AN ANALYSIS OF
THE IMPACT OF REDUCING PEDESTRIAN-WALKING-SPEED
ON INTERSECTION TRAFFIC MOES

A Thesis

by

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ABSTRACT

Pedestrian traffic is an important element in signalized intersection analysis. As a low-speed traffic component, pedestrians crossing the street may take up time that could be utilized by vehicles on the other street to pass through the intersection, and this causes an increase in the total delay at the intersection. Therefore, to minimize traffic delays and increase traffic efficiency, it is important to study the impact of pedestrian walking speed.

This study was conducted to analyze the impacts of pedestrian speed under different lane group combinations, median widths, volumes on major and minor streets, and pedestrian pushbutton horizontal offsets. The idea originated came from the reduction of pedestrian walking speed used for calculating the pedestrian intervals. The 2003 MUTCD specified a value of 3.5 ft/sec to calculate the pedestrian clearance time and this speed was reduced to 4.0 ft/sec in the 2009 MUTCD. Moreover, a second method using 3.0 ft/sec to calculate the total pedestrian intervals was added to the 2009 MUTCD. This change is likely to influence the signal timing plan of entire intersections and further increasing the intersection total delay.

The researcher used one of the most popular simulation software programs, Synchro 7, to simulate various types of intersections under different traffic circumstances and yield a series of datasets to analyze the impacts of the reduction in pedestrian walking speed. The data was analyzed both horizontally and vertically. By comparing the intersection total delay as well as the through lane group and the approach average delay, the researcher analyzed their differences mathematically as well as practically. According to the analysis results, if the cycle length of an intersection can be optimized, the change of pedestrian walking speed would not make significant impact on intersection delay; however, if under a given cycle length other than its optimum one, the intersection delay would increase significantly after the change of pedestrian walking speed in some circumstance. The extended pushbutton press function can be used to alleviate such delay increase.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

Pedestrian traffic is an important element in signalized intersection analysis. The two most widely used references in the United States, the *Highway Capacity Manual* (HCM) (*1*) and *the Manual on Uniform Traffic Control Devices* (MUTCD) (*2, 3*), contain information pertaining to pedestrian transportation. The HCM provides information on analyzing the movement of pedestrian traffic; the MUTCD also provides criteria for the use of pedestrian traffic control devices. However, the impacts of pedestrian traffic on overall traffic measures of effectiveness (MOEs) at intersections are limited in the HCM. As a low-speed traffic component, pedestrians crossing one street of an intersection may take up time that could be used by vehicles on the other street to pass through the intersection, and this causes an increase in the total delay at the intersection. Therefore, to minimize traffic delays and increase traffic efficiency, it is important to understand the impact of pedestrian walking speed on total intersection delay.

The 2009 edition of the MUTCD (*2*) decreased pedestrian walking speed for the pedestrian clearance time calculation from the 4.0 ft/sec used in the MUTCD 2003 (*3*) to 3.5 ft/sec. An exception can be made at locations "where an extended pushbutton press function has been installed to provide slower pedestrians an opportunity to request and receive a longer pedestrian clearance time" (*2*). As walking speed decreases, the pedestrian clearance time lengthens, which is likely to increase the optimal cycle length/ and/or the minor street green time to meet the pedestrians' crossing demands. This could also impact various traffic MOEs and increase overall intersection delays.

BACKGROUND

Pedestrian clearance time is "the time provided for a pedestrian crossing in a crosswalk, after leaving the curb or shoulder, to travel to the far side of the traveled way or to a median," according to the 2003 MUTCD (*3*). The 2009 edition of the MUTCD retains this definition. A pedestrian interval consists of a walk interval and pedestrian clearance time. Figure 1 shows their relationships.

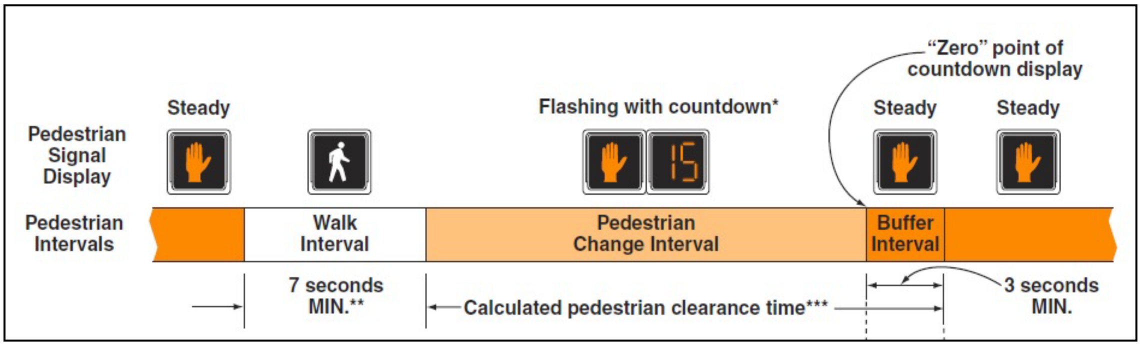


Figure 1: Pedestrian interval (*2*)

Pedestrian clearance time is determined based on the distance from curb to curb and pedestrian walking speed. In the 2009 MUTCD, the pedestrian walking speed used to calculate the pedestrian clearance time was decreased from 4.0 ft/sec to 3.5 ft/sec. Furthermore, according to a second calculation method that was introduced in the 2009 MUTCD (*2*), the total of the walk interval and the pedestrian clearance time should be no shorter than the interval value achieved by using the distance from the pedestrian detector to the far-side curb or to the median divided by 3 ft/sec. The "*Federal Register*" (*4, 5*) for the 2009 MUTCD explained that such changes were made to enhance road safety. These modifications are based on the pedestrian walking speed research included in National Cooperative Highway Research Program Report 562 (*NCHRP Report 562) (6)*. Moreover, these two changes incorporated into the 2009 MUTCD will surely lengthen the total pedestrian intervals (the sum of the pedestrian walk interval and the pedestrian clearance time) and further impact vehicle signal timing plans.

PROBLEM STATEMENT

Many studies focus on the impact of various traffic characteristics on traffic MOEs, such as signal phasing, proportion of left-turn vehicles, and heavy vehicles. However, studies on the impact of pedestrian walking speed on traffic MOEs are limited. Given that there is no definitive analysis on the impact of the change in pedestrian walking speeds, the traffic condition after applying the new pedestrian signal timing may finally increase delay and cause a failure of the existing vehicle signal-timing plan.

The pedestrian walking speed reduction in the 2009 MUTCD increased the total pedestrian interval needed by pedestrians to cross a given intersection. The width and the volume of the major street of an intersection are usually greater than those of the minor street of the intersection. When pedestrians are crossing a major street, the vehicles driving through the major street should get the red light while the vehicles driving through the minor street are allowed to pass. When the pedestrians crossing the minor street, the condition is similar. As a result, the *minimum green time* for the minor street through movement will be longer than that of the major street through movement, which may not be fully used by the minor street when the volume is low. Thinking about the decrease of the pedestrian walking speed leads to an increase of the minimum green time. Such change in the 2009 MUTCD may cause more delays on the major street and affect the entire intersection in some circumstances.

However, by providing an extended pushbutton, the pedestrian walking speed can remain at 4.0 ft/sec, which could reduce the impacts caused by the change of pedestrian walking speed in some circumstances. This project analyzed the impact of reducing the pedestrian walking speed on traffic MOEs at signalized intersections. Synchro 7 was used to comprehensively assess the *levels of service* (LOS) and delays for an entire intersection, as well as for each approach. The researcher discussed the traffic MOE differences brought about by the reduction of pedestrian walking. Furthermore, recommendations on how to use the extended pushbutton press function were made.

RESEARCH OBJECTIVE

This study has two major objectives. The first objective is to analyze the impact of the change in pedestrian walking speed on intersection traffic MOEs under different traffic conditions. The second is to provide recommendations on the use of the extended pedestrian pushbutton function. The subtasks listed below support the completion of these objectives:

- Evaluate traffic MOEs at intersections and approaches under the pedestrian signal calculation methods in the 2003 and 2009 MUTCDs; analyze the trends among different volume scenarios.
- Compare the delay differences under the two different walking speeds, analyze MOE differences at different intersections and under different traffic settings, and discuss the impact of pedestrian-walking-speed reduction on the traffic MOEs under different intersection traffic flows.
- Discuss if there is any significant impact on intersection MOEs when the pedestrian walking speed changes.
- Draw conclusions on the impact of the change in pedestrian speeds on traffic MOEs; provide recommendations and guidelines on how to best use the extended pushbutton press function according to the study results.

THESIS ORGANIZATION

This thesis consists of five chapters. Chapter I provides an introduction to the research efforts. Chapter II reviews relevant literature: the 2003 and 2009 editions of the MUTCD, characteristics and functions of the simulation software Synchro 7, traffic MOEs that are used as indexes for discussing the thesis objectives, and study methods. Chapter III discusses study methodologies. It describes study design (including transportation element selection, assumptions, scenario creation, and classification) and data processing (including Synchro 7 performance, data generation, and reduction). Chapter IV analyzes the data generated by Synchro 7, horizontally and vertically, and details the results obtained using said data. Chapter V provides the conclusions of this study and outlines a direction for future research.

CHAPTER II
LITERATURE REVIEW

To study the impact of the change in pedestrian walking speed on intersection traffic MOEs, it is necessary to first review the background and relevant knowledge. The following sections discuss the changes in pedestrian speed according to the MUTCD, simulation software used in this study, key points about intersection traffic MOEs, (such as definitions and equations), and the methodology used in this study.

MUTCD CHANGES

The MUTCD establishes standards for traffic control devices used in the United States. In addition, the MUTCD addresses, as a critical traffic component, pedestrian traffic control issues at signalized intersections, one of which is the walking speed used for calculating crossing times. The pedestrian speed used to calculate the length of pedestrian clearance time was changed between the 2003 and 2009 editions of the MUTCD.

The 2003 edition (*3*) states the following:

> "The pedestrian clearance time should be sufficient to allow a pedestrian crossing in the crosswalk who left the curb or shoulder during the WALKING PERSON (symbolizing WALK) signal indication to travel at a walking speed of *1.2 m (4 ft) per second*, to at least the far side of the travelled way or to a median of sufficient width for pedestrians to wait. Where pedestrians who walk slower than 1.2 m (4 ft) per second, or pedestrians who use wheelchairs, routinely use the crosswalk, a walking speed of less than 1.2 m (4 ft) per second should be considered in determining the pedestrian clearance time. "

In the 2009 edition (*2*), the items corresponding to the pedestrian walking speed for calculating the pedestrian clearance time was changed:

> "The pedestrian clearance time should be sufficient to allow a pedestrian crossing in the crosswalk who left the curb or shoulder at the end of the WALKING PERSON (symbolizing WALK) signal indication to travel at a walking speed of *3.5 feet per second* to at least the far side of the travelled way or to a median of sufficient width for pedestrians to wait."
>
> and
>
> "A walking speed of up to *4 feet per second* may be used to evaluate the sufficiency of the pedestrian clearance time at locations where *an extended pushbutton press function has been installed* to provide slower pedestrians an opportunity to request and receive a longer pedestrian clearance time. Passive pedestrian detection may also be used to automatically adjust the pedestrian clearance time based on the pedestrian's actual walking speed or actual clearance of the crosswalk. "

In the 2009 MUTCD, the pedestrian walking speed used as the basis for calculating the pedestrian clearance time was separated into two parts: 4.0 ft/sec with an extended pushbutton press function and 3.5 ft/sec under other circumstances.

Additionally, the 2009 MUTCD offers a second method to calculate the complete pedestrian interval:

> "The total of the walk interval and pedestrian clearance time should be sufficient to allow a pedestrian crossing in the crosswalk who left the pedestrian detector (or, if no pedestrian detector is present, a location 6 feet from the face of the curb or from the edge of the pavement) at the beginning of the WALKING PERSON (symbolizing WALK) signal indication to travel at a walking speed of 3 feet per second to the far side of the traveled way being crossed or to the median if a two-stage pedestrian crossing sequence is used. Any additional time that is required to satisfy the conditions of this paragraph should be added to the walk interval. "

After calculation, the longer pedestrian intervals can be used for determining the walk interval and the pedestrian clearance time.

SYNCHRO STUDIO

To manipulate traffic conditions at different types of intersections, the author uses Synchro 7, a popular simulation software package, for analysis.

Synchro Studio is a traffic-signal-timing optimization and coordination software program. It was developed by the Trafficware Company and is based on the HCM. Its features include traffic analysis, timing optimization, and simulation applications (*7*).

Synchro Studio primarily consists of the macroscopic analysis and optimization software application, Synchro, which includes the traffic simulation software application SimTraffic and a 3D Viewer application. There are additional software modules, such as Warrants, TripGen, SimTraffic CID, and Intersection Capacity Utilization (ICU), in the Synchro Studio package (*8*). In this research, Synchro 7 is used to simulate the studied traffic scenarios.

TRAFFIC CONCEPTS AND TRAFFIC MOES

In this research, many traffic elements and factors need to be clarified beforehand. The author picks up the concepts that are significant/likely to be confused here and makes necessary explanations. Traffic MOEs are significant indexes to evaluate traffic conditions. In this research, all the analyses were based on traffic MOEs.

Traffic Concepts

The traffic concepts explained in this part are volume, signal phase, and the dual-ring structure. Dual-ring structures are now widely used as tools for building intersection signal-timing plans.

Volume

Volume relates to the total number of vehicles or other roadway users that pass over a given point or section of a lane or roadway during a given time interval, often 1 h (*1*). Demand volume is the number of vehicles that arrive to use the facility (*1*).

Demand volume is one of the most important traffic concepts. Different demand volumes could directly impact traffic MOEs. As the demand volumes in different parts of an intersection change, the delay experienced by the vehicles at that intersection changes as well.

Signal Phase

This study uses the standard National Electrical Manufacturers Association (NEMA) numbering sequence methodology (*1*) for signal phase identification. This method uses odd numbers to indicate left turns and even numbers to express through movements and left turns in a clockwise manner. Phases 2 and 6 are used for major streets and phases 4 and 8 are used for minor streets, as shown in Figure 2 (*9*).

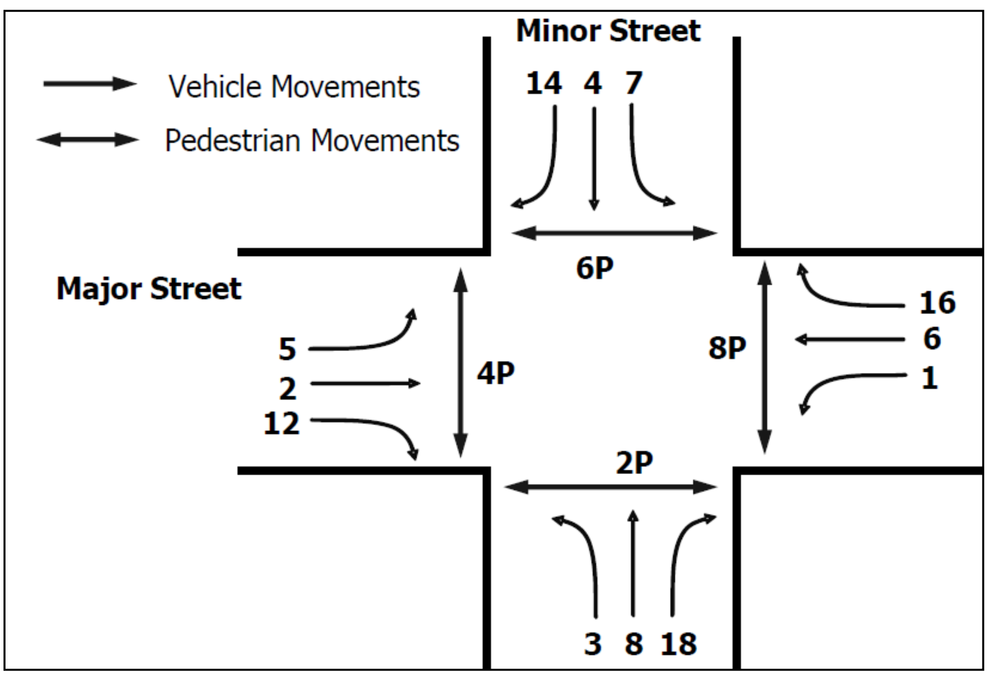


Figure 2: NEMA phases (*1*)

Dual-ring

Dual-ring structures are used to implement signal phasing. It allows one green indication to be presented concurrently to two phases. Each phase serves one or more non-conflicting movements. A commonly used eight-phase dual-ring structure is shown in Figure 3.

In this research, the author used barriers to avoid overlaps among phases.

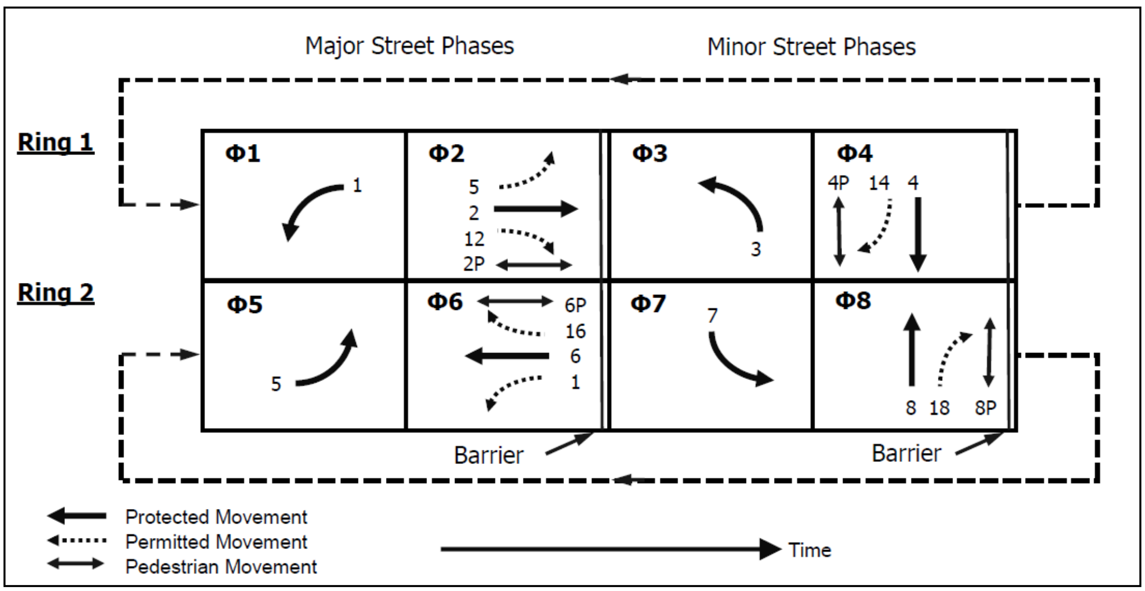


Figure 3: Dual-ring structure example (*1*)

Traffic MOEs

According to the 2010 HCM, control delay, speed, number of stops, queue length, volume-to-capacity (demand-to-capacity) ratios, pedestrian space, bicycle speed, number of meeting/passing events, and LOS are key performance measures used for evaluating the operation of motorized vehicles on interrupted-flow roadways. Generally, traffic delay is commonly used for assessing traffic conditions. Control delay is one of the indexes used for determining the LOS at a signalized intersection (*1*).

Delay

According to the 2010 HCM, there are three components of control delay: *uniform delay*, *incremental delay, and initial queue delay*. Uniform delay occurs when arrivals are assumed to be random throughout the cycle length. Incremental delay consists of two components: delay due to an occasional demand-exceeds-capacity situation and delay due to sustained oversaturation. Initial queue delay accounts for the additional delay due to an initial queue (*1*).

Synchro has a different delay system, including control delay, queue delay, and total delay. Control delay is the component of delay due to the downstream control devices and does not include queue delay; queue delay presents an analysis of the impacts of queues and blockages in short links and short turning bays; and total delay is the sum of control delay and queue delay (*10*). In this research, because there are no short turning bays or short links (only one intersection per scenario), queue delay is always equal to 0.

Synchro uses a different method called the *percentile delay method* to calculate traffic delays. The percentile delay method looks at five levels of traffic arrivals so that signals can be evaluated under different traffic loads, which makes the final results more practical (*10*).

In addition to delay, traffic engineers often take LOS as an important reference when dealing with traffic conditions.

LOS

The HCM defines six levels for representing the operation conditions, ranging from A to F. LOS A represents the best traffic condition, whereas LOS F represents the worst one. LOS is widely used in road designs and traffic condition assessments. One of the classification methods is based upon average control delay, as summarized in Table 1.

In Synchro, LOS is based on Synchro control delay.

Table 1: LOS Criteria (*1*)

Control Delay (sec/veh)	**LOS by Volume-to-Capacity Ratio**	
	≤ 1.0	**> 1.0**
≤ 10	A	F
> 10–20	B	F
> 20–35	C	F
> 35–55	D	F
> 55–80	E	F
> 80	F	F

TRAFFIC SIGNAL CALCULATIONS

In this research, all data were yielded by Synchro 7. Synchro calculated the cycle length and splits for each scenario automatically. However, the *red clearance interval*, *yellow change interval*, and *pedestrian intervals* (e.g. walk interval and pedestrian change interval) needed to be calculated beforehand. Formulas from NCHRP 731 were used to compute red clearance intervals and yellow change intervals. The 2003 and 2009 editions of the MUTCD were used to calculate pedestrian intervals. The details are shown in the following parts.

Red Clearance Interval

The red clearance interval is "a brief period of time following the yellow indication during which the signal heads associated with the ending phase and all conflicting phases display a red indication" (*1*). The *National Cooperative Highway*

Research Program (NCHRP) developed the following formula to calculate the red clearance interval; this is available in NCHRP Report 731 (*11*).

$$R = \frac{W+L}{1.47V} - 1 \qquad \textit{(Equation 1)}$$

Where:

R = Red clearance interval, sec;

W = Intersection width measured from the back/upstream edge of the approaching movement stop line to the far side of the intersection as defined by the extension of the curb line or outside edge of the farthest travel lane (ft). The width between the extended line of the facing curb and the stop line was set to 6 ft;

L = Length of vehicle (ft); set to 20 ft;

V = 85th percentile approach speed (mph).

If the calculated red clearance interval is smaller than 1.0 sec, 1.0 sec needs to be applied in practice; if it is larger than 1.0 sec, the calculated value is applied directly.

Furthermore, in this equation, when calculating the red time of the left-turn phase, the variable W refers to the length of the approaching vehicle's turning path. It should be measured "from the back/upstream edge of the approaching movement stop line to the far side of the intersection as defined by the extension of the curb line or outside edge of the farthest travel lane" (*11*). The variable V means approach speed. A value of 20 mph should be applied in all left-turn red clearance conditions, regardless of the approach speed limit.

Yellow Change Interval

Yellow change interval is "the period of time that the yellow indication is displayed to alert drivers to the impending presentation of a red indication" (*1*). The yellow change interval can be calculated using the following equation (*11*):

$$Y = t + \frac{1.47V}{2a + 64.4g} \qquad \textit{(Equation 2)}$$

Where:

Y = Yellow change interval, sec;

t = PRT (s); set to 1.0 sec;

a = Deceleration rate (ft/sec^2); set to 10 ft/sec^2;

V = 85th percentile approach speed (mph);

g = Approach grade (percent divided by 100, negative for downgrade).

Equation 2 can be used to calculate the yellow change interval of through movement. As for left-turn movements, the variable V refers to approach speed and "should be set at the approach speed limit minus 5 mph" (*11*).

In addition, there are differences in methods when dealing with protected-only, permissive-only, and protected/permissive left-turn movements. For the protected-only left-turn movements, the red clearance interval and the yellow change interval need to be calculated for each approach (*11*). This is the simplest processing method among the three types of left-turn movement signal phases.

Pedestrian Intervals

Pedestrian intervals consist of three parts: walk interval, pedestrian change interval, and buffer interval. According to the 2009 MUTCD, the value of pedestrian intervals is equal to the sum of the walk interval and the calculated pedestrian clearance time. Currently, there are two methods to calculate pedestrian intervals in accordance with the MUTCD.

The first method was used in both the 2003 and the 2009 MUTCDs. This method deals only with the pedestrian clearance time. The pedestrian clearance time is equal to the width of the intersection divided by the pedestrian walking speed, as shown below:

$$T_{pc} = \frac{W_p}{V_p} \qquad \textit{(Equation 3)}$$

Where:

T_{pc} = Pedestrian clearance time, sec;

W_p = Width from curb or shoulder where pedestrian left at the end of the WALKING PERSON (symbolizing WALK) signal to the far side of the traveled way or to a median of sufficient width for pedestrians to wait, ft;

V_p = Pedestrian walking speed, set at 4.0 ft/sec from the 2003 MUTCD and 3.5 ft/sec from the 2009 MUTCD.

The second method is mentioned only in the 2009 MUTCD. It considers the sum of the walk interval and the pedestrian clearance time. The 2009 MUTCD stated that there should be enough time for a pedestrian leaving the pedestrian detector on "the far side of the traveled way being crossed or to the median if a two-stage pedestrian crossing sequence is used." The associated equation is given below:

$$PI = \frac{W_p + W_{offset}}{V_{PI}} \qquad \textit{(Equation 4)}$$

Where:

PI = Pedestrian intervals, the sum of pedestrian walk interval and pedestrian clearance time, sec. $PI = T_{pc} + T_{pw}$;

T_{pc} = Pedestrian clearance time, sec;

T_{pw} = Pedestrian walking interval, which should be set to at least 7 sec, except under some special conditions (4 sec at least);

W_p = Width from the curb or shoulder where pedestrian left at the end of the WALKING PERSON (symbolizing WALK) signal to the far side of the traveled way or to a median of sufficient width for pedestrians to wait, ft;

W_{offset} = Width from the pedestrian detector to the near-side curb; if no pedestrian detector is present, a location 6 feet from the face of the curb or from the edge of the pavement, ft;

V_{PI} = Pedestrian walking speed, set to 3.0 ft/sec.

In this research, the author used 6 ft as the horizontal offset in all scenarios, except the scenarios used to study the influence of horizontal offset. Under such conditions, when the width of the street is more than 105 ft, the second method, (shown in Equation 4) can be used to calculate the real pedestrian intervals.

CHAPTER III
STUDY METHODOLOGY

The primary objective of this research is to study the impact of the change in pedestrian walking speeds on intersection traffic MOEs. The researcher used the Synchro 7 simulation software package to deal with designed intersection scenarios.

This chapter is divided into two parts. The first part, Study Design, describes the selected transportation elements, assumptions, scenario creation, and classification. The second part, Data Processing, details lab experience with Synchro 7 and data reduction aimed at eliminating the “noise points.”

STUDY DESIGN

In this phase, the study variances should be selected first. The study boundary is then defined by setting up research assumptions for ensuring study controllability. Constrained by said assumptions, scenarios are built based on the selected transportation features. Finally, these scenarios are classified to make the process of data analysis more effective.

Transportation Feature Selection

In practice, creating an intersection involves considering thousands of elements. As a transportation feature by itself, an intersection consists of a large number of smaller transportation features and, in reality, serves many other traffic features. The variances in a research must to be reasonable, operable, and necessary to control the study.

The study features are as follows:

- Only four-leg intersections with right angles between all adjacent approaches were considered in this research. This type of intersection is widely used all round the world and is considered the most common type of intersection.

- Lane groups are significant in intersection construction. They account for a large proportion when measuring the length of a pedestrian crosswalk. In this study, one left turning lane and one shared lane (that allows both through and right turning movements) were considered in each approach. In accordance with the given scenario, up to three through lanes were added into either a major or a minor street of an intersection.
- Medians are common in normal streets. They are applied for various reasons. Medians can act as reservations for future roadway construction; they can be applied to channelize opposing vehicle flows and can act as traffic islands to allow pedestrians cross the street over more than one pedestrian signal interval. The median composes the length of the pedestrian crosswalk as well. It makes a difference in the time that pedestrians need to cross the intersection. In this study, it was theorized that pedestrians never need a second interval to go across one street.
- If a pedestrian pushbutton is located on at least one side of the street, there should be a distance between the curb and the push button. If this distance is relatively long, the minimum walk interval may not able to support a pedestrian walking into the intersection area from the push button. Therefore, when identifying the total pedestrian cross interval, this distance should be taken into consideration as well.
- Vehicle volume is an important traffic feature. As the volume increases on a given street, the traffic conditions worsen and the cycle length of the traffic signal becomes increasingly critical. However, considering pedestrian walking speed, the phase splits of the minor street may have to be prolonged to provide sufficient time for pedestrians to cross the intersection. This is likely to increase the delay on the major street and the entire intersection, and may also decrease traffic effectiveness. The change in delay difference under different vehicle volumes is significant in this study. In this project, the volume of each approach is selected for

different types of roadways. The impact of the change in pedestrian walking speeds on the traffic MOEs is determined by analyzing incremental volume values at the studied intersections using Synchro 7.

- Different cycle lengths can cause totally different traffic MOEs at an intersection. Therefore, the author studied the impact that the change of pedestrian walking speed has on vehicle delay under optimum cycle length and the reasonable common cycles of each intersection.
- According to the 2003 and 2009 MUTCDs, three pedestrian walking speeds—4.0 ft/sec, 3.5 ft/sec, and 3.0 ft/sec—were used in this study. The second method in the 2009 MUTCD, with a pedestrian walking speed of 3 ft/sec, was applied in combination with the first method.

Assumptions

In addition, the author built a series of assumptions to define this research. All the assumptions are outlined below.

- Pedestrian walking speed is kept uniform during every simulation.
- The width of each lane is set to 12 ft.
- The post speed limit is 40 mph at major streets and 30 mph at minor streets. These two post speed limits are selected as the representative speed limits in cities. The 85% speed is 47 mph in the major street and 37 mph in the minor street, according to the estimate given in NCHRP 731. Vehicle speeds impact only yellow change intervals and red clearance intervals.
- A four-phase timing plan is applied to each scenario. All left turning signals are protected left turns, so that the left turning vehicles and pedestrians trying to cross the street will not disturb each other. To simplify the research, no overlap is allowed when running Synchro 7 to achieve the optimum signal timing plan.
- A fixed timing plan is applied in all scenarios.

- The volume of left turning vehicles is kept at 40 veh/h for all study scenarios; the percentage of right turning vehicle volume is always set to 15% of the entire approach volume.
- In all scenarios, the intersections are not connected with other intersections. Therefore, the upstream filtering adjustment factor, "I", is set to 1.0.
- In a given scenario, the volumes of two directions at one street are equal. This means the volumes at the eastbound and westbound approaches are the same, as are those at the northbound and southbound approaches.
- Weather is not taken into consideration.

Scenario Creation

By setting up the transportation features and assumptions, the researcher integrated those characteristics into the scenarios. The researcher first picked lane groups for each scenario. It was then decided whether or not there would be a median in a given intersection; if the answer was yes, its width was set. The basic volume value and space were then set based on the size of a given intersection.

Lane Group Creation

As mentioned in the "Transportation Feature Selection" section, there is one left turning lane and one shared lane (allowing both through and right-turning movements) in each approach. According to given scenarios, up to three through lanes are added to each direction of either the major or minor streets of an intersection. Furthermore, the total number of lanes on a minor street is never greater than that on a major street. Figure 4 shows the simplest intersection—both the major street and the minor street consist of one left-turning lane and one shared lane (which allows through movement and right turning movement) in each direction. Figure 5 shows the largest intersection without a median that was studied in this research. There is one left turning lane, one shared lane (which allows through movement and right turning movement), and three through lanes in each direction in both major and minor streets.

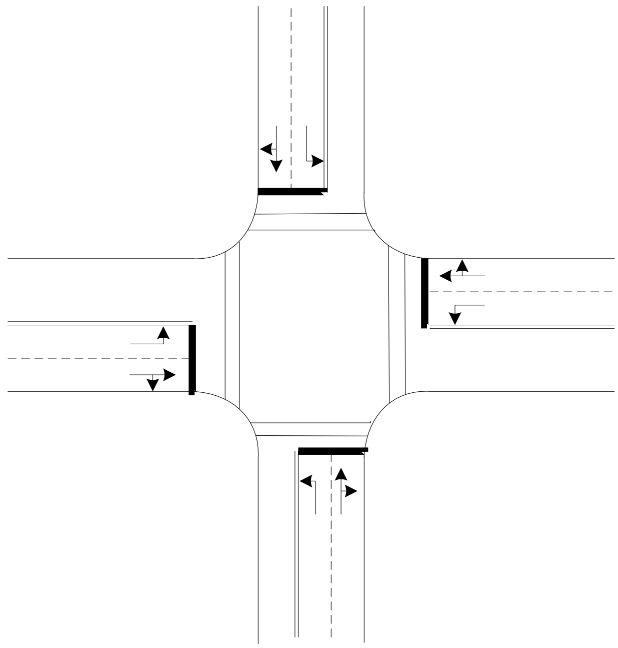


Figure 4: Smallest intersection considered in research

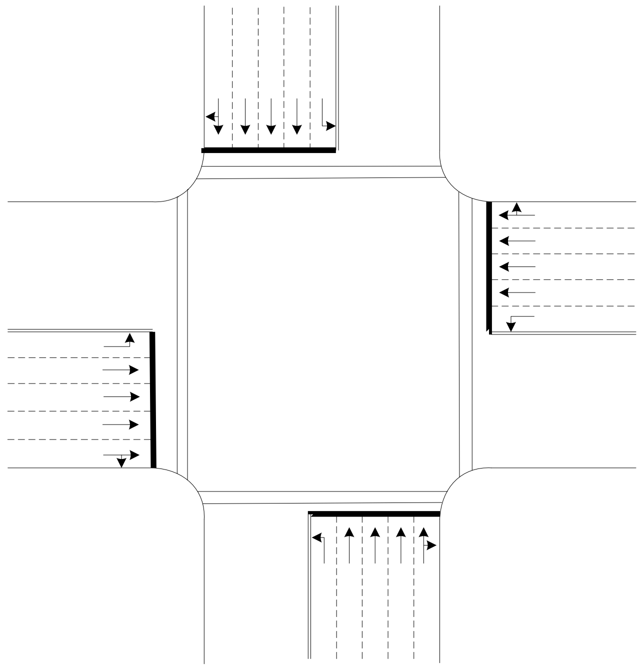


Figure 5: Largest intersection considered in research

Median Width and Offset Selection

Median width makes a difference in the time that pedestrians require to cross the intersection. This was included in pedestrian clearance-time calculations. To study different crosswalk lengths and how the modification of pedestrian walking speed makes an impact on the intersection delay, the researcher changed the median width. Different median widths can lead to different crosswalk lengths without indirect changes to other traffic features, such as the capacity. The width of the median was set to between 0 and 16 ft. According to the pedestrian-interval calculation methods in the 2003 and 2009 MUTCDs, the researcher set the median width to 0 ft, 8 ft, and 16 ft to estimate its influence.

The offset refers to the length from the pedestrian pushbutton to the corresponding curb. Based on the 2009 MUTCD (*2*), the value of this offset is set to 6 ft when no exact record is available. According to the two methods from the 2009 MUTCD for calculating pedestrian intervals, only the second method, which used 3.0 ft/sec to calculate entire pedestrian intervals (as detailed in Chapter II), is connected with the offset value. In conjunction with the range of horizontal offset of the pedestrian pushbutton (the pedestrian pushbutton should be set at no less than 1.5 ft and no farther than 6 ft from the near-side curb, according to the 2009 MUTCD), the researcher obtained marginal values of 1.5 ft and 6 ft by using the second calculation method.

Volume

Volume is the total number of vehicles that passes over a given point or section of a lane or roadway during a given time interval (*6*). On a given street, as the volume increases, the vehicle delay increases and the LOS declines, making the cycle length of the traffic signal increasingly critical. However, considering the pedestrian walking speed, the phase splits of the minor street may have to be extended to provide enough time for pedestrians to cross the intersection. This is likely to increase the delay on the major street and may increase the delay of the entire intersection and decrease traffic effectiveness.

Synchro 7 requires the volume in each movement direction to be known. The volume values were estimated coarsely based on the LOS of a given approach. In this research, the volume starts from a value that makes the traffic condition at the given intersection around LOS B, and increases evenly until the LOS of any part of the given intersection is F. In particular, in this research, the starting through-lane and shared-lane volume of an approach is set to150 veh/h. The incremental space of them is equal to 50 veh/sec. The left turning lane had a volume of 40 veh/h throughout this study. For example, as the intersection shown in Figure 5, its basic volume on the major street was 640 veh/sec (came from 150×4+40) in each direction and the incremental pace was 200 veh/h (came from 50×4). The researcher studied its traffic delay under the major street of 640 veh/h, 840 veh/h, 1040 veh/h, etc.

Signal Phasing Calculation

All study data were yielded in accordance with four-phase signal-timing plans. The red clearance intervals, yellow change intervals, and pedestrian intervals were calculated beforehand. The red clearance intervals and yellow change intervals were determined using the formulas in NCHRP 731 (*11*). The calculation of pedestrian intervals was made according to the 2003 and 2009 MUTCDs (*2, 3*). The details are provided in Chapter II.

According to NCHRP Report 731 (*11*), the left turning path should be measured in practice. However, in this study, all data were generated by the simulation software. Therefore, the researcher considered the left turning path of each vehicle as a ¼ ellipse. There is no exact formula to calculate the perimeter of an ellipse. The researcher used the following approximation formula (Equation 5), as put forth by the famous Indian mathematician Ramanujan:

$$P \approx \pi\left[3(a+b) - \sqrt{(3a+b)(a+3b)}\right] \qquad \textit{(Equation 5)}$$

Where:
P = Perimeter of ellipse, ft;
a = Major radius, shown in Figure 6, ft;
b = Minor radius, shown in Figure 6, ft.

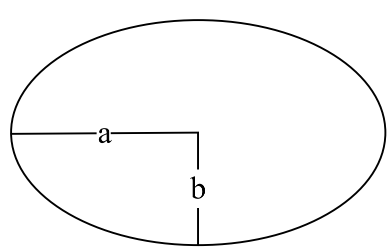


Figure 6: Ellipse

When calculating the left turning path in this study, several assumptions were made to ensure that the left-turn path was the most practical. The calculated path was measured from the path of the midpoint of the vehicle's front bumper. The width between the stop line and the extended line of the facing curb was measured as 6 ft at each approach. The ¼ ellipse was considered complete when the rear bumper of the test vehicle reached the extended curb line of the opposing approach. The vehicle length is set to 20 ft. The values "a" and "b" were measured as shown in Figure 7.

The left-turn path can be calculated using the following equation:

$$W = \frac{P}{4} \qquad \textit{(Equation 6)}$$

Where:

W = Length of left-turn path, ft;

P = Perimeter of "intersection ellipse."

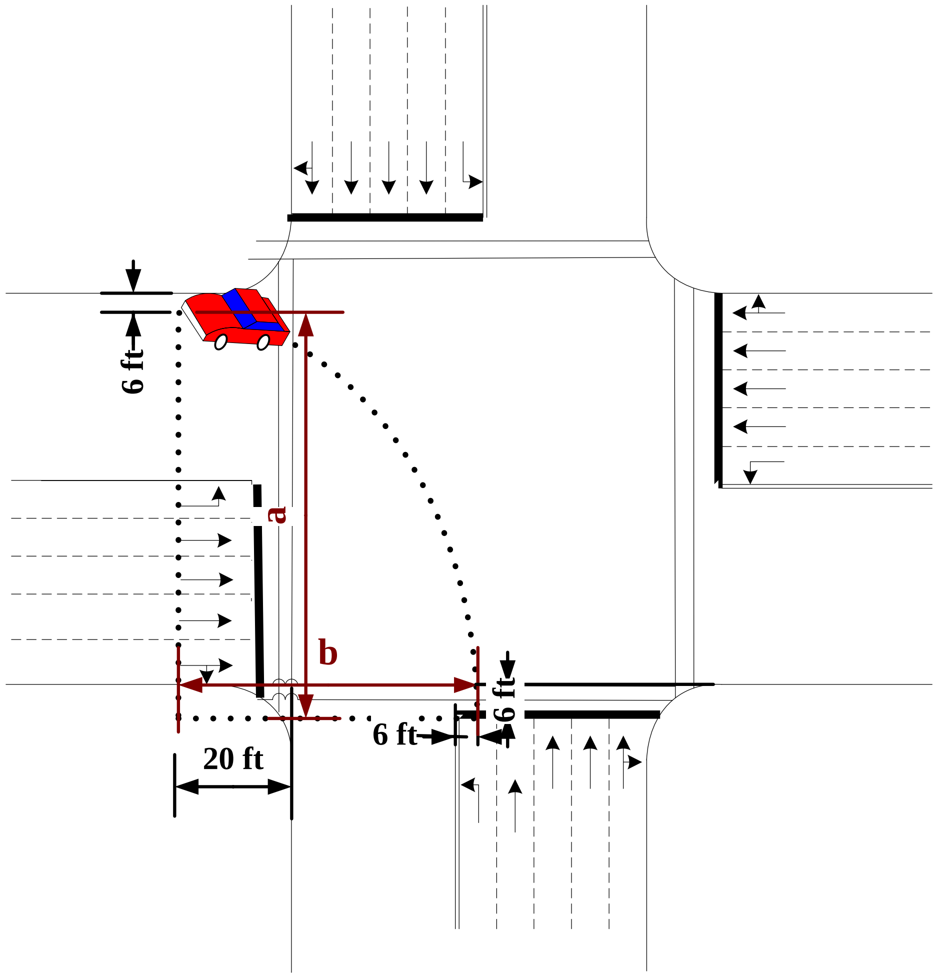


Figure 7: Diagrammatic sketch of left-turn path

Scenario Classification

Based on the four major variables—volume, lane group, pedestrian speed, and extra distances (median and offset)—the researcher created three large datasets (that included 13 scenarios) as parts of the entire study database: lane group datasets, median datasets, and horizontal setoff datasets. The scenario classification was made as a preparation of the later studies in this research. In each dataset, the volume values and pedestrian speeds were changed gradually to meet the study goals. The dataset creation process is described below.

Lane Group Dataset

10 out of 13 Scenarios in this research are related to the study of the change of lane numbers. In each scenario, both the major street and the minor street of the intersection had one left turning lane, one shared lane (for right turning and through movements) in each direction, and up to three extra through lanes in one direction. The details of these 10 scenarios are listed in Table 2.

Table 2: Lane Group Scenario Classification

Scenario No.*	One Direction in Major Street			One Direction in Minor Street		
	No. of left-turning lanes	No. of through lanes	No. of Shared lanes	No. of left-turning lanes	No. of through lanes	No. of Shared lanes
2	1	3	1	1	0	1
4	1	3	1	1	1	1
5	1	3	1	1	2	1
6	1	3	1	1	3	1
7	1	2	1	1	0	1
8	1	2	1	1	1	1
9	1	2	1	1	2	1
10	1	1	1	1	0	1
11	1	1	1	1	1	1
12	1	0	1	1	0	1

* Scenario No. reflects only the reference number in the researcher’s database.

Median Dataset

The median dataset was comprised of three basic median lengths: 0 ft (no median), 8 ft, and 16 ft for the median of the major street. In all scenarios, the minor street had no median.

Offset Dataset

Lateral offset was defined as the length from the pedestrian detector (pushbuttons or passive detection devices) to the near-side curb of the target crosswalk. The offset dataset included two different offset values, 1.5 ft and 6 ft. These two values were based on the pedestrian pushbutton guidelines in the 2009 MUTCD, as shown in Figure 8. The pedestrian detector lateral offset is considered in the second method for calculating the pedestrian walk interval according to the 2009 MUTCD. Therefore, different lateral offsets may yield different study results.

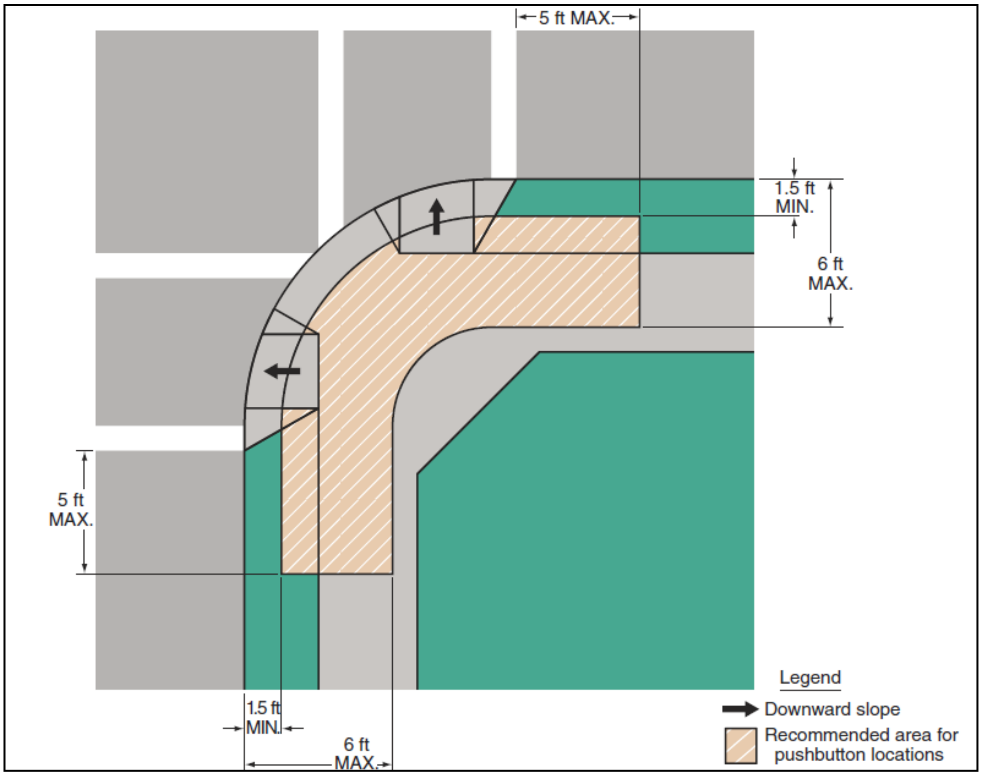


Figure 8: Pushbutton location area (*2*)

All the data sets and critical elements are shown in Table 3.

Table 3: Date Sets Summary

Scenario No.*	One Direction in Major Street							One Direction in Minor Street				
	No. of left turning lanes	No. of through lanes	No. of Shared lanes	Median Width (ft)	Pushbutton Horizontal Offsets (ft)	Basic Volume (veh/h)	Incremental Pace (veh/h)	No. of left turning lanes	No. of through lanes	No. of Shared lanes	Basic Volume (veh/h)	Incremental Pace (veh/h)
1	1	3	1	8	6	640	200	1	0	1	190	50
2	1	3	1	0	6	640	200	1	0	1	190	50
3	1	3	1	16	6	640	200	1	0	1	190	50
4	1	3	1	0	6	640	200	1	1	1	340	100
5	1	3	1	0	6	640	200	1	2	1	490	150
6	1	3	1	0	6	640	200	1	3	1	640	200
7	1	2	1	0	6	490	150	1	0	1	190	50
8	1	2	1	0	6	490	150	1	1	1	340	100
9	1	2	1	0	6	490	150	1	2	1	490	150
10	1	1	1	0	6	340	100	1	0	1	190	50
11	1	1	1	0	6	340	100	1	1	1	340	100
12	1	0	1	0	6	190	50	1	0	1	190	50
13	1	3	1	0	1.5	640	200	1	0	1	190	50

Signal Cycle Length Type

In each scenario, the researcher analyzed the traffic delays under two different signal cycle length types: the optimum cycle length and the reasonable common cycle length. The optimum cycle length analysis focuses on an isolated intersection. However, coordinated intersections are also common in cities. Under this condition, a cycle length (known as a common cycle length) should be shared within the coordinated intersections to allow continuous traffic flow over several intersections in one main direction. The traffic condition analyses involving common cycle lengths were considered in this research.

DATA PROCESSING

After all preparation was complete, the researcher used Synchro 7 for data generation. When the database for this research was generated, noise points were reduced from the original database to clarify the trends in the data.

Simulation Software Performance

In Synchro 7, the intersections were drawn using the “add link” default tool. All intersection and traffic parameters were set to be buttons, choices, or blank fillings. In this study, the parameters that varied in Synchro 7 were lane number and lane group, street name, link speed, traffic volume, turn type (permitted), ring and barrier, minimum initial (minimum green time), minimum split, yellow time, red time, recall mode, walk time, pedestrian walk speed, and median width. All other parameters were set to their default values. The final form of the intersection in Synchro 7 is shown in Figure 9.

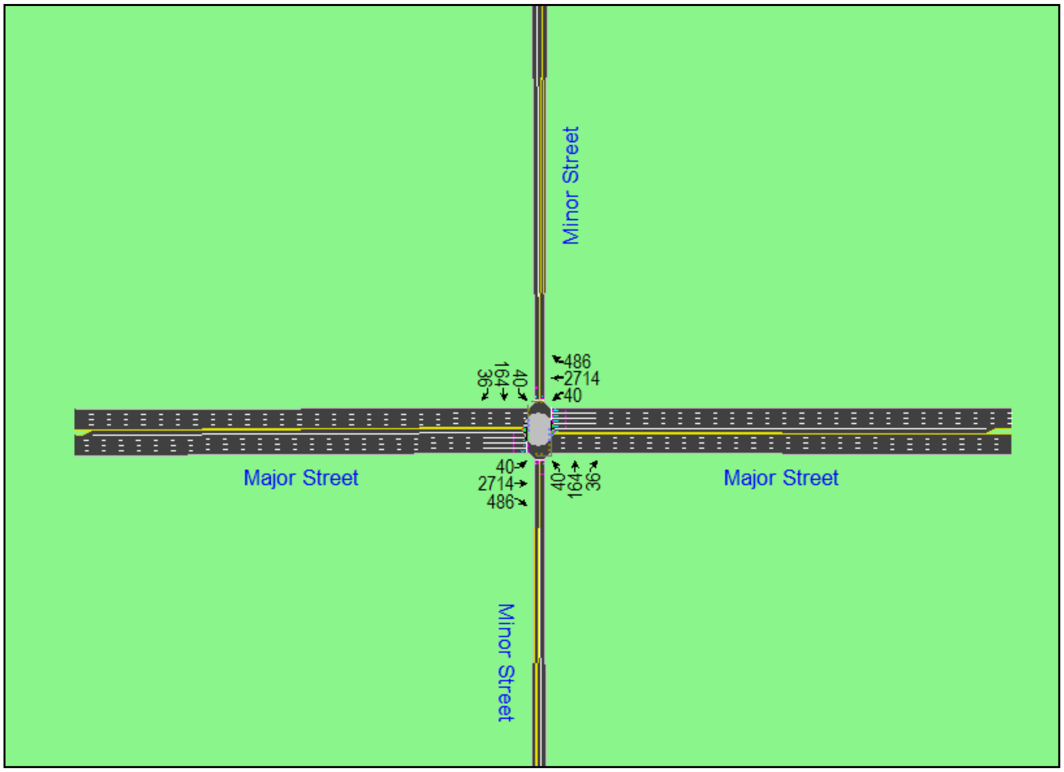


Figure 9: Intersection creation in Synchro 7

Each scenario involved more than 1000 cases. All cases can be classified into two groups:

1. Delay analysis with different volume pairs (major street volume and minor street volume) under the optimum cycle length;
2. Delay analysis with different volume pairs under common cycle length.

Data Reduction

Parts of the data had no research value. If these data had been left in the research database, they could act as noise and influence the study results.

As Table 4 shows, the delay difference Δd appears to be a negative number. However, in this case, Δd could never be less than 0 sec/veh. In the 2009 MUTCD, the pedestrian walking speed was decreased in both methods compared with the corresponding contents in the 2003 MUTCD, as mentioned in Chapter 2. This means that the pedestrian clearance time, according to 2009 MUTCD, is always longer than that in the 2003 MUTCD at the same intersection. In other words, if a signal timing plan meets the requirements of 2009 MUTCD, it surely could meet the requirements of 2003 MUTCD. However, the opposite is not always true. Under this condition, the optimum results of an intersection based on the 2003 MUTCD cannot be worse than that based on the 2009 MUTCD. However, the algorithm in Synchro 7 that calculates the splits sometime allocates too much green time to the left-turning movement, which causes a slightly larger delay. This data group has only four ∆d values, and three of them should be 0. Therefore, such data groups should be abandoned.

Table 4: Noises in Database

Cycle Length	Approach Delay (sec/veh) in 2003 MUTCD			Approach Delay (sec/veh) in 2009 MUTCD			∆d*
sec	M_j	M_n	Total	M_j	M_n	Total	sec/veh
100	34.3	26.4	32.5	34.4	25.4	32.3	-0.2
100	34.3	26.4	32.1	35.3	24.8	32.4	0.3
100	35.2	26.3	32.4	35.4	24.5	32.0	-0.4
100	35.2	27.1	32.4	35.4	25.1	31.9	-0.5

*∆d = Total delay according to 2009 MUTCD – Total according to 2003 MUTCD
M_j = Major Street; M_n = Minor Street.

CHAPTER IV
DATA ANALYSIS AND RESULTS

In the 2009 MUTCD, the pedestrian walking speed for calculating the pedestrian clearance time was changed from 4.0 ft/sec to 3.5 ft/sec, and a second method with a pedestrian walking speed of 3 ft/sec was added to supplement the original method. The reduction in the pedestrian walking speed could change the overall traffic condition at an intersection. In this thesis, the researcher tried to evaluate the impacts on traffic MOEs due to changes in pedestrian walking speeds at intersections of different sizes under different traffic volumes.

To this end, the researcher created 13 different scenarios, covered over 13,000 cases, and processed them using Synchro 7. In this study, the approach volume varied from 100 veh/h to more than 3000 veh/h; three types of lanes (left-turning lane, through lane, and shared lane), two different lane groups, three median widths (0 ft, 8 ft, and 16 ft), two pedestrian detector lateral offsets (1.5 ft and 6 ft), and two different practical fixed-timing plan patterns (optimum cycle length and common cycle length) were considered.

In addition, the author created two fitting models to represent the difference between total intersection delay values calculated with the 2003 MUTCD pedestrian-interval calculation method and the 2009 MUTCD pedestrian-interval calculation methods under the optimum cycle length and the common cycle length, separately. Furthermore, by applying the fitting model under common cycle lengths, suggestions were made about the installation condition of the extended pedestrian pushbutton.

INTERSECTION DELAY DIFFERENCE ANALYSIS

The researcher compared the differences, both vertical and horizontal, between the total delay at an intersection as calculated with the 2003 MUTCD pedestrian-interval calculation method and the 2009 MUTCD pedestrian-interval calculation methods. The vertical comparison focused on the study of regular patterns within a single intersection.

The horizontal comparison was an exploration of the single-intersection trends in various studied elements among intersections. This was an extension of the vertical comparison and was based on the vertical comparison.

The impacts of the change in pedestrian walking speeds on the intersection total delay within an intersection under different volumes are discussed first. Then, the impacts of the change in pedestrian walking speeds on the intersection total delay are discussed, with consideration to different major street and minor street through-lane numbers and different median widths at intersections. Finally, two fitting models, created using the combination of the *Levenberg-Marquardt Method* and the *General Global Optimization Method*, are described.

Vertical Comparison

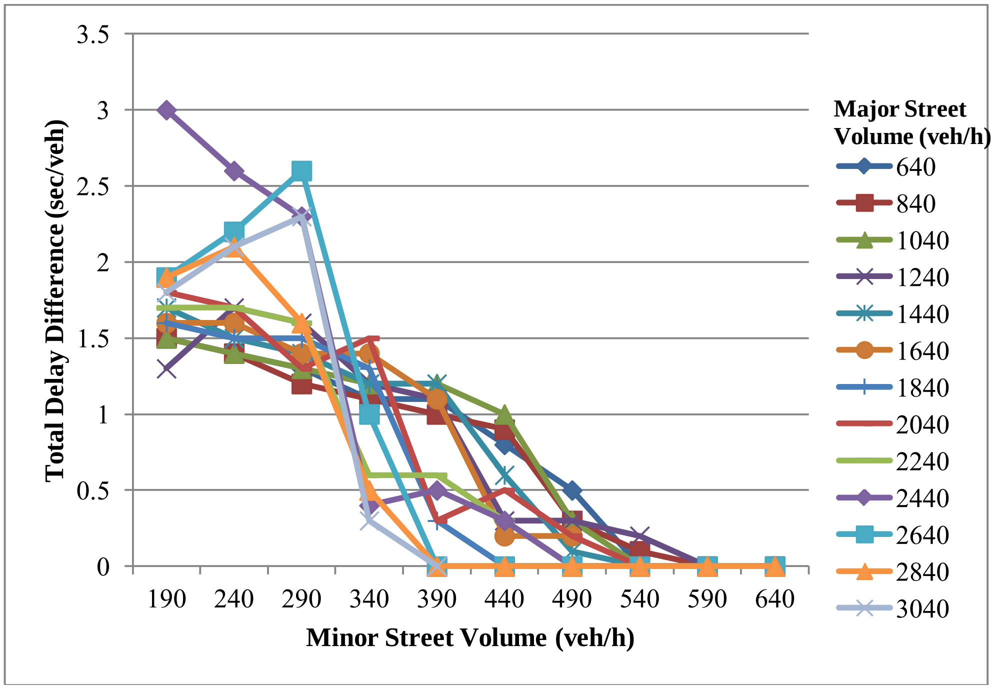
This comparison of delay was made on the basis of a single intersection with a given type of timing plans. The traffic delay under different pedestrian-interval calculation methods from the 2003 MUTCD and the 2009 MUTCD were compared. The volumes under which the intersection delay were significantly affected by the change in pedestrian walking speed were then determined in both mathematical and practical terms.

From the practical perspective, when pedestrian walking speed decreases, managers may not want to or may be unable to modify the signal cycle length to improve traffic conditions (e.g., if the given intersection is coordinated with other intersections). Reasonable and optimum cycle lengths were applied to the two different pedestrian walking speeds to assess the impact under such circumstances, and changes were observed in the delay values and traffic conditions.

Optimum Cycle Length Comparison

Single-Street Volume Increase. The author studied when the major street/minor street volume increased even, as the volume on the other street remained stagnant, and the manner in which the intersection total average delay changed between two different pedestrian walk interval conditions under the optimum cycle length. Figures 10–12 show the analysis results at three different simulated intersections ranging in size from large too small. The scenario numbers can be checked in Table 2. Each figure contains two charts, which represent the same dataset in different ways to show multiple perspectives of the relationship among the given data. In these figures, the vertical axis represents the difference between the intersection total delay calculated by 2009 MUTCD methods and that calculated by 2003 MUTCD methods (shortened to *total delay difference*). Unless otherwise noted, all vertical axes showing the total delay difference have the same meaning. The major street and minor street volumes shown in all figures were based on the 10 intersection sample datasets; the variation trends can be concluded as below:

- The total delay of an intersection based on the 2009 MUTCD pedestrian walk interval calculation method is always equal to or greater than the total delay based on the 2003 MUTCD;
- There is always a major street volume range and a minor street volume range for an intersection. Within these ranges, the total delay difference based on the 2009 MUTCD is larger than the total delay based on the 2003 MUTCD;
- Within the minor street volume range mentioned at the second point, when the major street volume remains constant, the total delay (sec/veh) difference may increase as the minor street volume increases when the minor street volume is relatively low. As the minor street volume continues to rise, the total delay difference starts to decrease, and finally reaches 0;
- When the major street volume increases, the minor street volume range (within which two different pedestrian walk interval calculation methods would yield different total delay values) decreases;
- When the minor street volume increases, the major street volume range (within which the two different pedestrian walk interval calculation methods would yield different total delay values) decreases.



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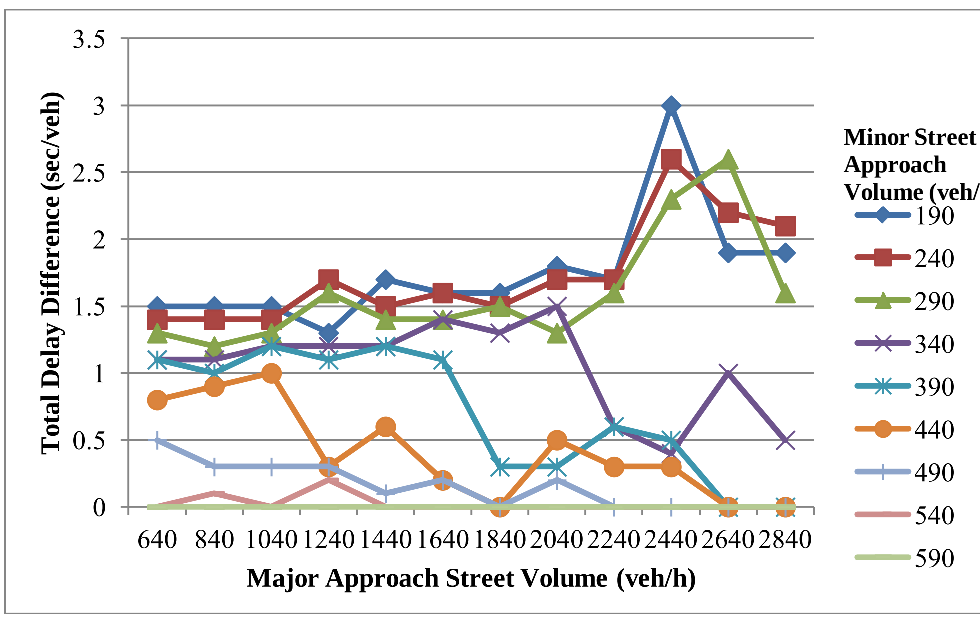
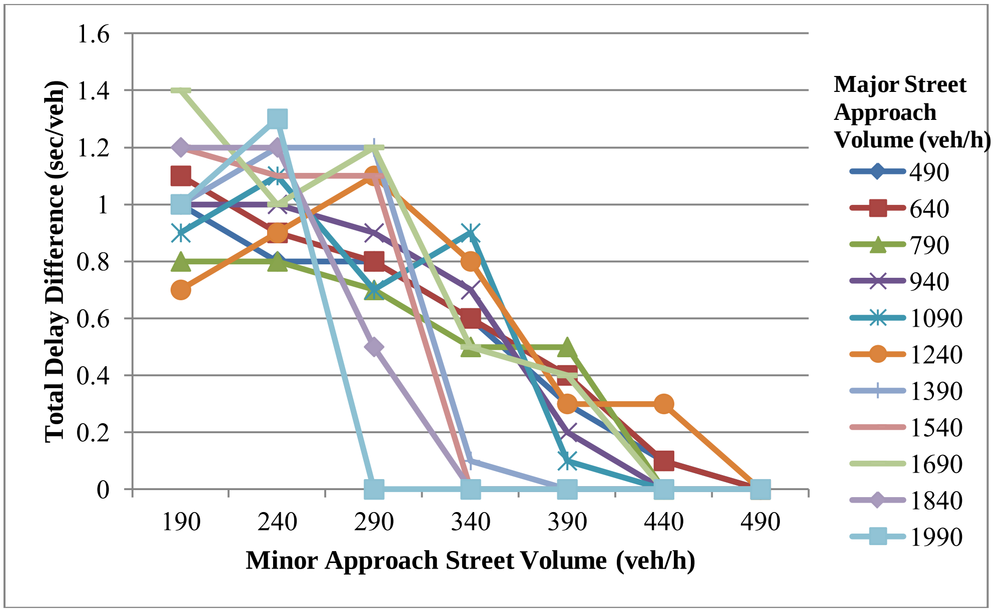


(b)

Figure 10: Delay difference related to different major and minor street volumes in Scenario 2



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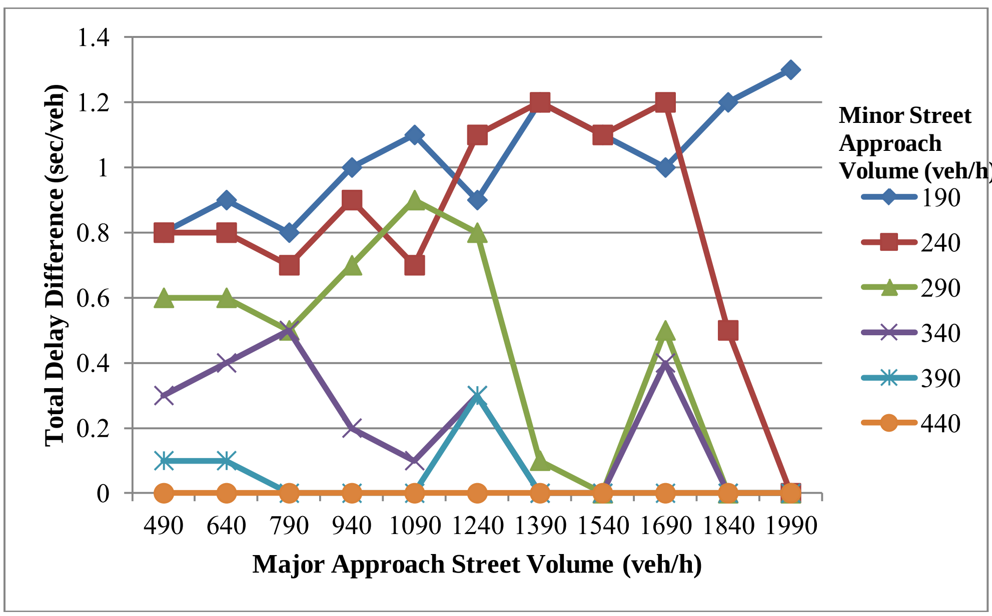

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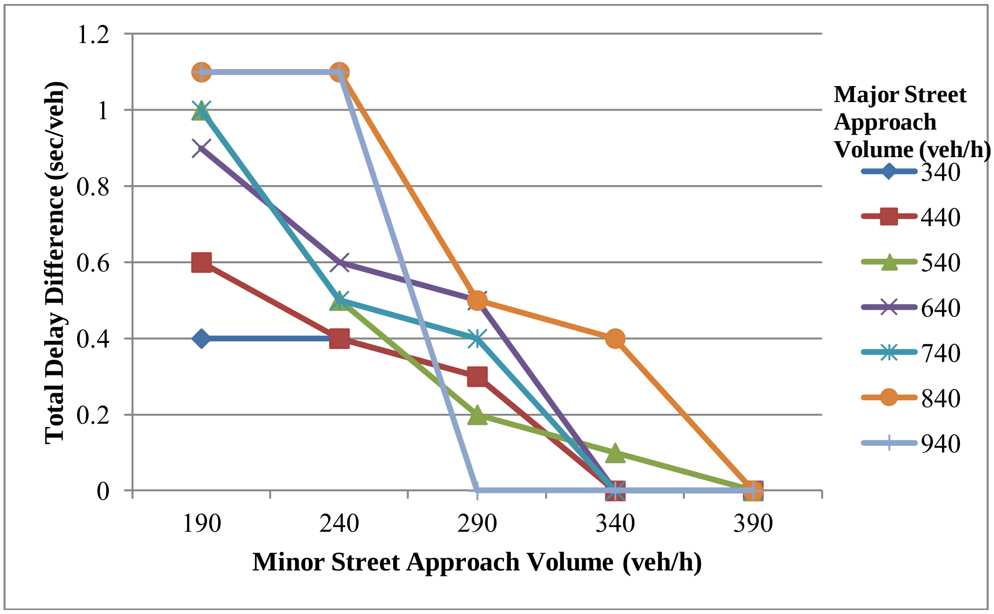
Figure 11: Delay difference related to different major and minor street volumes in Scenario 9



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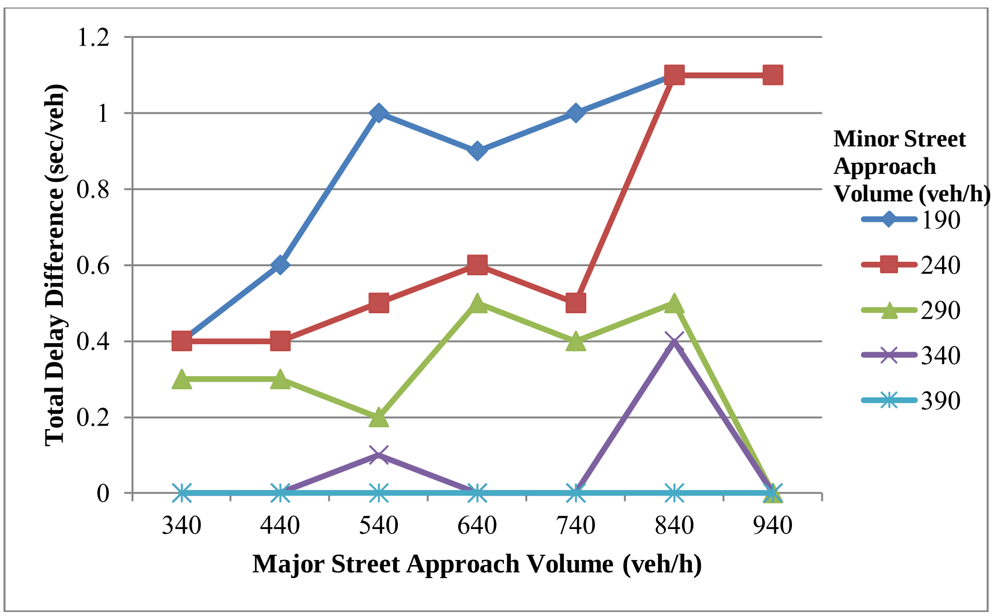


(b)

Figure 12: Delay difference related to different major and minor street volumes in Scenario 12

Common Cycle Length Comparison

In addition to the total delay comparison study under the optimum cycle length, the researcher discussed the total delay differences under given cycle lengths. This study focused on special signal controls and management requirements, such as traffic green bands. All traffic signals along the arterial street are interconnected to improve the traffic efficiency on the major street. In such a case, the cycle lengths of all intersections within this green band area need to either be equal or the multiple relationships of each other. Each intersection is assigned a common cycle length that can be changed only under certain circumstances changed.

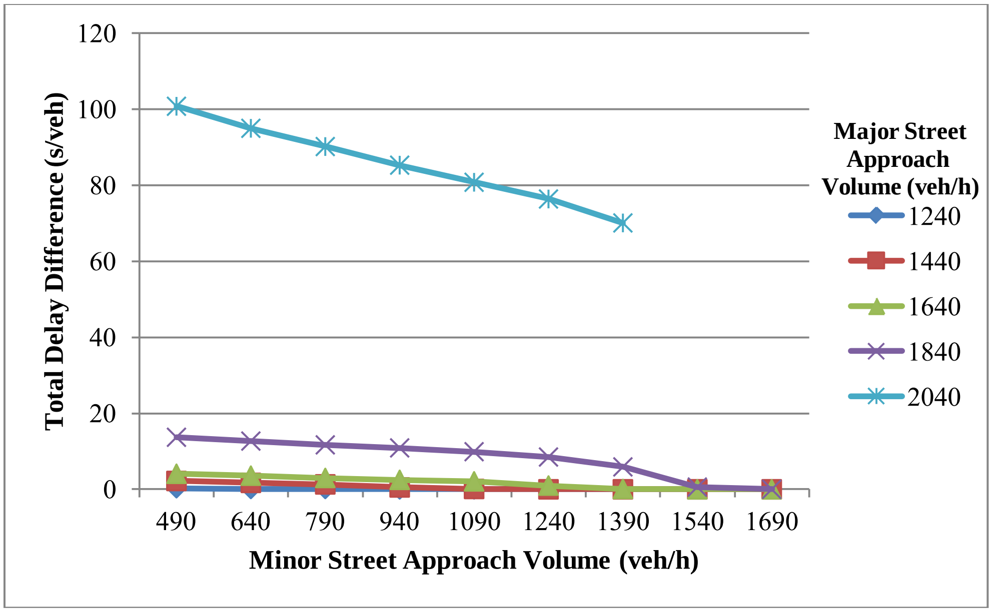
In this study, the author used cycle lengths of tens (e.g., 80, 90, and 100) to study the impacts of the change in the pedestrian walk interval prescribed in the 2009 MUTCD. The laws under the common cycle length condition can be summarized as below:

- Under a given cycle length, when the major street volume remains constant while the minor street volume increases, the total delay difference decreases;
- Under a given cycle length, when the minor street volume remains constant while the major street volume increases, the total delay difference increases at an exponential rate;
- Under the same major street volume and minor street volume, as the given cycle length increases, the total delay difference decreases at an exponential rate.

See Figure 13 and 14 for examples of this study.

Based on the above-mentioned results, the following two conditions are worthy of study:

- The critical delay difference that need to be taken care of when changing the pedestrian walk interval;
- The critical volume that causes congestion when changing the pedestrian walk interval.



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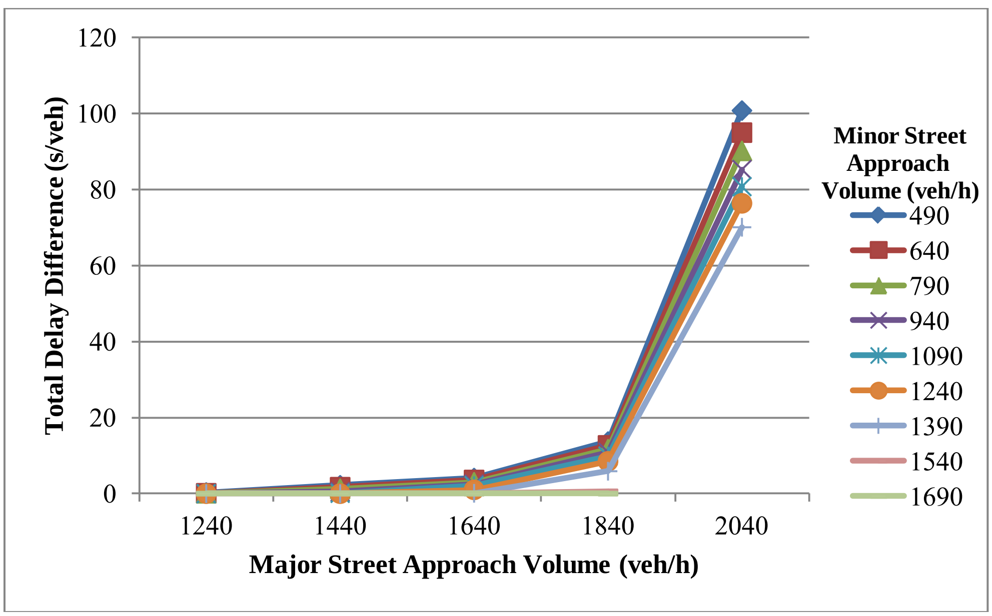
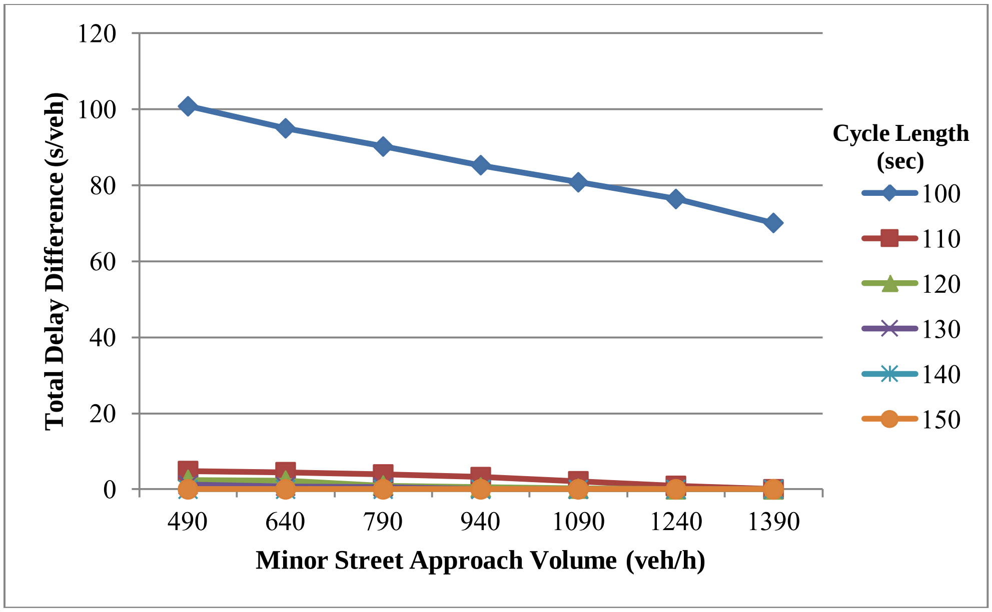
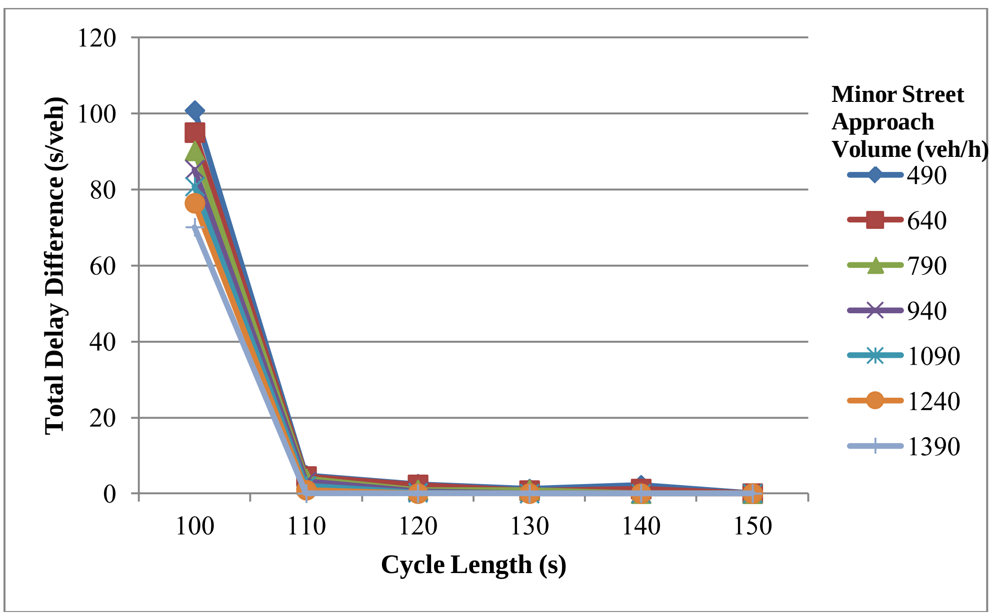


(b)

Figure 13: Total delay difference changes with different major street and minor street volumes under 100-sec cycle length in Scenario 6



(a)



(b)

Figure 14: Total delay changes with different minor street volumes and cycle length under 2040 veh/h major-street volume in Scenario 6

Because the vertical comparison considers only the regular patterns within one intersection, the intersection features cannot be formed logically by using mathematical and practical methodologies. Further research is required based on the horizontal comparison.

Horizontal Comparison

Horizontal comparison was used for analyzing the degree of the total delay impact at different intersections and for different signal-timing characteristics. The researcher mainly focused on the average delay difference due to the number and type of lanes and on the median width. Furthermore, in conjunction with the second method used for the pedestrian walk interval in the 2009 MUTCD, the author discussed the two limit values of pedestrian pushbutton horizontal offset, 1.5 ft and 6 ft.

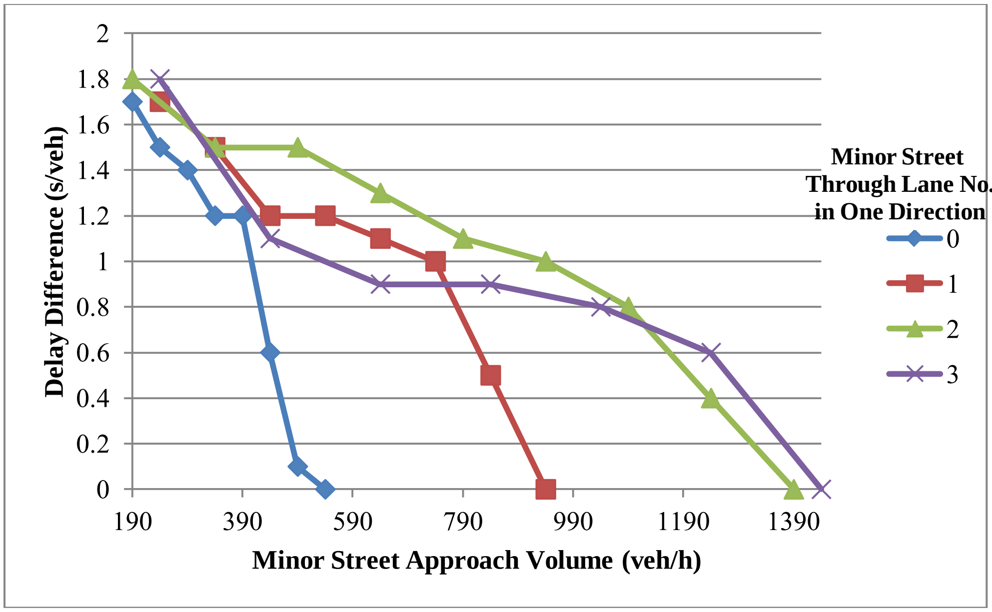
Influence of the Number of Through Lanes

In this research, all studied intersections had one left-turning lane and one shared lane for right turning and through movements. Only the number of through lanes can be changed. When the number of through lanes changes, the width of the intersection changes as well, which makes a difference on the pedestrian intervals. Different intersection widths result in different crosswalk lengths. By applying the interval calculation methods prescribed in the 2003 and 2009 MUTCDs, different crosswalk lengths lead to different pedestrian-interval differences, which further influences the intersection MOEs. However, as opposed to the change of median width, a change in the number of through lanes would change the distribution of through volume and the v/c (vehicle to capacity) ratio as well, leading to differences in the intersection MOEs. Superposition of the factors finally distinguished the results of the MOEs changes from those caused by the median-width alternation.

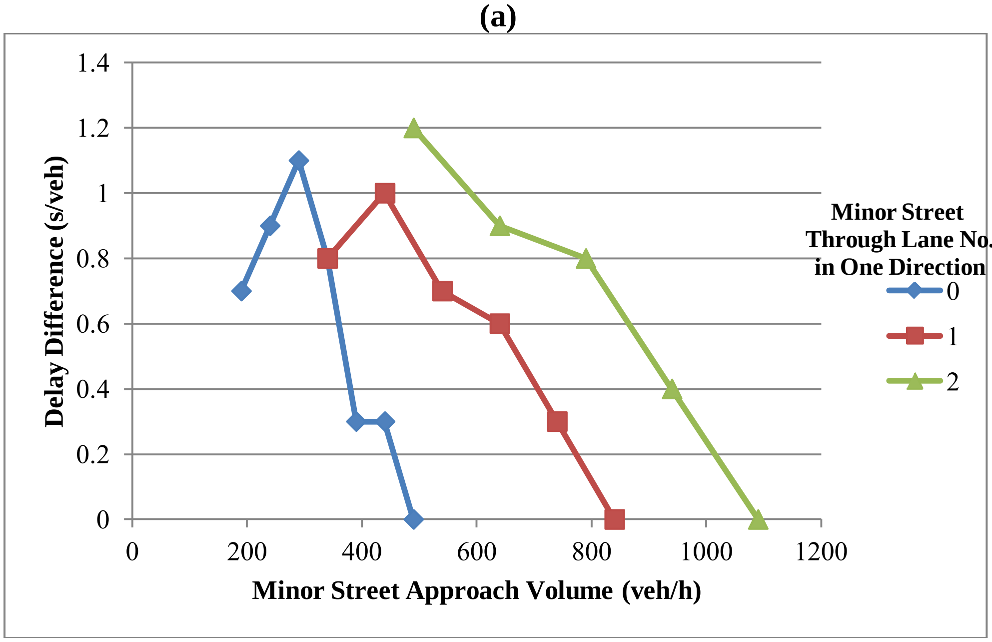
Influence of Minor Street Through Lane Number. Figure 15 shows the changes in delay differences in intersections at various numbers of minor street through lanes with their optimum cycle lengths.

In Figure 15, Chart (a) shows the intersections with three through lanes in the major streets and Chart (b) shows the intersections with two through lanes in the major streets. Each has the same minor street components. Several clear trends can be noted from this comparison:

1. As the number of minor street through lanes increases, the volume matrix that could cause the delay difference between two studied pedestrian-interval calculation methods becomes bigger, which means both the ranges of the major street volume and the minor street volume that could cause the delay difference between the two studied pedestrian-interval calculation methods become wider;
2. When the studied intersection had differences only in the number of minor street through lanes, with the same major and minor street volumes, the intersection total delay difference between the two studied pedestrian-interval calculation methods increased; the number of minor street through lanes increased from 0 to 2 in each direction. However, when the number of minor street through lanes reached 3 in each direction, the intersection total delay difference decreased instead.



(a)



(b)

Figure 15: Relationship between the delay difference and the number of minor street through lanes with 1240 veh/h at one major street approach under optimum cycle length

Given a common cycle length, as the number of minor street through lanes increases, the total delay difference increases as well (see Figure 16). As opposed to the delay difference trends under the optimum cycle length, the delay difference kept increasing from 0 minor street through lanes to 3 through lanes in each direction.

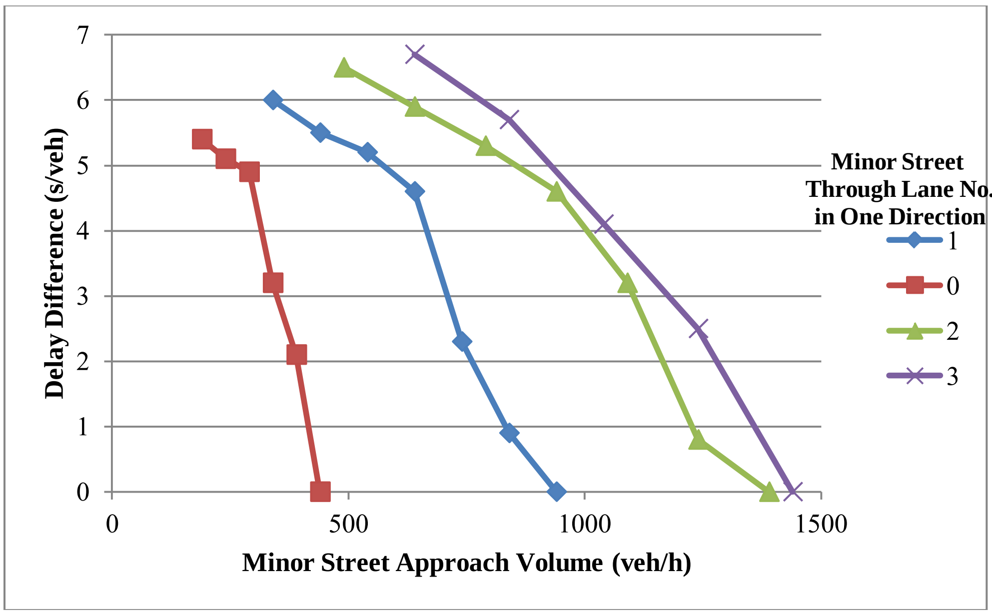


Figure 16: Relationship between the delay difference and the number of minor street through lanes under common cycle length

Influence of Number of Major Street Through Lanes. Figure 17 shows the change in the intersection average delay difference with various numbers of major street through lanes under the optimum cycle length. Two findings were revealed during this part of study:

1. As the number of major street through lanes increases, the volume matrix that could cause the delay difference between the two studied pedestrian-

interval calculation methods increases as well, which is similar to the case of adding the number of minor street through lanes;

2. When the studied intersection has differences only in terms of the number of major street through lanes, with the same major and minor street volumes, the intersection total delay difference between the two studied pedestrian-interval calculation methods increases as the number of minor street through lanes increases.

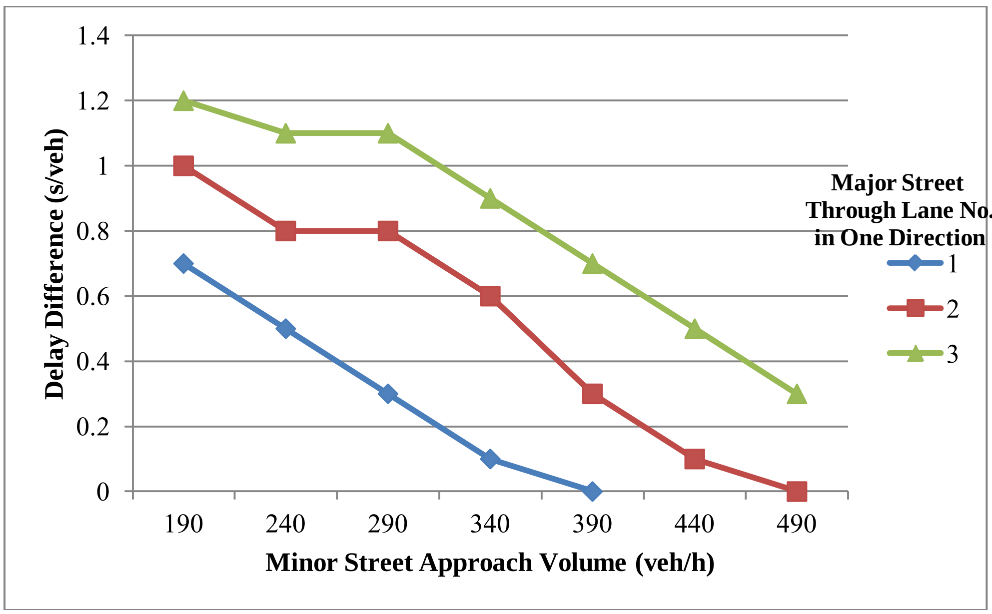


Figure 17: Delay Difference for different numbers of major street through lanes under optimum cycle length

The delay difference exhibited no clear pattern when the minor street approach volume is kept constant while increasing the major street approach volume. However, for a given cycle length, the intersection total delay difference exhibited a clearer trend under this circumstance. As Figure 18 shows, when the minor street approach volume is 190 veh/h, as the major street lane number increases, the total delay difference decreases first and then increases. This results from the balance of the capacity and the length of pedestrian intervals: more through lanes provide larger capacity and decrease total delay under a given cycle length; but wider major street results in longer minimum green time for the minor street movement and shorter for the major street, and could increase the total delay.

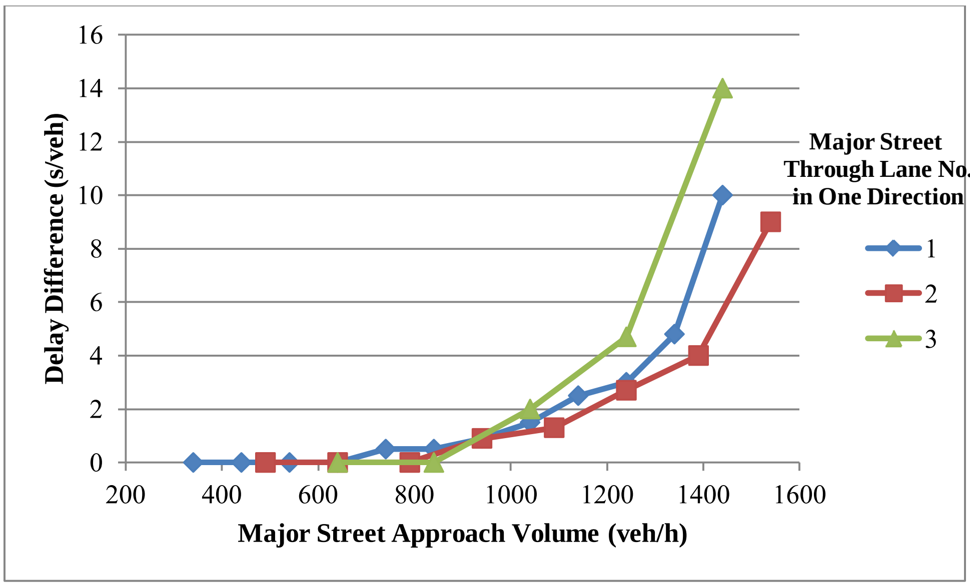


Figure 18: Delay Difference for different numbers of major street through lanes under common cycle length

Influence of Median Width

Focusing on the combined impacts of the crosswalk length and the pedestrian speed, the researcher changed the signalized intersection features that contribute to crosswalk length one by one, while maintaining the other features constantly. Because the crosswalk length affects the pedestrian clearance time directly, it is also the only element that can be studied to reflect the influence of the crosswalk length. A comparison of the traffic MOEs between two different crosswalk lengths, resulting from the number of lanes, reveals the possibility that changes in the MOEs will be influenced by changes in lane group features as well (e.g., if there are more lanes in one intersection than in the other).

Figure 19 shows the change in intersection total delay difference under three median widths with their optimum cycle lengths: 0 ft, 8 ft, and 16 ft. The data curves exhibit a clear trend: as the median width increases, the delay difference resulting from the two pedestrian-interval calculation methods studied herein increases. Figure 25 shows the change in intersection total-delay difference under three median widths with a common cycle length: 0 ft, 8 ft, and 16 ft. By comparing these two figures, it is clear that the influence of median width was greater under the common cycle length than under the optimum cycle length.

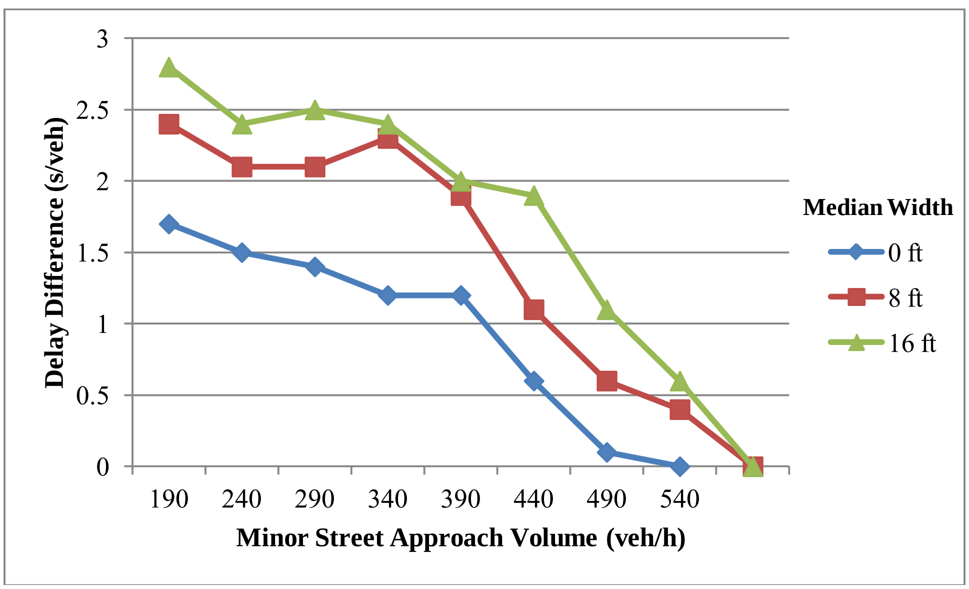


Figure 19: Effect of median width on delay difference with 1440 veh/h major street approach volume under optimum cycle length

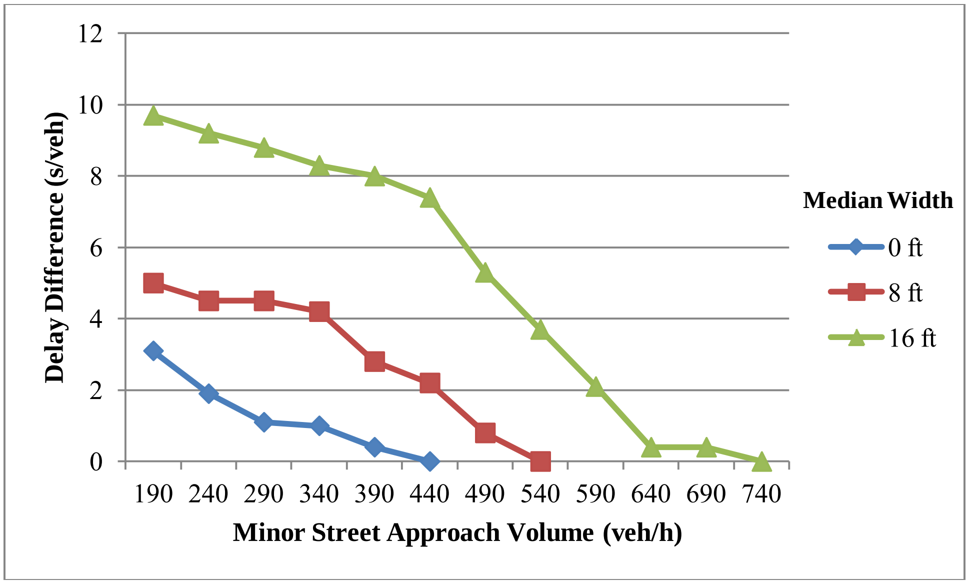


Figure 20: Effect of median width on delay difference with 1440 veh/h in one approach at major street under 100 sec

Influence of Horizontal Offset

According to the 2009 MUTCD, the two methods of calculating pedestrian intervals can be expressed as Equations 3 and 4, respectively, as in Chapter II. The values of the pedestrian intervals can be selected as expressed below:

$$PI = \begin{cases} \frac{W_p + W_{offset}}{V_{PI}^1}, & if\ \frac{W_p + W_{offset}}{V_{PI}^1} \geq T_{pc} + T_{pw}^* \\ T_{pc} + T_{pw}^*, & if\ \frac{W_p + W_{offset}}{V_{PI}^1} \leq T_{pc} + T_{pw}^* \end{cases}, sec \quad (Equation\ 7)$$

Where

PI = Pedestrian interval, sec;

T_{pc} = Pedestrian clearance time, sec. $T_{pc} = T_{pci} + T_{BI} = w_p / V^2_{PI}$;

T_{pci} = Pedestrian change interval, sec. Corresponding to FLASH DON'T WALK;

T_{BI} = Buffer interval, sec. 3-sec minimum;

T^{*}_{pw} = Pedestrian walking interval, should be set to at least 7 sec, except under some special conditions (4 sec at least);

W_p = Width from the curb or shoulder where pedestrian left at the end of the WALKING PERSON (symbolizing WALK) signal to the far side of the traveled way or to a median of sufficient width for pedestrians to wait, ft;

V^{2}_{PI} = Pedestrian walking speed, set to 3.5 ft/sec;

W_{offset} = Width from the pedestrian detector to the near-side curb; if no pedestrian detector is present, a location 6 feet from the face of the curb or from the edge of the pavement, ft;

V^{1}_{PI} = Pedestrian walking speed, set to 3.0 ft/sec.

The author calculated the major street pedestrian intervals for the intersection with three through lanes, as in the case of the intersection in Scenario 2. Moreover, this intersection had the greatest number of lanes in the major street among the intersections considered in this study.

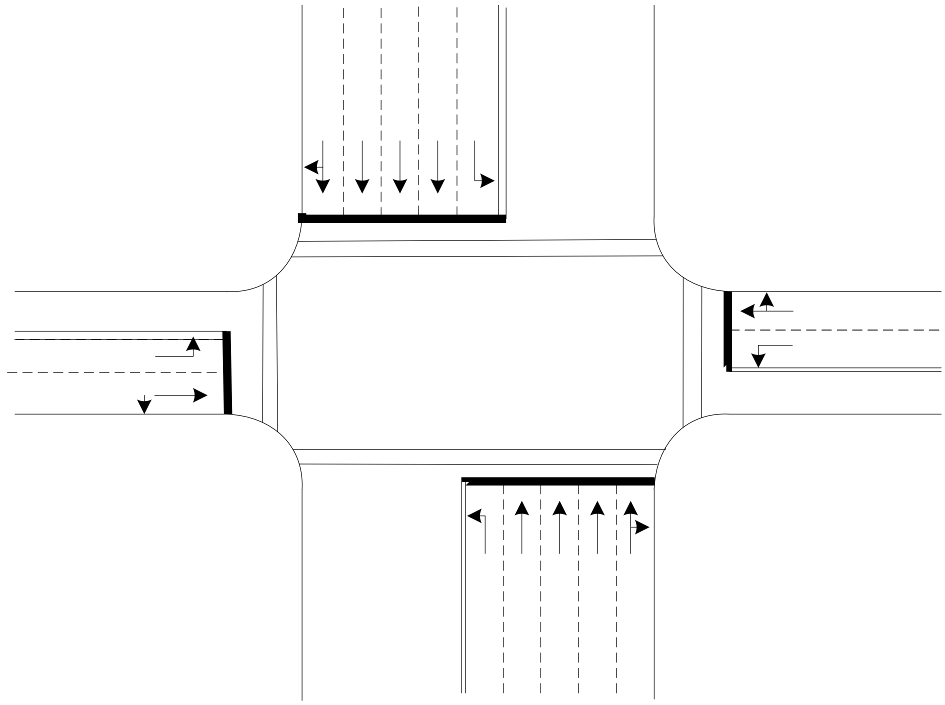


Figure 21: Intersection in Scenario 2

On the basis of the 2009 MUTCD, the researcher considered two boundary values of pedestrian pushbutton horizontal offset: 1.5 ft and 6 ft. The final results of the pedestrian intervals with these two values were 37.9 sec and 38.0 sec. This 0.1-sec difference could result in almost no difference to the lane groups and the approach, and to an even greater degree, the whole intersection. Therefore, the horizontal offset of the pedestrian pushbutton cannot make a difference on the intersection MOEs at this research scale. Furthermore, the width of the major street in Figure 21 could almost represent the largest signalized intersection width in cities. In such a case, the horizontal offset of the pedestrian pushbutton would barely influence the intersection MOEs.

Further Discussion

Because the data showed clear patterns under the optimum cycle length and common cycle lengths, the researcher tried to add the variables "minor street through lane number," "major street through lane number," and "median width" into the models that expressed the vertical comparison. If the addition is successful, the parameters in the model can be specified and expressed as equations. However, when adding the fourth variable ("minor street through lane number") to Equation 8, the researcher was unable to find a compatible model for fitting the relationship among those four variables. Furthermore, the same condition appeared for the common cycle length model when adding a fifth variable to Equation 10.

The research data were analyzed and it was found that the left turning vehicles were interference factors. At the beginning, a protected left turning phase was set up to avoid interference from left turning vehicles. However, although the left turning vehicles were not affected directly by the change in pedestrian speed and pedestrian intervals, the indirect impacts on them cannot be dismissed. As Figure 22 and 23 show, at least four elements exist between the pedestrian speed and the left turning delay under the optimum cycle length, and three exist under the common cycle length. In this study, to weaken the influence of left turning vehicles, the author set the volume to 40 veh/h for all left turning movements. This setting resulted in volatile model parameters. In other words, as an influence factor, different left turning volume would cause different total delay differences between the pedestrian-interval calculation methods in the 2003 and 2009 MUTCDs. By setting a constant left turning volume, this factor was actually ignored. However, its impact on the study result cannot be dismissed. Because of a lack of this factor when building the model, model biases came into being. Furthermore, according to Equation 1, the red time changes as the intersection width changes. Therefore, even under a common cycle length and constant left turning green time, the total left-turn timing plan affects through movement and the impact of the change in pedestrian walking speed. The combination impact of various factors finally revealed that the overall model cannot be built. Moreover, as variables increase, the impacts of such noises are amplified and can no longer be dismissed.

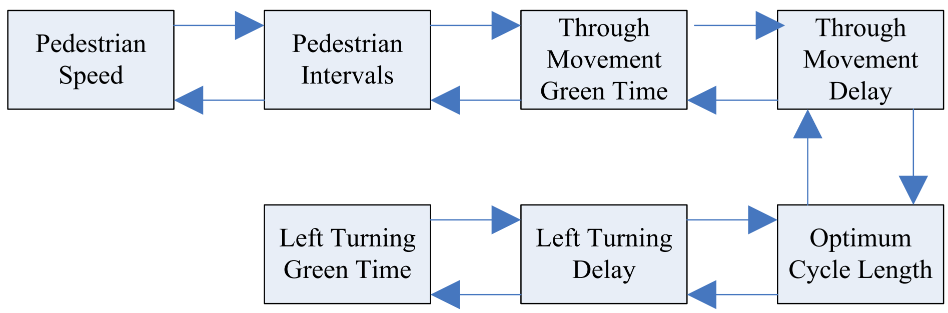


Figure 22: Delay and green time relationship under optimum cycle length

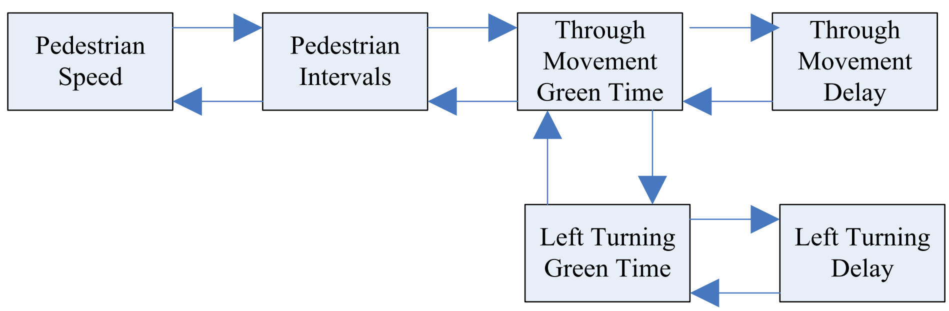


Figure 23: Delay and green time relationship under common cycle length

LANE GROUP AND APPROACH DELAY DIFFERENCE ANALYSIS

In addition to the intersection-delay analysis, the researcher also conducted approach-delay analysis and lane-group-delay analysis as a supplement to improve the total-delay-difference analysis. In this study, the two approach volumes along one street were always equal to each other, so the approach-delay analysis can also be considered street-delay analysis. The left turning volume was maintained at 40 veh/h. This setting was meant to weaken the impacts of left turning delay on the research as a whole because the researcher found that, for relatively long cycle lengths, the average control delay of the left turning vehicles can increase up to over 100 sec/veh, which is far beyond the average delay of the other lane groups. If the number of left turning vehicles is high, the left-turn-vehicle delay will become the leading factor in the total delay. The impacts of the pedestrian-walk interval on the through and right turning movements cannot be reflected on the surface. Furthermore, although a change in the pedestrian walk interval can influence the optimum cycle lengths, and in turn the total left-turn movement delay, many other elements, such as volume and capacity, can also handle the final optimum cycle length. Those elements are connected with each other and finally yield a comprehensive result in the form of left-turn delay values. Research on the correlation between the left-turn delay and the pedestrian walking speed is limited. Therefore, if the related elements between the left-turn delay and the modification of the pedestrian walking speed are not clear, the left-turn delay in this research has no value in this study. As a supplementary study, the author discusses only the impacts of the pedestrian walk interval on through and right turning movements under the conditions considered for the intersection analysis.

Lane Group Analysis

With regard to the optimum cycle length, there was no apparent regular pattern in the -delay difference when looking into the lane group containing the shared lane and through lanes, as shown in Figure 24 and 25. However, when examining the delay difference under a given cycle length, the data exhibited clear trends for both the major street and the minor street, as shown in Figure 31 and 32.

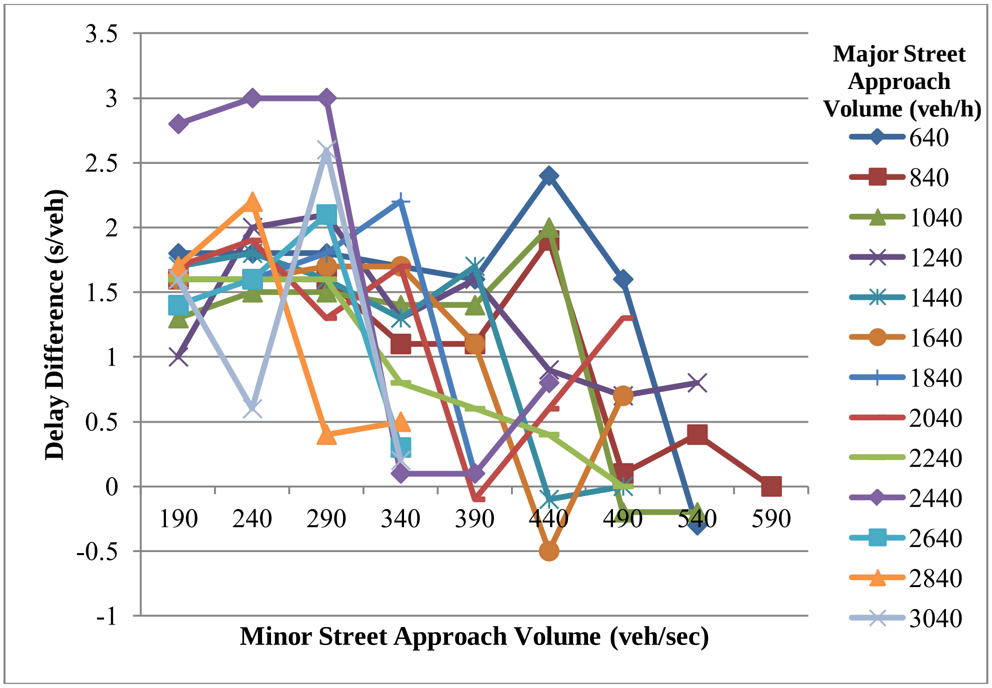


Figure 24: Major street lane group delay difference under optimum cycle lengths

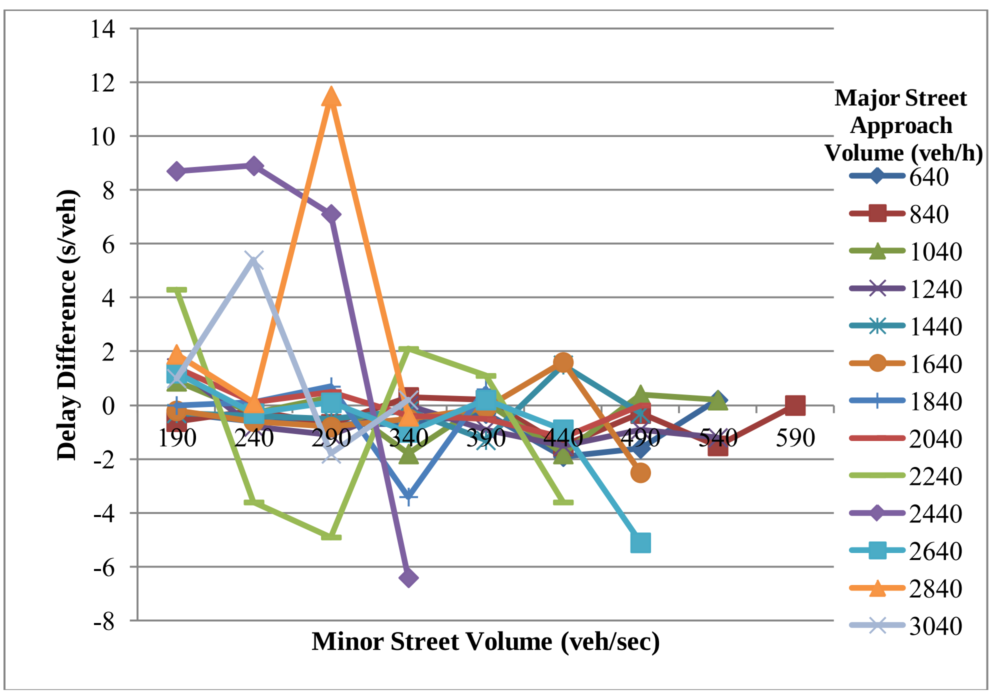


Figure 25: Minor street lane group under optimum cycle length

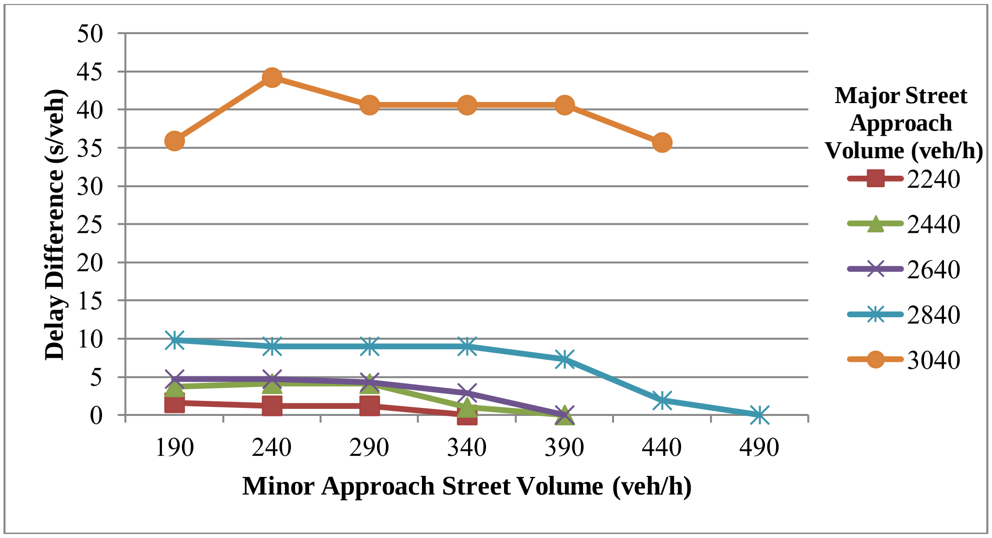


Figure 26: Major street lane group delay difference with cycle length of 130 s

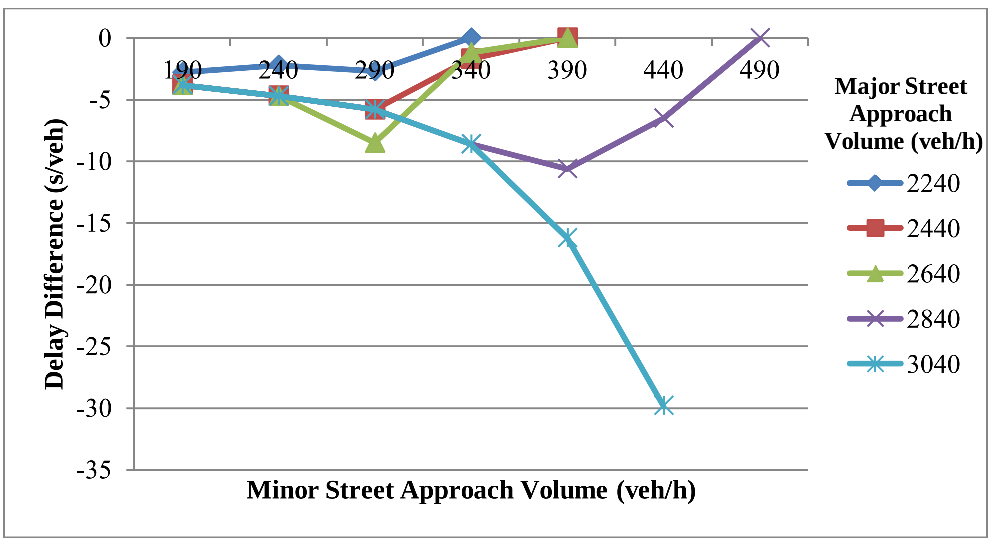


Figure 27: Minor street lane group delay difference with cycle length of 130 s

The data in Figure 26 were obtained at a cycle length of 130 sec in Scenario 2. Figure 27 shows the trend of the average delay difference of the major street lane group. This lane group contains through lanes and a shared lane (for right turning and through movements). In Figure 26, it is clear that when the major street volume is kept constant while the minor street volume increases, the trend of the average delay difference between the 2003 and 2009 MUTCD pedestrian walk interval methods remains relatively stable at first and then decreases to 0. Furthermore, as the major street volume increases for a constant minor street volume, the delay difference increases rapidly until the studied intersection is congested with traffic.

The data in Figure 27 was obtained under similar conditions as above, with the exception that it pertains to the minor street. The curves in Figure 27 exhibit a similar pattern: they start at a negative point, decrease first, and then increase to 0. The curve representing the change in average delay difference under the major street volume of 3040 veh/h does not revert to 0 because the curve is unfinished. Such changes result from different minimum green time caused by lengths of pedestrian intervals. The minimum green time based on the 2003 MUTCD is shorter than that based on 2009 MUTCD. When under a relatively low minor street volume, although none of the minimum green can be fully used, the minor street with longer green time suffers less delay. As the minor street volume increases, before Synchro allocating more green time to the minor street to reduce the total intersection delay, the delay of the minor street with shorter minimum green time (the one based on the requirements of 2003 MUTCD) increases faster than that with longer minimum green time (the one based on the requirements of 2009 MUTCD). When the green time of the minor street starts increasing, the increase rate of the delay of the one with longer minimum green time is larger than the one with shorter minimum green time. Finally, the delays reach the same value and the delay difference reaches 0.

By comparing the average delay difference patterns for the same scenario under the optimum cycle length and the common cycle length, the researcher conjectures that the delay and delay-difference patterns of left turning movement influence the average delay difference pattern of the lane group with right-turning and through movement. This influence is a function of the cycle length and left turning green time. The left-turning vehicles influence the optimum cycle length through control delay. This impact partly disarranges the original delay difference regular pattern of the other lane group.

Therefore, when the cycle length is constant, the right turning and through-movement lane group was barely affected by left turning movement, and its regular pattern became much clearer than that under the optimum cycle lengths.

Approach Analysis

Vertical Comparison

Under the optimum cycle lengths, no regular pattern existed in the approach delay differences, according to the two pedestrian-walk intervals and based on the 2003 and 2009 MUTCD. However, under the common-cycle-length condition, the average approach delay differences exhibited a clear pattern (see Figure 28 and 29).

Figure 28 and 29 show the average approach delay difference under the same conditions as those shown in Figure 26 and 27. By comparing Figure 26 and 28, as well as Figure 27and 29, the same curvilinear trend is observed, which confirms the conjecture that the author made in the lane group delay difference analysis: the disorderliness of the approach and lane group (containing right turning and through movement), which is evident from the optimum cycle length cases, is caused by disturbances from the left turning movement.

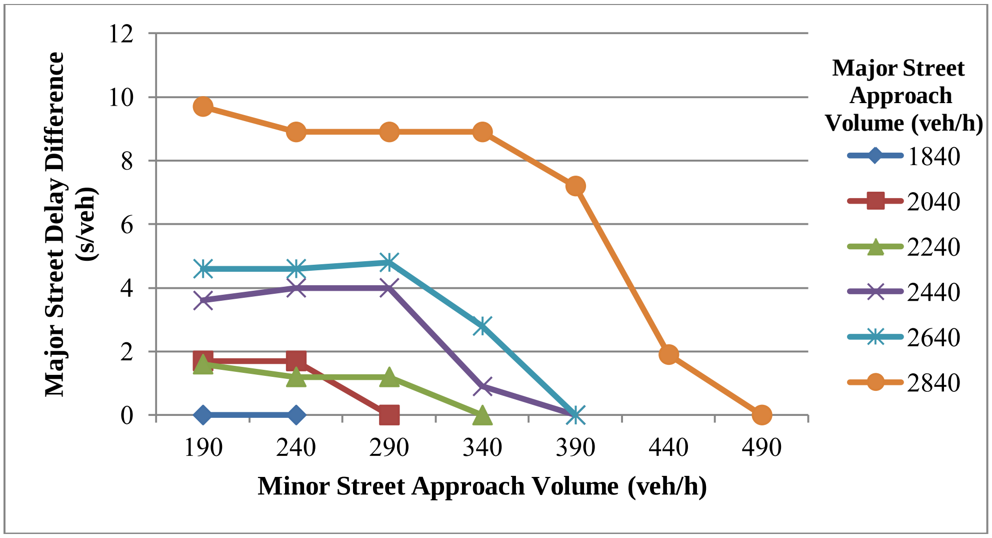


Figure 28: Major street approach delay difference with cycle length of 130 s

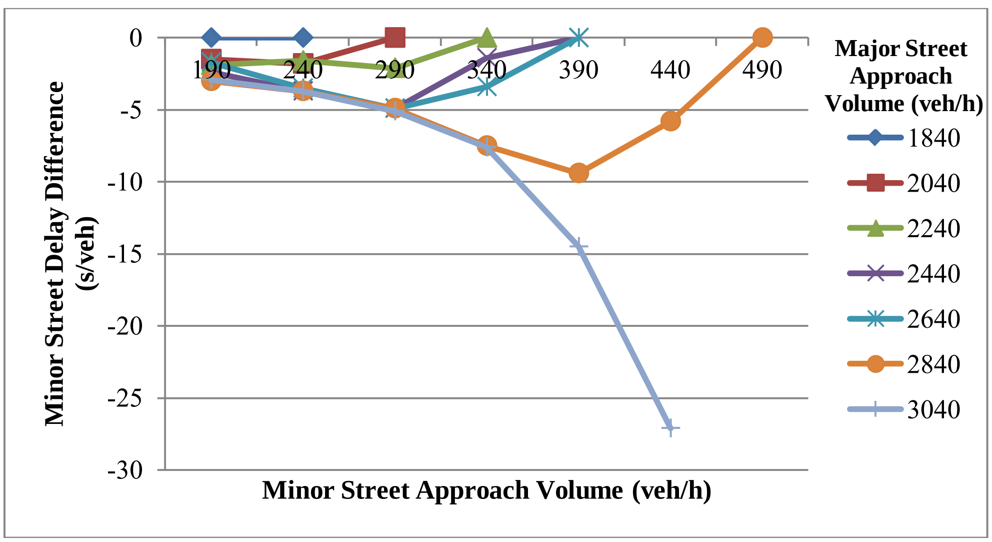


Figure 29: Minor street approach delay difference with cycle length of 130 s

When under different common cycle length, the major street delay difference shows a similar pattern as the intersection delay difference does: the major street delay difference increases exponentially as the cycle length increases, as shown in Figure 30. However, the minor street delay difference changes in a different way. As the cycle length increases, the minor street delay difference shows a similar pattern as it shows with the increase of major street approach volume; and the minor street delay calculated based on the 2009 MUTCD is always less than or equal to that based on the 2003 MUTCD.

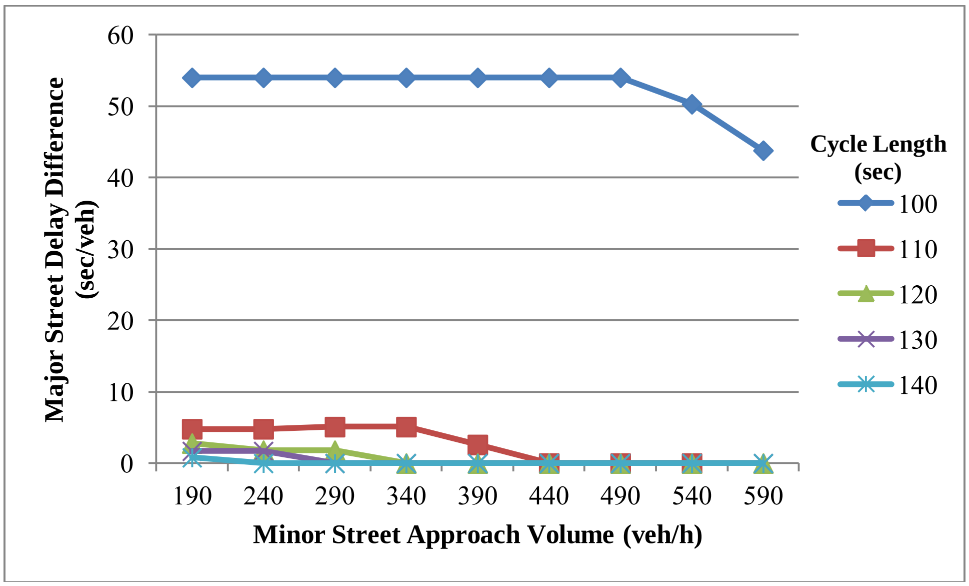


Figure 30: Major street approach delay difference with different cycle length

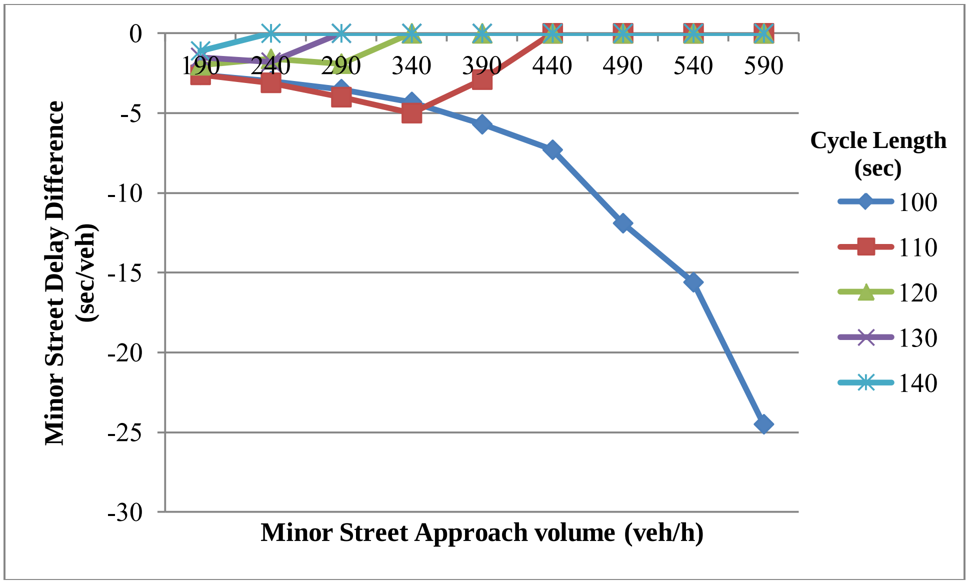


Figure 31: Minor street approach delay difference with different cycle length

Horizontal Comparison

Influence of the Number of Through Lanes. Under different numbers of major street and minor street through lanes, the approach delay difference exhibits differently. As Figure 32 and 33 show, the increase of minor street through lane numbers results in the increase of major street delay difference; and that also increases the value of the minor street volume that can make the minor street delays based on the two editions of MUTCDs equal.

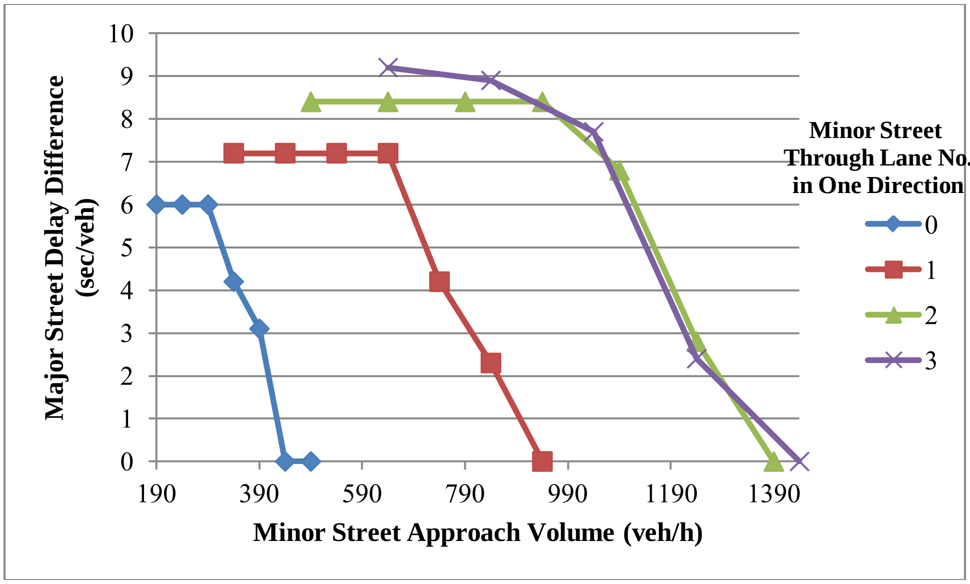


Figure 32: Major street approach delay difference with various minor street through lane numbers

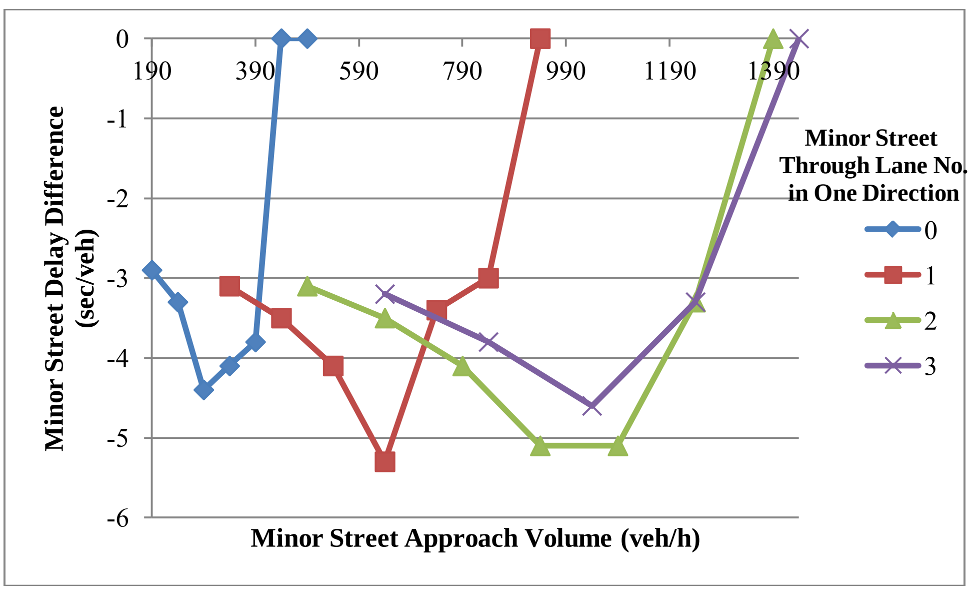


Figure 33: Minor street approach delay difference with various minor street through lane numbers

Figure 34 and 35 show the change of major street and minor street delay difference with different numbers of major street through lanes. The increase of major street lane numbers results in a decrease on major street delay difference first, then going up back to a relatively high major street delay difference level. The minor street delay difference shows the same trend as increasing the minor street through lane numbers.

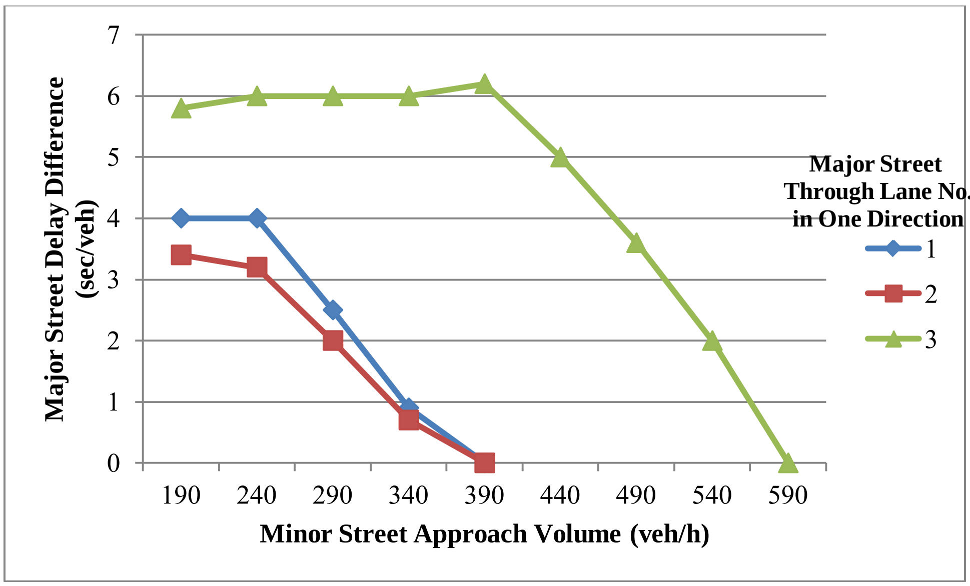


Figure 34: Major street approach delay difference with various major street through lane numbers

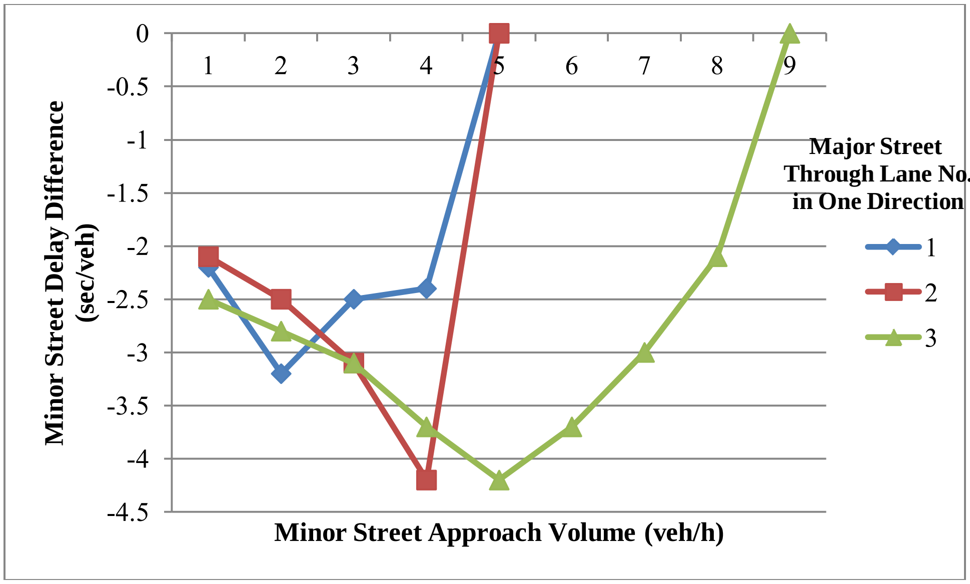


Figure 35: Minor street approach delay difference with various major street through lane numbers

Influence of Median Width. Under different median width, as Figure 36 and 37 shows, major street approach delay difference increases exponentially as the increase of median width; and the increase of median width also increases the value of the minor street volume that can make the minor street delays based on the two editions of MUTCDs equal.

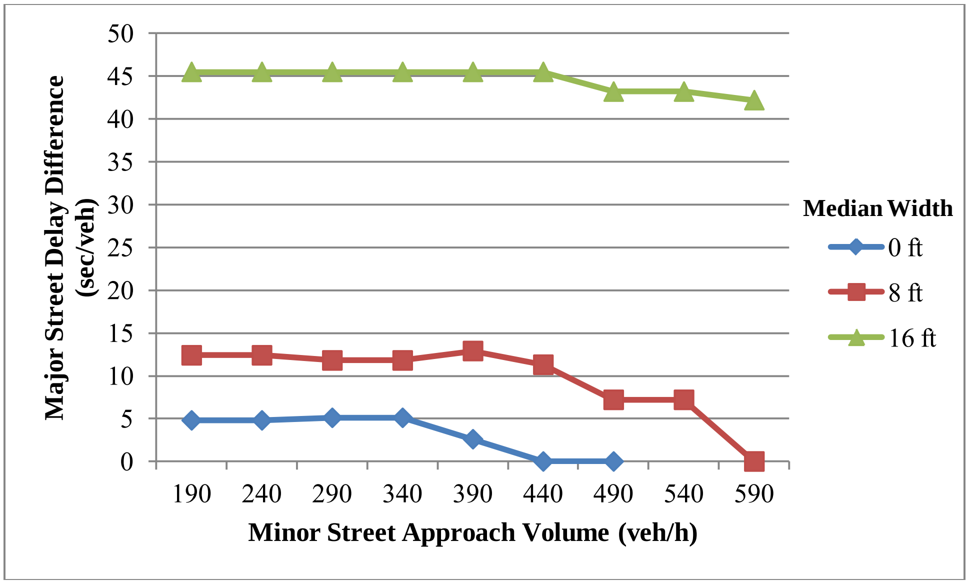


Figure 36: Major street approach delay difference with various median widths

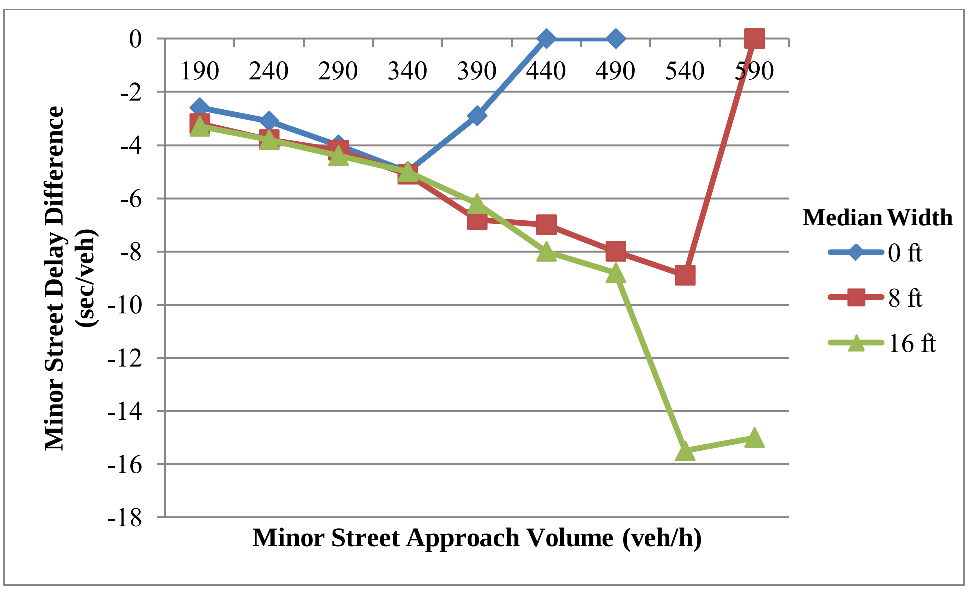


Figure 37: Minor street approach delay difference with various median widths

EXTENDED PUSHBUTTON USAGE DISCUSSION

In the 2009 MUTCD, although the pedestrian speed for calculating the pedestrian clearance time was decreased from 4 ft/sec to 3.5 ft/sec, an exception was made for the use of the extended pushbutton press function. This function is to “provide slower pedestrians an opportunity to request and receive longer pedestrian clearance times” (*2*). This option actuates additional accessibility features. To activate the features, the pushbutton must be pressed and held for more than one second (*12*). By using the extended pushbutton press function, the basic pedestrian clearance time can be calculated with the pedestrian speed of 4.0 ft/sec. The traffic MOEs are then able to partly revert to the traffic condition obtained by using the 2003 MUTCD pedestrian-interval calculation method. However, if the traffic MOEs change only slightly, there is no need to spend extra money to add this function. Therefore, the researcher attempted to discuss the condition that suited the installation of the extended pushbutton press function.

According to the study data, the researcher found that when using the optimum cycle lengths, the intersection total delay difference would not exceed 5.0 sec/veh. From the environmental and system engineering viewpoints, the additional total delay may cause a difference, but to drivers and the traffic LOS, 5 sec does not make much of a difference in practice. Therefore, in the researcher’s opinion, if one intersection has no connection with other intersections on the signal-control level, the timing plan can be changed directly from the 2003 MUTCD pedestrian standard to the 2009 MUTCD pedestrian standard without any extra installation.

When focusing on the common cycle length, a large deviation from the optimum-cycle-length condition surfaces. Figure 38 shows large differences in the intersection total-delay values calculated with the pedestrian-interval calculation method in the 2003 MUTCD and the 2009 MUTCD for the same cycle length. For a low minor street volume, the total delay—according to the 2003 MUTCD pedestrian-interval calculation method—was lower than 40 sec/veh (LOS D); whereas, according to the 2009 MUTCD pedestrian-interval calculation method, the delay was more than 80 sec/veh (LOS F), which would lead to congestion. In that case, the extended pushbutton press function should to be installed with consideration to the unchangeable cycle length. Considering the delay difference under optimum cycle length, the author suggests that the intersection with a delay difference larger than 5 sec/veh after the reduction of pedestrian walking speed should use the extended pushbutton press function to alliviate the intersection total delay.

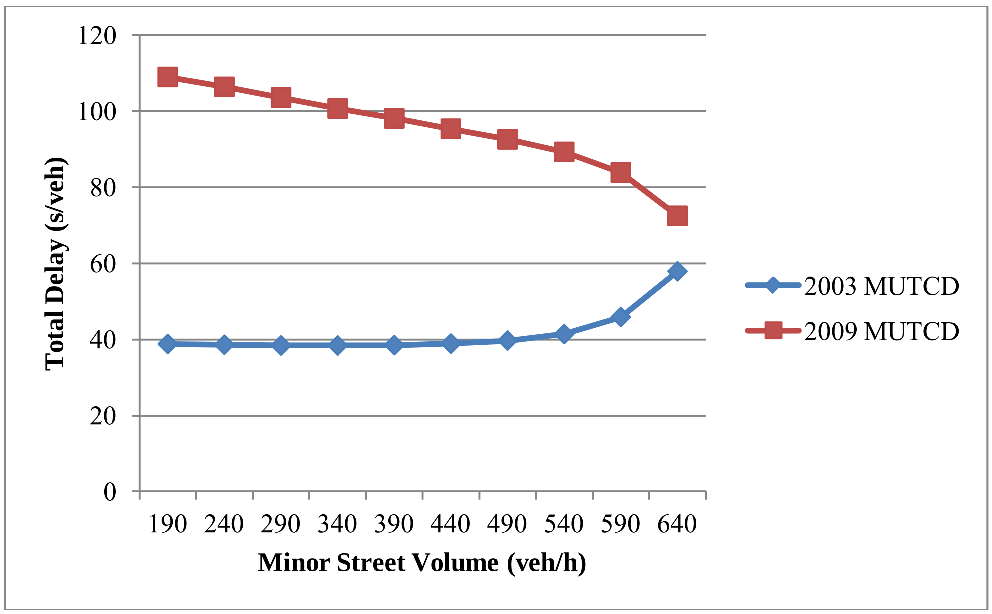


Figure 38: Total delay comparison with 2840 veh/h on one major street approach and 120 sec cycle length

CHAPTER V
SUMMARY AND RECOMMENDATIONS

This study was conducted to analyze the impacts of pedestrian speed on signalized intersections under different lane group combinations, median widths, volumes on major and minor streets, and pedestrian pushbutton horizontal offsets. The idea originated from the reduction of pedestrian walking speed used for calculating pedestrian intervals. The 2003 MUTCD specified a value of 3.5 ft/sec to calculate the pedestrian clearance time and this speed was reduced to 4.0 ft/sec in the 2009 MUTCD. Moreover, a second method using 3.0 ft/sec to calculate the total pedestrian intervals was added to the 2009 MUTCD. This change is likely to influence the signal-timing plan of entire intersections and to further increase the intersection total delay.

The researcher used one of the most popular simulation software programs, Synchro 7, to simulate various types of intersections under different traffic circumstances and yield a series of datasets to analyze the impacts of the reduction in pedestrian walking speed. The data were analyzed both horizontally and vertically, as explained in Section IV. By comparing the intersection total delay as well as the through-lane group and the approach average delay, the researcher analyzed their differences mathematically as well as practically.

In this chapter, the results and findings of this study are summarized. Subsequently, the limitations of this study are discussed. Recommendations for installing the extended pushbutton to reduce the impact of slower walking speed are made after describing the limitations. Finally, an outline for future research is given.

FINDINGS

The researcher used Synchro 7 to obtain a series of datasets based on the established scenarios. By comparing the delays shown in each scenario, the researcher tried to find regular patterns in traffic delays, as well as the differences in delay values as calculated using the prescribed pedestrian-interval calculation. In this part, all results and findings derived from this study are given.

Vertical Comparison

This comparison of delay difference was made considering a single intersection with a four-phase timing plan. In pace with the increase in volume, the intersection total delay was compared under different pedestrian speeds and the researcher discussed the regular patterns apparent in the data.

According to the datasets, the regular patterns within one intersection under the optimum cycle lengths can be concluded as follows:

- The total delay at an intersection, according to the 2009 MUTCD pedestrian walk-interval calculation, was always equal to or greater than the total delay according to the 2003 MUTCD.
- There is always a major street volume range and a minor street volume range for an intersection. Within these ranges, the total delay difference based on the 2009 MUTCD is larger than the total delay based on the 2003 MUTCD;
- Under the minor street volume range mentioned at the previous point, when the major street volume is kept constant, the total delay (sec/veh) difference may increase as the minor street volume increases from a small value. Subsequently, the total delay difference decreases as the minor volume increases and finally reaches 0.
- When the major street volume increases, the minor street volume range that would lead to total delay differences narrows.
- When the minor street volume increases, the major street volume range that would cause total delay differences narrows.

For a given cycle length, the trends apparent from the intersection total delay differences were clearer than those under the optimum cycle lengths:

- Under a given cycle length, when the major street volume is kept constant, the total delay difference decreases as the minor street volume increases.
- Under a given cycle length, when the minor street volume is kept constant, the total delay difference increases at an exponential growth as the major street volume increases.
- Under the same major and minor street volumes, as the given cycle length increases, the total delay difference decreases at a rate that decreases by degrees.

On the basis of the obtained data, the researcher created two fitting model types to express the patterns apparent in the delay difference data under the optimum cycle lengths and common cycle lengths.

Horizontal Comparison

The horizontal comparison was made with consideration to different intersections and signal timing characteristics. The researcher studied the influence of the major and minor street through lanes, median widths, and pushbutton horizontal offsets. The findings are as follows.

1. As the number of minor street through lanes increases, the volume matrix that could cause delay difference between two studied pedestrian–interval calculation methods becomes bigger. This means that the volume ranges of both the major street and the minor street that could cause the delay difference between two studied pedestrian interval calculation methods are widened.
2. When the studied intersection shows differences only in the number of minor street through lanes, with the same major and minor street volumes, the intersection total delay difference between the two studied pedestrian–interval calculation methods increases as the number of minor street through lanes increases from 0 to 2 in each direction. However, when the number of minor street through lanes reaches 3 in one direction, the

intersection total delay difference decreases under the optimum cycle length. For a given cycle, the total delay difference increases, as the number of minor street through lanes increases from 0 to 3 in one direction.

3. As the number of major street through lanes increases, the volume matrix that could cause the delay difference between two studied pedestrian–interval calculation methods becomes bigger as well, which is similar to what was apparent in the inclusion process of the number of minor street through lanes.
4. When the studied intersection has differences only in terms of the number of major street through lanes, with the same major and minor street volumes, the intersection total delay difference between the two studied pedestrian–interval calculation methods increases as the number of minor street through lanes increases.
5. As the median width increases, the delay difference resulting from the two pedestrian–interval calculation methods increases under both optimum cycle lengths and common cycles.
6. The pedestrian pushbutton horizontal offset length within the standard makes barely any difference on the total delay.

The major street approach delay difference showed a similar trend as the intersection delay difference did; while the minor street approach delay difference showed totally different trend. Such phenomenon indicated that the major street delay lead the change of intersection delay.

LIMITATIONS

The limitations of this study are as follows:

- Only four features were considered herein: median width, lane group, pedestrian walking speeds, and volume. Furthermore, the researcher studied only the condition in which each approach to the intersection contained one left-turning lane and one shared lane (which combines through movement and right-turning movement). The left-turning volume was always kept at 40 veh/h, and the right-turning volume was maintained at 15% of the approach volume in all scenarios. The directional distribution was equal in all scenarios. Other limitations pertaining to roadway construction restrict the applicability of the research results and findings, such as shoulders, bicycle lanes, and the width of the double-yellow line.

- In this study, the protected left turning phase was applied to all scenarios and no overlap was allowed. Therefore, the optimum signal timing plan may not be the “real” optimum signal timing plan.
- Only the fixed-cycle-length signal timing plan was studied herein. However, actuated signal timing plans are becoming increasingly common all over the country. Actuated control may lead to a totally different change trend in the total delay difference.
- All data were generated using the simulation software Synchro 7. The algorithms and data-generation rules of Synchro 7 are likely to induce biases in the results and findings.

RECOMMENDATIONS

The extended pushbutton press function can partially alleviate the hectic traffic condition caused by the modification of pedestrian–interval calculation in the 2009 MUTCD.

If the cycle length of an intersection is able to be optimized, the reduction of pedestrian walking speed based on 2009 MUTCD would not make significant impact on the intersection traffic delay and there is no need to use the extended pushbutton press function to improve the traffic condition. However, if the cycle length of an intersection cannot be changed, the reduction of the pedestrian walking speed would increase its traffic delay significantly in some circumstance. Therefore, the installation of the extended pushbutton press function would improve the traffic condition. The author suggests to use this function when the change of pedestrian walking speed causes more than 5 sec/veh intersection delay difference .

FUTURE RESEARCH

To improve and enhance the findings of this study, further work is needed on the following aspects:

- A greater number of transportation features should be taken into consideration. For example, shoulders, bicycle lanes, and widths of different traffic lines (e.g., white line, double-yellow line) need to be plugged in to study scenarios.
- Lane group type and number of lanes should be extended (e.g., by adding a right turning lane and a shared lane for left turning and through movement, and increasing the number of left-turning lanes, right-turning lanes, or shared lanes).
- Different types of signal-timing plans should be applied to different scenarios. Two phases, three phases, split phases, overlaps, and other signal-phasing modes should be considered in future studies.
- In this research, only Synchro 7 was used for obtaining datasets. Considering the limitations and special algorithms of Synchro 7, biases may have been introduced. In future studies, other simulation software programs should be used for confirming the final results. Furthermore, field data collection is necessary to ensure that the findings are more practical.
- According to the vertical comparison, these two models clearly have the same trends. Based on the lane group and the approach delay difference, the researcher considered that any undulation in the delay difference pattern under the optimum cycle lengths resulted from the impact of the left-turning vehicle delay. The left-turning vehicle delay was not directly

influenced by changes in pedestrian intervals, but changes in pedestrian intervals would influence the optimum cycle length and the splits, and, in turn, the left turning vehicle delay. Therefore, the impact of left turning vehicles on the intersection total delay difference should be studied in the future.

- Finally, this research studied only three different intersection elements: number of through lanes, median width, and pedestrian pushbutton horizontal offset. The intersections considered in this research were simplified. To create a detailed delay difference variation model, a greater number of elements should be studied.

REFERENCES

1. Highway Capacity Manual 2010. ISBN 0-309-06681-6, Transportation Research Board, Washington, D.C, 2010.
2. Manual on Uniform Traffic Control Devices. U.S. Department of Transportation, Federal Highway Administrator, 2009.
3. Manual on Uniform Traffic Control Devices. U.S. Department of Transportation, Federal Highway Administrator, 2003.
4. Federal Register Part Ⅱ. Federal Register, Vol. 74, No. 240, Wednesday, December 16, 2009.
5. Federal Register Part III. , Vol. 73, No. 1, Wednesday, January 2, 2008.
6. Improving Pedestrian Safety at Unsignalized Pedestrian Crossings. TCRP Report 112/NCHRP Report 562, 2006.
7. Trafficware. Planning & Analysis Software. http://www.trafficware.com/products/planninganalysis-software/, Accessed 11/4, 2013.
8. Synchro_China. Synchro. Jan 10th, 2013. http://baike.baidu.com/link?url=HG8quN4Xuxnt-YbxizQssWN8lz2aEqrZJeVzGuDWEClgnGzS6qO8CXrcmg25pH_P9wpbxMEyYevlWYt2sem6ca, Accessed 11/4, 2013.
9. Zhang, Y. Instruction: Traffic Signal Control (PPT), 2013.
10. Synchro Studio 7 User Guide. Trafficware Ltd., Sugar Land, TX, 2009.
11. McGee, S., Hugh, K. Moriarty, K. Eccles, and M. Liu. *Guidelines for Timing Yellow and all-Red Intervals at Signalized Intersections.* NCHRP report 731, Transportation Research Board, Washington, D.C., 2012.
12. National Cooperative Highway Research Program. Guidelines for Accessible Pedestrian Signals. http://www.apsguide.org/chapter4_press.cfm, Accessed 09/12, 2014.