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Effects of U-turns on capacity at signalized intersections and simulation of U-turning movement by synchro

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Effects of U-Turns on Capacity at Signalized Intersections

And Simulation of U-Turning Movement by Synchro

by

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Dedication

This work dedicates to all the people who ever gave me the help.

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ABSTRACT

The primary objective of this study is to evaluate the operational effects of U-turn movement at signalized intersections. More specifically, the research objectives include the following parts:

- To identify the factors affecting the operational performance of U-turning vehicles. In this case, we are particularly interested in the U-turn speeds of U-turning vehicles.
- To evaluate the impacts of U-turns on capacity of signalized intersections, and
- To simulate U-turn movement at signalized intersections using Synchro and validate the simulation results.

To achieve the research objectives, extensive field data collection work was conducted at sixteen selected sites at Tampa Bay area of Florida. The data collected in the field include:

- U-turning speed
- Left turning speed
- Turning radius
- Queue discharge time
- Control delay

- Hourly traffic volume, and
- Percentage of U- turning vehicles in left turn lane.

Based on the collected field data, a linear regression model was developed to identify the factors affecting the turning speeds of U-turning vehicles at signalized intersections. The model shows the turning speed is significantly impacted by the turning radius and the speed of U-turning vehicles increases with the increase of turning radius.

On the basis of field data field data collection, a regression model was developed to estimate the relationship between the average queue discharge time for each turning vehicle and the various percentages of U-turning vehicles in the left turn traffic stream. Adjustment factors for various percentages of U-turning vehicles were also developed by using the regression model. The adjustment factors developed in this study can be directly used to estimate the capacity reduction due to the presence of various percentages of U-turning vehicles at a signalized intersection.

The developed adjustment factors were used to improve the simulation of U-turn movement at signalized intersection by using Synchro. The simulation model was calibrated and validated by field data. It was found that using the developed adjustment factors will greatly improve the accuracy of the simulation results for U-turn movement.

CHAPTER 1

INTRODUCTION

1.1 Background

In Florida, the increase of the use of restrictive median and directional median openings has generated many U-turns at signalized intersections. For estimating the operational effects of U-turns, there are still no widely accepted theories or methods. As we all know, U-turning movements are considered as left turns for estimating the saturation flow rate. However, according to the real traffic features, the operational effects caused by U-turns and left turns are different. The Florida Department of Transportation mandated that all the new or reconstructed arterials of which the design speeds over 40 mph must be applied with restrictive medians. Moreover, Florida has replaced a lot of conventional median openings by directional openings. And according to the access management standards in Florida, direct left turn onto the major arterials are prohibited. As a result, direct left turn onto the roadway was taken place by the right turn followed by U-turn at the downstream signalized intersections. So, the quantity of U-turning movements keeps increasing. Apparently, the usage of restrictive median openings and directional median openings can improve the safety performance of arterials. However, the controversial issue has also been presented. The increasing of U-turn at the signalized intersection will negatively affect the capacity and Level of Service of the intersection. This is a pair of conflicts which need to be solved. But before resolving the problem, we need to understand what are the operational effects of U-turn and how does U-turn impact the intersection on capacity.

In this study, I chose the turning speed as the major feature of U-turning movements. Data were collected from 16 sites in Tampa Bay area. Basically, 375 U-turn speeds were collected along with the traffic volume, signal timing, and queue length for calculating the control delay. Three sites were selected to record queue discharge time. On the basis of the field data collection, one regression model was developed to estimate the relationship between U-turn speed and turning radius. From this model, it can be found that the U-turn speeds are significant related to turning radius and quantify the relationship between them.

Another regression model was established based on the field data for estimating the relationship between average queue discharge time for each turning vehicle under different U-turning vehicles' percentages in the U-turn and left turn mixed traffic stream. Also, U-turn adjustment factors for variable percentages of U-turning vehicles were determined by the regression model. The U-turn adjustment factors can be used to estimate the capacity reduction result from variable percentages of U-turning vehicles at signalized intersections.

Furthermore, 15 signalized intersections were selected to calibrate the Synchro simulation models. The simulation models created based on the field data. The results from Synchro simulation validated that the U-turn adjustment factors can be used to estimate the impact on capacity at signalized intersections.

1.2 Problem Statement

In terms of Highway Capacity Manual 2000, the U-turning movement is treated as left turn for estimating the saturation flow rate. Saturation flow rate is one of the most critical and important factor in evaluating the capacity of a lane or a lane group at a signalized intersection. However, based on the field data and real situation, the operational impacts of U-turns are different from which of left turns. From the field data, it is easily to find that the turning speed of U-turns and the turning speed of left turns are different. Thus, the saturation headway will be interrupted if the U-turning vehicles mix in the left lane. Due to the U-turn speed is lower than the left turn speed, the capacity of the lane will be reduced. According to the field data review and analysis, it is found that U-turning movement will increase the delay of the approach. As the control delay is the criteria for evaluating the Level of Service of a signalized intersection, thereby the U-turning movements have an adverse effect on Level of Service.

At present, there is no widely accepted theory or method for estimating the effects on capacity caused by U-turning movements. It is necessary to analyze the feature of U-turns and find out a method to estimate the effects of U-turning vehicles on capacity at a signalized intersection.

1.3 Research Objective and Outline of the Thesis

In this study, the essential part is that the U-turn adjustment factors for different percentage of U-turning vehicles were determined. The purpose of calculating these adjustment factors is to quantify the effects of U-turning movement on capacity at signalized intersections. The reduction of capacity will directly result in the descending of

Level of Service. The results of this study might help transportation practitioner to estimate the Level of Service of signalized intersection more adequately and to analyze the operational impacts for signalized intersection more rationally.

The primary objective of this study is to evaluate the operational effects of U-turn movement at signalized intersections. More specifically, the objective of this study can be summarized as following:

- To identify the factors affecting the operational performance of U-turning vehicles. In this case, we are particularly interested in the U-turn speeds of U-turning vehicles.
- To evaluate the impacts of U-turns on capacity of signalized intersections, and
- To simulate U-turn movement at signalized intersections using Synchro and validate the simulation results.

This thesis consists 6 chapters. The Introduction states the background of this research and presents the problems. The Literature Review goes over the past studies related to U-turning movements at signalized intersection which have been conducted. In the literature review, some important basic concepts were illuminated. Some methods for researching U-turn were also illustrated. The chapter on Methodology explains the methods in this study. It includes the methods for field data collection, regression model, filed control delay observing technique, Synchro simulation and sensitive analysis, etc. In the following chapter on Data Collection, the field data and the selection of study sites and field observational procedures for this study are presented. The next chapter focuses on data analysis, analyzing the related factor to impact the U-turn speed, developing model to estimating the U-turn adjustment factors under different percentage if U-turning vehicles and calibrating, validating the Synchro simulation models based on the field data.

The final chapter summarizes the results and findings of this study, draws conclusions, and proposes recommendations for future studies. Reference and Appendix follow at the end of the thesis.

CHAPTER 2

LITERATURE REVIEW

As discussed in the previous chapter, this thesis concentrates on the effects of U-turning movements on capacity at signalized intersections. In chapter 2, the contents of signalized intersections in Highway Capacity Manual (HCM) are briefly reviewed and the past researches related to U-turn at signalized intersections are reviewed as well. Specifically, the concerns are saturation flow rate, saturation headway, operational impacts of U-turn, conflicts between U-turning vehicles and left-turning vehicles, and some concepts or methods for analyzing the operational impacts by U-turn at signalized intersections.

2.1 The Capacity of Signalized Intersection

In the Highway Capacity Manual [HCM 2000], the analysis of capacity at signalized intersections focuses on the computation of saturation flow rates, capacities, v/c ratios, and level of service for lane groups. In this study, we consider the capacity of a certain lane group as the major factor for analyzing the operational impacts by U-turn. The capacity for each lane group is defined as the maximum rate of flow for a given lane group that may pass through an intersection under prevailing traffic, roadway, and signal conditions. The flow rate is generally measured or projected for a 15-min period, and capacity is stated in vehicles per hour (vph). Capacity at signalized intersections is based on the concept of saturation flow and saturation flow rate. Traffic conditions include volumes on each approach, the distribution of vehicles by movement (left, through, and right), the vehicle type distribution within each movement, the location and use of bus stops within the intersection area, pedestrian crossing flows, and parking movements on approaches to the intersection. Roadway conditions include the basic geometrics of the intersection, including the number and width of lanes, grades, and lane use allocations (including parking lanes). Signalization conditions include a full definition of the signal phasing, timing, and type of control, and an evaluation of signal progression for each lane group. The analysis of capacity at signalized intersections focuses on the computation of saturation flow rates, capacities, v/c ratios, and level of service for lane groups.

The saturation flow rate is defined as the maximum rate of traffic flow that may pass through a given lane group under prevailing traffic and roadway conditions, assuming that the lane group has 100 percent of real time available as effective green time. The flow ratio for a given lane group is defined as the ratio of the actual or projected demand flow rate for the lane group (vi) and the saturation flow rate (si). The flow ratio is given the symbol (v/s)i for lane group i. The capacity of a given lane group may be stated as shown in Equation:

$$C_i = S_i(g_i / C)$$

Where,

C_i = capacity of lane group i, vph;

S_i = saturation flow rate for lane group i, vphg; and

Green ratio defined as,

g_i / C = effective green ratio for lane group i.

The capacity formula indicates that the capacity at a signalized intersection determined by saturation flow rate and effective green ratios for the subject lane group.

Specifically, Saturation flow rate is a basic parameter used to derive capacity. It is defined as above. It is essentially determined on the basis of the minimum headway that the lane group can sustain across the stop line as the vehicles depart the intersection. Saturation flow rate is computed for each of the lane groups established for the analysis. A saturation flow rate for prevailing conditions can be determined directly from field measurement and can be used as the rate for the site without adjustment. If a default value is selected for base saturation flow rate, it must be adjusted for a variety of factors that reflect geometric, traffic, and environmental conditions specific to the site under study.

The computation of saturation flow rate begins with the selection of an ideal saturation flow rate. And then adjust for a variety of prevailing conditions which are not ideal. The equation is stated as below:

$$s = s_0 \times N \times f_w \times f_{HV} \times f_g \times f_p \times f_{bb} \times f_a \times f_{LU} \times f_{LT} \times f_{RT} \times f_{Lpb} \times f_{Rpb}$$

Where,

s = saturation flow rate for subject lane group, expressed as a total for all lanes in lane group (vph);

s_0 = base saturation flow rate per lane (pc/h/ln);

N = number of lanes in lane group;

f_w = adjustment factor for lane width;

f_{HV} = adjustment factor for heavy vehicles in traffic stream;

f_g = adjustment factor for approach grade;

f_p = adjustment factor for existence of a parking lane and parking activity adjacent to lane group;

f_{bb} = adjustment factor for blocking effect of local buses that stop within intersection area;

f_a = adjustment factor for area type;

f_{LU} = adjustment factor for lane utilization;

f_{LT} = adjustment factor for left turns in lane group;

f_{RT} = adjustment factor for right turns in lane group;

f_{Lpb} = pedestrian adjustment factor for left-turn movements; and

f_{Rpb} = pedestrian-bicycle adjustment factor for right-turn movements

The ideal conditions at a signalized intersection approach are:

- 12 foot lane witch
- level approach grade
- all passenger cars in the traffic stream
- no left or right turning vehicle in traffic stream,
- no parking adjacent to a travel lane within 250 ft of stop line,
- intersection located in a non-CBD area.

The procedure of directly measuring the saturation flow rate in field is described in the HCM 2000. The principle of direct measurement is based on the saturation flow rate and minimum departure headway (saturation headway)

$$s = 3600 / h_s$$

Where,

h_s =saturation headway, sec.

In this procedure, the HCM 2000 indicates that saturation headway is usually achieved after fourth to seventh vehicle has entered the intersection from a standing queue. The HCM 2000 recommends estimating the saturation headway by average the total time elapsed between the fifth vehicle and the vehicle at the end of the queue.

The cycle for given lane group has two simplified components: effective green time and effective red time. Effective green time is the time that may be used by vehicles on the subject lane group at the saturation flow rate. Effective red time is defined as the cycle length minus the effective green time. The effective green time is another important variable affecting the capacity of a signalized intersection. The effective green time for a lane group can be determined by subtracting the start-up lost time (experience at the beginning of the phase) and the clearance lost time (experienced at the end of the phase) from the total time (Green + Yellow + All-red) available for a lane group. It can be stated as:

$$g_i = G + Y_i - (t_{sl} + t_{cl})$$

Where,

G = actual green time, sec;

Y_i = sum of actual yellow time plus all-red clearance time, sec;

g_i = effective grren time for movement i, sec;

t_{sl} = start-up lost time, sec/cycl.

t_{cl} = clearance lost time, sec/cycle.

Meanwhile, the start-up lost time is typically measured as the cumulative extra time it takes for the n^{th} vehicle to pass the stop line (where n=4 as is assumed in the HCM 2000). Therefore, the start-up lost time can be calculated as:

$$t_{sl} = t_4 - 4 \times h_s$$

Where,

t_4 = total time from signal turning green to the rear axle of the fourth vehicle passing the stop line, sec; and

h_s = saturation headway, sec.

2.2 Past Studies on Saturation Flow Rate

Saturation flow rate is the maximum flow rate that can pass through a given lane group under prevailing traffic and roadway conditions, assuming that the lane group has 100 percent of real time available as effective green time. As previously discussed, saturation flow is fundamentally important in signalized intersection capacity estimation. It is the basic for determining traffic-signal timing and evaluating intersection performance. The saturation flow rate computations under prevailing conditions are based on the saturation flow rate under ideal conditions as well as on the adjustment factors for prevailing conditions. Ideal conditions assume clear weather, all passenger cars in the traffic stream, good pavement conditions, level terrain, 12ft minimum lane width, no heavy vehicle in traffic stream, and no local buses stopping within the intersection area.

The following Table 2-1 shows the saturation flow rate in some countries:

Table 2-1 Summary of Saturation Flow Results in Some Countries

[Niittymaeki and Prusula 1997]

Saturation Flow Values (per hour of green time per lane)		
Country	passenger car unit (pcu) / vehicle(veh)	Author, Year
United Kingdom	2080 pcu	Kimber 1986
Canada	1900 veh	Teply 1991
Australia	2475 veh	Troutbeck 1994
Australia	2000 veh	Troutbeck 1994
Israel	2176 veh	Hakkert 1994
Poland	1890 veh	Tracz, Tarko 1991
Yugoslav	2290 veh	Stanic 1994
South Africa	1928 veh	Stander 1994
Indonesia	600 pcu/m	Baeng 1994
Germany	2000veh	Brilon 1994
Hong Kang	1895 veh	Lam 1994
Lithuania	2045 veh	Noreika 1994
Japan	2000 pcu	Fujiwara 1994
Finland	1940 veh	Niittymaeki, Purula 1995
HCM 1994	1900 pcu	TRB 1994

In the past study, basically 2 alternatives were applied for estimating saturation flow rate. One is the queue discharge model, and the other is the discharge headway model. One of the most widely accepted queue discharge model is Webster's model. The following Figure 2-1 illustrates the discharge of vehicles at a loaded signalized intersection.

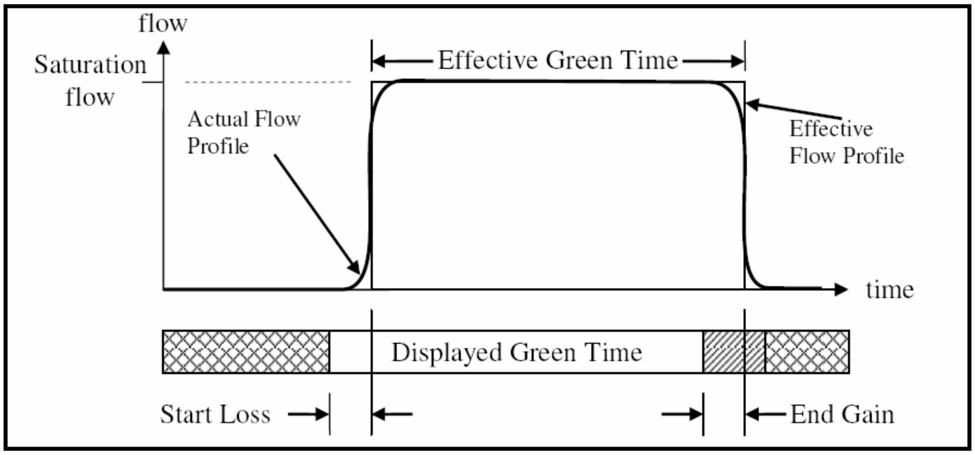

Figure 2-1 Signalized Intersection Queue Discharge Model [Shantaeu 1988]

It indicates when the vehicle queue is released by a traffic light turning to green; the flow rate gradually increases and reaches a steady average departure rate after several seconds. The departure flow remains around this value until the lights changes to yellow, then, it falls steadily to zero. This uniform departure flow rate is termed as the saturation flow rate, S [Shantaeu 1988].

2.3 Past Studies on Saturation Headway

As defined in Highway Capacity Manual (HCM), saturation flow rate is the equivalent hourly rate at which previously queue vehicles can traverse an intersection approach under prevailing conditions, assuming that the green signal is available at all time and no lost time is experienced [HCM]. HCM estimates a lane's "ideal" saturation flow rate to be 1,900 passenger cars per hour of green time per lane. Different adjustment factors are applied to address the impacts of prevailing conditions that do not meet the definition of "ideal" conditions, including lane width and lateral clearance, number of lanes, the presence of heavy vehicles and grades, turning movements, interchange density, lane distribution, and environmental factors. The discharge headway method is widely used to estimate the saturation flow rate at a signalized intersection. Numerous studies have indicated that the discharge headway would converge to a constant headway after the fourth to sixth discharged passenger car crossing the stop line after the beginning of the green phase. The constant headway is defined as the saturation headway, which can be measured in the field by recording the discharge headway after the fourth or fifth discharged vehicle. The relationship between saturation flow rate and saturation headway is shown in the following equation:

$$S=3600/h$$

Where,

s = saturation flow rate (vehicles per hour per lane);

h = saturation headway (s); and

3,600 = number of seconds per hour.

In HCM 2000, U-turns are treated as left turns for estimation of the saturation flow rate. However, the operational effects of U-turns and left turns are different. U-turning vehicles have slower turning speeds than left-turning vehicles. Thus, the increased U-turns at signalized intersections may adversely affect the intersection capacity. A study conducted by Adams and Hummer in 1993 evaluated the effects of U-turns on left-turn saturation flow rates. The research team selected four intersections with exclusive left-turn lanes and protected signal phasing and recorded the saturation flow rates and U-turn percentages for 198 queues during midday peaks on weekdays. The data analysis showed that "a saturation flow reduction factor appears necessary for left-turn lanes that had large percentages of U-turns. Saturation flow rates were significantly lower when queues have more than 65% U-turns". However, the analyses also showed no correlation between the saturation flow rate and the percentage of U-turns for queues with 50% U-turning vehicles or less. The results of this study suggested tentative saturation flow rate reduction factors of 1.0 for U-turn percentages below 65, 0.90 for U-turn percentages between 65 and 85, and 0.80 for U-turn percentages exceeding 85. The investigators also recommended that a follow-up investigation focus on intersections that have high percentages of U-turns, restrictive geometries, or high percentages of U-turning heavy vehicles. In 1996, Tsao and Chu recorded 600 headways of left-turning passenger cars and 160 headways of U-turning passenger cars in Taiwan Their research revealed that the average headways of U-turning passenger cars are significantly larger than those of left-turning passenger cars. The effects of U-turning vehicles depend on the percentage of U-turning vehicles in the left-turn lane, as well as the order of formation in the traffic stream. When it is preceded by a left-turning vehicle, the average headway of a U-turning passenger car is 1.27 times that of a left-turning passenger car. When it is preceded by a U-turning vehicle, however, the average headway of U-turning passenger cars is 2.17 times that of a left-turning passenger car. In their study, Tsao and Chu assumed that the discharge flow rate of the vehicle reaches a saturation state after the fourth or fifth discharged vehicle, and only the headways after the fifth discharged vehicle were recorded.

2.4 Past Studies on Safety and Operational Impacts

In the evaluation of safety and operational impacts of two alternative left-turn treatments from driveways/side streets, the research team selected 133 directly left turn sites and 125 right turn followed by U-turn sites, respectively. Crash data corresponding to these sites were compared. The results is that average number of crashes for sites with directly left turn is 16.35 and the average crash number for sites with right turn followed U-turn is 13.90, respectively. When crashes per million vehicle miles are considered the respective numbers of 3.2 and 2.63. Thus, the results of this research indicate that safety was greater for right turns followed by U-turns than for direct left turns.

The National Cooperative Highway Research Program (NCHRP) – Report 420 clarified the basic concept of alternative, summarized the safety and operational experiences in current practice, and presented application guidelines. The report indicated that directional median openings experienced 50% and 40% reductions in major and minor conflicts respectively compared with full median openings. They presented the main advantages of right turn followed by U-turns as compared with direct left turns as following:

1) Under moderate to high traffic volume, travel and delay could be less.
2) The capacity of a U-turning movement at the median opening is much higher than the capacity of a direct left-turning movement.
3) Right turn followed by U-turns have fewer conflicts than direct left turns.
4) A left turn lane at a median opening for facilitating directional left turn and U-turning movements can be designed to store several vehicles because storage is parallel to the through traffic lanes.
5) A single directional median opening can be used to accommodate traffic from several upstream driveways, especially when the driveway spacing is very close. Thus, when volumes are from moderate to heavy, the right turn followed by U-turn may demonstrate more advantages than direct left turns.

2.5 Summary of Past Studies

The past researches related to safety evaluation and operational effects of U-turn provide the basis for the decision maker to decide on the design mode for the future median opening and access management. If the designers take the results of the researches into consideration, apparently, more and more conventional full median openings will be replaced by directional median openings. Meanwhile, from the point of view for access management, more direct left turn onto the major arterial will be prohibited. Consequently, left turn egress maneuver from a driveway or side street will be converted to a right turn followed by U-turn at downstream median openings or signalized intersections. That means the number of U-turns will increases and the capacity of the signalized intersections which provide with U-turn will be effected negatively. Therefore, it is necessary to conduct researches for evaluating the effects of U-turns on capacity of signalized intersections. The past studies on the saturation flow rate provides us with the basis, fundamental concepts and some useful analytical methods for estimating the capacity of a lane or a lane group at signalized intersections.

In this thesis, the features of U-turning movements are presented and the regression model is developed to explain how the geometric factors affect the U-turn features. Moreover, the essential of this thesis is developing the regression model to determine the U-turn adjustment factors under varying percentages of U-turning vehicles. Eventually, the U-turn adjustment factors are validated by using Synchro Simulation based on the field data.

Briefly, this study can be summarized as three parts:

- Present the relationship between the U-turn speed and turning radius;

- Computing the U-turn adjustment factors;
- Calibrate the Synchro models and validate the U-turn adjustment factors.

CHAPTER 3

METHODOLOGY

In a left turn and U-turn mixed lane at a signalized intersection, the turning speed is a main conflict between the left-turning vehicles and U-turning vehicles and most of crashes in the left turn and U-turn mixed lane are rear-end crashes. In the first part of this study, the regression model is developed to analyze that the how the U-turn speed changes under different sites. In the second part of this thesis, another regression model is developed for determining the U-turn adjustment factors under varying percentages of U-turning vehicles. Finally, the third part focuses on calibrating the models in Synchro simulation software and validating the U-turn adjustment factors under some typical situations.

3.1 Methods to Analyze the U-turn Speed

By the observation on the selected research sites, it can be easily found that the turning speed of left-turning vehicles is significantly higher than the turning speed of U-turning vehicles. As a result, the phenomenon is usually that the left turn vehicle will apply a brake when it approaches the stop bar if there is a U-turn vehicle in front of it. So, it can be interpret as the difference between the left turn speed and U-turn speed causes the main conflict. Since the turning speed is the concern, thus the turning speed is treated as the major feature of U-turning movements. It is necessary to find out what kind of fact has a significant relationship to the turning speed and how the factors affect the turning speed as well. At the same time, it can be found that the turning radius has a highly significant effect on U-turn speed.

In this study, 15 signalized intersections with relatively high percentage of U-turning vehicles are selected as research sites. 375 U-turn speeds and the turning radius for every site are measured. The regression model is developed to describe the relationship between the U-turn speed and turning radius.

3.2 Method to determine the U-turn Adjustment Factors

Firstly, the average queue discharge time for each tuning vehicle was defined as the queue discharge time divided by the number of turning vehicles in the queue. Secondly, several regression models were taken into consideration, and the regression results were compared. It was found that three different kinds of regression models were appropriate in describing the relationship between the average queue discharge time and U-turn percentages. Specifically, they are a simple linear regression model, a linear regression model with an exponential form, and a linear regression model with a quadratic form (second degree polynomial regression model). Statistical analysis found that the second degree polynomial regression model had the best regression results and the best goodness of fit to the field data.

Finally, on the basis of the regression results above and the definition of the adjustment factors for turning movements, the equation for calculating U-turn adjustment factors for the left turn saturation flow rate can be presented. With this equation, the U-turn adjustment factors for various percentages of U-turning vehicles could be calculated. The U-turn adjustment factors developed in this study can be directly used to estimate the capacity reduction in a left turn lane due to the presence of U-turning vehicles when the signalized intersection has only one left turn lane in the subject approach.

3.3 Method to Validate the U-turn Adjustment Factors

In this part, the major method to validate the U-turn adjustment factors is using Synchro simulation. Specifically, three typical sites were selected to be calibrated. Because the Level of Service (LOS) of a signalized intersection depends on the control delay of every approach, the criteria for validating the U-turn adjustment factors focused on the control delay which was output from running the Synchro simulation. Therefore, another field data collection was conducted for measuring and calculating the control delay. Three typical signalized intersections were selected for calibrating. The method for measuring the control delay in the field will be specified in the following chapter. Consequently, the results from Synchro simulation indicates that by adjusting the saturation flow rate based on the U-turn adjustment factors, the control delay output from Synchro simulation will get closer to the real control delay values which were measured from field. This result means that by applying the U-turn adjustment factors, the capacity reduction due to U-turning movements in a left turn and U-turn mixed lane can be estimated.

CHAPTER 4

DATA COLLECTION

Field data collection at signalized intersection was very important in this study. Some aspects need to be considered before conducting the field data collection:

- Study Objective: different study objectives require different types of data.
- Study sites: the study sites should be chosen according to the study objective and data requirements.
- Methodology for data collection: in order to get the high quality field data, a detailed data collection plan is prepared before performing the field data collection.

4.1 Field Data Collection for Turning Speed Regression Model

In this part, the purpose of the field data collection is to get the U-turning speed and left turn speed at different signalized intersections, and compare the two groups of speeds for identifying the difference between the U-turn speed and left speed. Also, the turning radius needs to be measured for developing the regression model for describing the relationship between U-turn speeds and turning radius. Specifically, the followings criteria were used in the sites selection:

1. Grade of approaches were Level;
2. Protected signal phasing for U-turns and left turns;
3. U-turns and left turns share one lane;
4. Only one lane accept U-turns;

5. Relatively high percentages of U-turning vehicles.

The specified information of the selection study sites is listed as the following Table 4-1:

Table 4-1 Description of Selected Study Sites 1

Signalized Intersections	N1	N2	Left Turn Phase
Bruce B Downs Blvd @ Commerce Palms Blvd	Single	1	P
Fowler Ave @ 56th Street	Dual	0	P
Bruce B Downs Blvd @ Cross Creek Blvd	Single	1	P
Bearss Ave @ Florida Ave	Single	1	P
Bruce B Downs Blvd @ Highwoods Preserve Pkwy	Single	1	P
CR 581 (Bruce B Downs Blvd) @ County Line	Single	1	P
Dale Mabry HWY @ Fletcher Ave	Single	0	P
Dale Mabry HWY @ Stall Rd	Single	0	P
Waters Ave @ Dale Mabry HWY	Single	1	P
Dale Mabry HWY @ Waters Ave	Single	0	P
Dale Mabry HWY @ Mapledale Blvd	Single	0	P
Dale Mabry HWY @ Bearss Ave(Ehrlich Ave)	Single	0	P
Dale Mabry HWY @ Carrollwood SPGS	Single	0	P
Hillsborough Ave @ Armenia Ave	Single	1	P
Hillsborough Ave @ Lois Ave	Single	0	P

Notes:

N1 = number of exclusive left turn lanes;

N2 = number of exclusive right turn lanes from other approach of the intersection;

P = Protected Signal Phasing.

The following aerial map is a typical study site. It shows the location when I was measuring the speed and queue discharge time; the location of digital camera is marked up in the map as well.

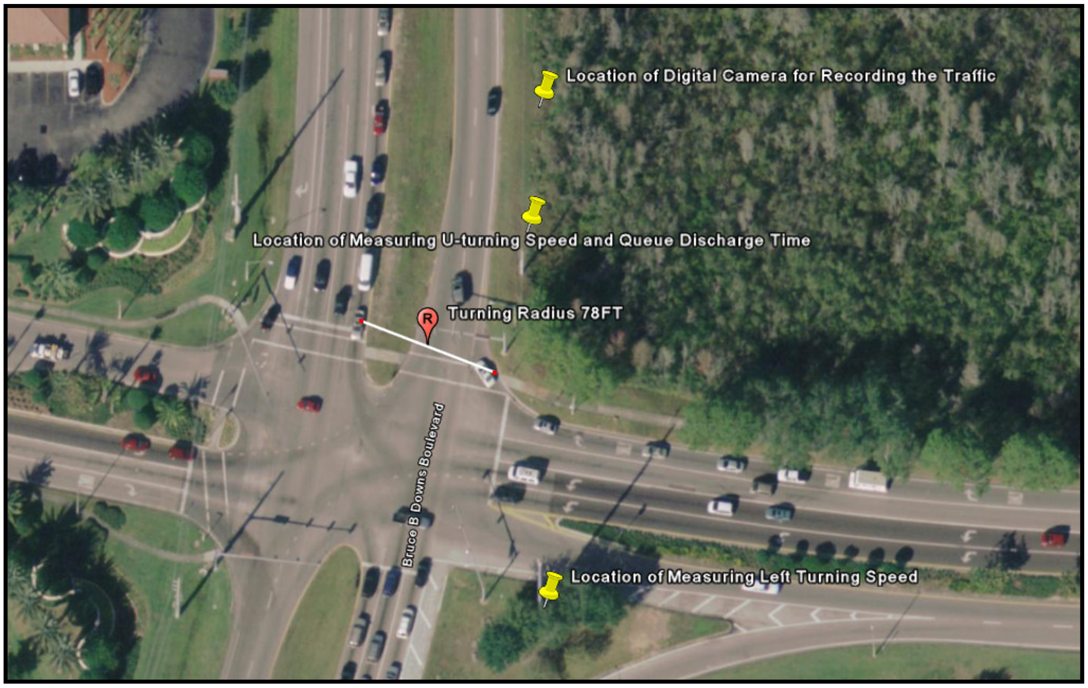

Figure 4-1 Aerial Map for Typical Selected Site Location

The U-turn speeds were measured by using the speed radar gun when the U-turning vehicles turn around and reach the stop bar. The left turn speeds were measured by using speed radar gun as well when the left-turning vehicles move to the center of the intersections. The turning radius were measured by the hand wheel from the edge the travel lane of the exclusive left turn lane to the edge the pavement of the corresponding exit lanes including width of medians.

4.2 Field Data Collection for Determining the U-turn Adjustment Factor

In this study, the effects of U-turns on the capacities of signalized intersections were quantified by analyzing the relationship between the percentage of U-turning vehicles the left-turn lane and the 76 Transportation Research Record 1920 average queue discharge time for each turning vehicle. Data were collected at three signalized intersections in the Tampa area of Florida. To separate the effects of U-turning vehicles from other factors that may influence intersection capacity, the following criteria were used in the selection of the study sites:

1. Lane widths were 12 ft;
2. The approach grade was level;
3. There was no parking adjacent to a travel lane within 250 ft of the stop line;
4. The intersections were located in a non-central business district area;
5. The intersections had exclusive left-turn lane and protected left-turn phasing for left turns;
6. There was insignificant disturbance from a bus stop;
7. There was insignificant disturbance from the right-turning vehicles during the U-turn phase in the other approach of the intersection (right-turning vehicles in the other approach of the subject signalized intersection are supposed to yield to U-turning vehicles when U-turns are accommodated by a protected left-turn phase; if significant disturbance was observed, the data were excluded from analysis); and
8. The selected street segment needed to have at least three traffic lanes (including through traffic lanes and an exclusive right-turn lane in the other approach) in each direction; passenger cars can normally make U-turns along a divided six-lane road (three

lanes each direction) without any geometric restrictions. The selected sites are listed in Table 4-2. The traffic flow data and signal timing were recorded by using two video cameras. Data collection typically started at 4:00 in the afternoon. Before recording began, the video cameras were synchronized so that the data extracted from the different videotapes could be matched. Data collection was conducted during weekday peak periods. Data were not gathered during inclement weather or under unusual traffic conditions. The following information was gathered by reviewing the videotapes: (*a*) the number of U-turning vehicles and left-turning vehicles in each queue and (*b*) the discharge time required for each queue, which was measured as the time that elapsed from the time that the green signal was initiated until the time that the rear wheel of the last vehicle in the queue crossed the stop line. The discharge time for each queue was recorded by using a Radio Shack liquid crystal display stopwatch, which could record discharge times with 0.01-s accuracy. To focus on the characteristics of passenger car flows, the data related to heavy vehicles and all vehicles behind a heavy vehicle were excluded from the analysis. Additionally, only those vehicles that had come to a complete stop before the initiation of the green signal were included in the analysis. In total, the study team recorded the queue discharge times for 260 queues, including 571 U-turning vehicles and 1,441 left-turning vehicles.

Table 4-2 Description of Selection Sites 2

Signalized Intersection	N1	N2	N3	Left Turn Phasing
Fowler Ave @ 56th Street	Dual	3	0	P
Bruce B Downs Blvd @ Newtampa Blvd	Single	2	0	P
Bruce B Downs Blvd @ Cross Creek Blvd	Single	2	1	P

Note:

N1 = number of exclusive left-turn lanes.

N2 = number of through-traffic lanes in each direction.

*N*3 = number of exclusive right-turn lanes from other approach of the intersection.

P = protected signal phasing.

4.3 Data Collection for Calibration and Validation

As discussed in previous chapters, the control delay is the criteria for determining the LOS of a signalized intersection. So, the control delay was selected as the major criteria for validating the Synchro simulation models and verifying the correctness the U-turn adjustment factors. In this part of field data collection, the measurement technique provided by HCM 2000 for obtaining the field control delay was applied. Three typical sites were taken into consideration for calibrating the models. The features of these 3 sites match the characteristics which were mentioned above. In addition, the turning radius of these 3 sites range from comparatively narrows to wide. Meanwhile, the U-turning vehicles percentages go from 40% to 55%. The Table 4-3 describes the selected sites in this field data collection

Table 4-3 Description of Selected Study Sites 3

Signalized Intersection	N1	N2	Left Turn Phase	Turning Radius (FT)	Percentages of U-turning vehicles
Bearss Ave @ Florida Ave	S	1	P	45	49%
Bruce B Downs Blvd @ Highwoods Preserve PKWY	S	1	P	72	53%
CR 581 (Bruce B Downs Blvd) @ County Line	S	1	P	153	41%

Notes:

N1 = number of exclusive left turn lanes;

N2 = number of exclusive right turn lanes from other approach of the intersection;

P = Protected Signal Phasing;

S = Single.

The following information should also be measured in the field for calibrating the Synchro simulation models:

1. Geometric design and lanes configuration of the selected signalized intersections;
2. Hourly traffic volume for each lane in each approach;
3. Signal timing;
4. Free-flow speed of the roadway.

Based on the above information, the simulation models are able to be calibrated.

4.4 Measurement Technique for Obtaining the Field Control Delay

In this study, the measurement technique for measuring the field control delay follows the method provided by HCM 2000. The procedure can be briefly stated as following:

1. Before going to the field, several initial parameters need to be determined:
    1) Number of observational lanes, N;
    2) Free-flow speed, FFS (mph);
    3) Survey count interval, I_s (s);
2. Count the number of vehicles in queue for each time interval; Count the hourly traffic flow in subject lane; Count the U-turning vehicles mixed in the left turn lane, and

3. Calculate the percentages of U-turning vehicles.

4. Compute the field control delay:

   1) Total vehicles arriving, V_{tot};

   2) Stopped-vehicles count, V_{stop};

   3) Total vehicles in queue, $\sum V_{iq}$;

   4) Time-in-queue per vehicle, $D_{vq} = I_s x \left(\frac{I_s x \sum V_{iq}}{V_{tot}} \right) x\, 0.9$, s;

   5) No. of vehicles stopping per lane each cycle; $\frac{V_{stop}}{N_c \times N}$;

   6) Accel/Decel correction factor, CF, (CF can be checked out in the following Table 4-4):

Table 4-4 Acceleration – Deceleration Delay Correction Factor, CF (s)

Free-Flow Speed	$\leq$ 7 Vehicles	8 - 19 Vehicles	20 - 30 Vehicle
$\leq$ 37 mi/h	5	2	-1
> 37–45 mi/h	7	4	2
> 45 mi/h	9	7	5

Vehicle-in-queue counts in excess of about 30 vehicles per lane are typically unreliable.

   7) Number of cycles surveyed, N_c;

   8) Fraction of vehicles stopping, $FVS = \frac{V_{stop}}{V_{tot}}$;

   9) Accel/Decel correction delay, $d_{ad} = FVS \times CF$ (s);

   10) Control Delay/vehicle, $d = d_{vq} + d_{ad}$ (s).

By following the procedure specified above, the field control delay can be obtained, and these control delay values can be used as the criteria for validating the Synchro simulation models as well as verifying the correctness of U-turn adjustment factors.

CHAPTER 5

DATA ANALYSIS

The tasks conducted in the data analysis of this study include: developing the regression model for describing the relationship among U-turn speed and different types of vehicles, turning radius and effect of right turn; developing the regression model for determining the U-turn adjustment factors under various percentages of U-turning vehicles; calibrating and validating the Synchro simulation models.

5.1 Data Analysis on U-turn Speed

As discussed in the previous chapters, the U-turn speed is significantly lower than left turn speed. This is the major reason for producing the conflicts and causing the rear-end crashes between the U-turning vehicles and left-turning vehicles. In this chapter, two linear regression models are developed to describe the relationship between U-turn speed and some other factors may affect U-turn speed.

Disaggregate linear regression model indicates the relationship among U-turn speed and some other external various factors which are likely to affect the U-turn speed for every U-turn vehicle. In this study, a disaggregate model is developed for identifying the factors that contribute to U-turn speed. The Turning radius, types of vehicles, and effect by right turn vehicles are selected as independent variables, the dependent variable is U-turn speed. Some other variables were also considered, including the posted speed limit and the lane width of the major street. However, adding these variables did not significantly improve the R^2 value of the model. The following Table 5-1 lists the descriptive statistics of dependent and independent variables:

Table 5-1 Descriptive Statistics of Dependent and Independent Variables for Disaggregate Regression Model

Variables	Frequency	Min.	Max.	Mean.	Std. Deviation.
U-turn Speed (MPH)	419	9	20	14	2.33
Number of Vehicles	419	NA	NA	NA	NA
(Sedan or Coupe)	235	NA	NA	NA	NA
(SUV)	111	NA	NA	NA	NA
(Van)	39	NA	NA	NA	NA
(Pick-up)	34	NA	NA	NA	NA
Turning Radius (FT)	15	43	153	71	29.14
Affected by Right Turn	31	NA	NA	NA	NA

Based on the selection of dependent variable and independent variables, an exponential liner regression model was developed by using SPSS. The following tables, from Table 5-2 to Table 5-4, show the model summary, ANOVA test and results of regression model.

Table 5-2 Summary for Disaggregate Regression Model

R	R Square	Adjust R Square	Std. Error of Estimate
0.452	0.204	0.195	0.15485

Table 5-3 ANOVA Test for Disaggregate Regression Model

Sum of Squares	Df	Mean Square	F	Sig.
2.541	5	0.508	21.194	0.000
9.903	413	0.024		
12.444	418			

Table 5-4 Statistical Results for Disaggregate Regression Model

Parameters	Coefficients	Std. Error	t	Sig.	VIF
Constant	1.787	.094	19.100	0.000	NA
SUV	-.020	.018	-1.140	.255	1.090
Van	-.070	.027	-2.599	.010	1.077
Pick-up	-.085	.028	-3.000	.003	1.055
LnRadius	.197	.022	8.919	.000	1.020
Affected by	-.052	.029	-1.833	.067	1.035
$R^2 = 0.204$, $R^2_{adj} = 0.195$					

Note: Dependent Variable- LnSpeed

The regression model has a relatively low R^2 value of 0.204 and an adjusted R^2 value of 0.195. This is because this exponential regression model is a disaggregate model, so the comparatively low R square is reasonable. The t-statistics show that the selected explanatory variables are all statistically significant at a 95% level of confidence. The VIF values are close to 1, it means that the collinearity among the independent variables is pretty low. The equation of the U-turn speed model was given as follows:

Ln (Speed) = 1.787-0.02SUV-0.07Van-0.085Pick-up+0.197Ln (Radius)-0.052RTimp

Also, the equation can be interpreted as:

$$Speed = 5.97 * Radius^{0.197} * \exp(-0.02SUV - 0.07Van - 0.085Pickup - 0.052RTimp)$$

Where:

SUV, Van, Pick-up are dummy variables;

RTimp = Right Turn Impact, (dummy variable).

The U-turn speed model shows that the U-turn speed has a positive relationship with turning radius. When turning radius increase, the U-turn speed will increase accordingly. At the same time, the model shows that the sedan and coupe vehicles have the highest U-turn speed and the U-turn speed will decrease proportionally if the turning vehicles are SUV, Van, or Pick-ups. From the regression model equation, it also indicates that the U-turn speed has a negative relationship with effects of right turn. Specifically, the U-turn speed will decrease when the turning vehicles are affected by the right turn vehicles from the other side of the approach. And the regression models quantify the variation among the U-turn speed and all the independents variables.

From the result of the above disaggregate regression model, it can be found that the unstandardized coefficient values of turning radius is the highest in all the independent variables. It means turning radius has the most significant effect to the U-turn speed. Since as discussed in the previous chapters, the major concern between U-turning vehicles and left-turning vehicles is turning speed. In the field observation, the left-turning vehicles usually applied a brake suddenly and slow down in emergency. This phenomenon happens just in couple of seconds, but it can indicate the issue between the

U-turn and left-turning vehicles. Therefore, it is necessary to develop a model to explain the relationship between U-turn speed and turning radius which is the most significant parameter to impact the U-turn speed. An aggregate regression model was developed for describing the relationship between U-turn speeds and turning radius. There are two variables in this aggregate regression model. U-turn speeds are the dependent variable and turning radius are independent variable. This regression model focuses on how U-turn speed varying under variable turning radius. It includes more details to tell us that how he turning radius effects the U-turn speeds. The sample size of U-turn speeds is 419 collected from 15 signalized intersections which have comparatively high percentages of U-turning vehicles. The following table 5-5 shows the statistical description of sample:

Table 5-5 Descriptive Statistics of Dependent and Independent Variable for Aggregate Regression Model

Variable	Frequency	Min.	Max.	Mean.	Std. Deviation.
U-turn Speed (MPH)	419	9	20	14	2.33
Turning Radius (FT)	15	43	153	71	29.14

Once the dependent variable and independent variable are determined, the regression model can be run by using SPSS. In this case, the exponential linear regression model was developed since it has a relatively high R square value. Table 5-6 is the summary of the aggregate regression model.

Table 5-6 Summary for Aggregate Regression Model

R	R Square	Adjust R Square	Std. Error of Estimate
0.71	0.505	0.467	0.06976

Subsequently, ANOVA test was conducted for analyzing the variance and residuals. The results of AVOVA test is described in the table 5-7.

Table 5-7 ANOVA Test for Aggregate Regression Model

Sum of Squares	df	Mean Square	F	Sig.
0.064	1	0.064	13.249	0.003
0.063	13	0.005		
0.128	14			

According to the results which were stated, the results of regression model can be listed as following:

Table 5-8 Statistical Results for Aggregate Regression Model

Parameters	Coefficients	Std. Error	t	Sig.
Constant	1.78	0.226	7.892	0.000
LnRadius	0.195	0.054	3.64	0.003

Notes: Dependent Variable: LnSpeed

In the result of aggregate regression model, the t test value of independent is 3.640; meanwhile the significance value is 0.003. These 2 values can indicate that the independent variable LnRadius is highly related to dependent variable LnSpeed. The equation of the regression model can be given as following:

$$Ln(Speed) = 1.780 + 0.195Ln(Radius)$$

Also the equation can be converted into:

$$Speed = \exp(1.780) \times Radius^{0.195}$$

In this aggregate regression model, the R square and adjusted R square values are 0.505 and 0.467, respectively. Thus, the R square values are satisfied and it means the independent variable can explain the dependent variable at a high level of percentage.

From the aggregate regression model, it can be found that U-turn speed has a positive relationship with turning radius. In another word, the U-turn speed will increase with the increment of turning radius. The variation has been indicated clearly in the above equations.

In the disaggregate regression model, the results can tell us the U-turn speed is effected by some parameters such as type of vehicles, turning radius, and effect of right turn vehicles. The sedan and coupe vehicles have the highest U-turn speed comparing to other types of vehicles. It may because the sedan and coupe vehicles have the smallest volume and least torque, but it is just an inference which weren't verified in this study. Another point in the disaggregate regression model is that the right turn vehicles from the other approach will effect the U-turn speed negatively.

In the aggregate regression model, the results focus on explaining the relationship between U-turn speed and turning radius. The turning radius will impact the U-turn speed positively. The U-turn speed will increase with the increment of turning radius which is provided at a signalized intersection. I have to point out that there probably some other factors will affect the U-turn speed, and the turning radius is not the only effective parameter. This part of research can be the focus of future work.

5.2 Determination of U-turn Adjustment Factors

The determination of a U-turn adjustment factor depends on a number of variables, including:

1. Whether U-turns are made from exclusive left-turn lanes or shared lanes,

2. The type of phasing (protected, permitted, or protected plus permitted), and

3. The proportion of U-turning vehicles in the left-turn lane.

In this study, only the condition in which U-turns being accommodated at an exclusive left-turn lane with protected signal phasing was considered.

As indicated before, vehicles making U-turns have slower turning speeds than those making left turns. Therefore, U-turning vehicles may cause the following left-turning vehicles to slow down because of the difference in speeds between these two movements.

When U-turning vehicles are mixed with left-turning vehicles in a left-turn traffic stream, the discharging queue will consume more green time than those queues with only left-turning vehicles. Theoretically, the difference increases with the increase in the percentage of U-turning vehicles in the queue. In this study, a regression model was developed to estimate the relationship between the various percentages of U-turning vehicles in the left-turn lane and the average queue discharge time for each turning vehicle. The average queue discharge time for each turning vehicle was defined as the queue discharge time divided by the number of turning vehicles in the queue, as shown in Equation 1:

$$h = \frac{T}{N_u + N_l} \tag{1}$$

Where

h = average queue discharge time for each turning vehicle (s);

T = queue discharge time (the time that has elapsed from the time of initiation of the green signal until the time that the rear axle of the last vehicle in the queue crosses the stop line) (s);

N_u = the number of U-turning vehicles in the queue; and

N_l = the number of left-turning vehicles in the queue.

The data collected were plotted with the average queue discharge time for each turning vehicle as the dependent variable and the various percentages of U-turning vehicles as the independent variable. Several regression models were considered, and the regression results were compared. It was found that three different kinds of regression models were appropriate in describing the relationship, including a simple linear regression model, a linear regression model with an exponential form, and a linear regression model with a quadratic form (second-degree polynomial regression model). Statistical analysis found that the second-degree polynomial regression model had the best regression results, for example, the best goodness of fit to the field data. The descriptive statistics are shown in Table 5-6, and the regression results are listed in Tables 5-7 to 5-8. The model is described in Equation 2:

$$h = 0.000033P_{UT}^2 + 0.003P_{UT} + 2.1399 \tag{2}$$

Where h is the average queue discharge time for each turning vehicle (s), and P_{UT} is the percentage of U-turning vehicles in the left-turn lane and is calculated as

$$P_{UT} = \frac{N_u}{N_u + N_l} \tag{3}$$

On the basis of the regression results, the model was statistically significant and the independent variables were also statistically significant. The adjusted R^2 value was 0.506. The unstandardized residuals were plotted against each independent variable. The residual plot for each independent variable was randomly distributed about the *x*-axis line, which indicated that the model was correctly specified and that the basic assumption about the homogeneous variance was not violated. By considering the intercept, which represents the average queue discharge time under ideal conditions if it is assumed that no U-turning vehicles were in the left-turn traffic stream, this model provided a reasonable value of 2.14 s.

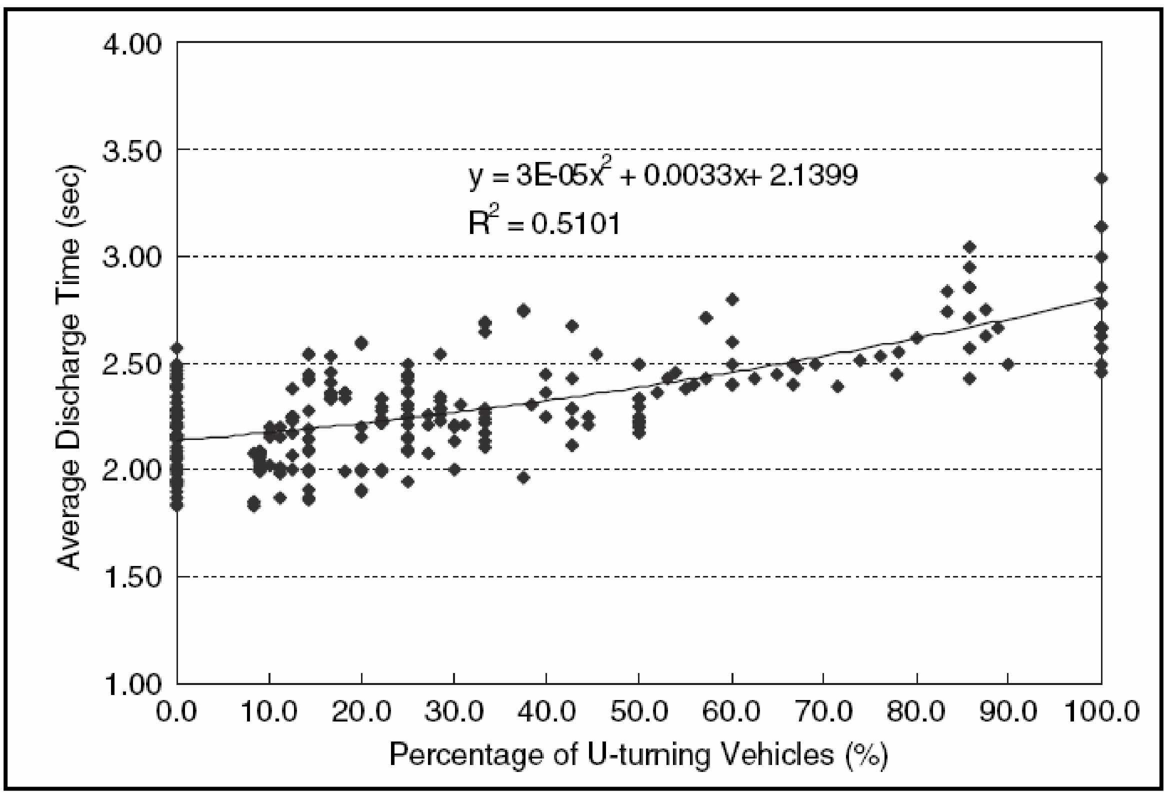

Figure 5-1 Plot of Average Queue Discharge Time Versus Various Percentages of U-turning Vehicles

On the basis of the definition of the adjustment factors for turning movements, the U-turn adjustment factor for the left-turn saturation flow rate can be estimated by using the following equation:

$$f_{UT} = \frac{(3600/h)}{(3600/h_0)} = \frac{h_0}{h}$$
$$= \frac{2.1399}{0.000033P_{UT}^2 + 0.003P_{UT} + 2.1399} \quad (4)$$

Where,

f_{UT} = adjustment factor for U-turning movement;

h = average queue discharge time for U-turn and left-turn mix flow (s);

h_0 = base average queue discharge time for left-turn-only flow (s);

P_{UT} = percentage of U-turning vehicles from inside left-turn lane.

With Equation 3, the U-turn adjustment factors for various percentages of U-turning vehicles were calculated and are listed in Table 5-9. The data in Table 5-9 show that U-turning vehicles have a considerable effect on the left-turn saturation flow rate, and the effect increases with the percentage of U-turning vehicles in the left turn lane. For example, the U-turn adjustment factor for the queue with 40% U-turning vehicles is 0.92, which implies an 8% capacity reduction in the left-turn lane. The adjustment factors developed in this study can be directly used to estimate the capacity reduction in a left-turn lane due to the presence of U-turning vehicles when the signalized intersection has only one left-turn lane in the subject approach. When the signalized intersection has dual left-turn lanes, the adjustment factors can be applied only to adjust the capacity of the inside left-turn lane, considering the fact that U-turns are usually accommodated from the inside left-turn lane. The adjustment factors developed in this study were compared with the results of the previous two studies cited in the literature review section. As shown in Figure 5-1, the curve of the proposed model generally conforms to but is somewhat lower than that in Adams and Hummer's study (*4*). Among those adjustment factors, Tsao and Chu's study predicts more severe effects than the other two studies (*5*). This finding is not a surprise, because their study was conducted in Taiwan and the study results may not reflect the behaviors of motor vehicle drivers in the United States

Table 5-9 U-Turn Adjustment Factors for Varying Percentages of U-Turning Vehicles

P_{UT} (%)	5	10	20	30	40	50	60	70	80	90	100
f_{UT}	0.99	0.98	0.96	0.94	0.92	0.90	0.87	0.84	0.82	0.79	0.76

Table 5-10 Descriptive Statistics for Data Collection in the Field

Statistical Parameter	h (sec)	P_{UT} (%)
N Valid.	260	260
Missing.	0	0
Mean.	2.30	30.5
Median.	2.26	22.2
Mode	2.00	.00
Minimum.	1.83	.00
Maximum.	3.37	100

Table 5-11 Regression Results (R^2 values) for Average Queue Discharge Model

R	R Square	Adjusted R Square	Std. Error
0.714	0.510	0.506	0.18425

Table 5-12 Regression Results (ANOVA Test) for Average Queue Discharge Model

Result	Sum of Squares	df	Mean Square	F	Sig.
Regression	9.085	2	4.542	133.813	.000
Residual	8.724	257	0.034		
Total	17.809	259			

Table 5-13 Regression Results (t-statistics) for Average Queue Discharge Model

Unstandardized Coefficients			Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
Constant	2.140	.021	NA	100.324	.000
P_{UT}^2	3.337E-05	.000	.355	2.480	.014
P_{UT}	.0033	.001	.367	2.564	.011

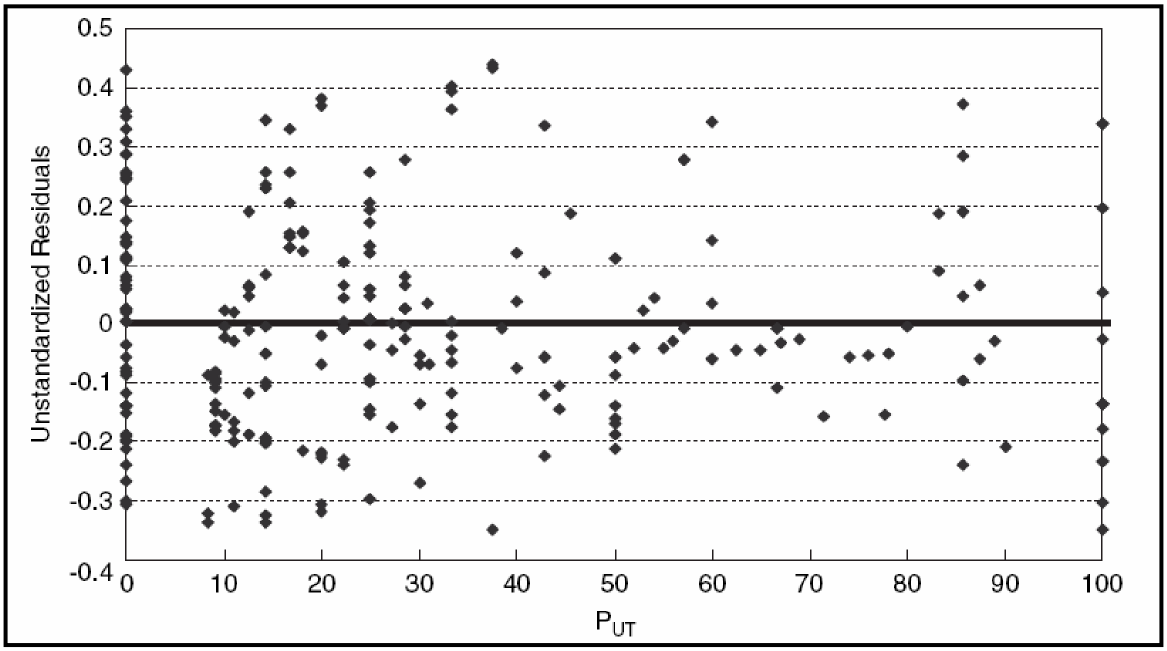

Figure 5-2 Plot of Unstandardized Residuals Versus the Independent Variable

(*P*UT)

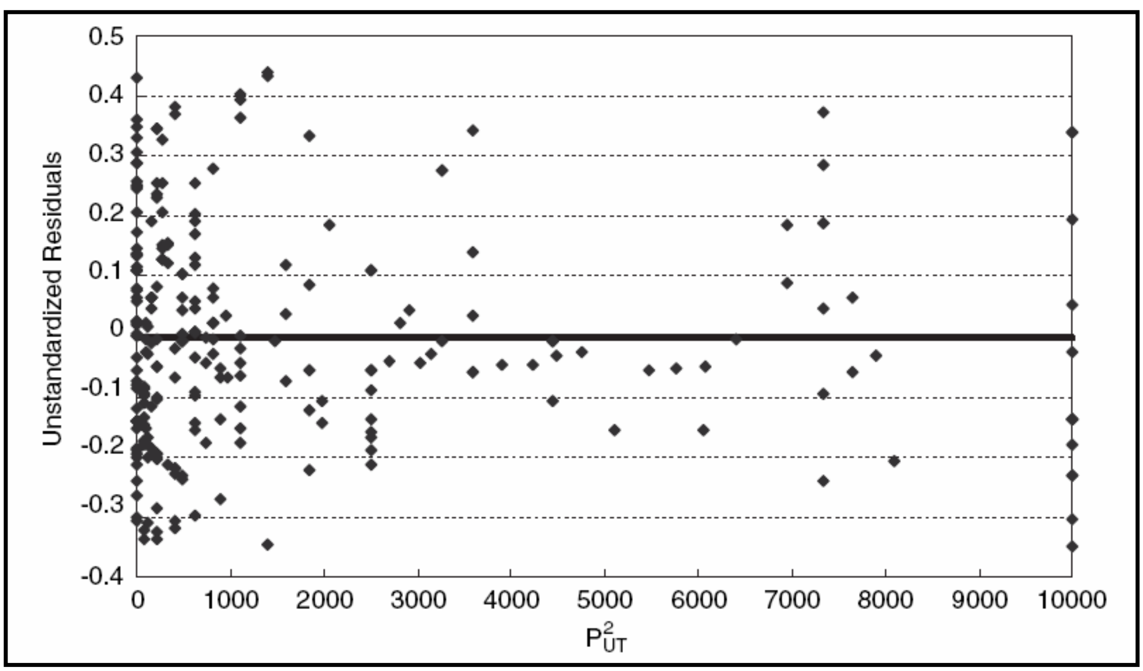

Figure 5-3 Plot of Unstandardized Residuals versus the Independent Variable (PUT^2)

5.3 Synchro Simulation

The tasks in this part of study are establishing the Synchro simulation models, calibrating and validating the models. The purposes of the simulation are verifying the correctness of U-turn adjustment factors and conducting a sensitive test about the relationship between the various percentages of U-turning vehicles and control delay values.

In this chapter, first of all, a brief introduction of Synchro simulation software package was stated. Subsequently, the contents showed the description of selected calibrating sites and the data collected from field for model calibration. Finally, the simulation models were run based on the field data for validating the models. From the results of simulation, it can be found that if the U-turn adjustment factors are considered as the initial input in the simulation models, the output control delay will be close to the field value. It demonstrates the correctness of U-turn adjustment factors for evaluating the effects of U-turns on capacity at signalized intersections, and it means U-turning movements can be simulated by adjusting the saturation flow rate according to U-turn adjustment factors. The sensitive test was conducted at last part of this study for testing the sensitivity of the control delay variation with different U-turn adjustment factors under various U-turn percentages of vehicles.

5.3.1 Introduction of Synchro Simulation Software Package

Synchro is simulative software especially for synchronizing the signal timing. It was published by Trafficware Company. And the Simtraffic come with the Synchro simulation software package. The main function of Simtraffic is simulating and analyzing the signalied intersection. The major output parameters are delay, queue, capacity, emission, and gas consumption, etc. The Synchro simulation software package can check and evaluate the operational conditions at a complicated signalized intersection. Basically, the simulations are able to be conducted by Synchro include:

- Pre-timed signal timing design;
- Actuated (semi-actuated) signal timing design;
- Freeway;
- Roundabout;
- Different types of vehicles;
- Pedestrian.

Synchro can provide us with enriched output report and detailed evaluation. It offers a lot of helpful information for the traffic practitioners.

However, what I want to point out is Synchro follows the algorithm based on HCM when it is simulating the signalized intersection. As discussed above, U-turning movements are treated as left turn for estimating the saturation flow rate. That actually means Synchro is not able to simulation the operational effects result from U-turning movements. Thus, it is necessary to find out a method to simulate the operational impacts caused by U-turns at asignalized intersections. In this study, to adjust the saturation flow rate by U-turn adjustment factors is applied for simulating the operational effects of U-turns.

5.3.2 Models Calibration

As discussed previously, the control delay value of the subject lane group was considered as the criteria for validating the models. So, another wave of field data collection was conducted which focuses on obtaining the field control delay values. Three typical sites were described in the following Table 5-14:

Table 5-14 Description of Selected Sites for Measuring Control Delay

Signalized Intersection	N1	N2	Left Turn Phase	Turning Radius (FT)	Percentages of U-turning vehicles in Left Turn Lane
Bearss Ave @ Florida Ave	S	1	P	45	49%
Bruce B Downs Blvd @ Highwoods Preserve PKWY	S	1	P	72	53%
CR 581 (Bruce B Downs Blvd) @ County Line	S	1	P	153	41%

Notes:

N1 = Number of exclusive left turn lanes;

N2 = Number of exclusive right turn lanes from other approach of the intersection;

P = Protected signal phasing;

S = Single.

Briefly, the main features of the selected study sites are that the turning radius provided for U-turn range from narrow to wide and the percentages of U-turning vehicles are relatively high. The details about hourly traffic volumes of every lane in each approach, approach lanes configurations, signal timing, free-flow speed are collected as well for establishing the simulation models. The field control delay measurement technique is provided by HCM 2000. The procedure for measuring and computing the field control delay has been stated in the previous chapters. The field data and the computation procedures are presented in the following tables:

Table 5-15 Computation Procedure for Control Delay of Site 1

Site 1 Bearss Avenue @ Florida Avenue	
CF	4
Nc	10
FVS	0.7
FFS (MPH)	45
dad=FVS*CF	2.9
Stopped Vehicles	87
U Percentage	49%
Number of Lane	1
Survey Count Interval, Is(s)	15
Total Vehicles Arriving, Vtot	122
Total Vehicles in Queue, Viq	478
Time in Queue Per Vehicle, dvq	53
Control Delay/Vehicle, d=dvq+dad	55.7
No. of Vehicles stopping per lane per cycle	9

Table 5-16 Computation Procedure for Control Delay of Site 2

Site 2. Bruce B Downs Blvd @ Highwoods Preserve PKWY	
CF	4
Nc	10
FVS	0.7
FFS (MPH)	45
dad=FVS*CF	2.8
Stopped Vehicles	80
U Percentage	53%
Number of Lane	1
Survey Count Interval, Is(s)	15
Total Vehicles Arriving, Vtot	116
Total Vehicles in Queue, Viq	444
Time in Queue Per Vehicle, dvq	52
Control Delay/Vehicle, d=dvq+dad	54.4
No. of Vehicles stopping per lane per cycle	8

Table 5-17 Computation Procedure for Control Delay of Site 3

Site 3. Bruce B Downs Blvd @ County Line	
CF	7
Nc	10
FVS	0.6
FFS (MPH)	45
dad=FVS*CF	4.0
Stopped Vehicles	49
U Percentage	41%
Number of Lane	1
Survey Count Interval, Is(s)	15
Total Vehicles Arriving, Vtot	86
Total Vehicles in Queue, Viq	320
Time in Queue Per Vehicle, dvq	50
Control Delay/Vehicle, d=dvq+dad	54.2
No. of Vehicles stopping per lane per cycle	5

5.3.3 Models Validation

After calibrating the simulation models, the next step of work is to run the simulation and get the output reports for validating the models. The method for validating models which was used in this study it to run the Synchro simulation under all parameters default and the left turn lane saturation flow rate adjusted according to the U-turn adjustment factors, respectively. The following Table 5-18 compares the results of the simulations:

Table 5-18 Comparison of Control Delay

Comparison of Control Delay (spv)			
	Default	Adjusted	Calculated
Site 1 Bearss Avenue @ Florida Avenue	49.3	55.3	55.7
Site 2 Bruce B Downs Blvd @ Highwoods Preserve	48.5	54.9	54.4
Site 3 Bruce B Downs Blvd @ County Line	46.6	54.2	54.8

Notes: spv = second per vehicle

By the results from Synchro simulation, it can be found that the control delay value is closer to the calculated value after adjusting the saturation flow rate of the left lane based on the U-turn adjustment factors. In this test, the results indicate the operational effects were simulated by adjusting the saturation flow rate in the object lane group. Therefore, if evaluation of LOS is conducted by Synchro simulation in the future, measuring the percentages of U-turning vehicles and adjusting the saturation flow rate will make the results more accurate. Because conventional Synchro simulation also treated U-turns as left turns for estimating the saturation flow rate and the results do not include the capacity reduction caused by U-turning movements in object lane group. However, to ignore U-turns' impacts will result in errors on evaluating LOS. Although, the results of adjusting saturation flow rate can not be 100% accurate for estimating the capacity reduction, this method works on reducing the errors on evaluating LOS and make the theoretical values closer to the field real values.

5.3.4 Sensitive Tests

At the last part of this study, a sensitive test was conducted for testing the sensitivity of the control delay values reacting to the adjustments of saturation flow rates. The procedure of this test is using the simulation models which have been calibrated and validated in the previous work and keeping all the conditions unchangeable. And then assume that the percentages of vehicles in the object left lane varying from 10% to 100%. Subsequently, run the simulations and get the results. 10 reports were output for each site. Figure 5-4, 5-5, 5-6, indicates the overall situation for control delaying values reacting to the variation of U-turning vehicles percentages. From the varying trend of control delay values under different percentages of U-turning vehicles, it can be roughly observed that the control delay values will increase with augment of U-turning vehicles' percentages. It can be interpreted as when the number of U-turning vehicles increases, the saturation flow rate of left turn lane will decrease accordingly. The U-turn adjustment factors which have been presented can be used to quantify this reduction of saturation flow rate. Thus, the capacity of the approach will reduce due to the decrease of saturation flow rate. The capacity of approach will directly affect on evaluating the LOS of a signalized intersection.

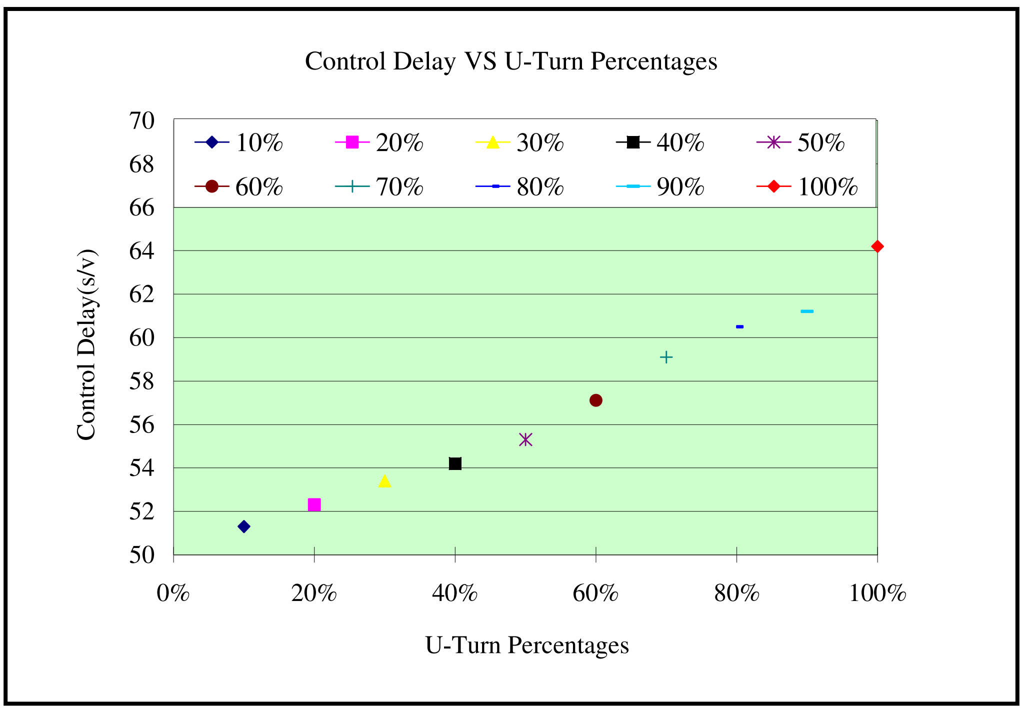

Figure 5-4 Trend of Control Delay Variation under Different Percentages of U-turning vehicles for Site 1

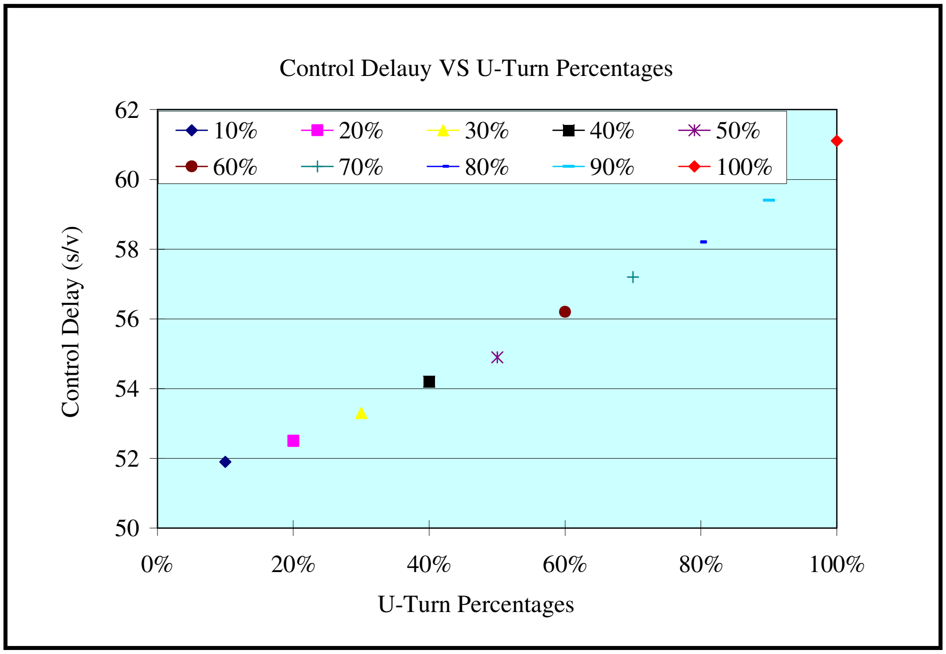

Figure 5-5 Trend of Control Delay Variation under Different Percentages of U-turning vehicles for Site 2

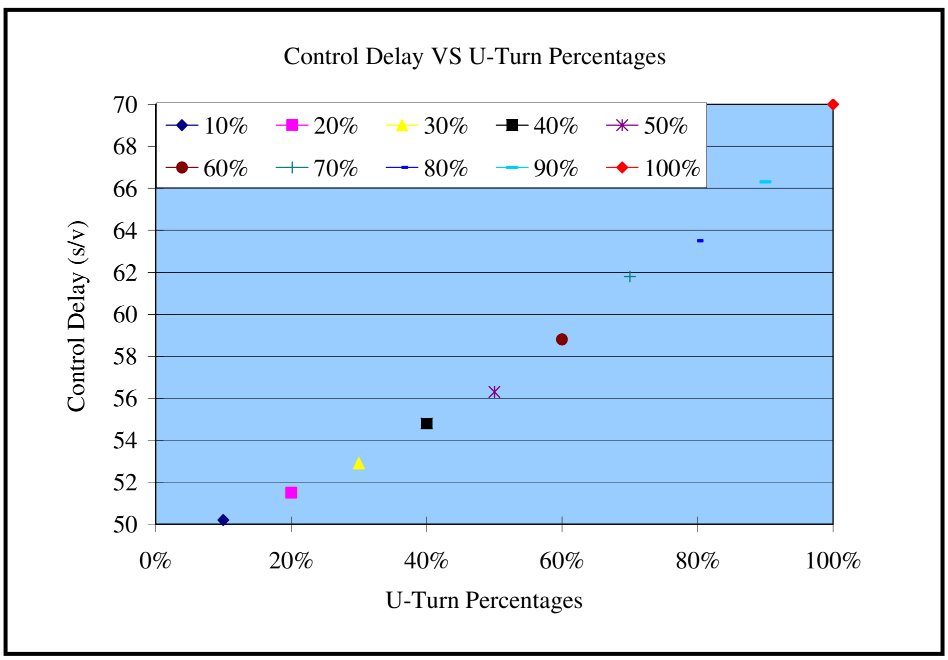

Figure 5-6 Trend of Control Delay Variation under Different Percentages of U-turning vehicles for Site 3

From the figures above, the trend of control delay under variable percentages of U-turning vehicles can be indicated. But in the figure, only the varying trends are shown up. By observing the figures above, several preliminary summaries can be obtained.

1: The control delay of the U-turn and left turn mixed lane at a signalized intersection will increase with the increment of the percentages of U-turning vehicles.

2: For each 10% variation of the U-turning vehicles, the value of control delay is about to increase 1.5s, accordingly.

But this is just a rough inference based on the figures, more details can be found in the following tables which list the values of control delay and U-turn percentages. The following Table5-19, 5-20, 5-21, show the exact values of the sensitive tests:

Table 5-19 Summary of Sensitive Test for Site 1

Site 1 Bearss Avenue @ Florida Avenue	
U Turning Vehicles Percentage	Control Delay (spv)
10%	51.3
20%	52.3
30%	53.4
40%	54.2
50%	55.3
60%	57.1
70%	59.1
80%	60.5
90%	61.2
100%	64.2

Table 5-20 Summary of Sensitive Test for Site 2

Site 2 Bruce B Downs Blvd @ Highwoods Preserve	
U Turning Vehicles Percentages	Control Delay (spv)
10%	51.9
20%	52.5
30%	53.3
40%	54.2
50%	54.9
60%	56.2
70%	57.2
80%	58.2
90%	59.4
100%	61.1

Table 5-21 Summary of Sensitive Test for Site 3

Site 3 Bruce B Downs Blvd @ County Line	
U Turning Vehicles Percentages	Control Delay (spv)
10%	50.2
20%	51.5
30%	52.9
40%	54.8
50%	56.3
60%	58.8
70%	61.8
80%	63.5
90%	66.3
100%	70

Notes: spv = seconds per vehicle

The objective of sensitive tests is quantifying the variation of control delay under varying percentage of U-turning vehicles. It indicates the sensitivity of varying percentages of U-turning vehicles to the LOS of a signalized intersection.

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

This study is composed by three major parts. In the first part, the exponential linear regression model was developed to describe the relationship among the U-turn speed and some other external various factors. The factors which significantly related to U-turn speed were indicated in the results of the regression model. And the model quantities the effects to U-turn speed. In the second part, the U-turn adjustment factors under various percentages of U-turning vehicles were determined by the quadratic regression model. The results of this part of study can be directly used for estimating the saturation flow rate of a U-turn and left turn mixed lane. Furthermore, it can be used for estimating the reduction of capacity at a signalized intersection and evaluating the LOS. The last part of this study is verifying the correctness of U-turn adjustment factors. The procedure includes calibrating models, validating models, and running the models. The results show that inputting the U-turn adjustment factors for adjusting the saturation flow rate of a subject lane or lane group can make the results of simulation more accurate. A sensitive test was also conducted. The objective of the sensitive analysis is to quantify the impacts of various percentages of U-turning vehicles on saturation flow rate and reduction of capacity.

6.2 Conclusions

As a result of this research, the following conclusions can be made:

1. U-turning vehicles adversely affect the capacities of signalized intersections; and the effect increases with the increase of percentages of U-turning vehicles in the left-turn lane.

2. When left-turning vehicles are mixed with U-turning vehicles in the left-turn traffic stream, the discharge flow rate does not display an easily identifiable steady maximum rate. Therefore, the traditional headway method, which measures the saturation headway of U-turning vehicles and left-turning vehicles in the field, may not be suitable for estimation of the effects of U-turning vehicles on the left-turn traffic stream.

3. U-turning vehicles consume more of the available green time and more of the lane's available capacity than left-turning vehicles. In addition, U-turning vehicles cause the following left-turning vehicles to slow down to avoid a rear-end collision. The extra time required by the queue to be discharged because of the presence of various percentages of U-turning vehicles can be quantified by use of the regression model developed in this study.

4. When the capacity of a signalized intersection is estimated, it is essential to account for the capacity reduction due to the presence of U-turning vehicles, especially when the percentage of U-tuning vehicles is relatively high (>40%). The effect can be quantified by applying the adjustment factors developed in this study.

6.3 Practical Meaning of the Study

As summarized in the previous contents, this study consists three major parts. The first part developed exponential linear regression models to identify the factors which affect the U-turn speed. From this segment of results, it can be found that the turning radius has a significant effect on U-turn speed. The U-turn speed increases with the increase of turning radius. Thus, if longer turning radius is provided for the U-turning vehicle, the U-turn speed will be higher. It may reduce the possibility of rear-end crash between U-turning vehicles and left turning vehicles. Furthermore, the results of the first part may offer some useful suggestions for traffic practitioner and roadway designer.

The second part focuses on presenting a method for estimating the reduction of saturation flow rate due to U-turning movement. The method achieved by developing U-turn adjustment factors. The results of this part show varying U-turn adjustment factors under various percentages of U-turning vehicles which change from 5% to 100% in the left turn lane. From the U-turn adjustment factors, it can be found that the reduction of saturation flow rate increases with increase of U-turning vehicles. The developed U-turn adjustment factors can be directly used to estimate the capacity reduction due to the presence of various percentages of U-turning vehicles at a signalized intersection. This is the meaning of developing the U-turn adjustment factors.

The third part of this study is Synchro simulation. First of all, Synchro simulation software is the most widely used tool in the traffic industrial field. A lot of transportation consulting companies use Synchro to evaluate the Level of Service at intersections. Also, Synchro simulation software is especially used for signalized intersections. Simulating signalized intersections is the advantage of Synchro simulation software comparing to other traffic simulation software. But the algorithm in Synchro follows by the Highway Capacity Manual. That causes the problems. As is discussed in the previous chapters, U-turns are treated as left turns for estimation of saturation flow rate. However, the operational effects of U-turns and left turns are different. Therefore, the results from Synchro simulation do not take the operational effects due to U-turns into consideration. That's why the control delay values output from Synchro without using U-turn adjustment factors do not match the measured control delay value. From the results of part three in this study, it can be found that the output control delay values are closer to field data if using U-turn adjustment factors to adjust the saturation flow rate in exclusive left lane. This phenomenon indicates using U-turn adjustment factors will improve the accuracy of simulation. It may be a new, feasible, and reasonable method for simulating the operational performance at signalized intersections and make it more accurate. The meaning of this segment of research is that the results may be directly applied in the traffic industrial field as a useful method to improve performance of Synchro simulation.

6.4 Limitations

Note that the adjustment factors in this study were developed under some simplified conditions. The simplified conditions include

1. Vehicles make left turns and U-turns from an exclusive left-turn lane;
2. Vehicles make left turns and U-turns under a protected signal phase;
3. The street segment has enough of a turning radius to accommodate U-turns;
4. All the turning vehicles are passenger cars and there are no commercial vehicles in the

left turn lane.

5. There is just minor disturbance from the right-turning vehicles during the U-turn phase in the other approach of the intersection.
6. All the field data collection is conducted in urban area. So, the condition of rural area is not taken into consideration.

6.5 Discussion and Recommendation

In this segment, three major concerns need to be pointed out and discussed:

1. Vehicle type
2. Study area, and
3. Disturbance by right-turning vehicles

In this study, all the turning speeds were measured from passenger cars. However, the features of commercial vehicles are different from those of passenger cars. The commercial vehicles have larger volume and longer torque comparing to passenger cars. In this study, the turning radius is enough to accommodate U-turning passenger cars. But the turning radius of street segment may be not enough for the commercial vehicles. It can result in the commercial vehicles unable to make U-turns or having U-turns in low speed. Obviously, this situation will cause more traffic problems.

Another concern is the research area in this study is urban area. All the selected sites are urban arterials or urban highways. However, the operational speed in urban area is different from that in rural area. Usually, the operational speed is higher in rural area. Since the operational speed is an important parameter which needs to be input for calibrating the simulation model, the results of this study may not be applied to rural area.

The third concern is that U-turning vehicles only have minor disturbance by the right turning vehicles in this study. However, in most cases, the right turns from the other approach do not have protected phase. So, the right turns usually have impacts on U-turning vehicles. If considering the disturbance from right turning vehicles during the U-turn phase in the other approach of the intersection, the saturation flow rate of left turn lane will decrease and the control delay of the intersection will increase. But in this study, the impact from right turning vehicles was barely taken into consideration.

Based on the limitations above, the future study can focus on enlarging sample size, bringing more types of vehicles into consideration, especially commercial vehicles, extending the study area to rural area, and considering the effects cause by right turning vehicles.

In additional, Several issues were not addressed in this study, including the impacts of U-turning vehicles on the start-up lost time and clearance lost time, the impacts of U-turning heavy vehicles on the capacities of signalized intersections, the impacts of U-turning vehicles under restrictive geometric conditions, and the impacts of U-turning vehicles with significant disturbance from right-turning vehicles in the other approach Further study should focus on these issues. Meanwhile, this study was conducted in central Florida. Validation of the model in other regions may prove useful.

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APPENDIX DESCRIPTIVE FIELD DATA OF U-TURN SPEED

Table A-1 Descriptive U-turn Speed Data of Bruce B Downs Blvd @ Commerce Palms Blvd

	Passenger Car (MPH)	SUV (MPH)	Van (MPH)	Pick-up (MPH)	Turning Radius (FEET)
Bruce B Downs Blvd @ Commerce Palms Blvd	15	9	12	10	64
	8	17	11	9	
	14	18	10	15	
	15	12	12		
	14	12	12		
	15	13			
	15	13			
	14	13			
	14	14			
	9				
	13				
	11				
	14				
	14				
	12				
	11				
	13				
	10				
	16				
	8				
	16				
	11				
	10				
Average Speed	13	13	11	11	

Table A-2 Descriptive U-turn Speed Data of Fowler Ave @ 56th Street

	Passenger Car (MPH)	SUV (MPH)	Van (MPH)	Pick-up (MPH)	Turning Radius (FEET)
Fowler Ave @ 56th Street	15	11	10	14	43
	17	16	10		
	10	13	12		
	11	12	12		
	11	18			
	14	14			
	17	15			
	13	15			
	10				
	14				
	16				
	12				
	14				
	13				
	10				
	11				
	14				
Average Speed	13	14	11	14	

Table A-3 Descriptive U-turn Speed Data of Bruce B Downs Blvd@CrossCreek Blvd

	Passenger Car (MPH)	SUV (MPH)	Van (MPH)	Pick-up (MPH)	Turning Radius (FEET)
Bruce B Downs Blvd @ Cross Creek Blvd	18	14	15	12	78
	16	12	14		
	20	18	15		
	16	18	13		
	17	14	16		
	16				
	20				
	20				
	19				
	20				
	16				
	16				
	15				
	13				
	17				
	14				
	14				
	13				
Average Speed	17	15	15	12	

Table A-4 Descriptive U-turn Speed Data of Bearss Ave @ Florida Ave

	Passenger Car (MPH)	SUV (MPH)	Van (MPH)	Pick-up (MPH)	Turning Radius (FEET)
Bearss Ave @ Florida Ave	11	12	10	11	45
	12	11	11	11	
	12	11	12	11	
	11	12	11	11	
	13	11	10		
	12	10			
	10	11			
	11	12			
	13	11			
	11	10			
	14	10			
	13	12			
	11	10			
	14				
	9				
	12				
Average Speed	12	11	11	11	

Table A-5 Descriptive U-turn Speed Data of Bruce B Downs Blvd @ Highwoods Preserve PKWY

	Passenger Car (MPH)	SUV (MPH)	Van (MPH)	Pick-up (MPH)	Turning Radius (FEET)
Bruce B Downs Blvd @ Highwoods Preserve PKWY	18	14	12	20	72
	16	15	13		
	13	14	17		
	14	18	17		
	18	11	16		
	13	17			
	16	17			
	18				
	19				
	16				
	18				
	16				
	15				
	14				
	15				
	18				
	9				
Average Speed	16	15	15	20	

Table A-6 Descriptive U-turn Speed Data of CR 581 (Bruce B Downs Blvd) @ County Line

	Passenger Car (MPH)	SUV (MPH)	Van (MPH)	Pick-up (MPH)	Turning Radius (FEET)
CR 581 (Bruce B Downs Blvd) @ County Line	19	15	16	12	153
	17	17		15	
	13	16		16	
	15	14		16	
	16	15			
	12	18			
	15	13			
	13	14			
	15	14			
	15				
	17				
	18				
	14				
	15				
	16				
	15				
Average Speed	15	15	16	15	

Table A-7 Descriptive U-turn Speed Data of Dale Mabry HWY @ Fletcher Ave

	Passenger Car (MPH)	SUV (MPH)	Van (MPH)	Pick-up (MPH)	Turning Radius (FEET)
Dale Mabry HWY @ Fletcher Ave	15	18	12	16	116
	15	12	15		
	16	15	14		
	15	11			
	8	13			
	12	16			
	16	10			
	16	14			
	17	13			
	17	16			
	15	16			
	14				
	14				
	15				
	12				
Average Speed	14	14	14	16	

Table A-8 Descriptive U-turn Speed Data of Dale Mabry HWY @ Stall Rd

	Passenger Car (MPH)	SUV (MPH)	Van (MPH)	Pick-up (MPH)	Turning Radius (FEET)
Dale Mabry HWY @ Stall Rd	15	12	12	15	72
	11	15		10	
	16	14			
	17	17			
	15	12			
	15	12			
	17	17			
	16	15			
	15	16			
	13	13			
	12	15			
	16				
	16				
	14				
	13				
	16				
Average Speed	15	14	12	13	

Table A-9 Descriptive U-turn Speed Data of Waters Ave @ Dale Mabry HWY

	Passenger Car (MPH)	SUV (MPH)	Van (MPH)	Pick-up (MPH)	Turning Radius (FEET)
Waters Ave @ Dale Mabry HWY	11	12		14	59
	12	14			
	15	11			
	13	13			
	13	15			
	13	14			
	10	12			
	14				
	13				
	14				
	11				
	12				
	15				
Average Speed	13	13		14	

Table A-10 Descriptive U-turn Speed Data of Dale Mabry HWY @ Waters Ave

	Passenger Car (MPH)	SUV (MPH)	Van (MPH)	Pick-up (MPH)	Turning Radius (FEET)
Dale Mabry HWY @ Waters Ave	16	14	11	11	66
	16	16		12	
	13	16			
	12				
	14				
	10				
	12				
	10				
	12				
	12				
	13				
	12				
	14				
	12				
	16				
	15				
	17				
Average Speed	13	15	11	12	

Table A-11 Descriptive U-turn Speed Data of Dale Mabry HWY @ Mapledale Blvd

	Passenger Car (MPH)	SUV (MPH)	Van (MPH)	Pick-up (MPH)	Turning Radius (FEET)
Dale Mabry HWY @ Mapledale Blvd	12	13	11	15	68
	12	16	15		
	15	15	14		
	11	11	11		
	12		14		
	13				
	12				
	12				
	12				
	18				
	13				
	13				
	12				
Average Speed	13	14	13	15	

Table A-12 Descriptive U-turn Speed Data of Dale Mabry HWY @ Bearss Ave(Ehrlich Ave)

	Passenger Car (MPH)	SUV (MPH)	Van (MPH)	Pick-up (MPH)	Turning Radius (FEET)
Dale Mabry HWY @ Bearss Ave(Ehrlich Ave)	14	13		10	43
	11	14		10	
	12	12		11	
	14	14		13	
	15	16			
	13	11			
	12	10			
	10	13			
	13	12			
	14	10			
	15				
	12				
Average Speed	13	13		11	

Table A-13 Descriptive U-turn Speed Data of Dale Mabry HWY @ Carrollwood SPGS

	Passenger Car (MPH)	SUV (MPH)	Van (MPH)	Pick-up (MPH)	Turning Radius (FEET)
Dale Mabry HWY @ Carrollwood SPGS	11	14	11	11	73
	15	13		17	
	13	12			
	16	14			
	15	15			
	13	16			
	14	10			
	15	15			
	10	13			
	9				
	13				
	13				
	15				
Average Speed	13	14	11	14	

Table A-14 Descriptive U-turn Speed Data of Hillsborough Ave @ Armenia Ave

	Passenger Car (MPH)	SUV (MPH)	Van (MPH)	Pick-up (MPH)	Turning Radius (FEET)
Hillsborogh Ave @ Armenia Ave	13	12	12	14	53
	11	13		11	
	14	11			
	11	12			
	13	10			
	12				
	13				
	13				
	12				
	13				
	13				
	11				
	13				
	12				
Average Speed	12	12	12	13	

Table A-15 Descriptive U-turn Speed Data of Hillsborough Ave @ Lois Ave

	Passenger Car (MPH)	SUV (MPH)	Van (MPH)	Pick-up (MPH)	Turning Radius (FEET)
Hillsborogh Ave @ Lois Ave	14	13	12	12	54
	13	12	13	15	
	13	10		8	
	15	15		10	
	11	12		13	
	13				
	14				
	12				
	13				
	15				
	13				
	12				
	12				
Average Speed	13	12	13	12	71