorded. Other information gathered in the field study included traffic volumes, signal parameters, and roadway geometrics.

Delay and travel time models were developed based on collected field data. The delay and travel time of vehicles making DLT, RTUT at median opening or RTUT at signalized intersection were determined as a function of conflicting volumes, signalization conditions, and roadway geometrics. Curves were developed based on regression results depicting operational differences between vehicles making a DLT versus those making a RTUT at median opening or signalized intersection.

In this project, the operations of two widely used U-turn approaches: U-turn at median openings in advance of signalized intersections and U-turn at signalized intersection were also compared by using the delay and travel time models developed in this study. Based on the comparison, it is clear that vehicles making RTUT at median openings in advance of signalized intersections will experience less delay and travel time as compared with the condition where U-turns are accommodated at signalized intersections.

In order to determine the minimum turning radius required by U-turning vehicles, from the operations point of view, an empirical model was developed to estimate the relationship between the turning radius and the average turning time required by each U-turning vehicle. This model can be directly used in estimating the average turning time required by U-turning vehicles under restricted geometric conditions. In addition, by analyzing the field data, the research team found that the average turning time of U-turning vehicles reaches a relatively saturated state after the turning radius accommodated by the intersection reaches around 48 ft, and this could be considered as the minimum turning radius required by most of the U-turning vehicles (except heavy vehicles) to finish the U-turn maneuver without taking extra turning time. Based on the minimum turning radius determined in this study, a procedure was developed to estimate the minimum median width required to facilitate U-turn maneuvers or other functions on 4-lane arterials.

ACKNOWLEDGEMENT

This project was sponsored by the Florida Department of Transportation. The assistance provided by FDOT is greatly appreciated. The authors also would like to thank the Graduate Research Assistants at the Department of Civil and Environmental Engineering of University of South Florida for their assistance in field data collection and data reduction. Specifically, the authors would like to express thanks to Gary H. Sokolow and Eric Larson, for their technical support and guidance.

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1 INTRODUCTION

1.1 Background

In the past few decades, many states and transportation agencies have started installing non-traversable medians on the state multilane highways to manage left turns and crossing movements. Since 1993, the FDOT mandated that all new or reconstructed multi-lane arterials with design speeds over 40 mph be designed with restrictive medians. In addition, Florida is installing directional median openings on the multilane arterials *(1)*. By closing median openings or replacing full median openings with directional median openings, Florida prohibits direct left-turn exits onto major arterials. Left turn egress movements from driveways or side streets onto major arterials would be replaced by turning right onto the major arterials and then making U-turns at nearby median openings or signalized intersections. *(2) (3)*.

The increased use of non-traversable medians and directional median openings reflects the increased attention given to access management. Recently, more and more states and transportation agencies came to realize the importance of access management to the modern traffic system. Access management techniques have been widely used to improve the traffic operations and safety along major arterials. In addition, many states have developed or are considering developing their statewide comprehensive access management program. In 1988, the Florida Legislature adopted the State Highway System Access Management Act, Statutes 335.18, which was considered as an important legal foundation of Florida statewide access management program

Access management has been defined as the systematic control of the location, spacing, design, and operation of driveways, median openings, interchanges, and street connections to a roadway *(4)*. By careful control of the location, type, and design of driveways and street intersections, access management helps to achieve the necessary balance between

traffic movement and property access, and this is accomplished by classifying highways with respect to the level of access and mobility they are expected to provide, and then, identifying and applying the most effective techniques to preserve that function. The benefits of access management include improved safety, improved traffic flow and fuel economy, increased capacity and reduced delay and vehicle emissions *(5)*.

One of the major principles of access management is to use non-traversable medians to manage left-turns and crossing maneuvers. Left-turn movements have been considered as one of the major resources of traffic operations and safety problems in multilane highways. Past studies indicated that left-turn maneuvers increase delays, conflicts, and crashes, and they reduce capacity and mobility in the major traffic. For example, as mentioned in Access Management Manual, a total of about 74% of access-related crashes involve left turning vehicles. Traffic engineers have often looked at other alternatives of facilitating left turns such as median U-turns also known as Michigan U, Bowtie, Superstreet, Paired Intersection, Jughandle and, recently, right turns followed by U-turns.

1.2 Right Turns Followed by U-turns

Increasingly, U-turns are used as alternatives to direct left turns. In Florida, non-traversable medians and directional median openings have been widely implemented on some major arterials. Drivers wishing to make a direct left turn egress movements from driveways or side streets onto major arterials would first turning right onto the major arterials, and then making U-turns at nearby median openings or signalized intersections.

Replacing full median openings with directional median openings has been found to substantially reduce crash rate *(6) (7) (8)*. In practice, however, to close an existing median opening could be sensitive and sometimes difficult to handle. Some business owners believe that the median project would have some adverse impacts on their business. In addition, arguments have been advanced by some opponents of median projects that the

increased U-turn volumes may pose safety and operations problems to the traffic system. Today, these issues are being hotly discussed. Various studies have been conducted and can be divided into different categories, based on different perspectives they focused on, including:

(1) The economic impacts of installing non-traversable medians *(9)(10)(11)(12)*;
(2) Safety effects of U-turns at unsignalized median openings and signalized intersections *(6)(7)(8)(13)(14)(15)(16)*;
(3) Operational impacts of U-turns at unsignalized median openings and signalized intersections *(13)(14)(15)(16)(17)(18)(19)(20)(21)*; and
(4) Geometric design and the selection of Un-conventional left-turn alternatives (*22) (23) (24) (25) (26) (27) (28) (29) (30)*.

These studies generally indicated that median projects have little or no overall adverse impact on business activity; and the increased U-turn volumes at median openings and signalized intersections can be used safely and effectively. However, most of these studies attributing capacity and safety gains to U-turns have only focused on the operations and safety effects of U-turn maneuvers, either at un-signalized median openings, or at signalized intersections, but not on the effects of the whole RTUT procedure. In practice, when a full median opening is closed or replaced with a directional median opening, drivers desiring to make a left turn would not only need to make a U-turn. The procedure would also involve making a right turn onto the major arterials, weaving to the inside lane, and then stopping at a nearby median opening or signalized intersection as well. Little documentation is available concerning this issue; and the operational and safety effects of using right turns followed by U-turns (RTUT) as alternatives to direct left-turns (DLT) are still largely unknown. For example, some people often oppose being directed to make a right-turn followed by a U-turn due to the perception that it may result in much longer delay and travel time than a direct left turn; or due to a believe that it is unsafe to make a RTUT since it requires drivers to weave on a certain stretch of the roadway and then to evaluate the available gaps for making the U-turn. Currently the FDOT and highway

agencies are not able to response to such arguments for lack of the necessary tools to quantify the effects. An extensive study was needed, not only for setting design policy, but also for addressing public concerns.

1.3 The USF Study About U-turns

The projects performed by the University of South Florida and sponsored by the FDOT in 2001 (USF 2001 study) and 2004 (USF 2004 study) have been completed successfully. The studies took three basic approaches in evaluating a widely used access management treatment – *Right-turns followed by U-turns at downstream median openings or signalized intersections on six-lane principle arterials as alternatives to direct left turns from driveways and side streets (31)(32)(33)(34)(35)*. Safety analysis was based on two main approaches including crash data analysis and conflict analysis, whereas operational characteristics were evaluated by using empirical models developed based on field data. The research team used five digital video cameras to collect field data, therefore the whole procedure of vehicles making right turns followed by U-turns could be covered. These two projects proved that under high major road through-traffic volume levels, direct left-turns could result in higher traffic conflicts, stop delay and travel time as compared with right turns followed by U-turns. These conclusions hold when U-turns are accommodated on urban or suburban principle arterials with 3 or more lanes in each direction.

The focuses of the previous USF studies were on safety and operational effects of U-turns on six to eight lanes urban or suburban arterials. In the real world, however, there are many other conditions where U-turn could be accommodated such as on 4-lane arterials. Little documentation is available concerning this particular situation; and as a consequence, the safety and operational issues of U-turns on 4-lane arterials are still not clear.

1.4 Research Statement

In practice, drivers usually have two alternatives when making left turns from a driveway or side street: (1) making direct left-turns from the driveway onto the arterial, (2) making right turns followed by U-turns at downstream median openings or signalized intersections, as shown in Figure 1-1, Figure 1-2, and Figure 1-3. The USF 2001 and 2004 studies have proved that at high through-traffic volume level, direct left-turns resulted in higher traffic conflicts, stop delay and travel time as compared with right turns followed by U-turns on multilane arterials with 3 or more lanes in each direction. In practice, however, there are many other conditions where U-turns could be accommodated on 4-lane arterials.

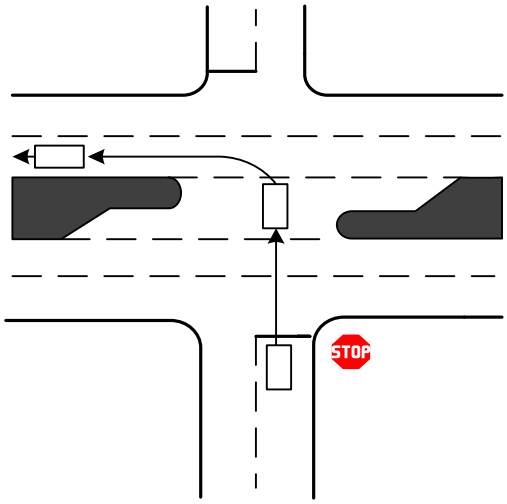


Figure 1-1 Direct left-turn movement on 4-lane arterial

Even though the right-turn followed by U-turn was identified as favorable from both traffic operational and safety points of views for major arterials with three or more lanes in each direction, the situation may not be the same for 4-lane facilities. One consideration behind this thinking is the shorter crossing distance needed by direct left turn vehicles in the case of 4-lane roadways since crossing 2 lanes at a time may not be as difficult as crossing three lanes. It may therefore be advisable to separately evaluate direct left turns

and right turns followed by U-turns on 4-lane facilities. It is also necessary to develop recommendations for U-turn locations on 4-lane roadways since such locations might have limited physical space (ex. narrow medians) to complete the maneuver, which was not an issue in the case of 6 lane roadways. Such tight locations on 4-lane roadways may also require extra pavements as well to complete the U-turn.

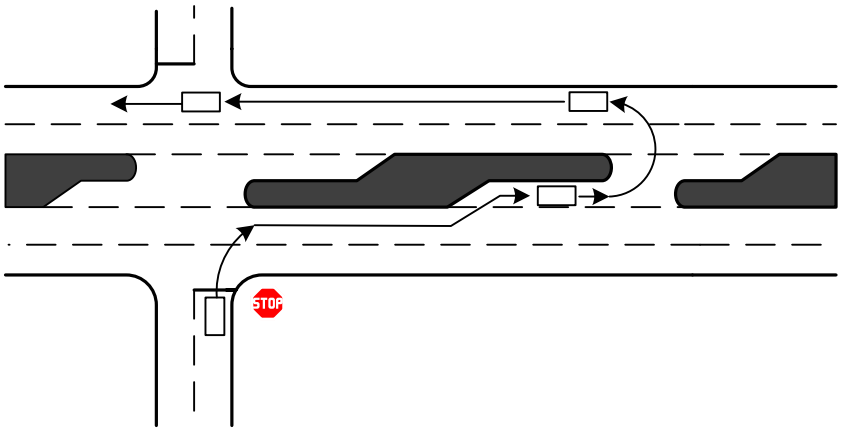


Figure 1-2 Right turn followed by U-turn at median opening on 4-lane arterial

In this study, field experiments were conducted to collect data at eight selected sites in the Tampa Bay area in Florida. Delay and travel time for each vehicle making a DLT or RTUT were used to quantify the operational effects of this specific access management technique. The research results can be directly applied to evaluate the operational effects of median treatments such as installing restrictive median, closing existing median openings, and replacing a full median opening with a directional median opening.

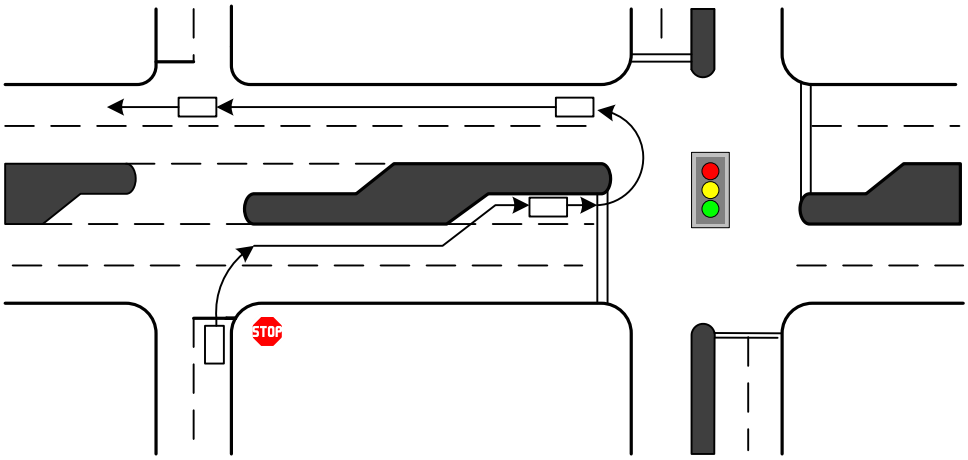


Figure 1-3 Right turn followed by U-turn at signalized intersection on 4-lane arterial

1.5 Research Purposes and Objectives

The primary purpose of this project was to conduct a detailed evaluation and investigation on a widely used access management technique: right-turns followed by U-turns at un-signalized median openings or signalized intersections on 4-lane arterials as an alternative to direct left turns from driveways. This research took two main approaches to evaluate technique including operational analysis and safety analysis. The focus of this report is on the operational effects of U-turns on 4-lane arterials, and which were quantified through field studies and data collection. Empirical models concerning the delay and travel time of each vehicle making a DLT or RTUT were developed based on collected field data. More specifically, the objectives consist of the following parts:

(1) To compare the delay and travel time of vehicles making DLT or RTUT on 4-lane divided arterials under certain roadway traffic or geometric conditions (major-road, left-turn-in, and driveway);

(2) To estimate delay and travel time for RTUT at median opening or signalized intersections on 4-lane divided arterials as a function of conflicting major and minor-road flow rates and signalization conditions;

(3) To estimate delay and travel time for RTUT at median opening or signalized intersections on 4-lane divided arterials as a function of conflicting major and minor-road flow rates;

(4) To estimate delay and travel time for DLT on 4-lane divided arterials as a function of conflicting major and minor-road flow rates;

(5) To compare the operational performance of two widely used U-turn approaches: U-turns at a median opening in advance of signalized intersection and U-turns at signalized intersection, on 4-lane divided arterials; and

(6) To estimate the minimum turning radius required by U-turning vehicles from the operations point of view.

1.6 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 General

Extensive work was conducted to search current rules and regulations, design standards, policies and state of practice in Florida and nationally. In addition, past studies and reports related to this topic were also searched and reviewed. Generally, the references can be categorized into three parts: median and roadway width to facilitate U-turns, delay and travel time models, operational effects of U-turns, and indirect left-turn treatments.

2.2 Median and roadway width to facilitate U-turns

The minimum median and roadway width required to facilitate U-turning vehicles are key factors in determining whether a U-turn movement is permitted at a median opening. The AASHTO GREEN BOOK *(3)* (*A Policy on Geometric Design of Highways and Streets*) contains some guidance on the relationship between median width and U-turn maneuvers. As indicated in the book, medians of 5.0 m (16 ft) and 15 m (50 ft) or wider are needed to permit passenger car and single-unit truck traffic, respectively, to turn from the inner lane (next to the median) on one roadway to the outer lane of a two-lane opposing roadway. Also, a median left-turn lane is highly desirable in advance of the U-turn opening to eliminate stopping on the through lane. This scheme would increase the median width by approximately 3.6 m (12 ft).

Normally, U-turn should not be permitted from the through lanes. However, where medians have adequate width to shield a vehicle stored in the median opening, through volumes are low and left-turn/U-turns are infrequent, this type of design may be permissible. The AASHTO GREEN BOOK defined the minimum widths of median to

accommodate U-turns by different design vehicles turning from the lane adjacent to the median as follows:

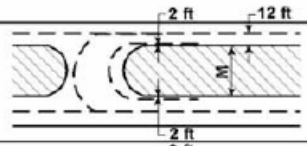
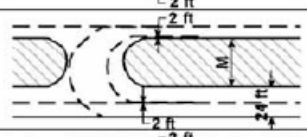
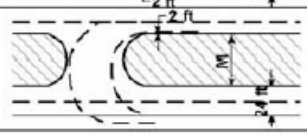
TYPE OF MANEUVER		M - MIN. WIDTH OF MEDIAN (ft) FOR DESIGN VEHICLE						
		P	WB-40	SU	BUS	WB-50	WB-60	TDT
		LENGTH OF DESIGN VEHICLE (ft)						
		19	50	30	40	55	65	118
INNER LANE TO INNER LANE		30	61	63	63	71	71	101
INNER LANE TO OUTER LANE		18	49	51	51	59	59	89
INNER LANE TO SHOULDER		8	39	41	41	49	49	79

Figure 2-1 AASHTO minimum median widths to accommodate U-turns (Source: AASHTO GREEN BOOK)

As mentioned in the AASHTO GREEN BOOK, these dimensions are for a four-lane divided facility. If the U-turn is made from a median left-turn/U-turn lane, the total median width needed would include an additional 12 ft for a single median turn lane.

Wherever possible, a newly designed divided highway should have a median width that can accommodate normal left-turns and passenger car U-turns by using a sufficient intersection design and a median storage lane that will protect and store the design-hour turning volume. If adequate median width does not exist for accommodating U-turns, then adding extra pavement width, through use of a taper, a flare or on the shoulder for example should be considered. The Florida Median Handbook *(28)* gave two examples of the use of loons, as shown in Figure 2-2 and Figure 2-3.

Another treatment to facilitate the larger turning path of U-turning vehicles along narrow medians is to use loons. As defined in the NCHRP report 524 *(14)*, a loon is an expanded paved apron on the shoulder opposite a median crossover, as shown in Figure 2-4. The

purpose of installing loons is to provide additional space for larger vehicles (particularly trucks) to negotiate turns, and thus, to allow the installation of conventional or directional median openings along narrow medians. The provision of loons to serve U-turns by large vehicles is a new technique that formalizes past use of paved shoulders for the same purpose.

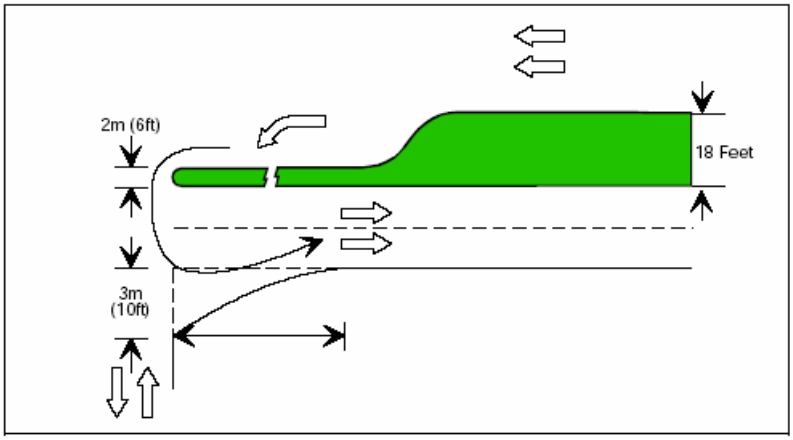


Figure 2-2 Flare to allow design P-Vehicle to make U-turn on 4-Lane divided roadway having curb and gutter

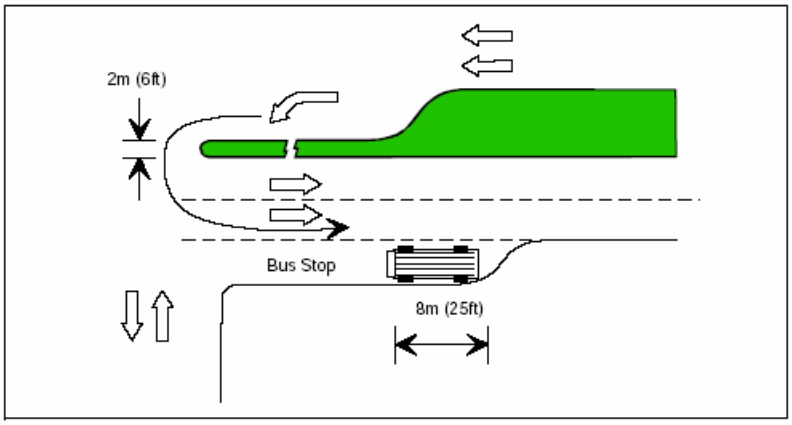


Figure 2-3 Design for P-Vehicle U-turn on 4-Lane divided roadway having curb and bus stop

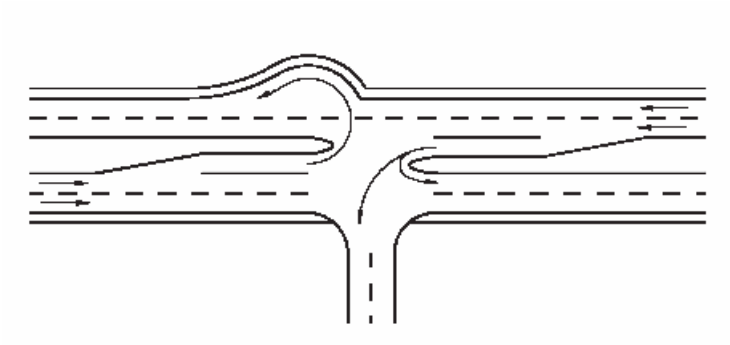


Figure 2-4 Conventional median opening with left-turn lanes and loons at three-leg intersection (Source: NCHRP report 524)

2.3 Delay and Travel Time Models

Delay and travel time are important measures of effectiveness (MOEs) of traffic operations. In practice, people often opposed being directed to make a right turn followed by a U-turn because many of them generally believe that vehicles making a RTUT will experience much longer delay and travel time than those would otherwise make a DLT. Past studies documenting the operational effects of U-turns have not focused on the delay and travel time of right turns followed by U-turns as a complete procedure.

2.3.1 Delay Models at Signalized Intersection

Delay is an important parameter that is used in estimating the level of service of signalized intersections. In addition, delay is a measure that most directly relates the driver's experience, in that it describes the amount of time consumed in traversing the intersection. There are many different ways to define delay. As presented in *Traffic Engineering (Second Edition) (36)*, the most frequently used forms of delay are defined below:

a. *Stopped Time Delay*: Stopped time delay is defined as the time a vehicle is stopped while waiting to pass through the intersection.

b. *Approach Delay*: Approach delay includes stopped time, but also includes the time lost when a vehicle decelerates from its ambient speed to a stop, as well as while accelerating from the stop back to its ambient speed. Sometimes it is very difficult to measure decelerate delay in the field without sophisticated tracking equipment.

c. *Travel Time Delay*: Travel time delay is defined as the difference between the driver's desired total time to traverse the intersection and the actual time required to traverse it.

d. *Time-in-Queue Delay*: Time-in-Queue delay is the total time from a vehicle joining an intersection queue to its discharge across the stop-line or curb-line.

Several studies have been conducted to estimate delay at signalized intersections. Among them, the most often quoted model is perhaps the Webster model. In this model *(37)*, Webster estimated delay at isolated traffic signals as a sum of uniform delay (d_u) and random delay (d_r). Uniform delay is the delay at signalized intersection assuming uniform arrival rate. As indicated in HCM 2000, the uniform delay can be expressed as:

$$d_1 = \frac{0.5C\left(1-\frac{g}{C}\right)^2}{1-\left[\min(1,X)\frac{g}{C}\right]} \quad \text{..... (2-1)}$$

where,

d_1 = uniform delay assuming uniform arrivals (s/veh);

C = Cycle length (s); cycle length used in pretimed signal control, or average cycle length for actuated control;

g = effective green time for lane group (s); green time used in pretimed signal control, or average lane group effective green time for actuated control

X = v/c ratio or degree of saturation for lane group.

The random delay can be expressed as:

$$d_r = \frac{X}{2c(1-X)} \quad \text{(2-2)}$$

where *c* is the capacity of a lane group. Webster also estimated an adjustment term by simulation and concluded that control delay can be approximated as $d = 0.9\ (d_u + d_r)$.

Webster model is a very classical delay estimation model and it was widely accepted as an accurate depiction of delay for the idealized case of uniform arrivals, stable flow and no initial queue. Following Webster's work, a number of stochastic models have been developed, including those by Newell *(38)*, Miller *(39) (40)*, McNeil *(41)*, and Heidemann *(42)*. These models generally assume that arrivals are Poisson distributed, with an underlying average rate of vehicles/unit time, and the system remains under-saturated over the analysis period. Therefore these models can not be directly used when traffic demand exceeds intersection capacity for a significant period of time.

The HCM 2000 *(43)* uses control delay as the criteria for LOS of both signalized and unsignalized intersections. In this manual, the total delay was defined as "the difference between the travel time actually experienced and the reference travel time that would result during base conditions, in the absence of incident, control, traffic, or geometric delay". Control delay was defined as the proportion of total delay attributed to control measures. Control delay includes initial deceleration delay, queue move-up time, stopped delay, and final acceleration delay. With respect to field measurements, control delay is

defined as the total elapsed time from the time a vehicle stops at the end of the queue to the time the vehicle departs from the stop line.

The HCM 2000 developed a procedure to estimate average control delay for a given lane group. The average control delay was divided into three components. The first component represents delay assuming the uniform arrival of vehicles. The second component adds an incremental delay to account for stochastic arrivals and occasional oversaturation. The third component adds delay as the result of an initial queue at the beginning of the analysis period. The average control delay per vehicle for a given lane group is given by the following equation:

$$d = d_1 (PF) + d_2 + d_3 \quad \text{(2-3)}$$

where,

d = control delay per vehicle (s/veh);

d_1 = uniform control delay assuming uniform delays (s/veh);

PF = uniform delay progression adjustment factor, which accounts for effects of signal progression;

d_2 = incremental delay to account for effect of random arrivals and oversaturation queues, and

d_3 = residual demand delay to account for initial queues.

In this model, d_1 has the same form as the uniform delay in Webster model (2-1). The incremental delay d_2 can be estimated by the following equation:

$$d_2 = 900T\left[(X-1)+\sqrt{(X-1)^2+\frac{8klX}{cT}}\right] \quad \text{(2-4)}$$

Where T is the length of the analysis period (hrs), k is the incremental delay factor that is dependent on controller settings, and I is the upstream filtering/metering adjustment factor. The model is adjusted for traffic-actuated control with factor k depending on unit extension and degree of saturation. For isolated pretimed signals k= 0.5 and I=1.0.

A set of research studies have been conducted to test and compare existing delay models *(44) (45) (46)*. Luttinen *(44)* compared the HCM2000, Danish DanKap, and Swedish Capcal 2 models with simulation data and indicated that HCM 2000 underestimate capacity and overestimate delay at high degrees of saturation (X>0.75). For traffic-actuated control HCM 2000 estimated somewhat too low delays at low degrees of saturation. Another problem with HCM 2000 model is that it does not consider the extra delay due to the blocking effect of short turning lanes. This effect is emphasized especially in the already problematic situation with high degrees of saturation and a large number of left-turning vehicles.

Qureshi (2003) *(46)* suggested using simulation software to estimate delay for intersections with actuated control. He also illustrated that using current analytical procedures to estimate delay at actuated controlled signalized intersection has the following limitations:

(1) The variability of traffic demand within a given control period cannot be fully considered. Analyses are typically using the average demand within a period;
(2) Unusual arrival and service patterns that do not follow traditional statistical distributions cannot be modeled; and
(3) The models cannot be used to analyze real-time traffic operations, as such operations are typically concerned with instantaneous and cyclic flows rather than average flows.

2.3.2 Delay Models at Unsignalized Intersection

There have been many studies on developing capacity and delay models to evaluate traffic operations at unsignalized intersections. Radwan and Kumares developed a delay-flow rate relationship for undivided and divided 4-lane highways *(47)*. In this study, delay was defined as seconds per vehicle for major and minor roads. The flow rate is the combination of major-minor flow rate. A linear fitting was tried between delay per vehicle in seconds and flow rates on major highways. It was found that the slope of the fitted line for the undivided highway case was much higher than that for the divided highway case. This result was as expected because the highway median permits drivers to perform their crossing maneuver in two steps and consequently, they experience less delay. Moreover, delay for the undivided highway was found to be less than the delay for divided highways as long as the major flow rates were less than 290 and 315 vph for minor rates of 100 and 50 vph (turning movements), respectively.

The Highway Capacity Manual 2000 developed a procedure to estimate the delay, capacity, and level of service of unsignalized intersections *(48)*. A study by Tian, Kyte and Colyar indicated that using the HCM procedure could overestimate delay and underestimate capacity when a minor street left-turn vehicle would cross the nearest approach and stop in the median position while waiting to join the major street traffic, resulting in a two-stage gap acceptance process *(49)*. The two-stage priority situation as it exists at many unsignalized intersections within multilane major streets provides larger capacities and smaller delay as compared to intersections without central storage areas *(50)*. A study by Robinson and Tian presented theoretical models to adjust the basic capacity or delay equations to account for some common occurrences at TWSC intersections: two-stage gap acceptance, flared minor-street approaches, effects of upstream signals, and effects of pedestrians *(51)*. However, these theoretical models have not been calibrated against empirical data.

The HCM 2000 provided updated models to calculate the capacity and delay of unsignalized intersections, including two-way stop-controlled (TWSC) and all-way stop-controlled (AWSC). The procedures for TWSC intersections also account for certain conditions such as effects of upstream signals and of median storage where minor street vehicles can proceed through the intersection in a two-stop process, namely a two-stage gap acceptance process. However, as stipulated in the HCM 2000 methodology, each major-street approach can have up to two through lanes and one exclusive right and/or left-turn lane. Each minor-street approach can have up to three lanes, a maximum of one lane for each movement. This is a limitation of the research on which the procedures are based. The HCM 2000 uses the following model to estimate control delay at TWSC intersections:

$$d = \frac{3600}{c_{m,x}} + 900T\left[\frac{v_x}{c_{m,x}} - 1 + \sqrt{\left(\frac{v_x}{c_{m,x}} - 1\right)^2 + \frac{\left(\frac{3600}{c_{m,x}}\right)\left(\frac{v_x}{c_{m,x}}\right)}{450T}}\right] + 5 \quad \text{(2-5)}$$

where,

d = control delay (s/veh);

v_x = flow rate for movement x (veh/hr);

$C_{m,x}$ = capacity of movement (veh/hr); and

T = analysis time period (hr) (T=0.25 for a 15-min period)

2.4 Safety and Operational Effects of Directional Median Openings and U-turns

Many states and transportation agencies have started taking strict restriction on median opening spacing to reduce the density of full median opening. The Access Management

Manual presented that “when providing a full median opening on the fringe of an urban area, it is important to consider the potential for future signalization. A full median opening that is located where signalized intersection will interfere with efficient traffic progression may need to closed or reconstructed as a directional median opening”. A directional median opening means an opening in a restrictive median which provides U-turn only, and/or left-turn in movements. Replacing a full median opening with a directional median opening will reduce conflict points, simplify driving tasks, and was found to significantly reduce crash rates (Figure 2-1)*(4)(6)(7)(8)*.

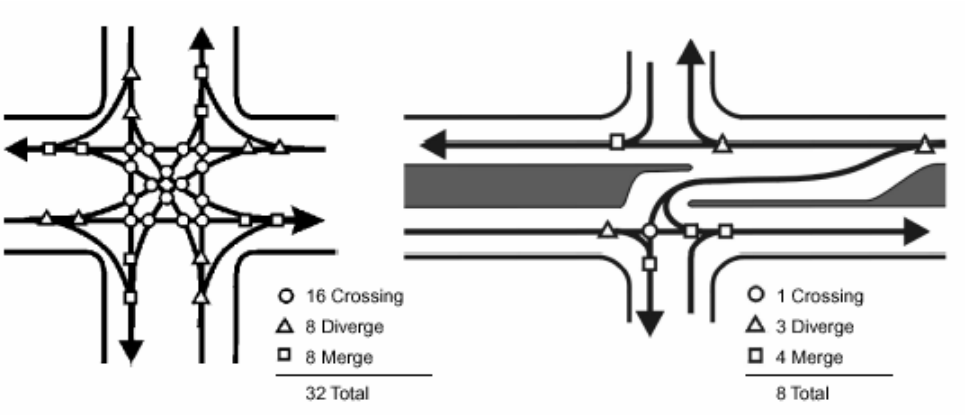


Figure 2-5 Vehicular conflict points at a typical four-way intersection versus a directional median opening.

(Sources: Access Management Manual)

Florida makes extensive use of directional median openings in the State Highway System. By closing existing median openings in some major arterial roads or replacing them with directional median openings, Florida prohibits left-turn exits onto major arterials. Left turn egress movements would be made by turning right onto the arterial road and then making U-turns at downstream median opening or signalized intersection (Figure 2-2).

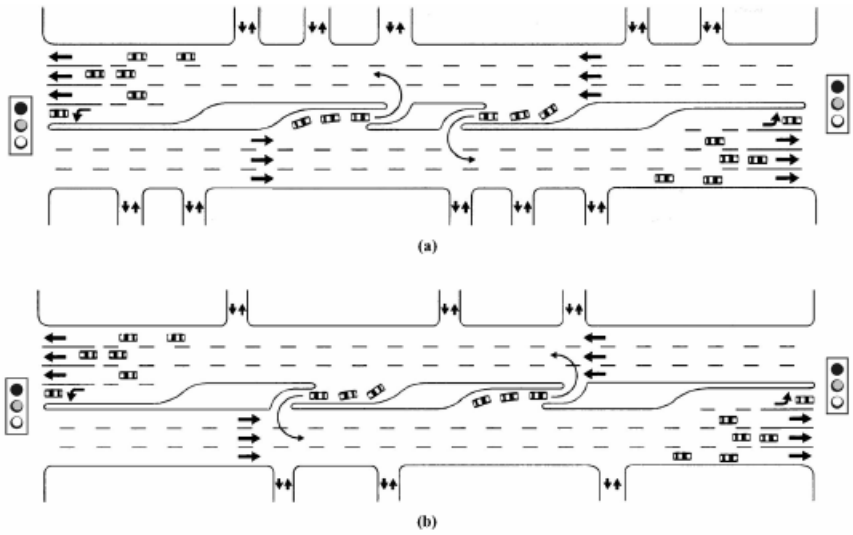


Figure 2-6 Un-signalized directional median openings. *(*a) downstream from the signalized intersections and *(*b) upstream from the signalized intersections. (Sources: Access Management Manual)

Several studies have been conducted to evaluate the operational effects of providing U-turns at median openings as an alternative to direct left turns from a driveway. An analytical model was developed and calibrated in NCHRP Report 420 *(13)* to estimate the travel time savings when unsignalized left turns are diverted for various distances. It can apply to both suburban and rural environments where there are no nearby traffic signals. The key findings are as follows:

(1) A right turn followed by a U-turn will require up to one minute of travel time, assuming a diversion distance of about 1,320 ft;

(2) A single-stage left-turn exit (where medians are too narrow to safely store two or more vehicles) will involve the following delays (not including acceleration times), as shown in Table 2-1. These values suggest that when arterial traffic exceeds 375 to 500 vphpl on a four-lane facility the computed delays would exceed those associated with the right turn/U-turn movement. Higher volumes (700-900 vphpl) that are common along many suburban arterials would produce

even higher left-turn egress delays in theory. In practice, motorists become impatient when gaps exceed 1 to 2 min and are attempt to avoid the direct left turn egress; and

(3) The two-stage left turn process, where medians can safely store waiting vehicles, reduces delays to left-turning traffic. Nevertheless, this process still results in long delays to left-turning vehicles when the volumes on the major street are relatively high (i.e., more than 2,000 vph), and the left turns exceeds 50 per hour. In these cases, even with substantial circuity (1,320 ft or 402m from the access drive to the U-turn median opening, or a 0.5 mi of additional travel) the right turn followed by a U-turn involves less time than calculated left-turn egress movements under moderate to high volumes.

Table 2-1 Left-turn delay under different volume conditions

(Source: NCHRP 420)

Volumes (vph)		Delay per Vehicle (Seconds)
Artery *(Two directions)*	Left-Turn Exit	
1,000	50	20
1,000	100	25
2,000	50	200
2,000	100	530

The USF 2001 and 2004 reports provided very useful information on the safety and operational effects of a widely used access management treatment – *Right-Turns followed by U-turns as an Alternative to the Direct Left Turns from Driveways and Side Streets on multilane highways with 3 or more lanes in each direction*. The study team used five video cameras to collect field data. Huge amount of field data were collected and followed by lengthy data reduction process. Delay and travel time models were developed based on collected field data to quantify the relationship between delay and travel time and explanatory variables such as: conflicting volume, roadway geometrics, and signalization

conditions of downstream signal. The previous two USF studies proved that under high volume conditions, vehicles making a RTUT at downstream median opening or signalized intersection on 6 or more lanes arterials could experience less delay and travel time as compared with those making a DLT; and the percentage of drivers making a RTUT other than a DLT increases with the major road through traffic volume, left-turn in volume from major road onto driveway, and decreases with the distance to downstream signalized intersection.

2.5. Indirect left-turn treatments

In order to address the operational and safety issues related with direct left-turns, Traffic engineers have often looked at other alternatives of facilitating left turns such as median U-turns also known as Michigan U, Bowtie, Superstreet, Paired Intersection, Jughandle and, recently, right turns followed by U-turns. In Wisconsin, U-turns are not permitted at signalized intersections. U-turn movements are provided at “pre-U-turn” openings near signalized intersections. Michigan uses U-turn channels on highways with wide medians and prohibits all turning turns at signalized intersections. U-turn lanes can be provided downstream of signalized intersection. It is also called Michigan “U”, as shown in Figure 2-3 and Figure 2-4. Increasingly, Florida is limiting unsignalized median openings to left turn ingress from the major arterials; hence, drivers desiring to make a direct left-turn onto major road from a driveway must turn right onto the major road and then make a U-turn downstream.

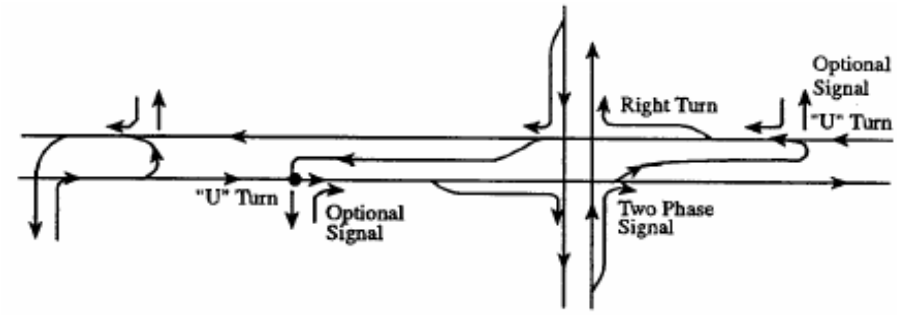


Figure 2-7 Michigan "U"

(Source: NCHRP report 420)

Figure 2-8 Example of median U-turn signing in Michigan

In the Florida Median Handbook, Sokolow *(28)* identified three different U-turn approaches which have been widely implemented in Florida and nationally, including U-turns at signalized intersections, U-turns in advance of signalized intersection and U-turns after signal. He also indicated that providing U-turns in advance of a signalized intersection would result in two successive left-turn lanes and unless there was a substantial length of full median width, drivers may mistakenly enter the U-turn lane. It was also recommended by the handbook that where medians are of sufficient width to accommodate dual left-turn lanes, U-turn could be provided from the inside left turn lane

at signalized intersections. For this specific situation, Florida Median Handbook identified three issues related with U-turn treatments that need to give special consideration to: (1) “Right-on-red” restrictions for side streets. (2) Remember to look at signal operation. (3) Don’t let the signalization intersection work against U-turns.

In the NCHRP report 420, Gluck and Levinson compared and analyzed three different kinds of U-turn approaches including providing U-turn lanes in advance of, at, or beyond signalized intersections. As indicated in this report:

(1) Left-turn lanes can be provided for U-turning vehicles in advance (i.e., upstream) of signalized intersections. This avoids concentrating development-related turning traffic at signalized junctions of major crossroads;
(2) Dual left-turn lanes can be provided at signalized intersections with the inner lane dedicated to U-turns. Many states now provide these lanes; however, they still require multiphase traffic signal controls; and
(3) Left- and U-turn lanes can be provided downstream of signalized intersection, thereby allowing two-phase traffic signal controls.

3 METHODOLOGY

The methodologies used in quantifying the operational effects of right-turn followed by U-turns on 4-lane roadways as an alternative to direct left turns are explained in this chapter. This chapter consists of two sections. The fist section explains the methodology used in the development of delay and travel time models. The second part deals with the estimation of the minimum turning radius required by U-turning vehicles, from operations point of view.

3.1 Delay and Travel Time Models

Vehicle's delay and travel time are very important parameters used by transportation professionals to evaluate the operational performance of intersections. The importance of vehicle delay and travel time is reflected in the use of these parameters in both design and evaluation practices. In addition, when implementing median modification projects, highway agencies often face some public concerns because some people believe that making a right turn followed by a U-turn may cause much longer delay and travel time as compared with those who would otherwise make direct left turns.

One of the major objectives of this project is to develop delay and travel time models of RTUT and DLT. In order to address public concerns, it is necessary to compare delay and travel time of RTUT versus DLT under specific traffic volume levels and roadway geometrics. In addition, from the decision maker's point of view, it is also necessary to quantify the relationship of delay and travel time to possible explanatory variables, including conflicting traffic flow rates, signalized intersection characteristics, and roadway geometric characteristics. This information is very useful for decision makers in determining what kind of median opening will be applicable under given traffic conditions and roadway geometrics.

3.1.1 Operations Analysis of Direct Left Turns

The Highway Capacity Manual 2000 identifies the priority of right-of-way given to each traffic stream at unsignalized intersection. Based on the definition, DLT egress from a driveway or minor street has the lowest priority. Theoretically, DLT egress must, therefore, yield to all other movements at unsignalized intersections. Thus, it is the most likely movement to be delayed. In practice, however, when drivers wishing to make a DLT wait for longer periods, they could become more aggressive and, sometimes, enter the median opening without yielding to other maneuvers, such as left-turn-in vehicles from the major road. On the arterials with wide medians, that can allow one or two vehicles to stop, a DLT maneuver may require four steps, as shown in Figure 3-1 and the specific steps are explained as follows.

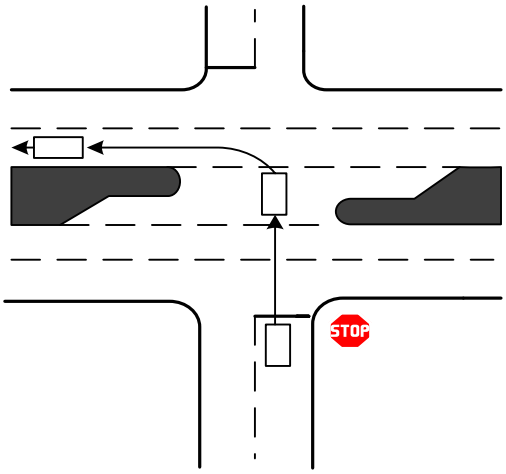


Figure 3-1 DLT egress movements

Step 1: Stopping and waiting at the driveways;

Step 2: Selecting a suitable gap, accelerating across major-road through-traffic lanes and coming to a stop at the median;

Step 3: Stopping at the median, and waiting for a suitable gap from right-side through-traffic. Some drivers only need to select a suitable gap for the inside lane, accelerate and merge into through traffic, whereas some others need at least two clear lanes. Sometimes when several left-turn vehicles stop parallel at the median opening, the vehicles stopped at the right side may block visibility for other drivers. This may result in crashes between left-turning vehicles and through traffic; and

Step 4: Accelerating to operating speed on the major roadway. This may force through traffic to decelerate or make a lane change when the left-turning drivers select a small gap.

Based on the operational analysis of a DLT movement, the average delay and total travel time of DLT can be defined by the following equations:

$$TT_L = t_{L1} + t_{L2} + t_{L3} \quad \text{(3-1)}$$

$$TD_L = t_{L1} + t_{L2} \quad \text{(3-2)}$$

where,

TT_L = average total travel time of DLT movements;

TD_L = average total waiting delay of DLT movements;

t_{L1} = average waiting delay of DLT vehicles at the driveway;

t_{L2} = average waiting delay of DLT vehicles at the median opening; and

t_{L3} = average running time for vehicles leaving the driveway till completing the left turn movement (not including t_{L1} and t_{L2}).

From the above equations, the average total delay of DLT is the sum of average waiting delay of left turns at a driveway and the average waiting delay at a median opening. The average total travel time of DLT is equal to the average total delay plus the average

running time from vehicles leaving the driveway till they stopping at the median opening (t_{L3}).

3.1.2 Operations Analysis of Right Turns plus U-turns

In order to eliminate problems associated with DLT movements, many states and transportation agencies have started installing restrictive medians and directional median openings on multilane highways. Left turn egress movements would be replaced by turning right onto the arterial road and then making U-turns either at downstream median opening or signalized intersection.

3.1.2.1 RTUT at Median Opening

Under high through-traffic volume conditions, left-turn egress becomes more difficult when there is relatively high left-turn-in volume. In this case, drivers would like to make a right turn followed by a U-turn especially when there is a downstream U-turn median opening within the sight distance. As shown in Figure 3-2, vehicles making a RTUT at downstream median opening require four steps.

Step 1: Stopping at the driveway, and making a right turn when there is a suitable gap from left-side through-traffic. This is much easier than left-turn egress because drivers do not need to yield to other movements at the unsignalized intersection at the same time. So, usually when the upstream signal for the major-road through-traffic turns red, there is a large gap created for right turns. There is a potential conflict between a right turn from a driveway and a U-turn at the median opening. Drivers can easily overlook this conflict, which can result in an accident when their attention is focused on the major-road through traffic;

Step 2: Accelerate, weave to the inside lane, and decelerate to a stop at the U-turn median opening. This movement will cause conflicts such as deceleration and lane change of through traffic. There may also be speed reduction of through traffic in the weaving section;

Step 3: Waiting a suitable gap to make a U-turn. Because vehicles making U-turns must wait for a gap on the all through-traffic lanes, these may take longer delays than left turn egress vehicles waiting at the median. U-turns at an exclusive U-turn median opening are much easier and safer than at a full median opening. Sometimes drivers are confused about which maneuver should have higher priority because there is no regulation on the priority of U-turns; and

Step 4: Accelerate to the operating speed of through-traffic. This step is similar to a DLT movement.

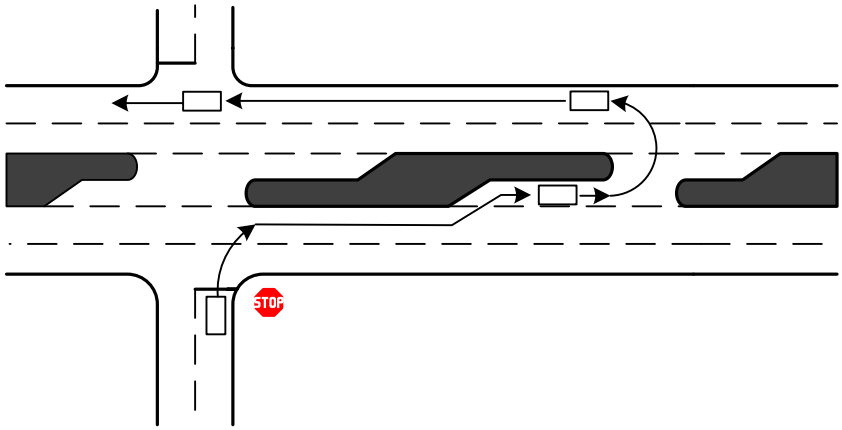


Figure 3-2 RTUT at median opening

Accordingly, to estimate total travel time for vehicles making RTUT at median opening, the following equations can be used:

$$TT_{RUM} = t_{RU1} + t_{RU2} + t_{RU3} + t_{RU4} \quad \text{(3-3)}$$

$$TD_{RUM} = t_{RU1} + t_{RU2} \quad \text{(3-4)}$$

$$t_{RU4} = \frac{l}{1.47 * V_T} \quad \text{(3-5)}$$

where,

TT_{RUM} = average total travel time of RTUT at median opening (seconds),

TD_{RUM} = average total waiting delay of RTUT at median opening (seconds),

t_{RU1}= average waiting delay of right-turn vehicles at the driveway (seconds),

t_{RU2}= average waiting delay of U-turn vehicles at the U-turn median opening (seconds),

t_{RU3}= average running time from leaving the driveway to stopping at the U-turn median opening(not including t_{R1} and t_{R2}) (seconds),

t_{RU4}= average running time of vehicles crossing the weaving distance at the posted speed of through-traffic (seconds),

l = offset distance from the subject driveway to the median U-turn opening(ft.) ($l=l_1+l_2$, as shown in Figure 3-3),

V_T = speed limit on the major arterials (mph).

1.47 = conversion factor from mph to ft/sec.

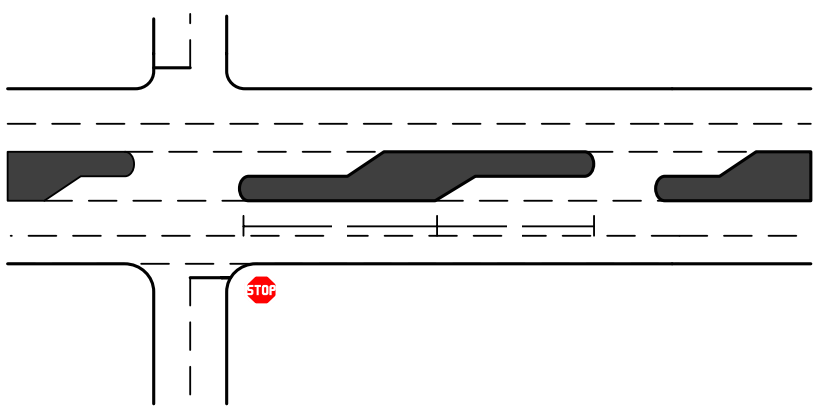


Figure 3-3 The offset distance from subject driveway to downstream median opening ($l=l_1+l_2$)

The average total waiting delay of vehicles making RTUT at downstream median opening includes the delay of right turns at the subject driveway (t_{RU1}) and the delay of U-turns at a median opening (t_{RU2}). The average total travel time of a vehicle making a RTUT at median opening is the sum of average total waiting delay, the average running time in the weaving section, and the average running time needed for a vehicle traversing the length of the offset distance at the operating speed of through-traffic.

3.1.2.2 RTUT at Signalized Intersection

As shown in Figure 3-2, a vehicle making a RTUT at downstream signalized intersection also requires four steps.

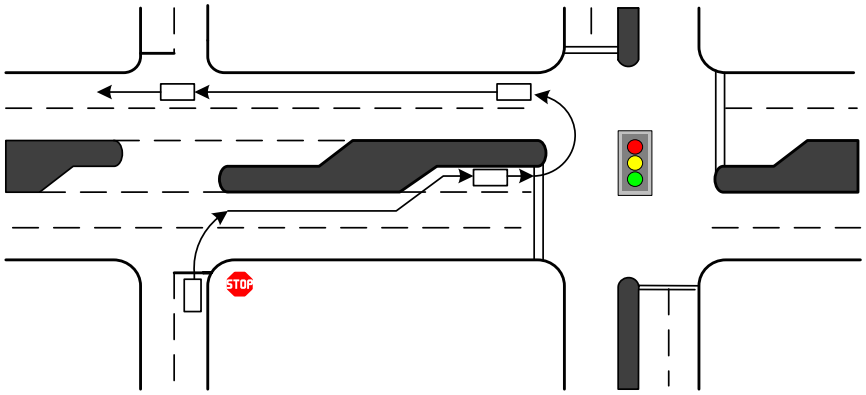


Figure 3-4 RTUT at signalized intersection

Step 1: Stopping at the driveway, and making a right turn onto major road when a suitable gap is available from left-side through-traffic. It is much easier for drivers to make a right turn than to make a left-turn egress at a driveway, due to the fact that vehicles making a right turn do not need to yield to other turning movements at the unsignalized intersection. Usually, when the upstream signal for the major-road through-traffic turns red, there is a large gap for right turns from driveways. Drivers can easily make a right turn without interference with

other turning maneuvers at median opening. It is important to note that there is a potential conflict between a right turn from a driveway and a U-turn at the median opening. Drivers can easily overlook this conflict, which can result in a crash when their attention is focused on the major-road through traffic;

Step 2: Accelerating, weaving to the inside lane, and decelerating to a stop at the exclusive left turn lane of the downstream signalized intersection. This movement will cause conflicts such as deceleration and lane change of through traffic. There may also be speed reduction of through traffic in the weaving section. Sometimes when the left turn lane is not long enough, U-turning vehicles may be blocked by through traffic already queued at the traffic signal. It will cause extra delay to RTUT vehicle;

Step 3: Waiting until the signal turns green to make a U-turn. Delay of U-turns at signalized intersection is highly correlated with signalization conditions and demand flow rate. Field study found that U-turning vehicles could experience relatively long delay at signalized intersection especially when the signal has long cycle length and/or heavy left-turn movements are present at the signal. If U-turn is made during protected signal phase, drivers making U-turns do not need to yield to the through-traffic in other direction of the road. Therefore there is no conflict between U-turning vehicles and through-traffic. For the condition when U-turn is provided during permitted signal phase, drivers making a U-turn must wait until a suitable gap is available from downstream through-traffic and then make a U-turn. This condition is very similar to the condition where U-turn is provided at median opening. It is important to note that there is a potential conflict between U-turning vehicles and right-on-red vehicles in the other approach of the road. Both U-turn drivers and right-turn drivers can easily overlook this conflict, which could result in a crash; and

Step 4: Accelerating to the operating speed of through-traffic. As compared with DLT movement, it does not result in speed reduction in through traffic if U-turn is made during protected signal phase.

Accordingly, to estimate total travel time for vehicles making RTUT movements, the following equations can be used:

$TT_{RU} = t_{RU1} + t_{RU2} + t_{RU3} + t_{RU4}$ ……...……. (3-3)

$TD_{RU} = t_{RU1} + t_{RU2}$……...…... (3-4)

$$t_{RU4} = \frac{l}{1.47 * V_T}$$ ……...……...…… . (3-6)

where,

TT_{RUS} = average total travel time of RTUT at signalized intersection (seconds),

TD_{RUS} = average total waiting delay of RTUT at signalized intersection (seconds)

t_{RU1} = average waiting delay of right-turn vehicles at the driveway (seconds);

t_{RU2} = average waiting delay of U-turn vehicles at the exclusive left turn lane of downstream signalized intersection (seconds)

t_{RU3} = average running time from leaving the driveway to stopping at the exclusive left turn lane (not including t_{R1} and t_{R2}) (seconds);

t_{RU4} = average running time of vehicles crossing the whole roadway section at the posted speed of through-traffic (seconds);

l = the distance form the studied driveway to the U-turn bay, including weaving distance and the left turn storage bay (ft), ($l=l_1+l_2$, as shown in Figure 3-5)

v_T = speed limit on the major arterials (mph); and

1.47 = conversion factor from mph to ft/sec.

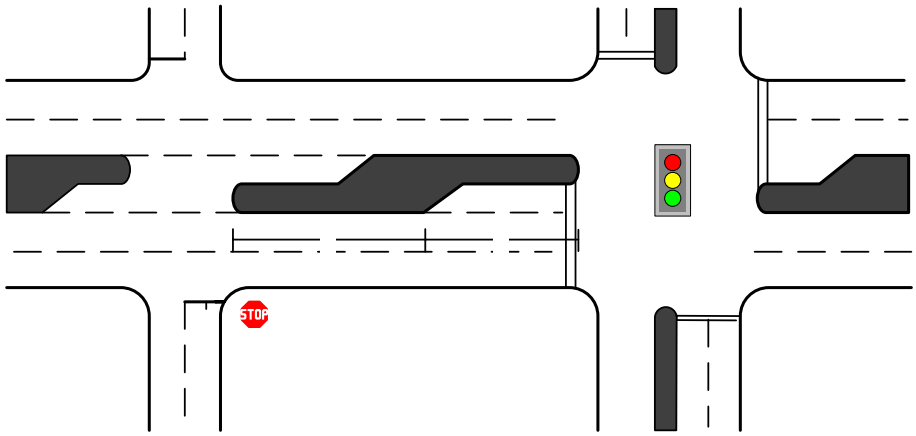


Figure 3-5 The offset distance from subject driveway to signalized intersection ($l=l_1+l_2$)

The average total waiting delay of vehicles making RTUT at signalized intersection includes the delay of right turns at the subject driveway (t_{RU1}) and the delay of U-turns at signalized intersection (t_{RU2}). The average total travel time of a RTUT movement is the sum of average total waiting delay, the average running time in the weaving section, and the average running time needed for a vehicle traversing the length of the whole roadway segment (weaving section plus exclusive left turn lane) at the operating speed of through-traffic. The average total delay and travel time were used to quantify the operational effects of RTUT vs. DLT.

3.2 Effects of Turning Radius on the Operations of U-turning Vehicles

For a satisfactory design for U-turn maneuvers, the width of the highway, including the median, should be sufficient to permit the design vehicle to turn from an exclusive left-turn lane in the median into the lane next to the outside shoulder or outside curb and gutter on the roadway of the opposing traffic lanes. Failure to provide sufficient turning radius at median opening or signalized intersection may pose operational problems to U-turning vehicles and the whole intersection. Under this condition, vehicles may make

“tight” U-turns which has slower turning speed and may require more time to finish the turning movement, therefore, not only affect the operations of U-turning vehicles, but also the vehicles following them.

In order to determine the minimum turning radius required by U-turning vehicles, from the operations point of view, an empirical model was developed to estimate the relationship between the turning radius and the average turning time required by each U-turning vehicle. The model was developed based on field data. The turning radius in this model includes the width of the median nose (R_1), receiving lane width (R_2), and, sometimes, the width of the flare or loons (R_3), as shown in Figure 3-6. The average turning time for a U-turning vehicle was defined as the total elapsed time from a vehicle starts making a U-turn until it finishes the turning movement.

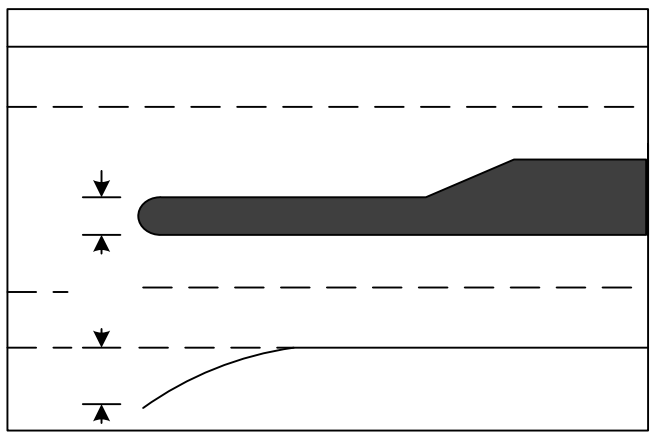


Figure 3-6 The combination of the turning radius ($R=R_1+R_2+R_3$)

4 DATA COLLECTION AND REDUCTION

This study consists of huge amount of field data collection work. Field measurement was conducted on sixteen urban or suburban arterials in Tampa Bay area in Florida, where extensive data were collected using video cameras. A total of more than 600 hours of field data was gathered. This chapter discusses the detailed efforts of data collection and data reduction work.

The major objective of this project is to quantify the operational effects of right turns followed by U-turns on 4-lane arterials as an alternative to direct left turns. The data needed to achieve this objective are listed as follows:

(1) Traffic volume: major-road through-traffic volume, left-turn-in volume from major-road, left-turn-out volume from driveway and side street and right turn followed by U-turn volume;

(2) Traffic delay: delay of left turns and right turns at the subject driveway, delay of left turns at median openings, delay of U-turns at median openings and delay of U-turns at signalized intersection;

(3) Traffic running time: average running time of RTUT crossing the weaving segment, and average running time of DLT crossing the through lanes;

(4) Signal parameters: green arrow time, cycle length, and left- turn volume from inside left turn lane;

(5) Geometric data: cross section, lane assignments, weaving distance, length of left-turn storage bay, and median type, median width, lane width, the width of extra pavements (flared curb, loons, etc.) to facilitate U-turns and

(6) Traffic control features: speed limit, traffic control signs and traffic signals.

4.1 Site Selection

The major purpose of site selection is to find compatible site with high RTUT and DLT volumes. More specifically, the geometric criteria for selecting specific sites include:

(1) The arterial should have a raised-curb median with either a full median opening or a directional median opening that can safely store waiting vehicles
(2) The arterial should have 4 through traffic lanes (2 in each direction);
(3) Speed limit on the arterial should be 40 mph or higher. The FDOT mandates that all new multi-lane projects with design speeds of 40 mph or greater be designed with a restrictive median;
(4) The subject driveway should have either two lanes (one for right-turn and another for the left-turn) or one wide lane with a flared curb so that the two movements do not interfere with each other;
(5) The driveway volumes should be high so that there were a considerable number of RTUT and/or DLT vehicles;
(6) The median width should be wide enough to store the left-turning vehicles, and
(7) The downstream signal should have exclusive left turn lane and protected left turn phasing in the subject approach. The condition in which U-turn movements being accommodated at permitted left turn phase is not considered in this study.

Based on these criteria, sixteen sites located in Tampa Bay area in Florida were selected for field measurement. Among the selected sites, eight of the sites accommodate U-turn at downstream median opening; and the other eight sites provide U-turns at downstream signalized intersection. Table 4-1 shows the geometric characteristics of the signalized intersection sites. The geometrics of median opening sites are shown in Table 4-2. The turning radius accommodated by each site was shown in Table 4-3. The turning radius in

this study was defined as the width of the median nose (R_1), plus the receiving lane width (R_2), and, sometimes, plus the width of the flare or loons (R_3), as shown in Figure 4-1. The turning radius was measured in the field by using measuring wheel.

Table 4-1 Description of selected signalized intersection sites

Site			N_1	N_2	Sp	Median Type	g/C	l(ft)
	Arterial	Location						
1	Bruce B. Downs Blvd.	New Tampa Blvd.	4	Single	45	D	0.35	930
2	Bruce B. Downs Blvd.	Cross Creek	4	Single	45	F	0.13	885
3	Bearss Ave.	22nd st.	4	Single	45	F	0.20	510
4	Fletcher Ave.	Dale Mabry Hwy.	4	Dual	45	F	0.11/0.17	570
5	Alexander	Redman	4	Single	40	F	0.16	285
6	Bruce B. Downs Blvd.	Tampa Palms	4	Dual	45	D	0.21	655
7	Gunn Hwy.	Sheldon	4	Single	45	F	0.20	785
8	56th St.	Fowler Ave.	4	Dual	50	D	0.12	290

Note: N1: # of through lanes; N2: # of exclusive left turn lanes at signalized intersection (single or dual); Sp: the speed limit of the selected arterial; D: directional median opening; F: Full median opening; l: the offset distance from subject driveway to downstream signalized intersection, including weaving distance and left-turn storage bay; and g/c: green cycle ratio. For actuated controlled signal, the g/c ratio here is defined as the maximum green arrow time for left turn phase divided by the average cycle length of the signalized intersection.

Table 4-2 Description of selected median opening sites

Site	N_1	Speed	Median Type	l(ft)

Arterial		Location				
9	Bruce B. Downs Blvd.	Pepple Creek.	4	45	D	800
10	Thonotosassa Rd.	Goldfinch Dr.	4	45	D	665
11	US 301	SR 60	4	45	D	695
12	US 301	Brittany	4	45	F	575
13	Bearss Ave	Dale Mabry Hwy	4	45	F	1150
14	Gunn Hwy.	Normandie	4	45	F	540
15	Gunn Hwy.	Anderson	4	45	F	850
16	Gunn Hwy.	Hangert	4	45	F	590
N1: # of through lanes; Sp: the speed limit of the selected arterial; D: directional median opening; F: Full median opening; l: the offset distance from subject driveway to downstream median opening, including weaving distance and left-turn storage bay;						

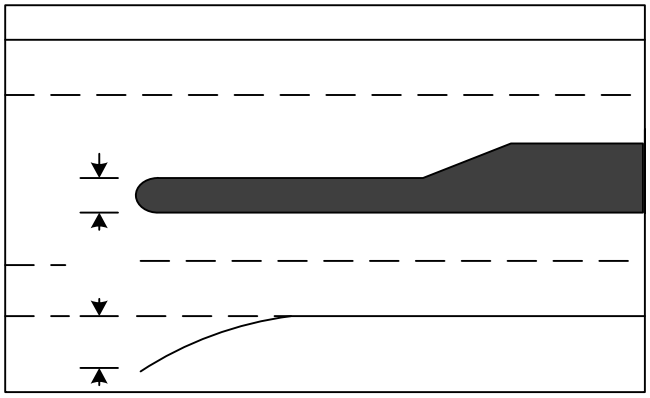


Figure 4-1 The combination of the turning radius

($R=R_1+R_2+R_3$)

Table 4-3 The turning radius accommodated for U-turns at each site

Traffic Signal Sites					
Site			N	R (ft)	
Arterial		Location		R_1	R_2
1	Bruce B. Downs Blvd.	New Tampa Blvd.	4	23	60
2	Bruce B. Downs Blvd.	Cross Creek	4	19	58
3	Bearss Ave.	22nd st.	4	5	29
4	Fletcher Ave.	Dale Mabry Hwy.	4	3	33
5	Alexander	Redman	4	16	24
6	Bruce B. Downs Blvd.	Tampa Palms	4	19	35
7	Gunn Hwy.	Sheldon	4	8	40
8	56th St.	Fowler Ave.	4	15	60
Median Opening Sites					
Site			R (ft)		
Arterial		Location	R_1	R_2	R_3
9	Bruce B. Downs Blvd.	Pepple Creek.	47	24	N/A
10	Thonotosassa Rd.	Goldfinch Dr.	3	24	8
11	US 301	SR 60	25	24	12
12	US 301	Brittany	8	24	21
13	Bearss Ave	Dale Mabry Hwy	18	24	0
14	Gunn Hwy.	Normandie	45	25	N/A
15	Gunn Hwy.	Anderson	21	25	N/A
16	Thonotosassa Rd.				
N: # of through lanes;					

4.2 Description of the Selected Sites

Site 1 is located in the city of Tampa, on Bruce B. Downs Boulevard and New Tampa Boulevard. Bruce B. Downs connects University of South Florida area to New Tampa area and it is a major arterial with two lanes southbound and northbound. The studied driveways is Bruce B. Downs Boulevard which serves a shopping plaza with Circuit City electronics store, a gas station, restaurants and some small businesses. The median opening at the driveway is a directional median opening which restricts direct left-turn movements. From the driveway to join northbound traffic of Bruce B. Downs Boulevard,

drivers need to make a right turn onto the major road followed by a U-turn at signalized intersection of Bruce B. Downs Boulevard and New Tampa Boulevard. The posted speed on Bruce B. Downs Boulevard is 45 mph.

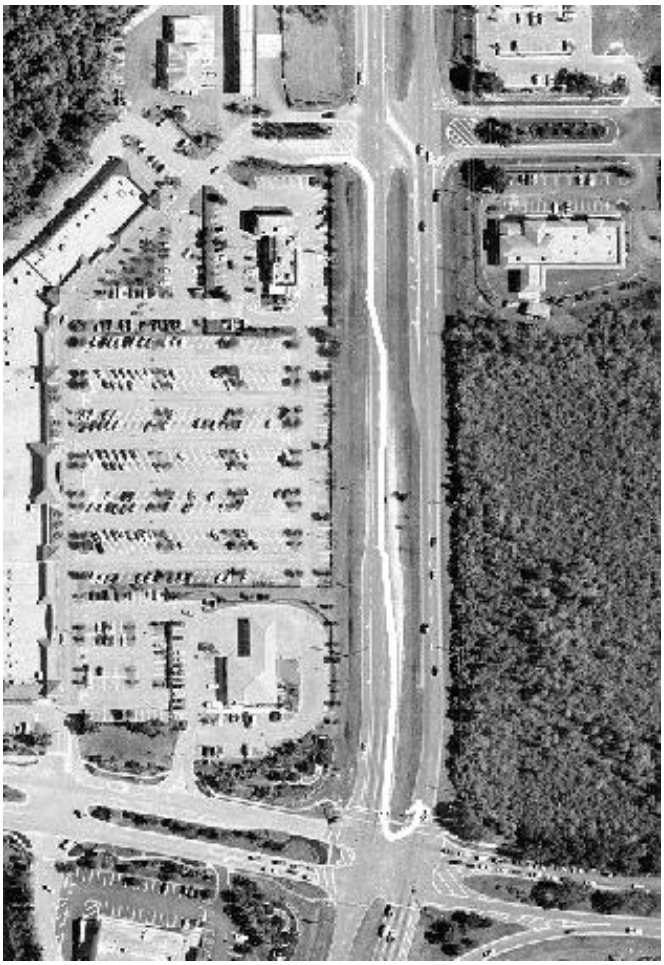


Figure 4-2 Aerial photograph of Site 1

Site 2 is located in the city of Tampa, on Bruce B. Downs Boulevard and Cross Creek Boulevard. The driveway is located on Bruce B. Downs Boulevard at this site and it is a side street that connects Bruce B. Downs Boulevard to residential areas and Winn Dixie Supermarket parking lot. The median opening at the driveway is a full median opening which accommodates direct left-turn egress maneuver. Drivers can either make a direct left turn from the driveway or make a right turn followed by a U-turn at Bruce B. Downs

Boulevard and Cross Creek Boulevard signalized intersection. The speed limit at this segment of Bruce B. Downs Boulevard is 45 mph.

Figure 4-3 Aerial photograph of Site 2

Site 3 is located in the city of Tampa, on Bears Avenue and 22nd Street. Bears Avenue is a major connector between Bruce B. Downs Boulevard and I-275 freeway with two lanes eastbound and westbound. The driveway is located on Bears Avenue and it serves a shopping plaza with Winn Dixie Supermarket and many small businesses. A full median opening is located at the driveway. Drivers can either make a direct left turn from the driveway or make a right turn followed by a U-turn at Bears Avenue and 22nd Street signalized intersection.

Site 4 is located in the city of Tampa, on Fletcher Avenue and Dale Mabry Highway. Fletcher Avenue is a major arterial with two lanes eastbound and westbound. The driveway is located on Fletcher Avenue and serves a shopping plaza with restaurants and

many small businesses. The median opening at the driveway is a full median opening. The drivers egressing of the driveway to join eastbound Fletcher Avenue can either make a direct left turn or make a right turn to westbound Fletcher Avenue followed by U-turn at Fletcher Avenue and Dale Mabry Highway signalized intersection. The posted speed limit on Fletcher Avenue is 45 mph.

Figure 4-4 Aerial photograph of Site 3

Site 5 is located in the city of Plant City, on West Alexander Street and JI Redman Parkway. Alexander Street is a major arterial with two lanes eastbound and westbound. The driveway is located on West Alexander Street and it serves a shopping plaza with Publix supermarket, fast food restaurants, and many small businesses. A full median opening is located opposite the driveway. The drivers egressing the driveway to join westbound West Alexander Street can either make a direct left turn or make a right turn to eastbound West Alexander Street followed by U-turn at West Alexander Street and JI Redman Parkway signalized intersection. The posted speed limit on West Alexander Street

is 40 mph.

Figure 4-5 Aerial photograph of Site 4

Site 6 is located in the city of Tampa, on Bruce B. Downs Boulevard and Tampa Palms Boulevard. This segment of Bruce B. Downs Boulevard had two lanes northbound and southbound. The driveway is located on Bruce B. Downs Boulevard and serves a shopping plaza with Olive Garden and Red Lobster restaurants, fast food restaurants and some other small businesses. A directional median opening is located opposite the driveway. Drivers who want to join northbound Bruce B. Downs Boulevard can only make a right turn to southbound followed by a U-turn at Bruce B. Downs and Tampa Palms Boulevard signalized intersection. Posted speed at this segment of Bruce B. Downs Boulevard is 45 mph.

Figure 4-6 Aerial photograph of Site 5

Figure 4-7 Aerial photograph of Site 6

Site 7 is located in the city of Citrus Park, on Gunn Highway and Sheldon Road. Gunn Highway is an arterial with two lanes eastbound and westbound. The driveway is located on Gunn Highway and it serves a shopping plaza with Target Supermarket and many small businesses. A full median opening is located opposite the driveway. Drivers who want to join eastbound Gunn Highway can either make direct left turn or make a right turn to westbound Gunn Highway followed by a U-turn at Gunn Highway and Sheldon Road three-leg signalized intersection. The posted speed limit on Gunn Highway is 45 mph.

Site 8 is located in the city of Tampa, on 56th Street and Fowler Avenue. 56th Street is major connector between Fletcher Avenue and Fowler Avenue at this segment with two lanes southbound and northbound. The driveway is located on 56th Street and it serves Eckerd Pharmacy and Taco Bell fast food restaurant. There is no median opening located opposite the driveway. Drivers only have the choice of right turn to southbound 56th Street followed by U-turn at 56th Street and Fowler Avenue signalized intersection to join northbound 56th Street. The posted speed on this segment of 56th Street is 50mph.

Figure 4-8 Aerial photograph of Site 7

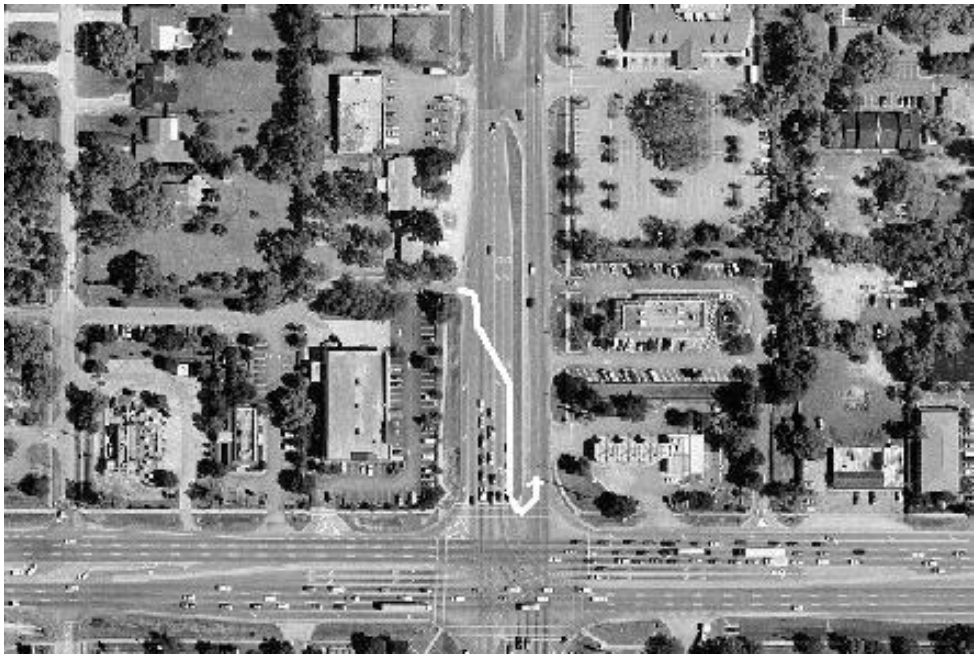


Figure 4-9 Aerial photograph of Site 8

Site 9 is located in the city of Tampa, on Bruce B. Downs Boulevard and Pebble Creek. Bruce B. Down Boulevard has two lanes southbound and northbound at this segment. The driveway is Pebble Creek Boulevard which connect big residential areas and some small businesses' parking lots to Bruce B. Downs Boulevard. The driveway has one lane for the egress of vehicles and the median restricts DLT movements. The speed limit at this segment of Bruce B. Downs Boulevards is 45 mph.

Site 10 is located in the city of Plant City, on Thonotosassa Road and Goldfinch Drive. Thonotosassa Road is one of the major connectors between I-4 freeway and Plant City and has two lanes in each direction. Driveway is located on Thonotosassa Road and it serves a shopping plaza with Publix supermarket and many small businesses. A directional median opening is located opposite the driveway. Right turn followed by a U-turn is the only choice for the drivers who want to join northbound traffic of Thonotosassa Road. The speed limit is 50 mph.

Figure 4-10 Aerial photograph of Site 9

Site 11 is located in the city of Brandon, on US 301 Highway and State Road 60. US 301 Highway has two lanes southbound and northbound. Driveway is located on US 301 Highway and it serves a plaza and major parking lot. A directional median opening is located opposite of the driveway. The posted sped limit on this segment of the US 301 highway is 50 mph.

Site 12 is located in the city of Brandon, on US 301 Highway and Brittany Road. US 301 Highway at this segment still has two lanes at each direction. Driveway is a connector street between US 301 Highway and major business area. Full median opening located opposite the driveway allows drivers to make both direct left turn and right turn followed by a U-turn. The posted speed limit is 50 mph.

Figure 4-11 Aerial photograph of Site 10

Figure 4-12 Aerial photograph of Site 11

Figure 4-13 Aerial photograph of Site 12

Site 13 is located in the city of Tampa, on Ehrlich Road and Dale Mabry Highway. Ehrlich is a major divided arterial oriented in the east-west direction with two lanes each direction. The driveway is located on Ehrlich Road and it serves a shopping plaza with many restaurants, chain stores and small business. A full median is located opposite the driveway. The posted speed limit on Ehrlich road is 45 mph.

Site 14 is located in the city of Tampa, on Gunn Highway and Henderson Road. Gunn Highway is a major divided arterial with two lanes eastbound and westbound. The driveway is located on Gunn Highway and it serves a shopping plaza with Wal-Mart Supermarket, fast food restaurants, and some small businesses. A full median opening is located of opposite the driveway. The posted speed limit is 45 mph.

Figure 4-14 Aerial photograph of Site 13

Figure 4-15 Aerial photograph of Site 14

Site 15 is located in the city of Tampa, on Gunn Highway and Anderson Road .At this segment Gunn Highway still has two lanes at each direction. The driveway is located on Gunn Highway and it serves a shopping plaza with Winn Dixie Supermarket, Burger King fast food restaurant, and some small businesses. A full median opening is located of opposite the driveway. The posted speed limit at this segment of Gunn Highway is 45 mph.

Site 16 is located in the city of Plant City, on Thonotosassa Road and Goldfinch Drive. Thonotosassa Road is one of the major connectors between I-4 freeway and Plant City and has two lanes in each direction. The drive is Goldfinch Drive at this site which is a connector between Thonotosassa Road and residential areas. A full median opening is located opposite the driveway. In this segment the posted speed limit is 45 mph.

Figure 4-16 Aerial photograph of Site 15

Figure 4-17 Aerial photograph of Site 16

4.3 Data Collection

In this study, equipments used for data collection include 5 video cameras, VCRs, batteries, inverters, and TVs. In order to cover the whole right turn followed by U-turn procedure, the two-story scaffoldings were installed in the field. Figure 4-9 shows that cameras were set up at the top of a 15-feet high scaffolding. The equipments used for data collection are shown in Figure-10 and Figure-11. The basic cameras locations in the field are shown in Figure 4-12, median opening sites; and Figure 4-13, for signalized intersection sites.

A typical data collection day generally starts at 7:00 in the morning. Before start recording, all video cameras were synchronized so that the data extracted from different videotapes can be matched. Data collection usually was conducted during weekday 7:00 AM to 7:00PM. More than 30 hours data were collected in each site. Data were not collected during inclement whether or when there were unusual traffic conditions in the road.

Figure 4-18 Equipments setup in the field

Figure 4-19 Equipments setup in the field

Figure 4-20 Equipments setup in the field

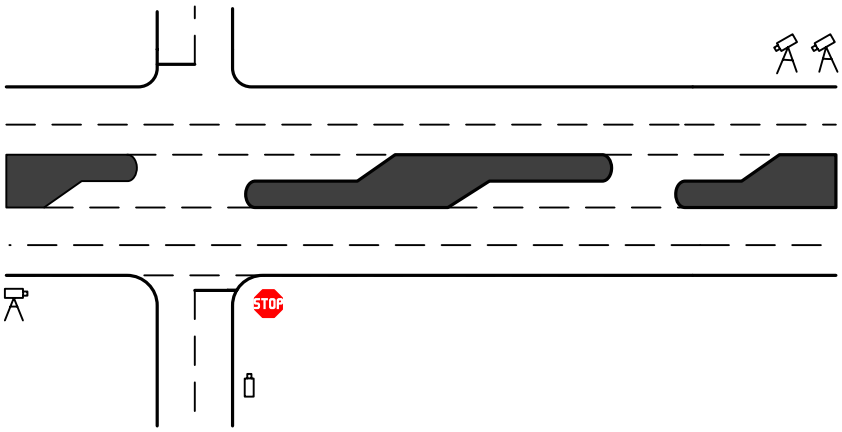


Figure 4-21 Basic camera locations in the field (median opening sites).

4.4 Data Reduction

The collected videotapes were reviewed in office. In this project, the reduction of field data is very hard and timing consuming since there were more than 600 hours videotapes to be reviewed. Each videotape was reviewed for five to six times in order to gather

different categories of data needed for further analysis. Each vehicle coming from the driveway making a DLT or a RTUT was tracked. Since all video cameras have already been synchronized in field, data collected by different video cameras can be matched. By reviewing videotapes, the following information was recorded:

(1) Waiting delay: waiting delay of DLT and RTUT vehicles at driveway; waiting delay of DLT vehicles at median opening; waiting delay of U-turning vehicles at media opening and waiting delay of RTUT vehicles at signalized intersection;
(2) Travel time: the total travel time of DLT and RTUT vehicles;
(3) Traffic volume: major-road through-traffic volume, left-turn-in volume from major-road, left-turn-out volume from driveway, and right turn followed by U-turn volume; and
(4) Signal parameters: green arrow time, cycle length, queue discharge time, queue discharge headways for left-turning and U-turning vehicles, and left turn volume from inside left turn lane.

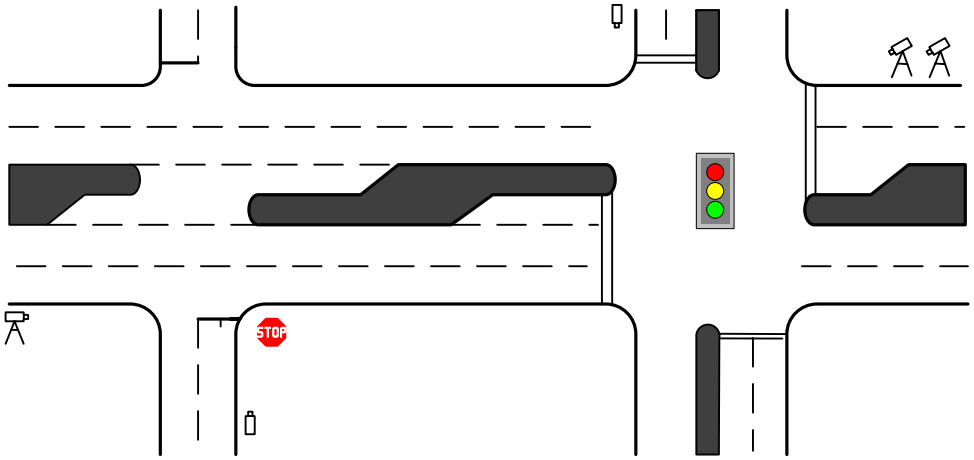


Figure 4-22 Basic camera locations in the field (signalized intersection sites).

Total delay of each vehicle at driveway is measured from a vehicle stops at the waiting queue until it exits the stop line. The definition of delay here consists of queue time and service time. This definition is a little bit different from the definition of average control delay in HCM, since vehicles' deceleration and acceleration were not considered when estimating delay in this project. The waiting delay of left-turns at a median opening was measured by recording the time from the vehicle stops at the median until it leaves the median. The waiting delay of U-turning vehicles at median opening was recorded as the time from the vehicle stops at the median until it starts making a U-turn. The waiting delay of U-turning vehicles at signalized intersection was recorded as the time from the vehicle stops at the inside left turn lane until it starts making a U-turn. By tracking each individual vehicle, the total travel time of each DLT or RTUT vehicle can also be recorded.

The reduction of field data is based on five-minute time interval. In each interval, the average total delay and travel time for vehicles making DLT or RTUT were recorded. In addition, traffic volume data, including major-road through-traffic volume, left-turn-in volume from major-road, left-turn-out volume from driveway, right turn followed by U-turn volume, and left-turn volume from inside left-turn lane at the signalized intersection, were also counted based on this time interval.

5 ANALYSIS OF OPERATIONAL EFFECTS

5.1 General

In this study, the operational effects of right turns followed by U-turns on 4-lane arterials as alternatives to direct left turns is analyzed through the following approaches:

(1) The comparison of the average delay of DLT and RTUT under various levels of traffic volume and roadway geometrics. This objective was accomplished through the development of delay models for these two maneuvers

(2) The comparison of the average total travel time of DLT and RTUT under various levels of traffic volume and roadway geometrics. This goal was attained by building travel time models for these two maneuvers; and

(3) The comparison of the operations of two widely used U-turn treatments, providing U-turns at a median opening in advance of signalized intersection and U-turns at signalized intersections, were also compared based on the delay and travel time models developed in this study.

The delay and travel time models were built based on field data gathered from selected sites. As mentioned before, the reduction of field data was based on five-minute time interval. When specifying models, the original data at five-minute intervals were aggregated to fifteen-minute intervals. In this study, statistical analysis was performed by the use of the SPSS software.

In addition, in order to determine the minimum turning radius required by U-turning vehicles, from the operations point of view, an empirical model was developed to estimate the relationship between the turning radius and the average turning time required by each U-turning vehicle.

5.2 Average Delay

Delay is an important measure of effectiveness (MOE) of traffic operations. The HCM 2000 uses control delay as the criteria to evaluate the level of service (LOS) of signalized intersections. Control delay is defined as the proportion of total delay attributed to control measures, which includes initial deceleration delay, queue move-up time, stopped delay, and final acceleration delay. Delay defined in this study does not include vehicles' deceleration and acceleration time; because it is very difficult to measure deceleration and acceleration in the field without sophisticated tracking equipment. In this study, delay is defined as the total elapsed time from the time a vehicle stops at the end of the queue to the time the vehicle departs from the stop line.

5.2.1 Delay Model for Direct Left Turn

Data collected from sites with full median openings were used to build delay model for direct left turn movements. As mentioned earlier in this chapter, the original data set at five-minute intervals were aggregated to fifteen-minute intervals when specifying models. Figure 5-1 shows the conflicting volumes affecting the delay of DLT movement.

Statistical analysis showed that both linear and exponential forms are suitable for describing the relationship between the average delay of DLT movement and conflicting volumes. However, the exponential form was found to have better goodness of fit to field data. The delay model was described as Equation 5-1.

$$TD_L = e^{a_1 TV + a_2 SPLIT + a_3 DLTV + a_4 LTIN + a_0} \quad \text{..... (5-1)}$$

Where,

TD_L = average total delay of DLT (sec/ veh),

TV = flow rate of major-road through-traffic (vph),

DLTV = flow rate of DLT from a driveway (vph),

LTIN = flow rate of left-turn-in from major roads (vph),

SPLIT = percentage of upstream through traffic flow rate,

SPLIT=TV1/ (TV1+TV2), and

a_0, a_1, a_2, a_3, a_4 = parameters

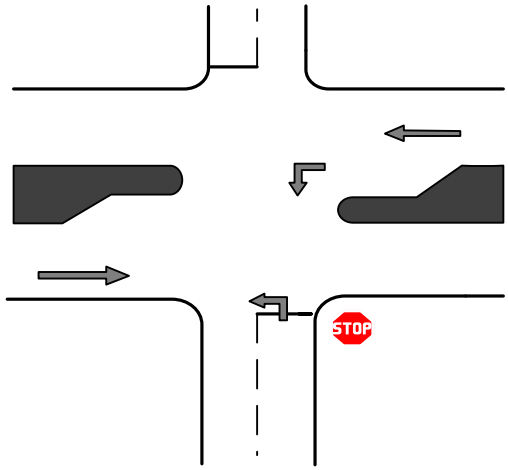


Figure 5-1 Traffic flows affecting the delay of DLT

In total, 464 observations at fifteen-minute intervals were used to estimate the delay model for DLT movement. The dependent variable (average total delay of DLT) refers to average total waiting delay per vehicle making a left turn during a fifteen-minute period. The independent variables, including left-turn-in flow rate, through traffic flow rate, and DLT flow rate, are equal to four times traffic volume at fifteen-minute intervals. Multiple regression analysis was carried out to determine the best model by testing different independent variables. The statistical characteristics of collected data are given in Table 5-1. The final regression results are listed in Table 5-2.

As shown in Table 5-2, all independent variables are significant at a 95 percent level of confidence. The adjusted R square value is 0.33. The residual plot for each independent variable was obtained from the results of regression analysis. It was found that the residual

for each independent variable was randomly scattered about the x-axis line, which indicated that the model was correctly specified. According to these parameter estimates, the developed regression equation is:

$$TD_L = 6.81e^{0.0003TV+0.446SPLIT+0.0034DLTV+0.001LTIN} \quad \text{(5-2)}$$

Where,

TD_L = average total delay of DLT (sec/ veh),

TV = flow rate of major-road through-traffic (vph),

DLTV = flow rate of DLT from a driveway (vph),

LTIN = flow rate of left-turn-in from major roads (vph), and

SPLIT = percentage of upstream through traffic flow rate,

SPLIT=TV1/ (TV1+TV2).

Table 5-1 Descriptive statistics of the DLT dalay data

	N	Range	Minimum	Maximum	Mean	Std. Deviation
TV	464	3617.44	898.56	4516.00	2315.72	557.12134
SPLIT	464	.39	.34	.73	.5111	.09602
DLTV	464	92.00	12.00	104.00	41.5345	20.91944
LTIN	464	639.84	20.00	659.84	132.454	112.53878
TD	464	77.95	5.67	83.62	25.9036	12.20055

Based on Equation 5-2, curves for the average delay of DLT under different levels of traffic volumes can be developed. Figure 5-2 shows a group of curves for average delay of DLT assuming the left-turn-in flow rate from the major road is 100 vph, split is 0.5, and the flow rate of DLT is made equal to 50, 100, and 150 vph, respectively. The x-axis represents the flow rate of two-directional through-traffic on the major road. The y-axis represents the average total delay of DLT.

Table 5-2 Regression results for delay models of DLT

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.575	.33	.325	.37178

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	31.400	4	7.850	56.793	.000
Residual	63.443	459	.138		
Total	94.842	463			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	1.9181	.168		11.391	.000
TV	.0003	.000	.389	7.851	.000
SPLIT	.4460	.209	.095	2.131	.034
DLTV	.0034	.001	.156	3.876	.000
LTIN	.0010	.000	.250	5.728	.000

Dependent Variable: lnTD

5.2.2 Delay Model for RTUT at Median Opening

Field data collected from site nine to site sixteen were used to develop the delay model for RTUT at median opening. Sites nine, ten and eleven had directional median openings and therefore, only right turn followed by U-turn was allowed. Other sites had both DLT and RTUT options where the intervals with only RTUT movements were included in the analysis data set.

The average total delay model for RTUT at median opening can be described as follows:

$$TD_{RUM} = e^{a_1 TV + a_2 RUV + a_3 SPLIT + a_0} \quad \text{(5-3)}$$

where,

TD_{RUM} = average total delay of RTUT at median opening. (sec./ veh),

TV = flow rate of major-road through-traffic (vph),

RUV = flow rate of RTUT (vph),

SPLIT = percentage of upstream through-traffic flow rate,

SPLIT=TV1/ (TV1+TV2), and

a_0, a_1, a_2, a_3 = parameters.

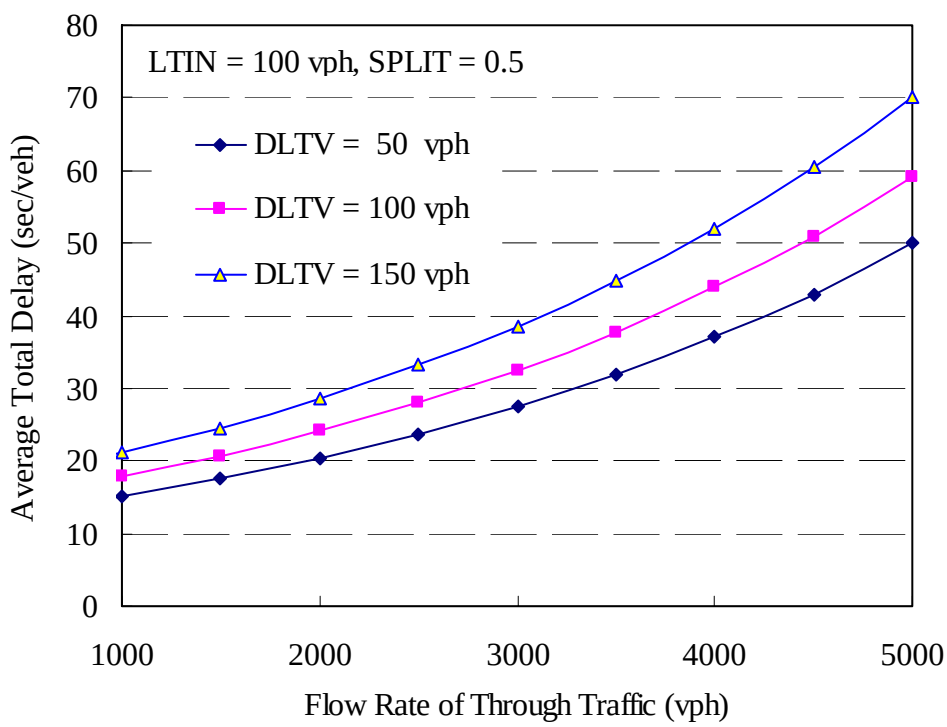


Figure 5-2 Curves for the average total delay for DLT (LTIN=100 vph, Split=0.5)

The dependent variable was the average total delay of vehicles making RTUT at median opening, including the average delay of right turns at the subject driveway and average delay of U-turns at the median opening at fifteen-minute intervals. As shown in Figure 5-3,

variables expected to affect the average delay of RTUT at median opening included two-directional through-traffic flow rate (TV), split, and RTUT flow rate (RUV). RUV refers to the number of vehicles making a right turn at the driveway followed by a U-turn at the downstream median opening in one hour.

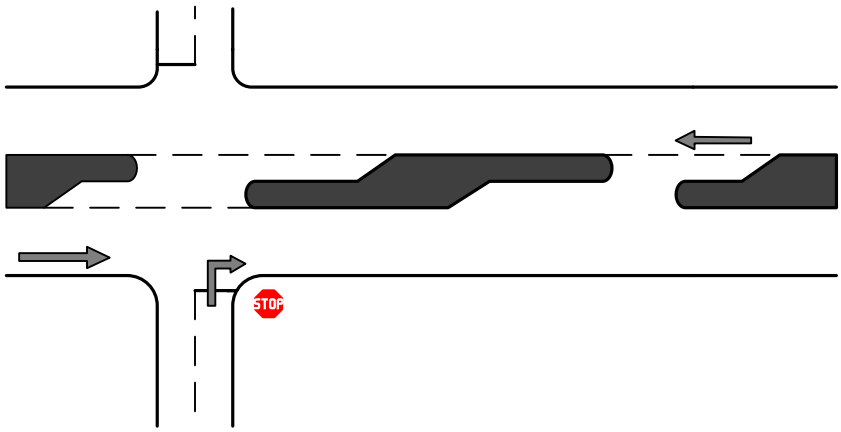


Figure 5-3 Traffic flows affecting the delay of RTUT at median opening

A total of 358 observations at fifteen-minute intervals were used to perform the regression analysis. Table 5-3 illustrates the descriptive statistics of the collected data. The mean of average total delay of RTUT (19.7 sec. /vehicle) was less than the mean of average total delay of DLT (25.9 sec./vehicle). The sample standard deviation for average delay of RTUT was much less than those for DLT. The split of through-traffic flow-rate has the range from 0.4 to 0.7. The maximum and minimum through-traffic flow rate is 1496 vph and 5184 vph, respectively.

The regression results for RTUT delay at median opening are given in Table 5-4. The model includes three independent variables, major-road through-traffic flow rate, RTUT flow rate, and split. The regression analysis suggested that major-road through-traffic flow rate and SPLIT were significant at a 95% confidence level. The independent variable RUV was significant at a 90 percent confidence level. The negative sign for SPLIT implies that

the downstream through-traffic flow rate has a greater impact on the delay of RTUT movements. The adjusted R-square of the model was about 0.31.

Table 5-3 Descriptive statistics of RTUT delay at median opening

	N	Range	Minimum	Maximum	Mean	Std. Deviation
TV	358	3688	1496	5184	2407.30	535.336
SPLIT	358	.30	.40	.70	.5223	.05169
RUV	358	152	12	164	64.44	35.704
L	358	610	540	1150	774.12	113.880
TD	358	36.64	8.40	45.04	19.7355	6.99707

Based on regression results, the equation for the average delay of vehicles making RTUT at median opening was as follows:

$$TD_{RUM} = 13.2e^{0.00037TV - 1.152SPLIT + 0.0008RUV} \quad \text{(5-4)}$$

where,

TD_{RUM} = average total delay of RTUT at median opening. (sec./ veh),

TV = flow rate of major-road through-traffic (vph),

RUV = flow rate of RTUT (vph), and

SPLIT = percentage of upstream through-traffic flow rate,

SPLIT=TV1/ (TV1+TV2)

A group of curves for the average total delay of RTUT can be developed based on Equation 5-4. Figure 5-4 shows a group of curves for average total delay of RTUT assuming that the SPLIT is equal to 0.5 and the RTUT flow rates are made equal to 50, 100, and 150 vph, respectively. The x-axis represents the major-road through-traffic flow rate; the y-axis represents the average total delay of RTUT. The three curves are very close because the average delay is not very sensitive to the flow rate of RTUT.

Table 5-4 Regression results for delay models of RTUT at median opening

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.561	.315	.309	.28095

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	12.837	3	4.279	54.212	.000
Residual	27.942	354	.079		
Total	40.779	357			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	2.579	.154		16.694	.000
TV	.00037	.000	.592	10.795	.000
SPLIT	-1.152	.338	-.176	-3.411	.001
RUV	.0008	.000	.080	1.681	.094

Dependent Variable: lnTD

5.2.3 Delay Model for RTUT at Signalized Intersection

In this study, the total delay of vehicles making RTUT at signalized intersection includes vehicles waiting delay at driveway and delay at signalized intersection. Field measurement found that the delay of U-turning vehicles at signalized intersection was decided by the signalization conditions and demand flow rate, including g/c ratio, cycle length, and left-turn flow rate from inside exclusive left-turn lane. Variables expected to affect the delay of U-turning vehicles at driveway include major-road through-traffic flow rate, split and RTUT flow rate, as shown in Figure 5-5.

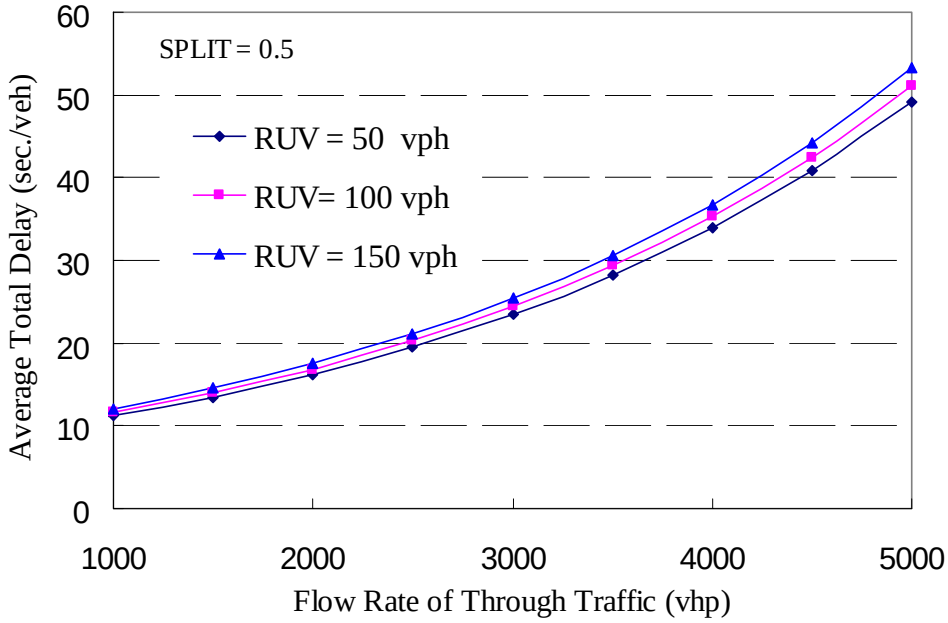


Figure 5-4 Curves for the average total delay for RTUT at median opening

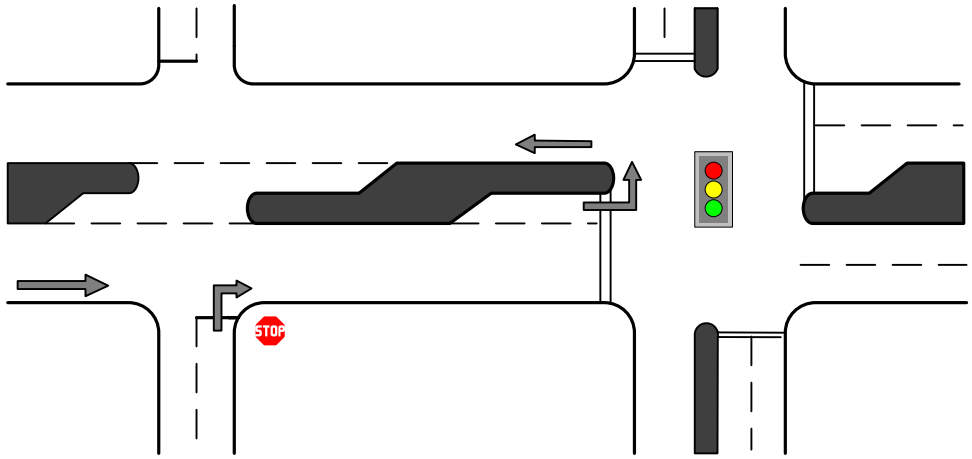


Figure 5-5 Traffic flows affecting the delay of RTUT at signalized intersection

The average total delay model for vehicles making RTUT at downstream signalized intersection is described as follows:

$$TD_{RUS} = e^{a_1 TV + a_2 SPLIT + a_3 RUV + a_4 LTV + a_5 G/C + a_6 C + a_0} \quad \text{(5-5)}$$

Where,

TD_{RUS} = average total delay of RTUT at signalized intersection (sec/ veh),

TV = flow rate of major-road through-traffic (vph),

RUV = flow rate of RTUT from a driveway (vph),

G/C = g/c ratio for exclusive left turn phase,

C = Cycle length (sec); cycle length used in pretimed signal control, or average cycle length for actuated control;

LTV = left-turn flow rate from inside left turn lane (vph);

SPLIT = percentage of upstream through traffic flow rate,

SPLIT=TV1/ (TV1+TV2), and

a_0, a_1, a_2, a_3, a_4, a_5, a_6 = parameters

The dependent variable in this model is the average total waiting delay per vehicle making a right turn followed by a U-turn at downstream signalized intersection during a fifteen-minute interval. In this study, g/c ratio is defined as the green arrow time for left-turn phase divided by the cycle length of selected signal. If the study site is an actuated signal with varying cycle and phase length, g/c ratio is defined as the maximum green arrow time for left-turn phase divided by average cycle length.

A total of 424 observations at fifteen-minute intervals were used to perform the regression analysis. The statistical characteristics of collected data are given in Table 5-5. The regression results are listed in Table 5-6.

Table 5-5 Descriptive statistics of RTUT delay at signalized intersection

	N	Range	Minimum	Maximum	Mean	Std. Deviation
TV	424	3184	1056	4240	2202.92	610.725
SPLIT	424	.37	.35	.72	.4594	.04705
RUV	424	136	12	148	35.17	22.326
C	424	120	80	200	149.31	16.515
G/C	424	.25	.11	.35	.2275	.10920
LTV	424	360.00	4.00	364.00	164.415	63.27887
TD	424	130	18	149	78.50	20.448

Table 5-6 Regression results for delay models of RTUT at signalized intersection

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.564	.318	.308	.23579

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	10.809	6	1.801	32.403	.000
Residual	23.183	417	.056		
Total	33.992	423			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	2.726	.211		12.895	.000
TV	6.822E-05	.000	.147	2.383	.018
SPLIT	.289	.284	.048	1.018	.309
RUV	.00184	.001	.145	2.242	.025
C	.009	.001	.527	10.315	.000
G/C	-.851	.163	-.328	-5.220	.000
LTV	.00058	.000	.130	1.956	.051

Dependent Variable: lnTD

As shown in Table 5-6, all independent variables are significant at a 95 percent level of confidence, except the variable SPLIT. The adjusted R square value is 0.31. The residual plot for each independent variable was obtained from the results of regression analysis. It was found that the residual for each independent variable was randomly scattered about the x-axis line, which indicated that the model was correctly specified. According to these parameter estimates, the final developed regression equation is:

$$TD_{RUS} = 15.3e^{0.0001TV+0.289SPLIT+0.0018RUV+0.009C-0.851G/C+0.0006LTV} \quad \text{..... (5-6)}$$

Where,

TD_{RUS} = average total delay of RTUT at signalized intersection (sec/ veh),

TV = flow rate of major-road through-traffic (vph),

RUV = flow rate of RTUT from a driveway (vph),

G/C = g/c ratio for exclusive left turn phase,

C = Cycle length (sec); cycle length used in pretimed signal control, or average cycle length for actuated control;

LTV = left-turn flow rate from inside left turn lane (vph); and

SPLIT = percentage of upstream through traffic flow rate,

SPLIT=TV1/ (TV1+TV2)

As shown in Equation 5-4, the coefficient of TV is very small (0.0001), which implies that the average total delay of RTUT is not sensitive to the change in flow rate of through-traffic. The coefficient for G/C is negative, which suggests that providing a large g/c ratio for left-turn phase will reduce RTUT delay at signal. Obviously, a long cycle length will result in long waiting delay for vehicles at signalized intersection. Therefore, the coefficient for C is positive.

Based on Equation 5-6, different curves can be developed under different volume and roadway geometric conditions. Curves in Figure 5-6 are developed assuming a g/c ratio of

0.25, cycle length of 150 sec, SPLIT of 0.5, and left-turn flow rate from inside left turn lane at signalized intersection of 150 vph. In this figure, the x-axis represents the flow rate of major-road through-traffic; and the y-axis refers to the average total waiting delay per vehicle making a right turn followed by a U-turn at downstream signalized intersection during a fifteen-minute interval.

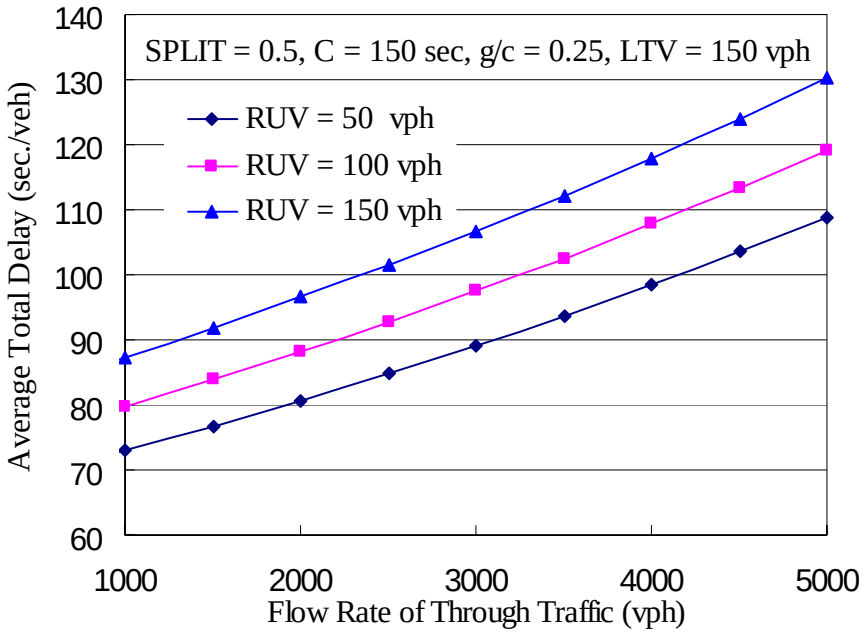


Figure 5-6 Curves for the average total delay for RTUT at signalized intersection (SPLIT=0.5, LTV=150vph, G/C=0.25, C=150sec)

5.2.4 Delay Comparison

One of the major objectives of this project is to compare delay of three different left-turn treatments on 4-lane arterials under specific traffic and roadway geometric conditions. The comparison of the delay was based on the field data and delay models developed in this model.

The USF 2001 and 2004 studies have proved that at under high through-traffic volume level, direct left-turns resulted in longer stop delay as compared with right turns followed

by U-turns on multilane arterials with 3 or more lanes in each direction. However, Even though the right-turn followed by U-turn was identified as favorable from both traffic operational and safety points of views for major arterials with three or more lanes in each direction, the situation may not be the same for 4-lane facilities. One consideration behind this thinking is the shorter crossing distance needed by direct left turn vehicles in the case of 4-lane roadways since crossing 2 lanes at a time may not be as difficult as crossing three lanes. In addition, traffic volume on 4-lane roadway is usually lower than the volume on six to eight lanes arterials. Under low volume conditions, sometimes, it is quite easy for drivers to make a DLT, without waiting at the driveway for very long time. Therefore, it may be advisable to separately evaluate direct left turns and right turns followed by U-turns on 4-lane facilities.

The average delay of each vehicle making a DLT, or a RTUT at downstream median opening or signalized intersection was compared based on the field data, as shown in Figure 5-7. It is clear that, among the three different left-turn treatments on 4-lane arterials, vehicles making a RTUT at downstream median opening will experience the lowest delay. Averagely, vehicles making a RTUT at signalized intersection will experience around 55 seconds extra delay than those making a DLT or a RTUT at median opening.

In Table 5-7, the field data were divided into different categories based on the through traffic volume and the direct left-turn volume/RTUT volume. In each category, the average delay of vehicles making DLT or RTUT at median opening or signalized intersection were calculated and compared. The comparison in Table 5-7 got similar conclusion as that from the comparison in Figure 5-7. In each category, vehicles making a RTUT at median opening experience lest delay, then DLT, and then RTUT at signalized intersection.

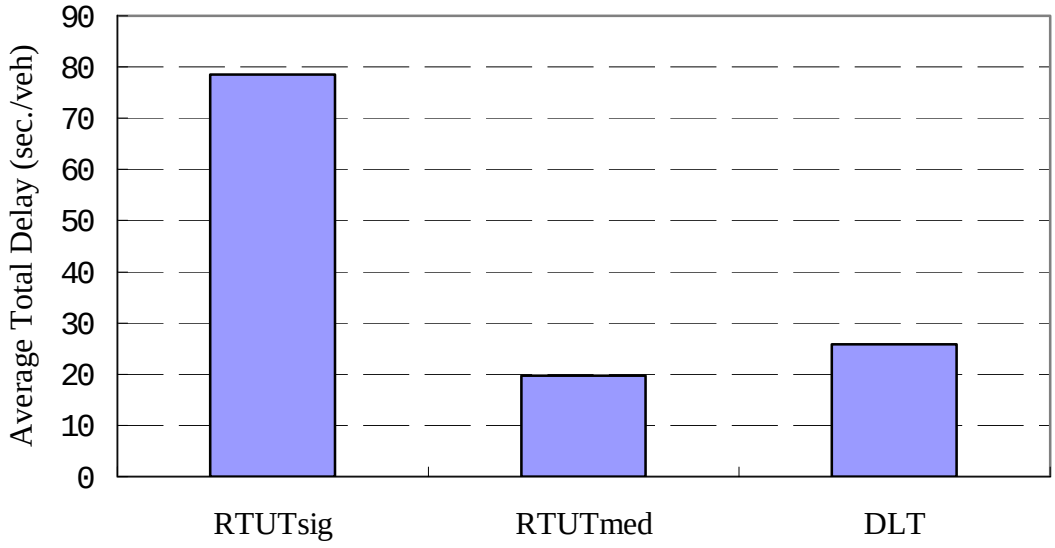


Figure 5-7 Comparison of the average delay

Table 5-7 Comparison of the average delay in different volume categories

Traffic Volume (vph)		Average Waiting Delay (sec)		
Through Volume	Left-turn/U-turn Volume	RTUT (sig)	RTUT (med)	DLT
1000 - 1999 vph	0 - 49 vph	76.9	15.4	18.3
2000 - 2999 vph		82.6	18.7	24.8
3000 - 3999 vph		82.9	24.3	36.5
>=4000 vph		N/A	N/A	45.2
1000 - 1999 vph	>= 50 vph	76.1	17.8	18.7
2000 - 2999 vph		82.7	20.8	28.0
3000 - 3999 vph		83.1	29.5	36.9
>=4000 vph		79.4	38.0	46.1

Note: Through Volume: the major road through traffic volume in both directions of the arterials; N/A: no data points in the specific category.

One of the major objectives of this study is to compare the delay of three different left turn treatments under certain roadway traffic and geometric conditions. This objective was achieved by comparing the delay models developed in this study. Curves in Figure 5-2,

Figure 5-4 and Figure 5-6 were combined together. The Figure 5-8, Figure 5-9, and Figure 5-10 illustrated the delay comparison of DLT versus RTUT at median opening. The Figure 5-11 illustrated the delay comparison of DLT versus RTUT at signalized intersection. In Figure 5-12, the operations of two widely used U-turn treatments, U-turns at median opening in advance of signalized intersection and U-turns at signalized intersection, were also compared.

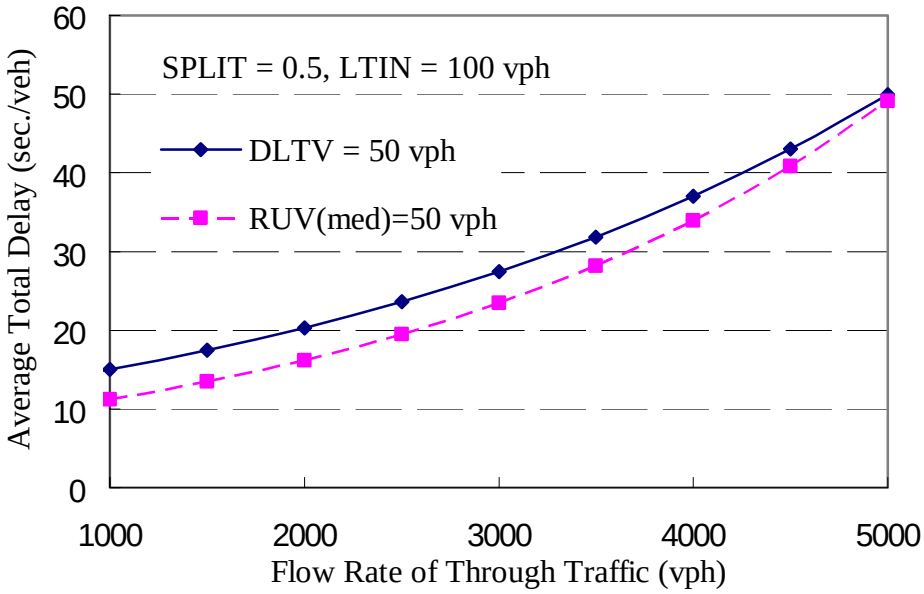


Figure 5-8 Comparison of average delay

(Direct left-turn vs. U-turn at median opening, DLTV/RUV=50 vph)

The curves based on the delay models presented a good picture of the operational effects of three different left-turn treatments on 4-lane roadway, including direct left-turn, RTUT at median opening and RTUT at signalized intersection. Based on these curves, it is clear that vehicle making a RTUT at downstream median opening will experience less delay than those making a DLT. However, when U-turn is accommodated at downstream signalized intersection, vehicles making a RTUT will experience longer delay. The difference could be quantified by using the delay models developed in this study.

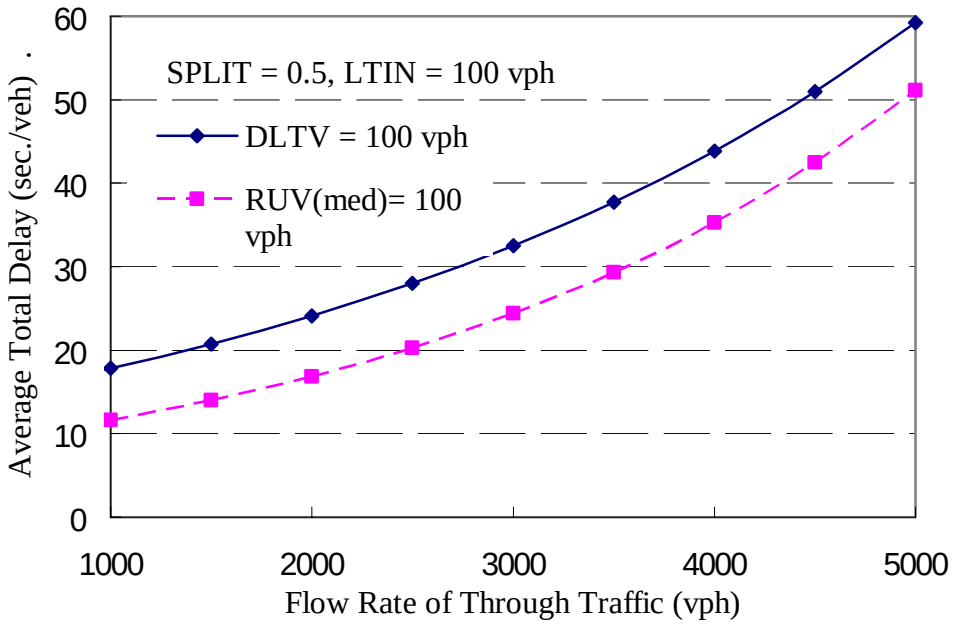


Figure 5-9 Comparison of average delay

(Direct left-turn vs. U-turn at median opening, DLTV/RUV=100 vph)

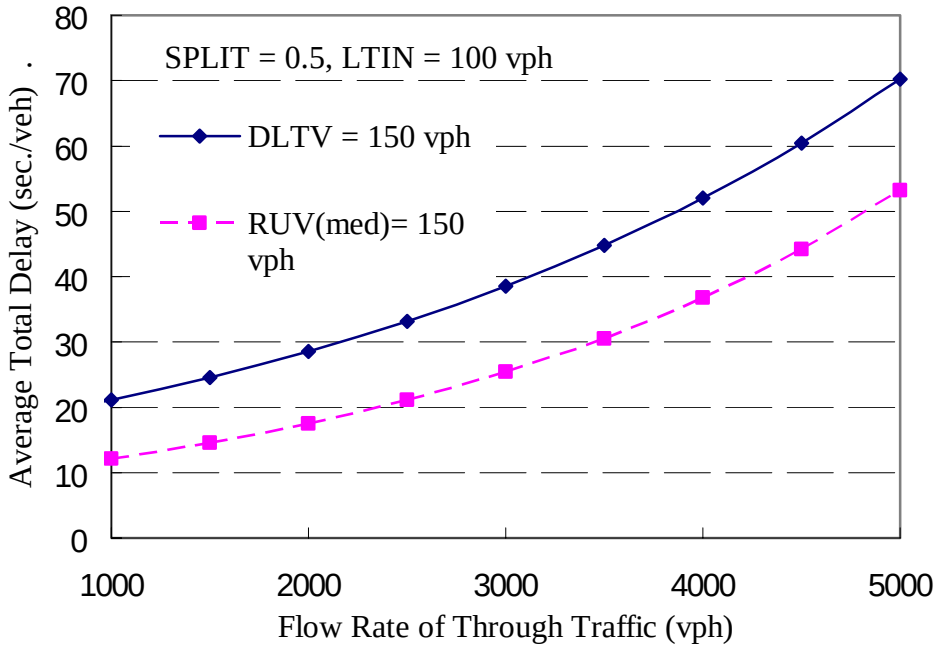


Figure 5-10 Comparison of average delay

(Direct left-turn vs. U-turn at median opening, DLTV/RUV=150 vph)

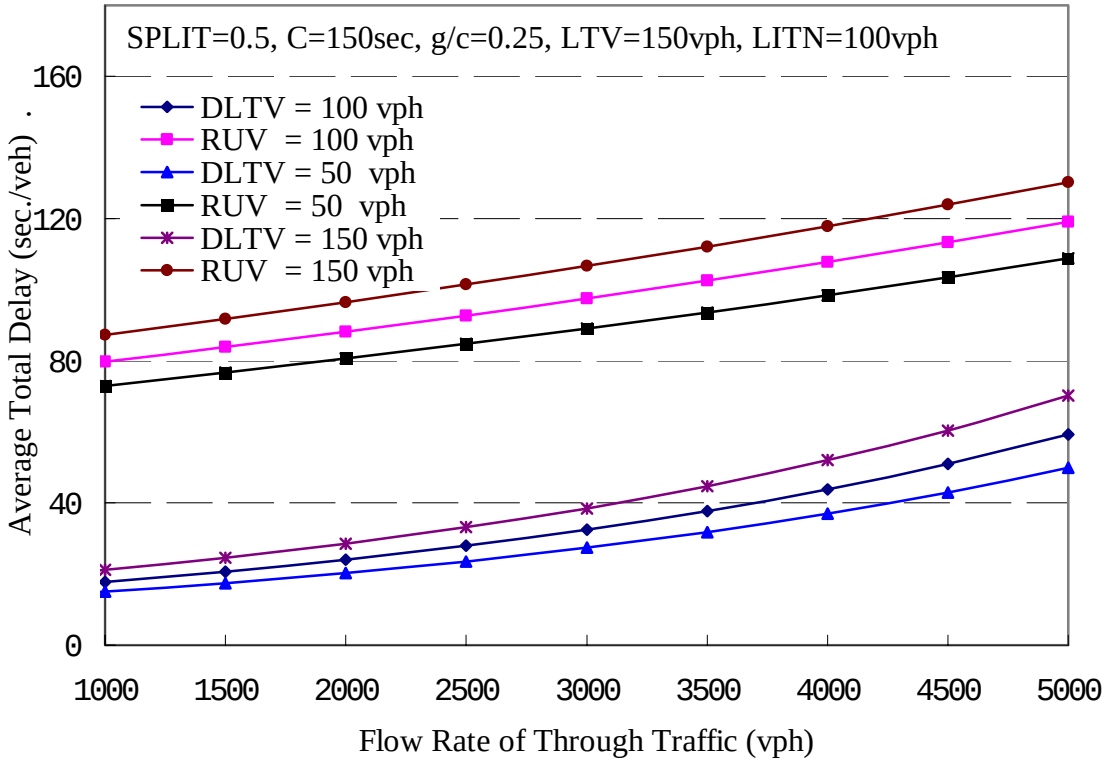


Figure 5-11 Comparison of average delay

(Direct left-turn vs. U-turn at signalized intersection)

5.3 Average Total Travel Time

In this study, the average total travel time of DLT is defined as the sum of average total waiting delay and the time for DLT vehicles crossing the through lanes. The average total travel time for RTUT at median opening includes the average total waiting delay, the running time from vehicle leaving the driveway until it stops at the median, plus the travel time from U-turn bay back to the median opening at driveway. The average total travel time for RTUT at signalized includes the average total waiting delay, the running time from vehicle leaving the driveway until it stops at the exclusive left-turn lane in the signalized intersection, plus the travel time from the signalized intersection back to the median opening at driveway.

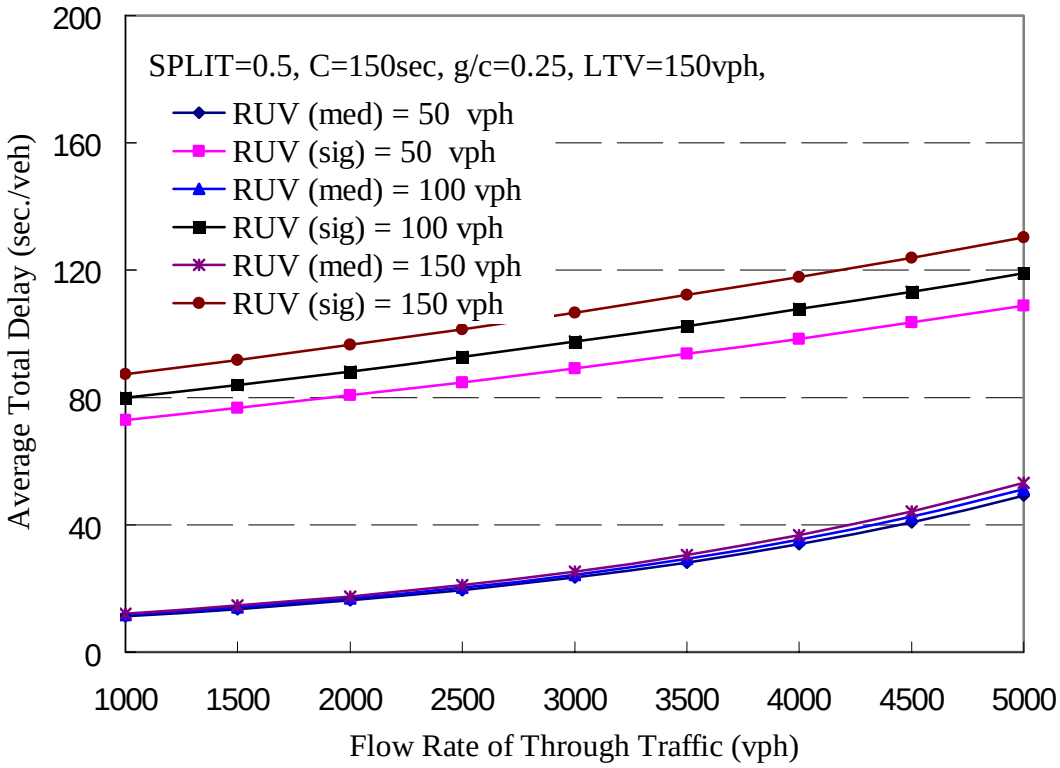


Figure 5-12 Comparison of average delay

(U-turn at median opening vs. U-turn at signalized intersection)

5.3.1 Travel Time Model for DLT

Data collected from the sites with full median openings were used to build travel time model for direct left turn movements. The dependent variable is the average total travel time for DLT movements at fifteen-minute intervals. The independent variables include the flow rate of major-road through-traffic, split, the flow rate of left-turn-in traffic from a major roadway, and the flow rate of DLT. The same datasets for the delay models were used to develop the travel time model for DLT and RTUT.

$$TT_L = e^{a_1 TV + a_2 PLIT + a_3 DLTV + a_4 LTIN + a_0} \quad \text{(5-7)}$$

Where,

TT_L = average total travel time of DLT (sec/ veh);

TV = flow rate of major-road through-traffic (vph);

DLTV = flow rate of DLT from a driveway (vph);

LTIN = flow rate of left-turn-in from major roads (vph);

SPLIT = percentage of upstream through traffic flow rate, and

a_0, a_1, a_2, a_3, a_4 = parameters

A total of 464 observations at fifteen-minute intervals were used to perform the regression analysis. The statistical characteristics of collected data are given in Table 5-8. The final regression results are listed in Table 5-9.

Table 5-8 Descriptive statistics of the DLT travel time data

	N	Range	Minimum	Maximum	Mean	Std. Deviation
TV	464	3617.44	898.56	4516.00	2315.72	557.12134
SPLIT	464	.39	.34	.73	.5111	.09602
DLTV	464	92.00	12.00	104.00	41.5345	20.91944
LTIN	464	639.84	20.00	659.84	132.454	112.53878
TT	464	77.74	9.33	87.08	29.9565	12.23736

As shown in Table 5-9, all independent variables are significant at a 95 percent level of confidence. The adjusted R square value is 0.33. The independent variable SPLIT has a positive coefficient, which suggests that the upstream through-traffic flow rate (TV1) has a greater impact on the total travel time than corresponding downstream stream flow rate (TV2). According to these parameter estimates, the final developed regression equation was shown in Equation 5-8.

Table 5-9 Regression results for travel Time models of DLT

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.579	.336	.330	.31613

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	23.172	4	5.793	57.965	.000
Residual	45.871	459	.100		
Total	69.043	463			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	2.263	.143		15.809	.000
TV	.0003	.000	.391	7.903	.000
SPLIT	.3796	.178	.094	2.133	.033
DLTV	.0031	.001	.166	4.121	.000
LTIN	.0008	.000	.247	5.691	.000

Dependent Variable: lnTT

$$TT_L = 9.61e^{0.0003TV + 0.380SPLIT + 0.0031DLTV + 0.008LTIN} \quad \text{(5-8)}$$

Where,

TT_L = average total travel time of DLT (sec/ veh);

TV = flow rate of major-road through-traffic (vph);

DLTV = flow rate of DLT from a driveway (vph);

LTIN = flow rate of left-turn-in from major road (vph); and

SPLIT = percentage of upstream through traffic flow rate.

Based on Equation 5-8, curves for the average total travel time of DLT can be developed. Figure 5-7 shows a group of curves for average total travel time of DLT assuming the left-turn-in flow rate from the major road is 100 vph, split is 0.5, and the flow rate of DLT is made equal to 50, 100, and 150 vph, respectively. The x-axis represents the flow rate of two-directional through-traffic on the major road. The y-axis represents the average total travel time of DLT.

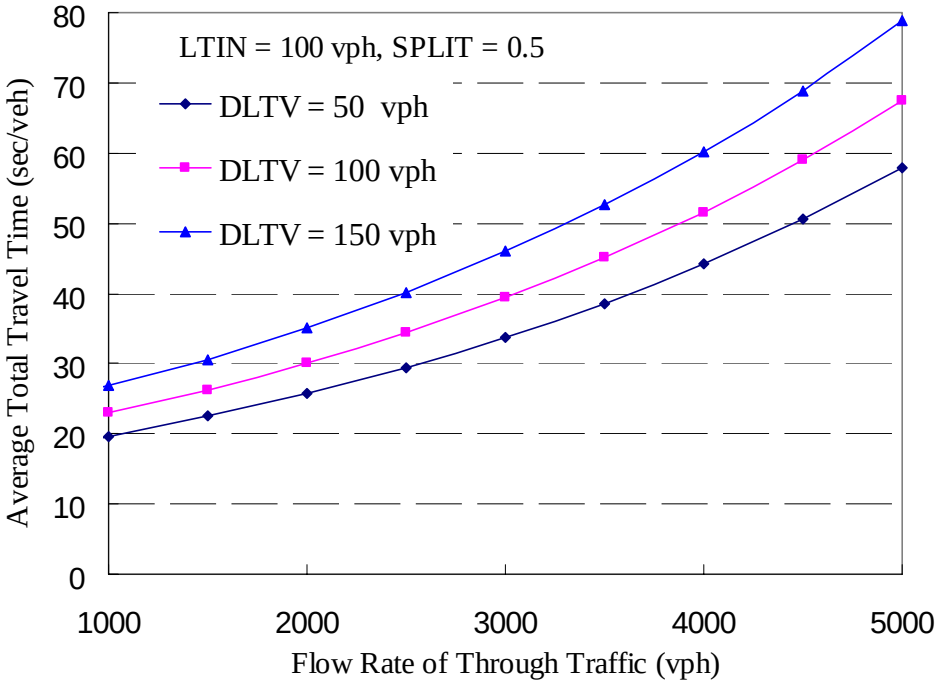


Figure 5-13 Curves for the average total travel time for DLT

5.3.2 Travel Time Model for RTUT at Median Opening

As defined earlier, the average total travel time of RTUT at median opening includes average total delay, average running time in the section between the subject driveway to the median opening, and running time for a vehicle traversing the offset weaving distance at posted speed.

The travel time model for RTUT was developed using regression by considering average total travel time at fifteen-minute intervals as the dependent variable. In addition to the independent variables considered for the delay model, the offset distance from the subject driveway to downstream median opening was also considered as potential independent variables. The descriptive statistics of the field data was listed in Table 5-10, and the regression results are listed in Table 5-11.

Table 5-10 Descriptive statistics of RTUT travel time at median opening

	N	Range	Minimum	Maximum	Mean	Std. Deviation
TV	358	3688	1496	5184	2407.30	535.336
SPLIT	358	.30	.40	.70	.5223	.05169
RUV	358	152	12	164	64.44	35.704
L	358	610	540	1150	774.12	113.880
TT	358	38.85	40.63	79.47	53.9417	7.49296

The empirical equation for average total travel time of RTUT is as follows:

$$TT_{RUM} = 44.4e^{0.0002TV - 0.703SPLIT + 0.0001RUV + 0.00018L} \quad \text{(5-9)}$$

where,

TD_{RUM} = average total travel time of RTUT at median opening (sec/ veh),

TV = flow rate of major-road through-traffic (vph),

RUV = flow rate of RTUT from a driveway (vph),

L = the distance from driveway to downstream signalized intersection,

SPLIT = percentage of upstream through traffic flow rate,

SPLIT=TV1/ (TV1+TV2), and

Based on Equation 5-9, curves for the average total travel time of RTUT at median opening can be developed. Figure 5-8 is an example which assumes that SPLIT is 0.5, and

the distance form driveway to downstream signal is 750 ft. Three different curves represent different volume conditions in which flow rate of RTUT is 50, 100, and 150 vph respectively. In Figure 5-8, the x-axis resents the flow rate of two-directional through-traffic on the major road. The y-axis represents the average total travel time of RTUT. The three curves are very close because the average total travel time is not very sensitive to the flow rate of RTUT.

Table 5-11 Regression results of travel time model for RTUT at median opening

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.667	.445	.438	.09943

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	2.794	4	.699	70.661	.000
Residual	3.490	353	.010		
Total	6.284	357			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	3.794	.068		56.055	.000
TV	.00017	.000	.687	13.349	.000
SPLIT	-.70304	.121	-.274	-5.794	.000
RUV	7.591E-05	.000	.020	.476	.634
L	.00018	.000	.153	3.694	.000

Dependent Variable: lnTT

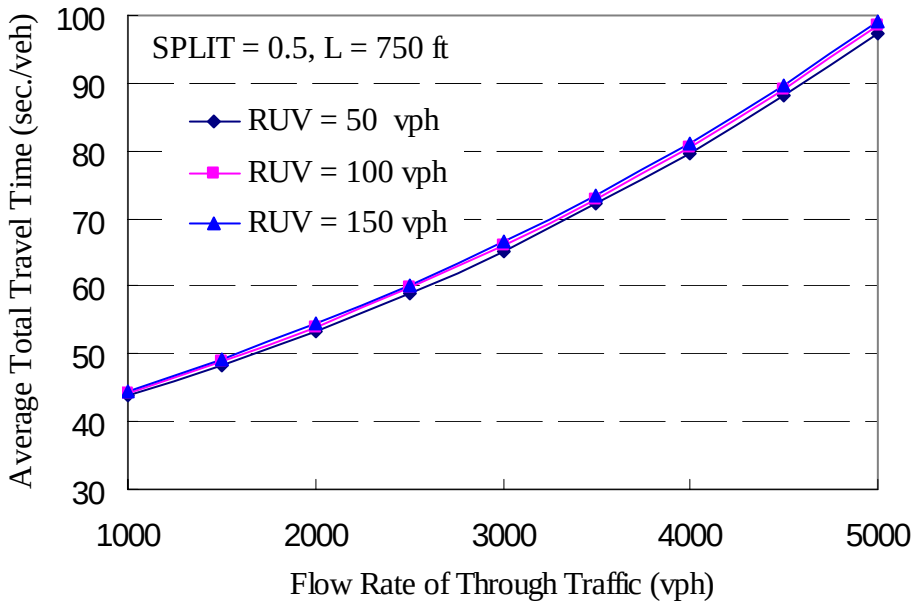


Figure 5-14 Curves for the average total travel time for RTUT at median opening

5.3.2 Travel Time Model for RTUT at Signalized Intersection

The average total travel time of RTUT includes the average total waiting delay, the running time from vehicle leaves driveway until it stops at exclusive left turn bay, plus the travel time from U-turn bay back to median opening at driveway. The statistical characteristics of collected data are given in Table 5-7.

Table 5-12 Descriptive statistics of RTUT travel time at signalized intersection

	N	Range	Minimum	Maximum	Mean	Std. Deviation
TV	424	3184	1056	4240	2202.92	610.725
SPLIT	424	.37	.35	.72	.4594	.04705
RUV	424	136	12	148	35.17	22.326
C	424	120	80	200	149.31	16.515
G/C	424	.25	.11	.35	.2275	.10920
LTV	424	360.00	4.00	364.00	164.415	63.27887
TT	424	132.74	48.71	181.44	108.184	21.51682

A regression model was developed to estimate the average total running time for each vehicle making a RTUT at signalized intersection. The average running here includes the running time from vehicle leaves driveway until it stops at exclusive left turn bay, plus the travel time from U-turn bay back to median opening at driveway. Figure 5-15 presents the distribution of collected data. The average running time model was described as Equation 5-10.

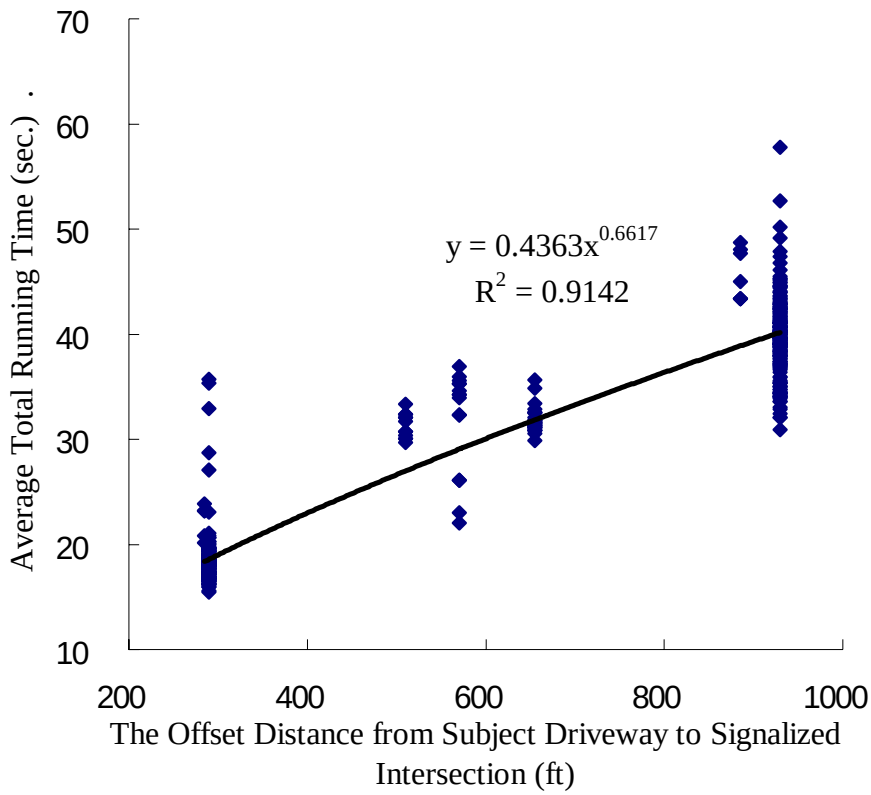


Figure 5-15 Average running time for vehicles making RTUT at signalized intersection versus the offset distance from driveway to downstream signal

$$TT_R = 0.436L^{0.662} \quad \text{(5-10)}$$

where,

TT_R = average running time of vehicles making RTUT at signalized intersection (sec/ veh); and

L = offset distance from driveway to downstream signalized intersection (ft); and

The R-square value for the model is 0.91, which is pretty high. The range of the offset distance at the selected sites is from 285 ft to 930 ft. Combined with the delay model developed in this study, the average travel time for a vehicle making a RTUT at signalized intersection could be estimated by the following equation:

$$TT_{RUS} = 15.3e^{0.0001TV+0.289*SPLIT+0.018*RUV+0.009*C-0.851*G/C+0.0006*LTV} + 0.436L^{0.662} \quad \text{..... (5-11)}$$

where,

TT_{RVS} = average total travel time of RTUT at signalized intersection (sec/ veh);

TV = flow rate of major-road through-traffic (vph)(in both directions);

RUV = flow rate of RTUT from a driveway (vph);

LTV = left-turn flow rate from inside left turn lane;

G/C = g/c ratio for exclusive left turn phase;

C = Cycle length (sec); cycle length used in pretimed signal control, or average cycle length for actuated control;

SPLIT = percentage of upstream through traffic flow rate;

L = distance from driveway to downstream signalized intersection (ft); and

Based on Equation 5-11, curves for the average total travel time of RTUT can be developed. Figure 5-16 is an example which assumes that the g/c ratio is 0.25, cycle length for downstream signal is 150 sec, SPLIT is 0.5, left-turn flow rate from inside left turn lane is 150 vph, and the distance form driveway to downstream signal is 600 ft. Three different curves represent different volume conditions in which flow rate of RTUT is 50,

100, and 150 vph respectively. In Figure 5-16, the x-axis resents the flow rate of two-directional through-traffic on the major road. The y-axis represents the average total travel time of RTUT.

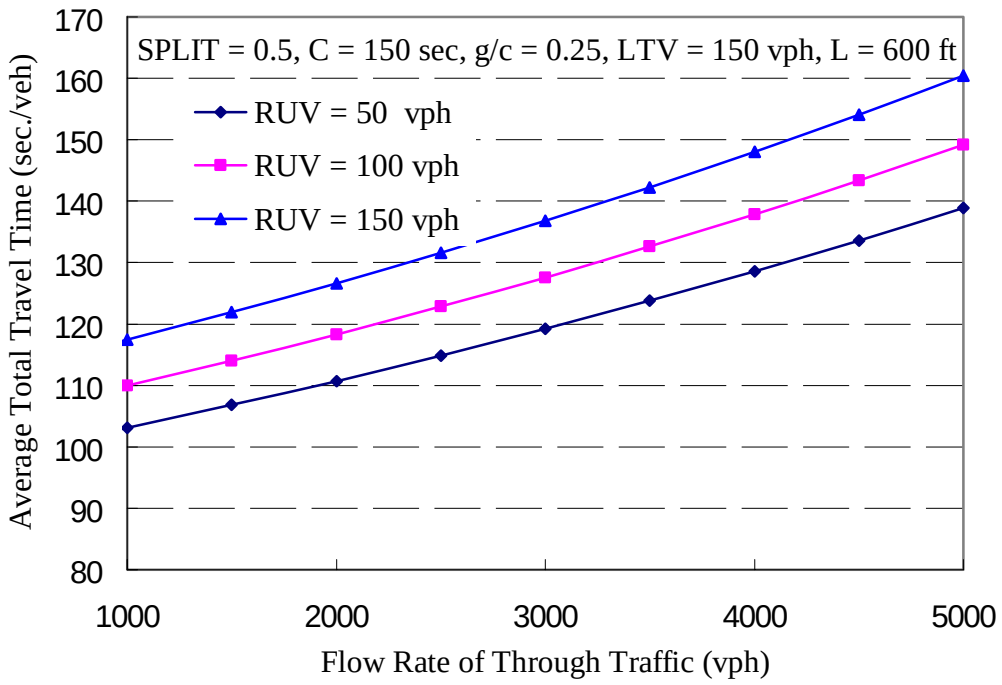


Figure 5-16 Curves for the average total travel time for RTUT at signalized intersection

5.3.3 Travel Time Comparison

The average total travel time of each vehicle making a DLT, or a RTUT at downstream median opening or signalized intersection was compared based on the field data, as shown in Figure 5-17. It is clear that, among the three different left-turn treatments on 4-lane arterials, vehicles making a DLT have the lowest travel time. Averagely, vehicles making a RTUT at signalized intersection will experience around 90 seconds extra travel time than those making a DLT or a RTUT at median opening.

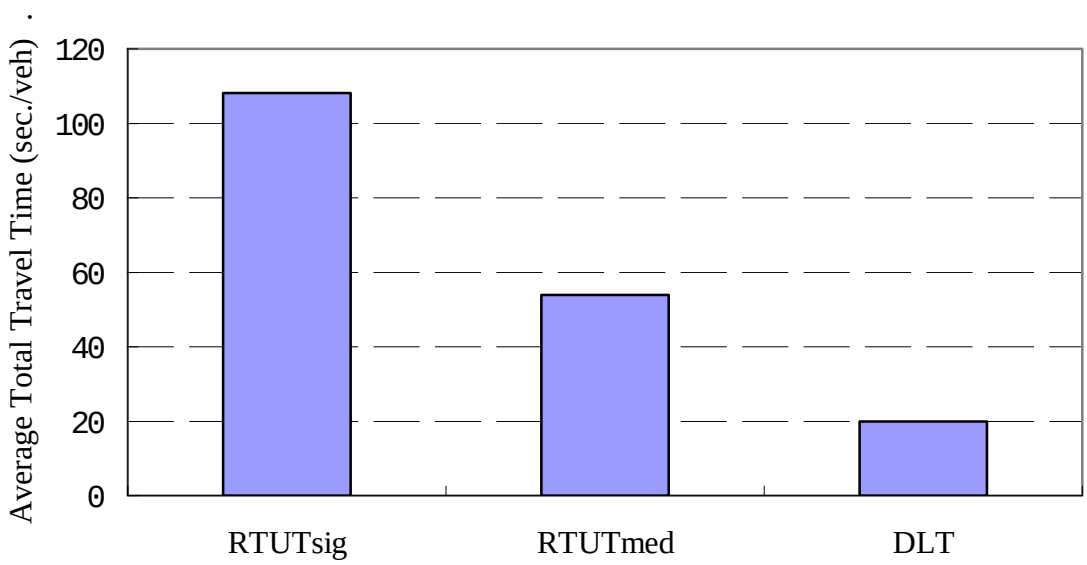


Figure 5-17 Comparison of the average total travel time

In Table 5-13, the field data were divided into different categories based on the through traffic volume and the direct left-turn volume/RTUT volume. In each category, the average total travel time of vehicles making DLT or RTUT at median opening or signalized intersection were calculated and compared. It is shown in Table 5-13 that, in each defined category, vehicles making a DLT have the shortest travel time, then RTUT at median opening, and then RTUT at signalized intersection.

Given the travel time models for DLT, RTUT at median opening and RTUT at signalized intersection, the average total travel time of these three different left-turn treatments can be compared under different traffic and roadway geometric conditions. To achieve this objective, Curves in Figure 5-13, Figure 5-14 and Figure 5-16 were combined together. The Figure 5-17, Figure 5-18, and Figure 5-19 illustrated the travel time comparison of DLT versus RTUT at median opening. The Figure 5-20 illustrated the travel time comparison of DLT versus RTUT at signalized intersection. In Figure 5-21, the operations of two widely used U-turn treatments, U-turns at median opening in advance of signalized intersection and U-turns at signalized intersection, were also compared.

Table 5-13 Comparison of the average total travel time in different volume categories

Traffic Volume (vph)		Average Travel Time (sec)		
Through Volume	Left-turn/U-turn Volume	RTUT(sig)	RTUT(med)	DLT
1000 - 1999 vph	0 - 49 vph	101.2	48.1	22.2
2000 - 2999 vph		114.1	53.3	28.8
3000 - 3999 vph		115.2	74.3	40.5
>=4000 vph		N/A	N/A	49.7
1000 - 1999 vph	>= 50 vph	116.7	50.8	22.8
2000 - 2999 vph		122.6	55.1	32.2
3000 - 3999 vph		114.7	64.2	40.8
>=4000 vph		111.4	72.6	48.7
Note: Through Volume: the major road through traffic volume in both directions of the arterials; N/A: no data points in the specific category.				

The curves based on the travel time models presented a good picture of the operational effects of three different left-turn treatments on 4-lane roadway, including direct left-turn, RTUT at median opening and RTUT at signalized intersection. Based on these curves, it is clear that, vehicles making RTUT at downstream median opening will, sometimes, experience longer travel time than those making a DLT. The difference can be quantified by using the travel time models developed in this study. For example, vehicles making RTUT at downstream median opening will take around 20 seconds extra travel time than those making DLT when the offset distance from subject driveway to the median opening is 750 ft. Twenty seconds difference will not pose significant operational problems, and therefore, the access management technique of using U-turns at downstream median opening at alternatives to direct left-turns could be used effectively.

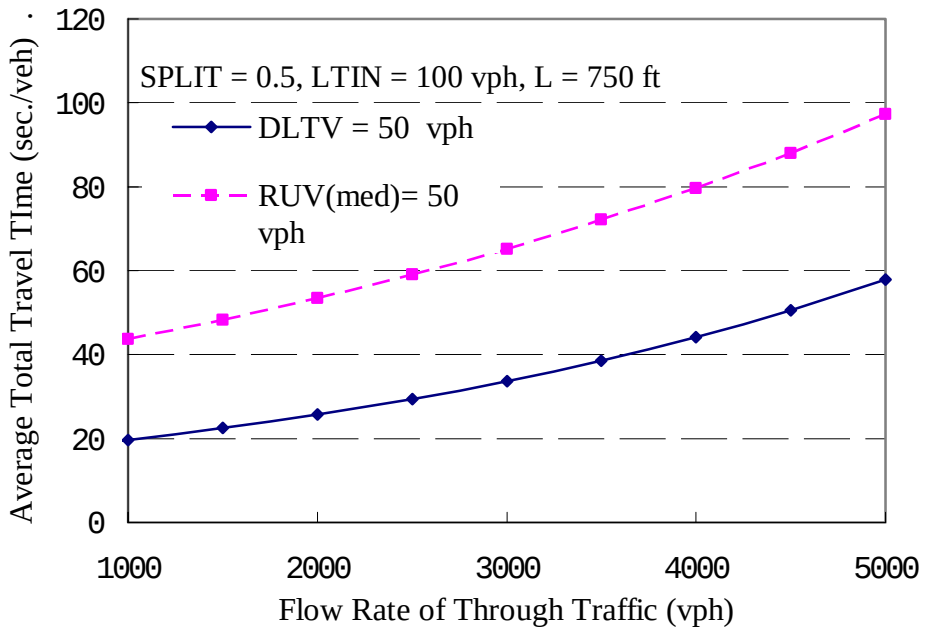


Figure 5-18 Comparison of average total travel time

(Direct left-turn vs. U-turn at median opening, DLTV/RUV=50 vph)

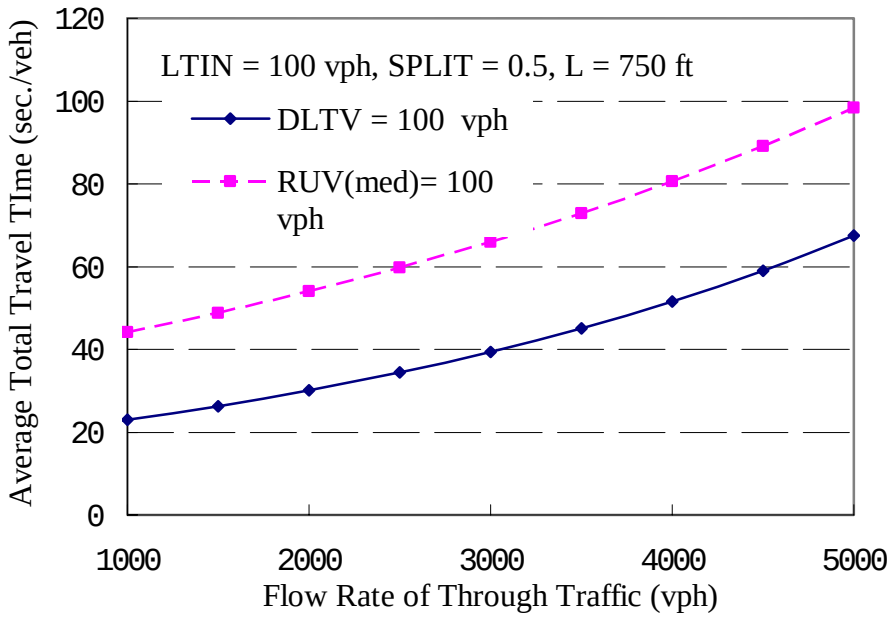


Figure 5-19 Comparison of average total travel time

(Direct left-turn vs. U-turn at median opening, DLTV/RUV=100 vph)

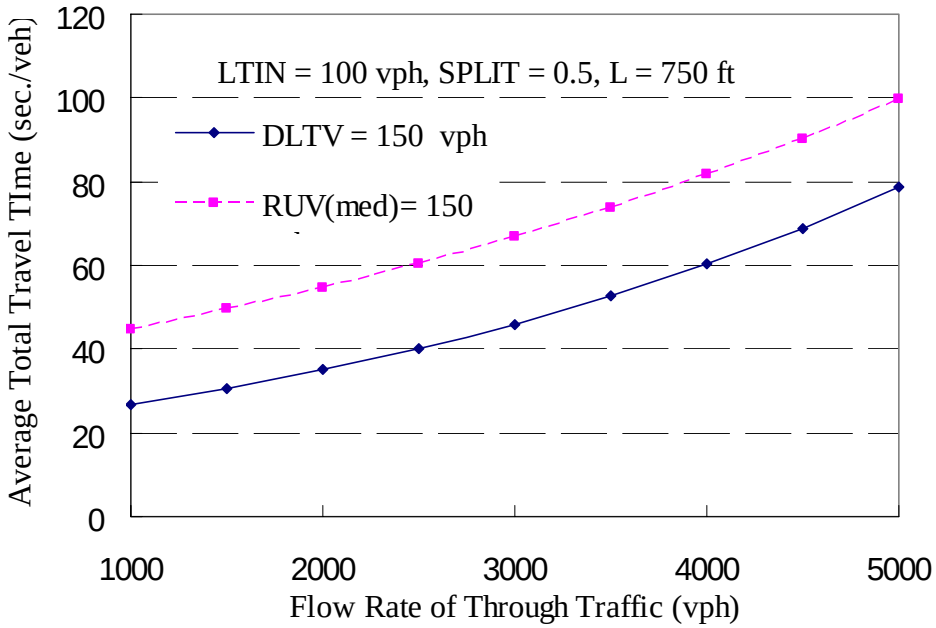


Figure 5-20 Comparison of average total travel time

(Direct left-turn vs. U-turn at median opening, DLTV/RUV=100 vph)

Vehicles making RTUT at downstream signalized intersection will take around 75 seconds extra travel time as compared with those making a DLT, and around 55 second extra travel time than those making RTUT at downstream median opening. In practice, vehicles' delay at signalized intersection is often relatively long. Vehicles delay at signalized intersection is the major component of the total delay to vehicles making RTUT at signalized intersection. However, some drivers are still in favor of making a U-turn at signalized intersection with the perception that making a U-turn at signalized intersection does not have major conflict with the through traffic in the other direction of the road; and therefore, could be a safe choice.

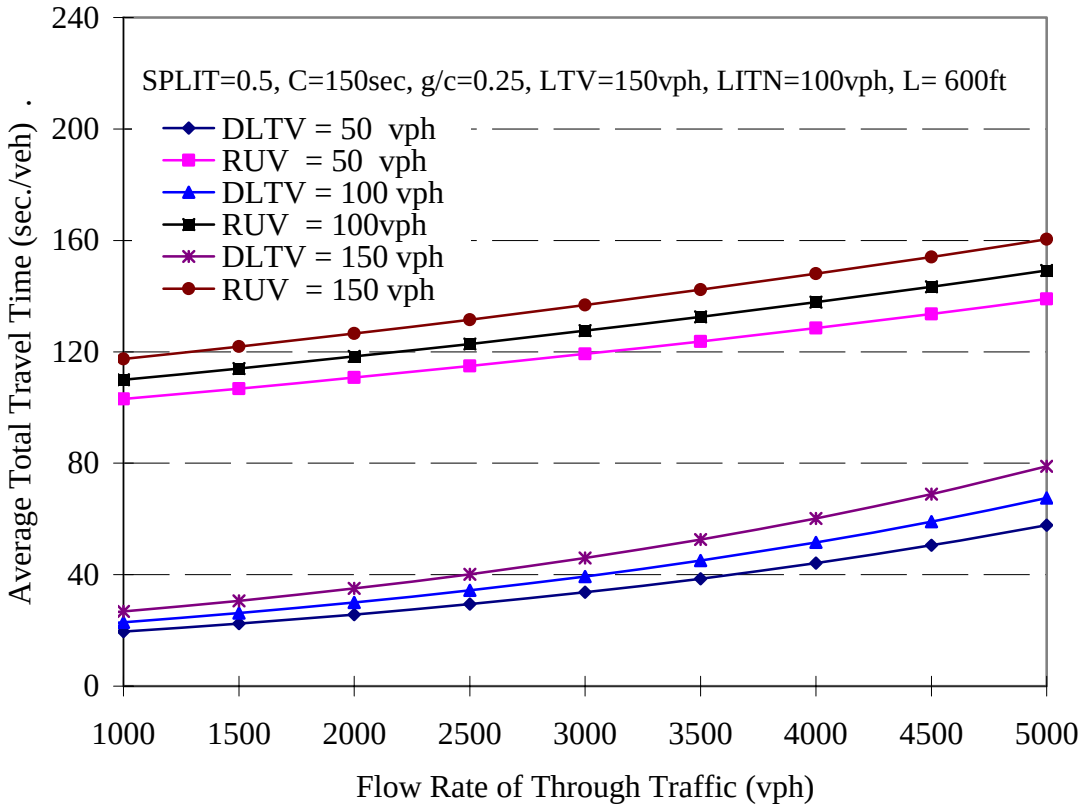


Figure 5-21 Comparison of average total travel time

(Direct left-turn vs. U-turn at signalized intersection)

5.3 Effects of Turning Radius on the Operations of U-turning Vehicles

One of the key factors that affect the operations of U-turning vehicles on 4-lane arterials is the turning radius accommodated for U-turns. For a satisfactory design for U-turn maneuvers, the width of the highway, including the median, should be sufficient to permit the design vehicle to turn from an exclusive left-turn lane in the median into the lane next to the outside shoulder or outside curb and gutter on the roadway of the opposing traffic lanes. The turning radius of the design vehicle should be accommodated by the combination of the median width (R_1), receiving lane width (R_2) and, if necessary, the

width of the flare or loons (R_3), as shown in Figure 3-6. A shorter turn radius will cause slower speeds for U-turning vehicles, and will result in more delay to following vehicles.

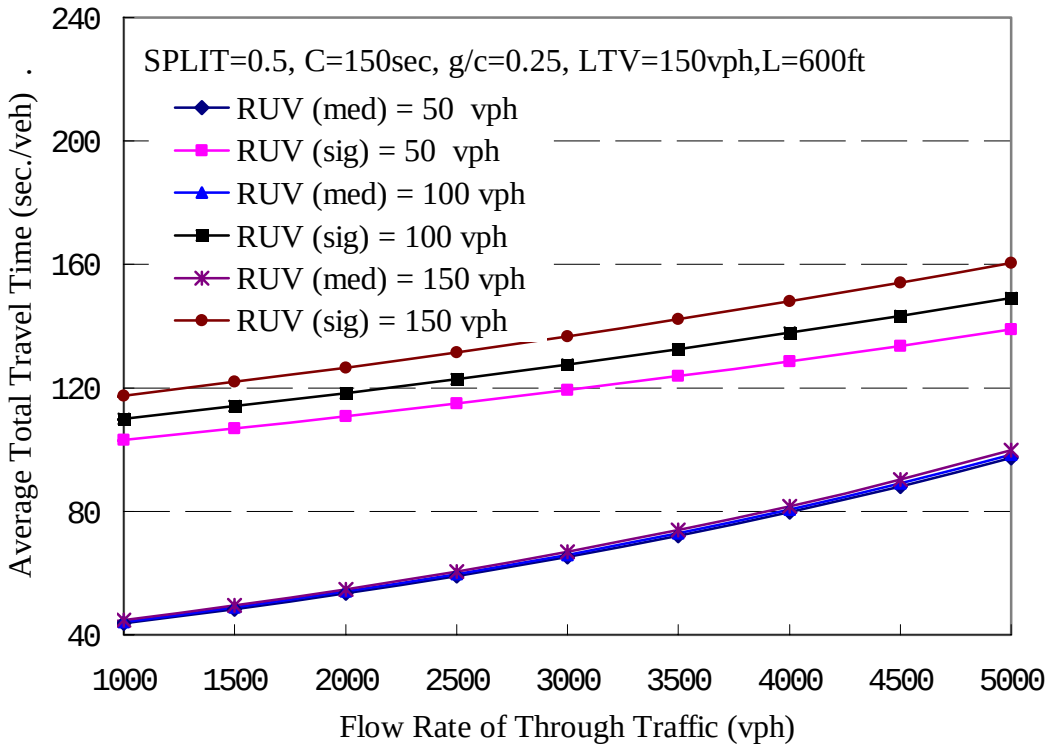


Figure 5-22 Comparison of average total travel time

(U-turn at median opening vs. U-turn at signalized intersection)

In order to determine the minimum turning radius required by U-turning vehicles, from the operations point of view, an empirical model was developed to estimate the relationship between the turning radius and the average turning time required by each U-turning vehicle. The model was developed based on field data. The dependent variable is the average turning time for U-turning vehicles in each selected. The independent variable is the turning radius accommodated by each site. The turning radius in this model includes the width of the median nose (R_1), plus receiving lane width (R_2), plus the width of flares or loons (R_3). The average turning time for a U-turning vehicle was defined as the total elapsed time form a vehicle starts making a U-turn until it finishes the turning

movement. In this model, different vehicles types were not analyzed separately, except heavy vehicles, which were not considered in this study. The logic behind this methodology is that the combination of the different vehicle types in the selected sites reflects the combination of vehicle types in other place of Florida. Figure 5-23 presents the distribution of collected data and the equation of the model. The regression resulted were shown in Table 5-14.

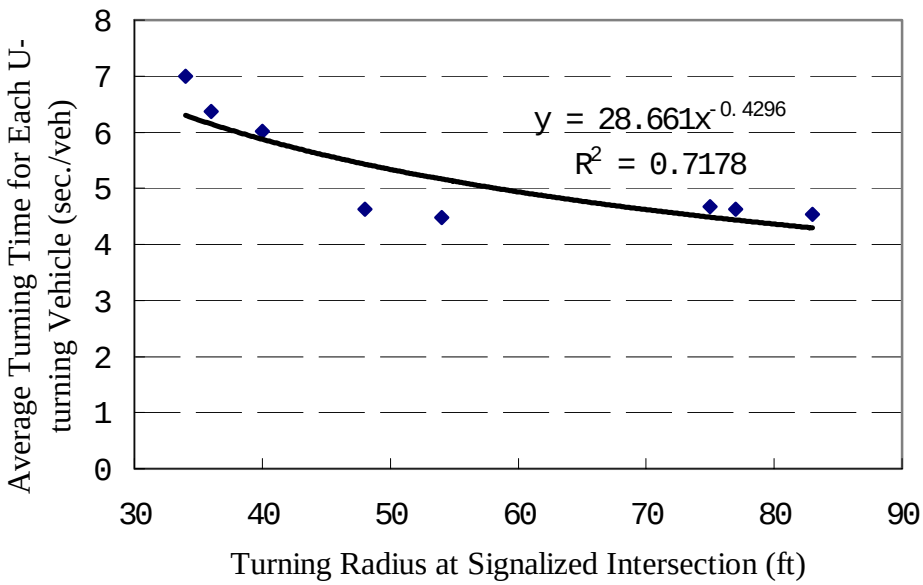


Figure 5-23 Average turning time for U-turning vehicles versus the turning radius accommodated by the roadway

The R-square value of this model is 0.72, which is pretty high. The model is statistically significant and the independent variables are significant too (p=0.01). This model can be directly used in estimating the average turning time required by U-turning vehicles under restricted geometric conditions. In addition, from Figure 5-23, it can be seen that, the average turning time of U-turning vehicles reaches a relatively stable state after the turning radius accommodated by the intersection reaches around 48 ft, and this could be

considered as the minimum turning radius required by most of the U-turning vehicles (except heavy vehicles) to accomplish the U-turn maneuver without causing extra turning time.

Table 5-14 Regression results of the turning radius model

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.847	.718	.671	.10417

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.166	1	.166	15.26	.008
Residual	.065	6	.011		
Total	.231	7			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	3.356	.438		7.664	.000
lnR	-.430	.110	-.847	-3.906	.008

Dependent Variable: lnTTu

The minimum turning radius determined in this study could be directly used in the design of a median opening which was designed to accommodate U-turning vehicles. For example, a median was designed on 4-lane arterials to facilitate U-turns and exclusive left-turn lanes, the minimum median width required for a satisfactory U-turn maneuver can be estimated as follows:

$$M_w = 48 - 2*L_w + N*L_L \quad (5\text{-}12)$$

Where:

M_w = median width (ft);

L_w = lane width of each through traffic lane(ft);

N = Number of left-turn storage lanes at the intersection; and

L_L = lane width of each left-turn storage lane.

If the minimum median width cannot be satisfied, the installation of flares or loons should be considered. It is important to note that heavy vehicles were not considered in this study. The heavy vehicle here is defined as the vehicle with more than or equal to 6 tyres on the ground.

6 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

Florida uses restrictive medians and directional median openings in the State Highway System to manage left turn egress movements from driveways and side streets. By installing raised curb medians and replacing full median openings with directional median openings in some places, direct left turn movements are substituted by making a right-turn followed by a U-turn at downstream median opening or signalized intersection.

This report is one of the reports that evaluate the safety and operational effects of a widely used access management treatment: right turn followed by a U-turn as an alternative to direct left turn. The focus of this report is on the operational effects of U-turns on four-lane urban or suburban arterials. The primary objectives of this study were to explore methodologies for evaluating the operational effects of U-turns as alternatives to direct left turns on four-lane arterials; and to provide information on the potential operational impacts of these alternatives under various conditions.

To achieve these objectives, field studies were conducted at sixteen selected sites in the Tampa Bay area in Florida. Over 600 hours of traffic data were collected using video cameras. While reviewing videotapes, each vehicle coming from the driveway making DLT or RTUT was tracked. Delay and travel time for each vehicle making DLT or RTUT were recorded. Other information gathered in the field study included traffic volumes, signal parameters, and roadway geometrics.

Delay and travel time models were developed based on collected field data. The delay and travel time of vehicles making DLT, RTUT at median opening or RTUT at signalized intersection were determined as a function of conflicting volumes, signalization conditions, and roadway geometrics. Curves were developed based on regression results depicting operational differences between vehicles making a DLT versus those making a RTUT at median opening or signalized intersection.

In this project, the operations of two widely used U-turn approaches: U-turn at median openings in advance of signalized intersections and U-turn at signalized intersection were also compared by using the delay and travel time models developed in this study. Based on the comparison, it is clear that vehicles making RTUT at median openings in advance of signalized intersections will experience less delay and travel time as compared with the condition where U-turns are accommodated at signalized intersections.

In order to determine the minimum turning radius required by U-turning vehicles, from the operations point of view, an empirical model was developed to estimate the relationship between the turning radius and the average turning time required by each U-turning vehicle. This model can be directly used in estimating the average turning time required by U-turning vehicles under restricted geometric conditions. In addition, by analyzing the field data, the research team found that the average turning time of U-turning vehicles reaches a relatively saturated state after the turning radius accommodated by the intersection reaches around 48 ft, and this could be considered as the minimum turning radius required by most of the U-turning vehicles (except heavy vehicles) to finish the U-turn maneuver without taking extra turning time. Based on the minimum turning radius determined in this study, a procedure was developed to estimate the minimum median width required to facilitate U-turn maneuvers or other functions on 4-lane arterials.

6.2 Conclusions and Recommendations

This study evaluated the operational effects of U–turns on 4-lane arterials. Based on this study, conclusion can be made that, the access management technique, providing U-turns at downstream median opening on 4-lane arterials as alternatives to direct left-turns from driveway or side streets, could have better operational performance than direct left turns under certain traffic and roadway geometric conditions. When U-turns are accommodated at downstream signalized intersection, vehicles making a RTUT could experience longer

delay and travel time than those making a direct left-turn or a RTUT at downstream median opening. More specifically, the findings of this study include:

(1) Vehicle making a RTUT at downstream median opening will experience less delay than those making a DLT. However, when U-turn is accommodated at downstream signalized intersection, vehicles making a RTUT will, sometimes, experience longer delay than those making a DLT. The difference could be quantified by using the delay models developed in this study;

(2) Vehicles making RTUT at downstream median opening will, sometimes, experience longer travel time than those making a DLT. The difference can be quantified by using the travel time models developed in this study. For example, vehicles making RTUT at downstream median opening will take around 20 seconds extra travel time than those making DLT, when the offset distance from subject driveway to the median opening is 750 ft;

(3) Vehicles making RTUT at downstream signalized intersection, sometimes, will experience longer travel time than those making a DLT or a RTUT at median opening. On the average, vehicles making RTUT at downstream signalized intersection will take around 75 seconds extra travel time as compared with those making a DLT, and around 55 seconds extra travel time than those making RTUT at downstream median opening; and

(4) The average turning time of U-turning vehicles reaches a relatively saturated state after the turning radius accommodated by the intersection reaches around 48 ft, and this could be considered as the minimum turning radius required by most of the U-turning vehicles (except heavy vehicles) to finish the U-turn maneuver without taking extra turning time.

The findings of this study are helpful in providing local and state transportation agencies with recommendations for the design and selection of median treatments on 4-lane urban

or suburban arterials. The potential median treatments include the installation of restrictive medians, closing median openings, and replacing a full median opening with a directional one.

This study found that vehicles making a right turn followed by a U-turn at downstream median opening in advance of signalized intersection will generally experience less waiting delay than those making a direct left-turn. Depends on the offset distance from the subject driveway to downstream median opening, vehicles making a RTUT at median opening, sometimes, could experience longer travel time than those making a DLT. For example, vehicles making RTUT at downstream median opening will take around 20 seconds extra travel time than those making DLT when the offset distance from subject driveway to the median opening is 750 ft. Twenty seconds difference in total travel time will not pose significant operational problems to both U-turning vehicles and other turning vehicles at the driveway, and therefore, the access management technique of using U-turns at downstream median opening at alternatives to direct left-turns could be used effectively.

Vehicles making RTUT at downstream signalized intersection will take around 75 seconds extra travel time as compared with those making a DLT, and around 55 second extra travel time than those making RTUT at downstream median opening. In practice, vehicles' delay at signalized intersection is often relatively long. Vehicles delay at signalized intersection is the major component of the total delay to vehicles making RTUT at signalized intersection. However, some drivers still in favor of this option with the perception that making a U-turn at signalized intersection does not have major conflict with the through traffic in the other direction of the road; and therefore, could be safer.

The minimum turning radius determined in this study could be directly used in the design of a median opening which was designed to accommodate U-turning vehicles. In this study, a procedure was developed to estimate the minimum median width required for a satisfactory U-turn maneuver. If the minimum median width cannot be satisfied, the installation of flares or loons should be considered. Failure to provide sufficient turning

radius at median opening or signalized intersection may pose operational problems to U-turning vehicles and the whole intersection. Under this condition, vehicles may make "tight" U-turns which has slower turning speed and may require more time to finish the turning movement, and therefore, not only affect the operations of U-turning vehicles, but also of the vehicles following them. In this condition, the U-turn prohibition should be considered.

It is also important to note that the operational performance of RTUT or DLT is not the only criterion for design and selecting median treatment. For example, vehicles making a right turn followed by a U-turn will experience longer travel time if the offset distance from driveway to downstream median opening or signalized intersection is relatively long. Field measurement found that the offset distance of 600 ft is suitable from the operations point of view; in that it will not cause too much extra travel time to U-turning vehicles. However, such distance may not be enough from the safety point of view. In this condition, decisions should not be made only from operations standpoint. In general, when selecting a median treatment, safety should have the first priority in decision making.

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