University of Nevada, Reno

Minimizing Signal Transition Impact at Intersections Caused by Pedestrian Crossings

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in
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by

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ABSTRACT

The objective of a signal timing plan is to provide enough green time according to the traffic demands on each approach of the intersection, which includes motorized and non-motorized transportation modes. Pedestrian timing is crucial in the design since this time depends on the length of the crosswalk and typical walking speed of pedestrians, meaning that the minimum pedestrian crossing time is a predetermined value.

There are two scenarios when handling pedestrian timing in a timing plan development process: accommodated or not accommodated. Accommodated pedestrian timing implies that the corresponding phase green is equal to or greater than the WALK and Flashing-Don't-Walk (FDW) intervals of the pedestrian phase. Because pedestrians crossing a major street generally require a longer time, it is not always efficient to accommodate pedestrian timing if the side street vehicular traffic demand is low. However, if pedestrian timing is not accommodated, the signal will go into transition whenever there is a pedestrian call. The major consequence of a signal transition is disruption to signal coordination. The primary objective of this research is to analyze the impact of signal transition on intersection operations and provide recommendations on how to minimize the impact of this transition process.

A good signal coordination timing plan should produce the least traffic delay and number of stops through a corridor. When a transition occurs, signal coordination is disrupted, causing an increased number of stops and traffic delays. This research particularly focused on cases where pedestrian time cannot be accommodated due to constraints on further reducing the main street green times.

Signal controllers by various manufacturers have implemented different transition methods to minimize the transition impact. The focus of this research was on two transition methods within the 900 ATC Series controller by Cubic/Trafficware: Shortway (from 0 to 24%) and Longway (from 0 to 50%). The research question is which method is better depending on the circumstances of each intersection in a corridor? To answer this question, traffic volumes, cycle length, phasing sequence, and other factors must be analyzed along with their impact on transition time and intersection performance. The intersection in Reno at Oddie Boulevard and Silverada Boulevard was used as a case of study in the research.

Virtual controller and hardware-in-the-loop simulation were used for conducting the analysis. The results suggested that the Shortway (Subtract) method had shown shorter transition times compared to the Longway method. Phase sequence had also shown an impact on the transition time, i.e., a shorter transition time occurred when lagging the pedestrian phase. The Longway method resulted in a fewer number of stops than Shortway when the intersection was saturated. Longway also showed to be more effective when there were a high number of pedestrian calls.

DEDICATION

I dedicate this to my mother, Elsa, who has been a constant source of support and encouragement during graduate school and life. I also dedicate this to my friends who have supported me throughout this process.

ACKNOWLEDGEMENTS

First and foremost, I am extremely grateful to my thesis advisor Dr. Zong Tian for his support, advice, and patience through this process. His mentoring through my degree has been very much appreciated and I look forward for the following challenges as I become a Ph.D student.

I want to express my gratitude to Dr. Hao Xu and Dr. Scott Kelly for being part as my advisory committee members.

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CHAPTER 1. INTRODUCTION

1.1 Background

Literature is constantly showing that proper design, operation, and maintenance of traffic signals can lead to economic and social benefits by reducing delay, improving safety, and reducing vehicle emissions and fuel consumption. Overall provide a better quality of life to the users.

Since the first traffic signal implementation in the United States in 1912 for mainly preventing traffic crashes by assigning rights of way, the functions of these systems have greatly changed [1]. In 2006, there were more than 272,000 traffic signals in the United States [2]. They play an important role in the performance of the transportation system. According to the Urban Mobility Report, the average auto commuter spends 54 hours in congestion and wastes 21 gallons of fuel due to congestion for $1,080 in wasted time and fuel [3].

Appropriately designed, located, operated, and maintained traffic signals can provide smooth flow of traffic along streets and highways. This would reduce congestion, increase intersection capacity, improve vehicular mobility, and reduce number of vehicles stops, which would reduce fuel consumption and hazardous emissions [2].

One of the most common factors that increases delay and number of stops in a corridor is transition. Transition can be caused by various events such as emergency vehicle preemption calls, switching signal timing plans during the day, and pedestrian calls where its timing is not accommodated in the vehicle phase. When a signal goes into transition, the coordination of the corridor gets disrupted for a period of time until the signal goes back to coordination.

1.2 Problem statement

One of the factors that affect signal coordination in a corridor is transition. Transition is a period or mode of operation in which signal timing is modified to achieve coordination [4]. When transition occurs, a signal goes out of coordination. Several events can lead to a signal transition: emergency vehicle preemption calls, switching signal timing plans during the day, pedestrian calls where its timing is not accommodated in the vehicle phase, power loss and restoration, and more.

One of the common causes of signal transition regularly discussed among traffic engineers is when pedestrian crossing time is not accommodated in the vehicle phase split of a coordinated timing plan. This is indicated by the sum of Walk and Flashing-Don’t-Walk (FDW) intervals exceeding the relevant phase green interval. A signal transition occurs whenever there is a pedestrian call to this phase.

To avoid a signal transition, the pedestrian crossing time would have to be accommodated but this is not always an option, depending on the circumstances of the intersection or corridor of interest. Whether and when pedestrian crossing time should be accommodated or not has always been an issue facing practicing traffic engineers. The case is mostly related to side street phases where pedestrian crossing time is high while traffic demand is low.

A signal transition would disrupt normal signal coordination; thus, its impact should be minimized. However, the transition impact is related to many factors, including transition algorithms, transition parameters, controller features, and traffic conditions. The purpose of this study is to analyze these parameters and provide recommendations regarding the best way to deal with transition.

1.3 Research objectives

Research related to transition, when caused by a pedestrian call, has been studied briefly, and the results from these studies vary due to the use of different controllers. The objectives of this research aimed to provide valuable information about transition algorithms and features on the Naztec Series 900 ATC controller, which is used in the Reno-Sparks area. Additionally, a better understanding of the various transition elements needs to be achieved, such as phase sequence, transition algorithm, recall modes, number of pedestrian calls, volume-to-capacity ratio level, and amount of non-accommodated time. Recommendations will be provided about the best transition method and parameter values under different conditions to minimize the transition impact.

1.4 Organization of the Thesis

The organization of this thesis is described as follows. The first chapter introduces the background of the study problem, the problem statement, and the objectives of this research. Chapter 2 presents a comprehensive literature review regarding transition modes, causes, and controller features. Chapter 3 documents the research methodology and process. The results and recommendations are summarized in Chapter 4. Finally, Chapter 5 outlines the conclusions and future directions of the research.

CHAPTER 2. LITERATURE REVIEW

Transition can play a significant role in the operation of signal systems, including time-of-day (TOD) operations, traffic-responsive pattern selection (TRPS), adaptive control, emergency preemption, railroad preemption, and transit priority [4]. According to the Signal Timing Manual, transition is the process of either entering into a coordinated timing plan or changing between two plans [1]. This definition is not accurate since several factors play a role in a transition. According to Shelby et al., transition is a period or mode of operation in which signal timing is modified to achieve coordination [4]. Coordination is reached when the coordinated phase displays the green phase according to the offset or predefined cycle schedule. Fully understanding signal transition cannot be solely obtained by literature but through other channels such as reading user manuals, working with controllers, gaining experience from field engineers, and speaking to vendors representatives.

2.1 Transition modes

Signal controllers manufactured by different vendors may have different transition modes. The most common transition modes in the United States are Dwell, Max Dwell, Add, Subtract, and Shortway, as shown in Figure 1. The Dwell transition mode relies on increasing the cycle length, while keeping the controller in the coordinated phase until the desired offset is achieved. Max Dwell corresponds to the Dwell method with one major difference. This difference is summarized by fixing a maximum period of time for the controller to stay in the coordinated phase. Generally, this results in a smoother transition compared to Dwell. Add or Longway transition methods consists of increasing the phases by a fixed percent, inducing a longer cycle length. The Subtract transition method is the opposite of the Add method where it reduces all the phases by a percent inducing a shorter cycle length. However, it ensures that the minimum green of each phase be obtained. The Shortway or Minimax method chooses either Add or Subtract based on whichever achieves a shorter period of time to reach the desired offset [1].

There are several major traffic signal controller manufacturers in the United States. Each contains features that do not necessarily result in the same behavior between controllers or even models depending on the controller software. Shelby et al. [4] created a valuable table (Table 1) through interviewing the vendors of the following controller models: Eagle EPAC300, Econolite ASC2S, Siemens NextPhase, and Naztec Model 980.

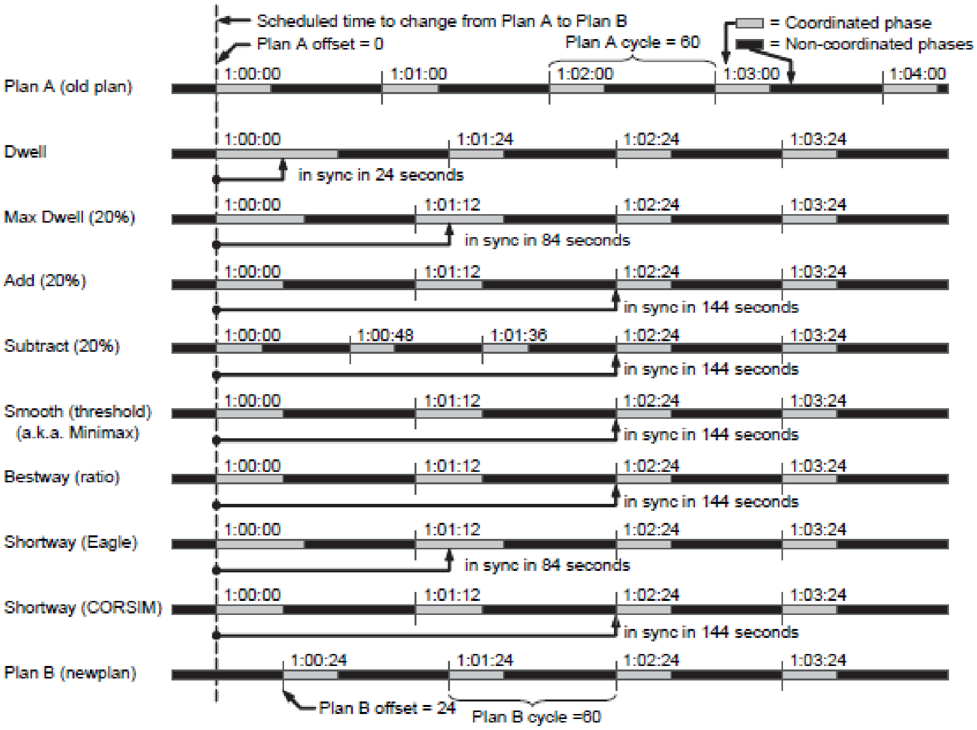


Figure 1. Most common transition modes in the United States [4].

Table 1. Transitions methods available on controllers [4].

Method	Eagle EPAC300	Econolite ASC2S	Siemens NextPhase	Naztec Model 980
Dwell	Dwell (or Infinite Dwell) holds until synchronized.	Dwell holds to sync or set limit per cycle of up to 99% of new cycle length or up to 255 s.	Dwell holds until synchronized.	Dwell holds to sync of set limit per cycle of up to 99 s. Set limits per plan. Set Long and Short to zero.
Max Dwell	Max Dwell (or Dwell with Interrupt) holds to sync of set limit per cycle, ranging from 1 to 999 s. Shortway+ holds to sync or fixed limit per cycle of 18.75%.	Dwell holds to sync or set limit per cycle, ranging from 0% to 99% or 1 to 255 s 0 indicates default value of 20%.	Max Dwell holds to sync or set limit per cycle, defined in seconds, per plan.	Dwell holds to sync or set limit per cycle, ranging from 1 to 99 s. Set limits per plan. Set Long and Short to zero.
Add	Shortway+ adds to sync phases only, as needed, up to fixed limit per cycle of 18.75%.	Add Only adds proportionally to all phases as needed up to fixed limit per cycle of 20% of new cycle length.	Add (formerly Longway) adds to all phases as needed up to specified max transition splits, configurable for each phase, for each plan.	Long (formerly Longway) adds proportionally to all phases as needed up to set limit per cycle, ranging from 1% to 99% of new cycle length. Set limits per plan. Set limit to zero to disable.
Subtract	Subtract is not a directly selectable option, but this approach is selectable by the Shortway method. Subtracts as needed up to 18.75% of cycle, taking from all phases.	Subtract is not a directly selectable option, but this approach is selectable by the Smooth method. Subtracts as needed up to 17% of cycle, taking from all phases.	Subtract (formerly Shortway) shortens as needed down to specified minimum durations from all phases. Set minimum durations per phase, per plan.	Short (formerly Shortway) subtracts from all phases as needed up to set limit per cycle, ranging from 0% to 24% of new cycle length. Set limits per plan. Set Long limit to zero for Short only. Set limit to zero to disable.
Shortway	Shortway selects Add for 0% to 50% adjustment, or otherwise Subtract. If Subtract will take more than 5 cycles owing to minimum phase constraints, then Add transition is used. Shortway2 is similar, but adds to all phases.	Smooth selects Add for 0% to 50% adjustment, or otherwise Subtract. If Subtract correction results in the minimum cycle length or less, Add is used.	Shortest (formerly Bestway) selects between Add and Subtract (as described above) based on which uses fewest cycles to correct, calculated for each method as a ratio of total correction to available correction per cycle.	Short/Long, with both limits set to non-zero, will choose the faster of the two methods, which operate as described above.

2.2 Transition causes and impacts

Signal transition can be caused by a variety of events: preemption by an emergency vehicle, switching between timing plans during the day, non-accommodated pedestrian time, correction to the controller clock, manual operator selection, or power loss and restoration, and more. [1]. The first three causes are explained in more detail in the following section.

2.2.1 Emergency vehicle preemption

An emergency vehicle signal preemption system consists of a signal emitter located on an emergency vehicle, emergency vehicle detectors, or sensors installed on the road or on/near traffic signals, a traffic signal controller, and traffic signal indicators [5], as shown in Figure 2. When an emergency vehicle has to cross an intersection immediately, its emitter sends a preemption signal to the sensors located on the road or on/near traffic signals, which trigger the traffic signal controllers to instruct signal indicators to interrupt normal operation and provide green until the emergency vehicle crosses the intersection [5].

Figure 2. Emergency Vehicle Signal Preemption Example [1].

After an emergency vehicle crosses the intersection, the signal control needs to go back to coordination. The most commonly used transition algorithms for this recovery are Smooth transitioning also known as Shortway, Add only and Dwell [6].

According to a study done by Nelson et al., on a principal arterial with 4 intersections and 7 different preemption paths, they found that a single preemption had a minimal effect on the network; however multiple emergency vehicle preemptions in a short time period had a larger impact on delay and queueing [6]. The Smooth transition algorithm performed the best in most scenarios. The authors pointed out that the impact depends on the intersection spacing, transition algorithm, level of saturation of the intersection, duration of preemption, and amount of slack time available in each intersection's cycle. This study was done by Hardware-in-the-loop simulation using TSIS/CORSIM.

An article written by Yun et al. compared diverse emergency vehicle preemption methods using VISSIM-based Hardware-in-the-loop system and 170E controllers, on a test site of 4 intersections in Chantilly, Virginia. The authors evaluated Shortway and Dwell transition methods with different cycles, and evaluated network-wide performance measures such as throughput (veh), average delay (sec/veh), and average stop (stops/veh). They concluded that Shortway transition method outperforms the Dwell transition [7].

Studies conducted by X. Qin et al. and I. Yun, et al., concluded that a smarter emergency vehicle preemption algorithm using vehicle infrastructure integration technology should be implemented to mitigate the negative effects of preemption [5, 7].

2.2.2 Switching timing plans

Switching between timing plans is another cause of signal transition. These delays are not considered in the process for deciding when to change timing plans in a coordinated system. The time used to adjust the new timing plan is defined as the transition phase. This transition begins when the first intersection starts adjusting timing plans and ends when the last intersection completes adjusting timing plans [8].

K. Balke et al. described several problems when changing timing plans: green displays that are so short that drivers get confused and can potentially cause rear-end crashes, excessive queues on intersection approaches due to extended red intervals, and some approaches becoming “starved” for vehicles due to long red displays upstream of the signal. The authors pointed out that the benefits, when changing timing plans, diminish with the increase in delays caused by transition to the new timing plans [8].

In another study performed by Ross, the best method of transitioning between timing plans was to either extend the main-street green or gradually adjust the offset over multiple cycles by adding or reducing the green of each phase, what is known by some controllers as Shortway method [9].

Studies that evaluate the social cost caused by transitioning between timing plans were performed by R. Peñabaena-Niebles et al. The findings suggested that timing plans that transition very quickly or very slowly were associated with high social costs such as delay and gas emissions [10].

2.2.3 Unaccommodated pedestrian times

Pedestrian time accommodation is a regular discussion when designing signal timing plans on coordinated signal systems. The debate between accommodating or non-accommodating the pedestrian time is constant and there are no guidelines addressing this query.

Pedestrian timing is designed according to the length of the crosswalk and the speed of the pedestrian. The Manual on Uniform Traffic Control Devices (MUTCD) suggests a fixed value for the pedestrian speed equaling to 3.5 ft/s [11]. Because pedestrians crossing a major street generally require a longer time, it is not always efficient to accommodate pedestrian timing if the side street vehicular traffic demand is low. However, if pedestrian timing is not accommodated, the signal will go into transition whenever there is a pedestrian call. The major consequence of a signal transition is disruption to signal coordination.

When designing according to pedestrian minimums, signal coordination can be guaranteed regardless if there is a pedestrian call or not. The pedestrian crossing a side street can be easily accommodated since the splits on the main street are usually larger than the pedestrian minimums. However, pedestrian minimums crossing the main street are often larger than the vehicle demand on the side street. Even though coordination can be achieved using this strategy, early returns on the main street can cause unnecessary vehicle stops at the downstream intersections. Then there is no pedestrian call on the side street, the phase will gap out returning to the main street phases [12].

If the signal timing plan is designed according to the vehicle minimums, phase splits will not necessarily satisfy the pedestrian crossing time. When a pedestrian call is triggered, the vehicle phase will extend past the force-off point, causing the signal to be out of coordination [12].

Z. Tian et al., evaluated the advantages and disadvantages of both possibilities: to accommodate (pedestrian minimum) or non-accommodate the pedestrian timing (side street vehicle demand) [12]. This study used the TRACONEX controller and TRANSYT-7F as modeling software. Side street phasing scheme and max recall feature were considered in the report. The author's suggested that accommodating pedestrian time will likely require a longer cycle length compared to the optimal cycle. Nonetheless, the corridor will remain in coordination, meanwhile non-accommodating the pedestrian time will likely use shorter cycle lengths. Additionally, developing timing plans based on pedestrian minimums must consider the early release effect [12]. Lead/Lag phasing scheme for the side street was suggested by Z. Tian. et al., when designing a timing based on pedestrian minimums, instead of the dual left-turn leading phasing scheme. This was conducted to minimize the effect of using a larger cycle length. The maximum recall feature was suggested to better manage the queue length on an oversaturated arterial when designing for pedestrian minimums. The same operational efficiency was achieved between both scenarios. Accommodating the pedestrian time was recommended when long cycle lengths are required on the system and pedestrian crossing activities are between medium to a high level [12].

2.3 Naztec Series 900 ATC controller

As seen in Table 1, even though many controllers can base their algorithm on the same general principles, they do not necessarily operate the same way. The controller used in this study was Naztec Series 900 ATC, shown in **¡Error! No se encuentra el origen de la referencia.**. The transition methods and features used in this controller are described in this section.

The Subtract algorithm is available for this controller, though it identifies as Shortway algorithm. This method sets the percent reduction for each split time by a value between 0-24%. The controller ensures the split time for each phase during the Shortway transition to be at least the minimum green time. Split times that do not satisfy the minimum green time will cause a failure in the diagnostic step. In this case, the feature “No short phases” must be used in the controller. This excludes a maximum of four phases to be shortened.

When using this method, the controller starts at 0, counts clockwise to add the error (or the amount of difference between offsets), and counts counterclockwise to get back in sync. If there are multiple pedestrian calls or transitions, the controller will keep adding the difference and then keep counting counterclockwise.

On the other hand, the Longway algorithm sets the percent extension for each phase split by a value between 0-50% of each split. This feature does not have constraints similar to the case of Shortway. In this case, the controller counts counterclockwise and starts from the cycle length minus 1. When multiple transitions are being served, the controller will keep counting counterclockwise the number of seconds of error (difference between offsets) until it is in sync.

An important feature to consider is the Stop-in Walk. Stop-in Walk allows a split time of a phase to be less than the minimum pedestrian time without failing the diagnosis. This feature stops the local cycle counter for the time needed to complete the pedestrian phase. The user’s manual recommends using this feature when pedestrians’ actions are infrequent. For this study, Stop-in Walk must be on. When Stop-in Walk is enhanced by Shortway, the offset correction can usually synchronize within one cycle when ped clearance only exceeds between 5-10 seconds of the phase split [13].

Another feature that needs to be considered is the minimum permissive window for pedestrians (MinPerm/P). This feature modifies the permissive window for a pedestrian call to be triggered. Depending on the feature status, on or off, this feature places the pedestrian call accordingly, modifying the time between the local and master clock. The permissive window is determined by two values, pedestrian yield (PedYld) and pedestrian apply (PedApply). The default value for PedYld is the end of green of the coordinated phase and PedApply is calculated in two different ways depending on if this feature is on or off. If MinPerm/P is off, PedApply will be the end of the green for the pedestrian phase minus 5. If MinPerm/P is on, PedApply will be right before the beginning of the pedestrian phase, and it will minimize the pedestrian permissive window. Figure 4 illustrates the MinPerm/P process. The MinPerm/P feature is considered in this study due to its popularity in the Reno-Sparks area.

Figure 3. Naztec Series 900 ATC Controller.

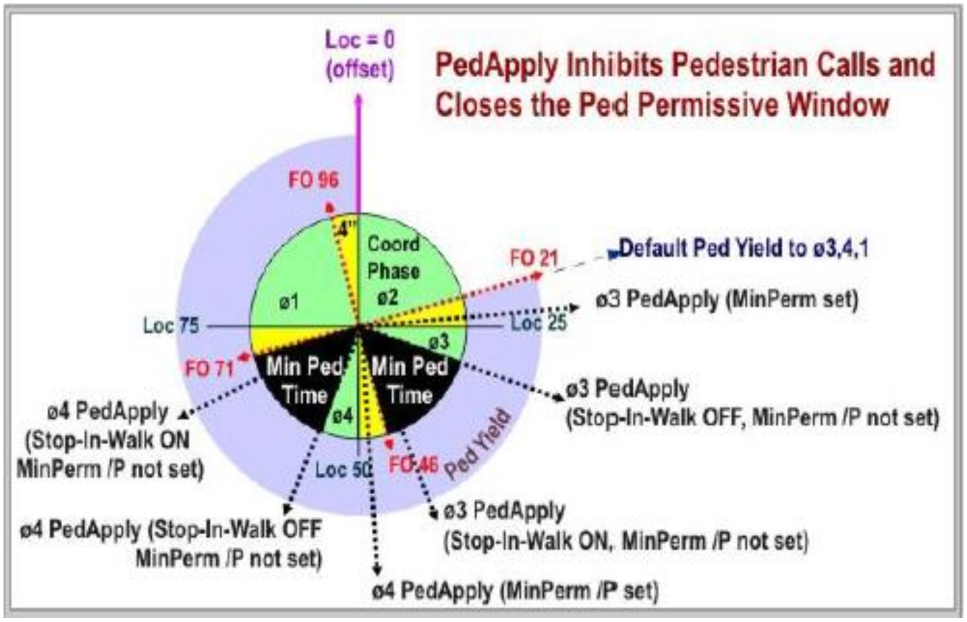


Figure 4. PedApply points [13].

CHAPTER 3. RESEARCH METHODOLOGY

Limited literature is available discussing transitions caused by un-accommodated pedestrian time under different traffic conditions, using hardware-in-the-loop simulation with the 900 ATC Naztec controller. Therefore, this study analyzes one isolated intersection evaluating the operational response under different traffic conditions. This provides a better understanding of the controller when a transition is happening, on a microscale. Three intersections were initially intended to be analyzed, however, limitations were encountered and those are described in Section 3.4 .

3.1 Intersection of study

Oddie Boulevard and Silverada Boulevard in Reno, Nevada (as shown in Figure 5), is analyzed. This intersection has a high number of pedestrian calls throughout the day and is the most saturated intersection along the coordinated arterial segment. The analysis focuses on the PM peak timing plan which had a 100 second system cycle length. The Oddie Boulevard PM timing plan was developed by the author of the thesis in conjunction with the Regional Transportation Commission of Washoe County (RTC).

As it can be seen, the cycle length could not accommodate the pedestrian timing for the southbound direction (i.e., phase 6). This was due to the main street phases that could not be reduced due to high demand, nor the cycle length could be increased since the side street delay would also increase along the corridor. Table 2 shows the timing parameters of the PM peak timing plan.

Table 2. PM Peak signal timing plan for Oddie Blvd/Silverada Blvd.

	Phase Number and Direction							
Time (s)	**1 SBL**	**2 NBT**	**3 WBL**	**4 EBT**	**5 NBL**	**6 SBT**	**7 EBL**	**8 WBT**
Min Green	4	6	4	6	4	6	4	6
Gap, Ext	2	2.5	2	2.5	3	2.5	2	2.5
Max 1	15	25	15	35	15	25	25	35
Yellow	3	3.4	3.2	4.1	3	3.4	3.2	4.1
Red	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Walk	0	0	0	0	0	8	0	0
Ped Clr	0	0	0	0	0	25	0	0
Split	18	28	18	36	16	30	25	29
Ref. Phase				X				

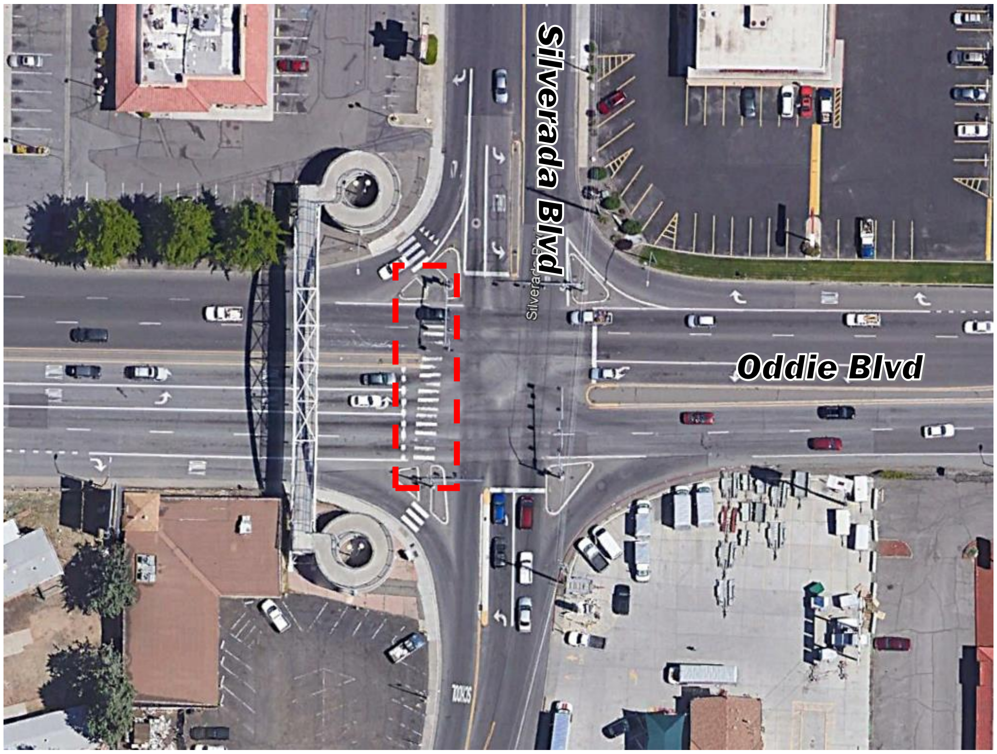


Figure 5. Oddie Blvd and Silverada Blvd intersection.

3.2 Parameters analyzed

Various parameters were analyzed to understand the behavior of the controller under different scenarios. This research limits the study to the ones describe in the following sections.

3.2.1 Phasing sequence

Different phase sequences were analyzed, including lead-lag, lag-lead, lagging, leading, and split phasing for the side street, as shown in Figure 6. Pedestrian calls were placed on phase 6. The phase sequence on the main street was kept constant in the scenarios analyzed.

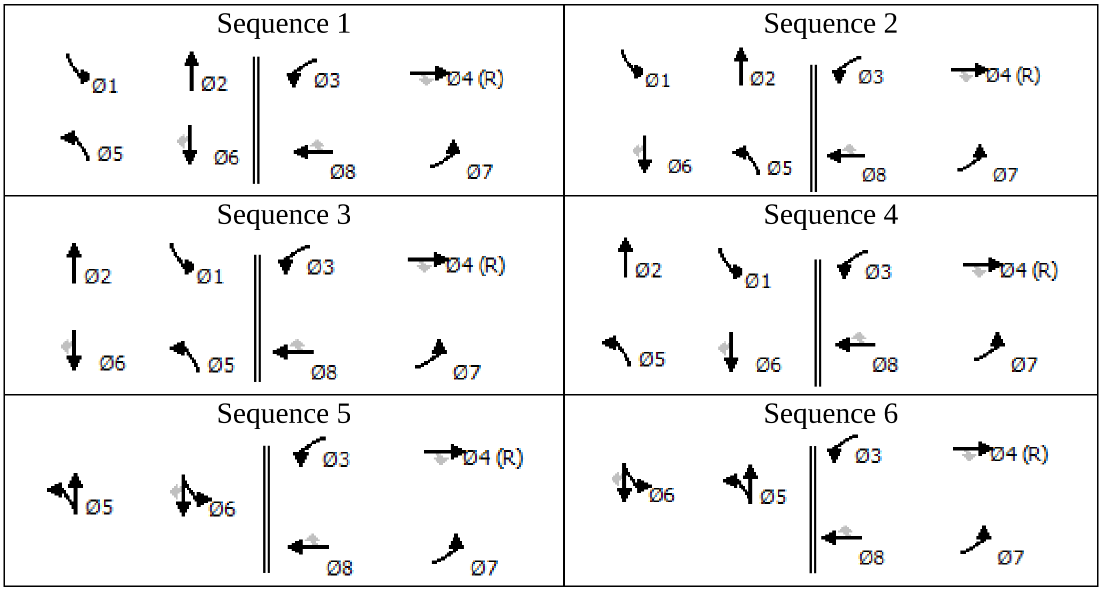


Figure 6. Sequences analyzed in this study.

3.2.2 Transition methods

Naztec Series 900 ATC controllers offer three different transition methods. However, only two were considered in the analysis: Shortway (Subtract) and Longway (Add). The percent values for each method were set as follows: (1) Shortway has 5, 15, and 24%; (2) Longway has 10, 25, and 50%.

3.2.3 Recall modes as traffic demand level

One way traffic demand can be simulated is by setting the recall mode as follows: maximum recall, minimum recall, and none recall. Therefore, three different scenarios were considered: (1) maximum recall for all the phases as an oversaturated intersection, (2) maximum recall for the main street and minimum recall for the side street, and (3) maximum recall for the through movements on the main street and minimum recall for the through movements on the side street, similar to an undersaturated intersection.

3.2.4 Pedestrian calls served per time interval

A different number of pedestrian calls per time interval were tested, including 0, 1, 3, 5, and 10 pedestrian calls per 30-minute interval. The pedestrian calls were placed manually and randomly through the controller's screen.

3.2.5 Volume-to-capacity ratio (V/C)

Traffic demand levels, defined by the volume-to-capacity ratio at the intersection were simulated using Synchro to investigate the transition behavior. As shown in Table 3, two different volume-to-capacity ratios were considered: 0.87 as a near-saturated conditions and 0.58 as a undersaturated conditions.

Table 3. Vehicle volumes and V/C ratio of the analyzed intersection.

	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Vol.	261	830	162	70	549	40	105	114	66	90	110	141
V/C	0.41	0.87	0.29	0.32	0.70	0.08	0.58	0.46		0.42	0.28	0.28
V/C = 0.87												
Vol.	150	550	95	40	350	20	45	65	20	40	45	60
V/C	0.23	0.58	0.18	0.18	0.44	0.04	0.25	0.22		0.19	0.11	0.12
V/C = 0.58												

3.2.6 Non-accommodated pedestrian time

Three non-accommodated pedestrian times were analyzed to provide a better understanding related transition effect in the intersection. Table 4 shows the different times analyzed.

Table 4. Non-Accommodated pedestrian time analyzed.

Vehicle Split (s)	Walk (s)	FDW (s)	Y+AR (s)	Difference (s)
30	8	25	4.9	7.9
	10	25	4.9	9.9
	12	25	4.9	11.9

3.3 Simulation setups

The virtual Naztec Series 900 ATC controller was used to analyze the transition behavior of the intersection. The expected result of this analysis was the duration of transition time. This simulation was not based on vehicle demand, but rather approximated based on recall modes.

Hardware-in-the-loop simulation technology relies on vehicle or pedestrian calls generated by a simulation model, in this case, SimTraffic 11. Vehicle calls are sent from SimTraffic to the Naztec controller through the CID (controller interface device), meanwhile, pedestrian calls are placed through the controller screen. The controller has the signal timing plan(s) of the programmed intersection. The performance measurements such as vehicle delay and stops are generated using the traffic simulation software.

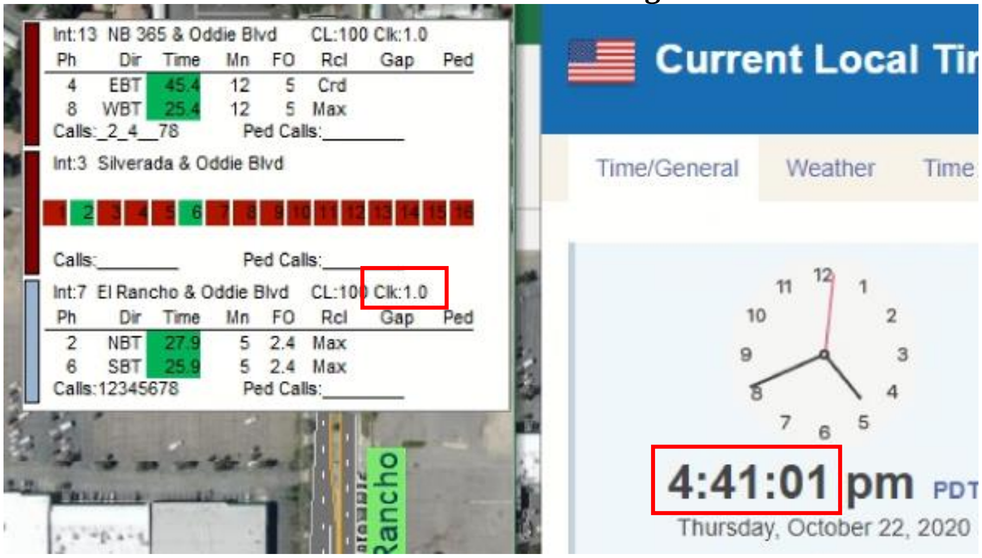
3.4 Limitations

Three intersections were modeled using SimTraffic and the hardware-in-the-loop technology. However, due to the availability of only one CID, only the intersection in the middle was modeled using a real controller, while the two remaining intersections were controlled by SimTraffic.

While conducting the simulation, SimTraffic and the Naztec controller clocks were found to be out of sync. SimTraffic clock was getting behind the controller's clock. This caused the corridor to be out of coordination.

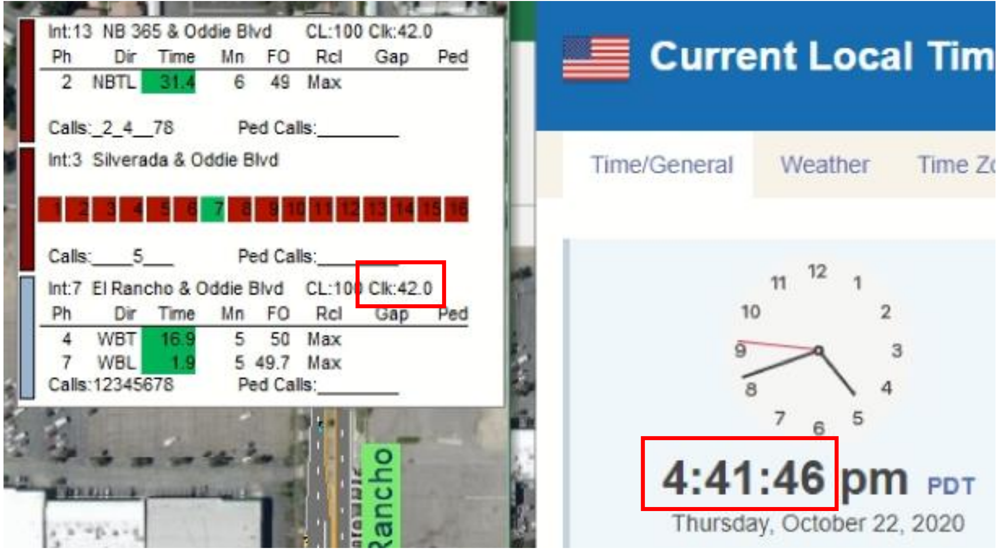
Trafficware Company was contacted about the clock issue but they never responded. This part of the analysis is expected to resume once the research team gets an answer and a solution from the company since it is a merely software problem. Figure 7 illustrates the differences between the clocks. A difference of 4 seconds in the first minute of the simulation was encountered, and this difference was cumulative with time.

SimTraffic Clock: 1 s **Regular Clock: 0:00:01 s**



```
Int:13  NB 365 & Oddie Blvd     CL:100 Clk:1.0
Ph     Dir   Time    Mn   FO    Rcl    Gap    Ped
 4     EBT   45.4    12    5    Crd
 8     WBT   25.4    12    5    Max
Calls:_2_4__78          Ped Calls:________
Int:3  Silverada & Oddie Blvd
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Calls:________          Ped Calls:________
Int:7  El Rancho & Oddie Blvd   CL:100 Clk:1.0
Ph     Dir   Time    Mn   FO    Rcl    Gap    Ped
 2     NBT   27.9     5   2.4   Max
 6     SBT   25.9     5   2.4   Max
Calls:12345678          Ped Calls:________
```

SimTraffic Clock: 42 s **Regular Clock: 0:00:46 s**



```
Int:13  NB 365 & Oddie Blvd     CL:100 Clk:42.0
Ph     Dir   Time    Mn   FO    Rcl    Gap    Ped
 2     NBTL  31.4     6   49    Max

Calls:_2_4__78          Ped Calls:________
Int:3  Silverada & Oddie Blvd
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Calls:____5___          Ped Calls:________
Int:7  El Rancho & Oddie Blvd   CL:100 Clk:42.0
Ph     Dir   Time    Mn   FO    Rcl    Gap    Ped
 4     WBT   16.9     5   50    Max
 7     WBL    1.9     5   49.7  Max
Calls:12345678          Ped Calls:________
```

Figure 7. SimTraffic clock mismatch.

CHAPTER 4. RESULTS AND ANALYSIS

This chapter contains the results from various simulations of the controller under different traffic conditions.

4.1 Minimum permissive window for pedestrian (MinPerm/P)

This feature was analyzed by using the virtual controller and assuming Stop-In-Walk on. Sequence 1, shown in Figure 8, was used for this analysis.

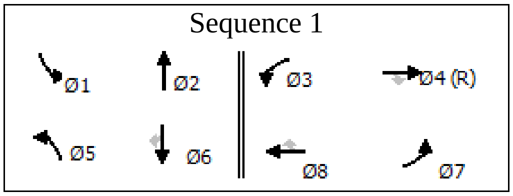


Figure 8. Sequence number 1 analyzed in this study.

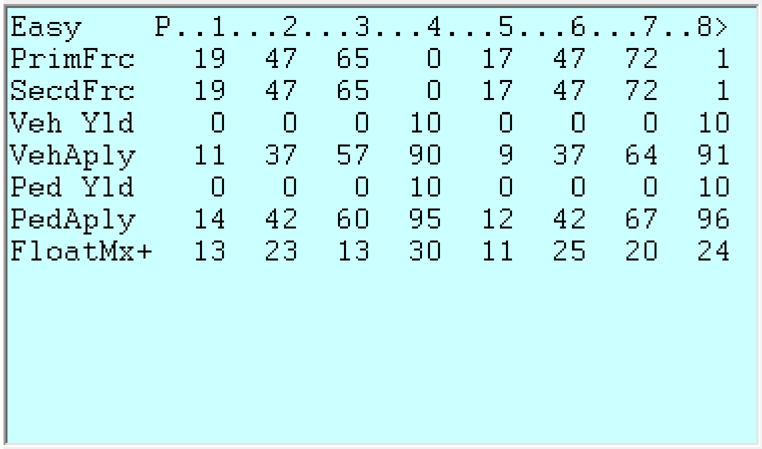
Two parameters define this feature, PedApply and PedYld. PedYld is a default value of the local clock at the end of the green of the coordinated phase. PedApply depends on whether this feature is on or off.

When MinPerm/P is off, PedYld should be 0 and PedApply should be 42 (5 seconds before the force-off point of phase 6 which is 47), as shown in Figure 9. This implies that any pedestrian call placed, within this time window, should be served. At the time this was tested, different outcomes were observed as shown in Table 5.

Table 5. Results for MinPerm/P is off.

Pedestrian call placed at (local clock)	Expected	Real
35	Served	Served
36	Served	Vehicle phase 6 was served with the minimum green but not the pedestrian time.
37	Served	Not served
40	Served	Not served

There were some contradictions encountered with the permissive window. The permissive window coded in the controller was shorter, in this case, for 7 seconds. This means that PedApply was 35 instead of 42. If a pedestrian call was placed at 36, the controller would serve the minimum green for phase 6 instead of the pedestrian phase even if there was no vehicle call placed. There was a maximum difference of 28 seconds between the master clock and the local clock.



```
Easy     P..1...2...3...4...5...6...7..8>
PrimFrc    19  47  65   0  17  47  72   1
SecdFrc    19  47  65   0  17  47  72   1
Veh Yld     0   0   0  10   0   0   0  10
VehAply    11  37  57  90   9  37  64  91
Ped Yld     0   0   0  10   0   0   0  10
PedAply    14  42  60  95  12  42  67  96
FloatMx+   13  23  13  30  11  25  20  24
```

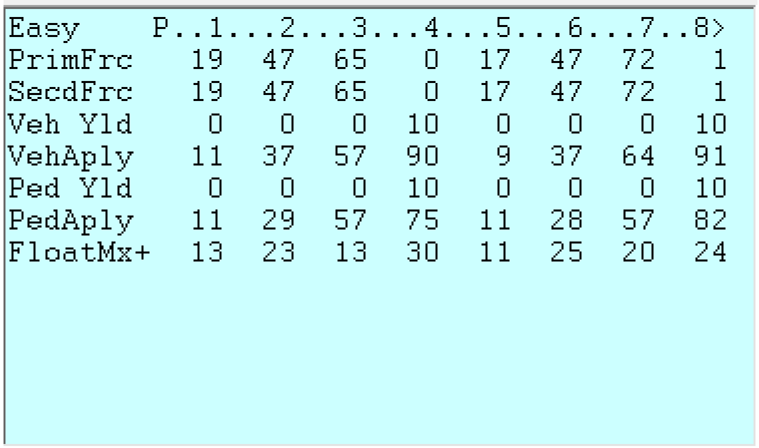
Figure 9. Easy Calculations window when MinPerm/P is off.

When MinPerm/P is on, PedYld should be 0 and PedApply should be 28, according to Figure 10. Following ¡Error! No se encuentra el origen de la referencia., PedApply should be before the beginning of phase 6 (when the local clock was at 21). When this was tested, the following outcomes were observed as shown in Table 6.

Table 6. Results for MinPerm/P is on.

Pedestrian call placed at (local clock)	Expected	Real
21	Served	Served
22	Served	Vehicle phase 6 was served with the minimum green but not the pedestrian time.
36	Not served	Vehicle phase 6 was served with the minimum green but not the pedestrian time.
37	Not served	Not served

For the permissive window, PedApply was coded to be 21 (beginning of phase 6), even though the controller’s screen showed a value of 28. For this case, the maximum difference between the master and local clock was 14 seconds. However, if a pedestrian call was placed between 22 and 36 seconds on the local clock, the minimum green on phase 6 would be served even without placing vehicle calls. This corresponds to an unexpected behavior form the controller.



```
Easy    P..1...2...3...4...5...6...7..8>
PrimFrc   19  47  65   0  17  47  72   1
SecdFrc   19  47  65   0  17  47  72   1
Veh Yld    0   0   0  10   0   0   0  10
VehAply   11  37  57  90   9  37  64  91
Ped Yld    0   0   0  10   0   0   0  10
PedAply   11  29  57  75  11  28  57  82
FloatMx+  13  23  13  30  11  25  20  24
```

Figure 10. Easy Calculations window when MinPerm/P is on.

In conclusion, when MinPerm/P was on, the difference between the master clock and local clock was smaller, which infer that transition should be faster. The values for the permissive window, according to the controller, were not correct. Thus, manual calculations are recommended to figure out the actual permissive window at each intersection. Therefore, the MinPerm/P feature was turned on for the upcoming analysis.

4.2 Phasing sequence

The following results were achieved using the virtual controller. Transition times were obtained from six different phasing sequences and two transition methods. The pedestrian call was placed at the same moment for each scenario to maintain consistency. Transition time was calculated as the time between the controller stopping the local clock and going back to synchronization.

Various transition percents were used in this analysis. For the Shortway method, 5%, 15%, and 24% were used, whereas in the Longway method, 10%, 25%, and 50% were adopted. Table 7 summarizes the result obtained from the simulation. From Appendix A to L, the detailed results for each phase and cycle are illustrated.

Table 7. Transition times according to the sequence, recall modes and transition algorithm.

Transition time (s)						
Seq.	Maximum recall on all the phases					
	Shortway (%)			Longway (%)		
	5	15	24	10	25	50
1	163.96	48.74	34.93	1008.5	463.06	280.83
2	187.99	63.45	40	996.33	458.55	279.72
3	167.78	63.56	39.78	997.18	457.9	278.87
4	164.06	56.06	34.96	1008.3	463.8	280.86
5	164.15	55.97	34.87	1008.3	462.45	281.16
6	187.98	64.03	39.84	996.07	457.97	278.81
Seq.	Maximum recall on Main Street- Minimum recall Side Street					
	Shortway (%)			Longway (%)		
	5	15	24	10	25	50
1	36.03	12.8	8.51	1072.4	489.17	294.4
2	188.18	64	39.97	996.47	457.12	279.45
3	188.16	64.08	39.88	996.07	458.36	279.03
4	36.06	12.59	8.51	1072.5	489.73	294.45
5	35.5	13.18	8.68	1072.7	489.53	294.45
6	187.68	63.71	40.07	995.92	458.09	279.22
Seq.	Max recall on Through movement on Main St.- Min recall Through movement on Side St.					
	Shortway (%)			Longway (%)		
	5	15	24	10	25	50
1	0	0	0	0	0	0
2	188.07	57.12	36.07	1006.6	462.51	281.08
3	167.67	57.14	36.05	1006.5	462.12	281.22
4	0	0	0	0	0	0
5	36.04	12.9	8.65	1072	489.02	294.41
6	187.47	63.87	40.19	996.01	458.17	279.26

There was a big difference between transition times and the transition methods used to get back to coordination. Shortway resulted in shorter transition times. As expected, the higher the transition percentage value, the faster the signal goes back to coordination. Similar behavior was observed for the Longway method.

Sequences 1, 4, and 5 had shorter transition times among the evaluated scenarios, in the three sequences, phase 6 was lagging. Independently of the recall modes that simulates traffic demands, transition time from sequences 2, 3, and 6 had the same duration. However, in the case of sequences 1, 4, and 5, transition time changed in every recall mode scenario. Only sequences 1, 4, and 5, when there was minimum recall or none recall, transition time was shorter or skipped.

The relationship between transition time and transition percentage values fit a logarithmic function as shown in Figure 11 and Figure 12. Using medium-to-high percent values could almost guarantee similar transition times as the maximum percent value and reduce the transition time significantly.

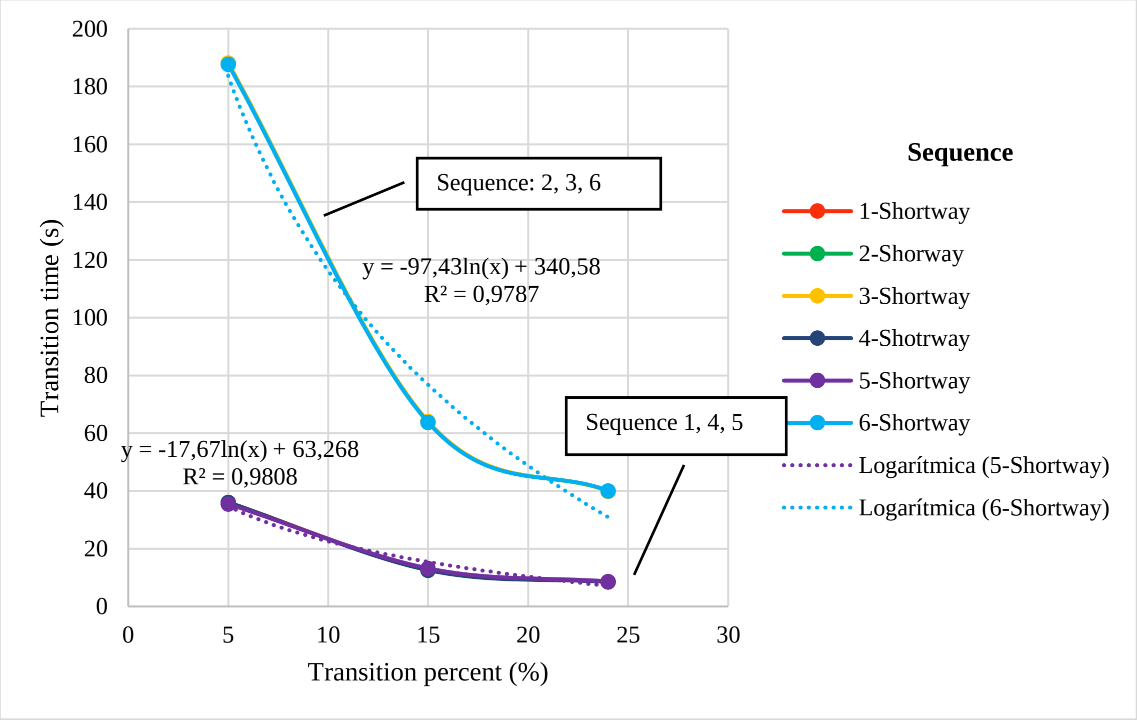


Figure 11. Transition time for Shortway method when max recall was on the main street and min recall was on side street.

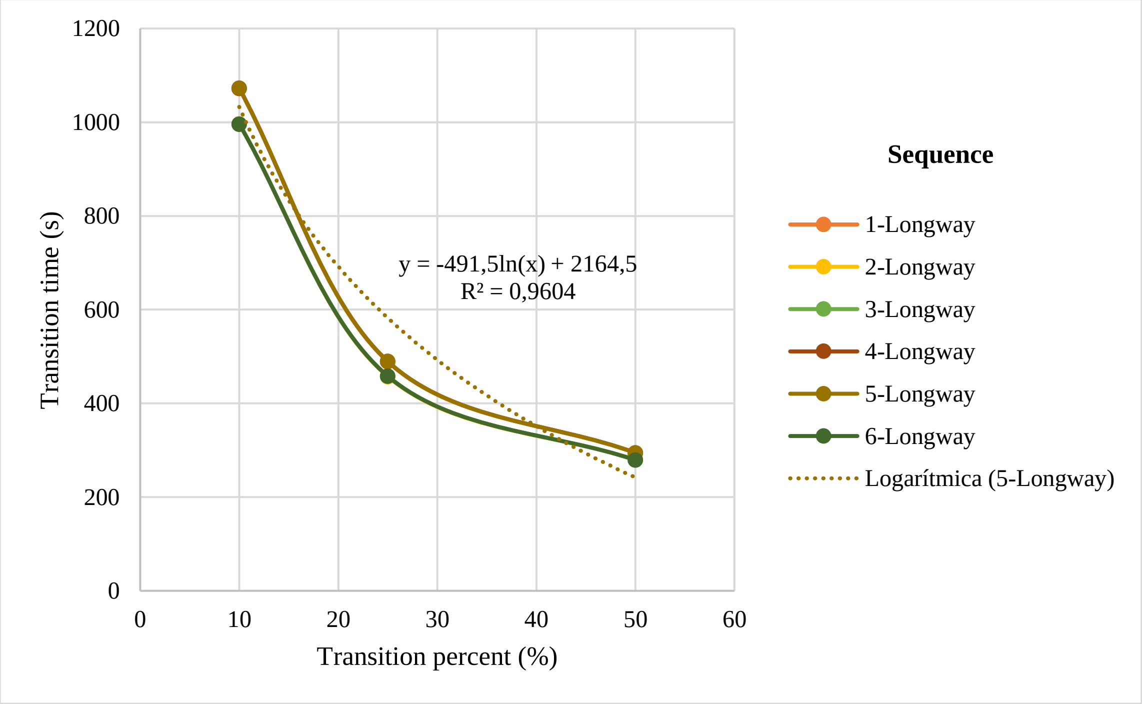


Figure 12. Transition time for Longway method when max recall was on main street and min recall was on side street.

4.3 Pedestrian calls served per time interval and volume-capacity ratio

The number of pedestrian calls per time interval can influence an intersection's performance. This impact could be measured by vehicle delay and stops during the analysis period.

For this analysis, the traffic volume was simulated in SimTraffic 11 with a 30-minute analysis period and with a 10-minute seeding period. The pedestrian calls were simulated by the controller's "Screen Calls" option, and these calls were inputted manually and randomly.

Two different transition scenarios were analyzed, Longway (24%) and Shortway (10%), at two different volume-to-capacity ratios (V/C): 0.87 and 0.58. The V/C ratios represent near saturated, 0.87, and undersaturated, 0.58, conditions. Phase sequence 1 was used for all these simulations. Table 3 shows the volumes by movement and the V/C ratios.

The intersection of Oddie Blvd and Silverada Blvd was analyzed using the hardware-in-the-loop simulation, and the results are presented in Table 8, Table 9, Figure 13, Figure 14, and Figure 15.

Table 8. Delay (veh/s) and number of stops obtained for an intersection with V/C = 0.87.

V/C=0.87	**Delay (s)**		**Total stops**	
Num. ped calls	**Shortway**	**Longway**	**Shortway**	**Longway**
0	20.1	20.1	733	733
1	21.9	22.5	777	778
3	21.4	25.3	744	782
5	24.6	25.6	837	779
10	25.2	26.9	843	766

Table 9. Delay (veh/s) and number of stops obtained for an intersection with V/C = 0.58.

V/C=0.58	Delay (s)		Total stops	
Num. ped calls	Shortway	Longway	Shortway	Longway
0	16.3	16.3	353	353
1	17.7	17.6	364	373
3	17.4	18.7	357	354
5	17.4	19.2	353	366
10	18.6	18.6	378	373

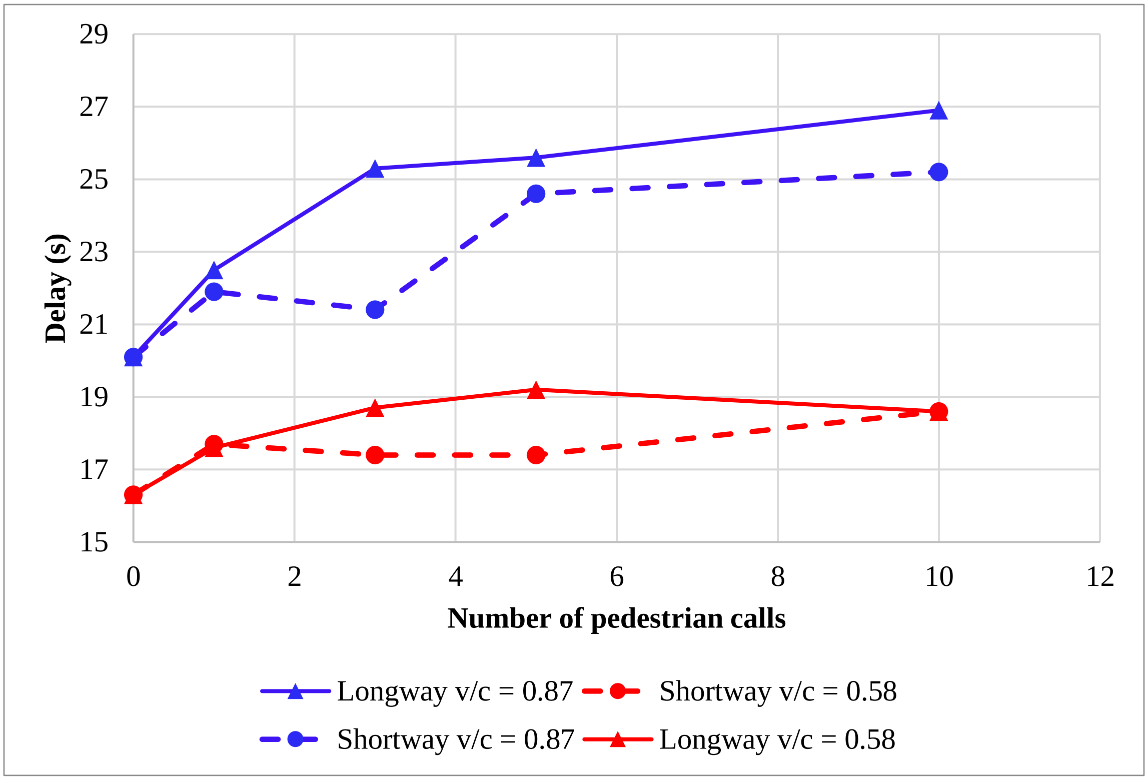


Figure 13. Delay(s) obtained for the intersection.

Table 8 and Table 9 show that the delay increased with the number of pedestrian calls. Same tendency was observed with the number of stops. The Longway method caused a longer delay than the Shortway method. However, for an unsaturated intersection, as shown in Table 8, the differences for the delays between Longway and Shortway were smaller compared to those with the near-saturated cases shown in Table 9.

According to the number of stops, when the number of pedestrian calls was high, the Longway method caused fewer stops than the Shortway method. This outcome is more common in a near-saturated intersection. Additionally, this result indicates that Longway transition method is more beneficial for near-saturated intersections compared to undersaturated intersections.

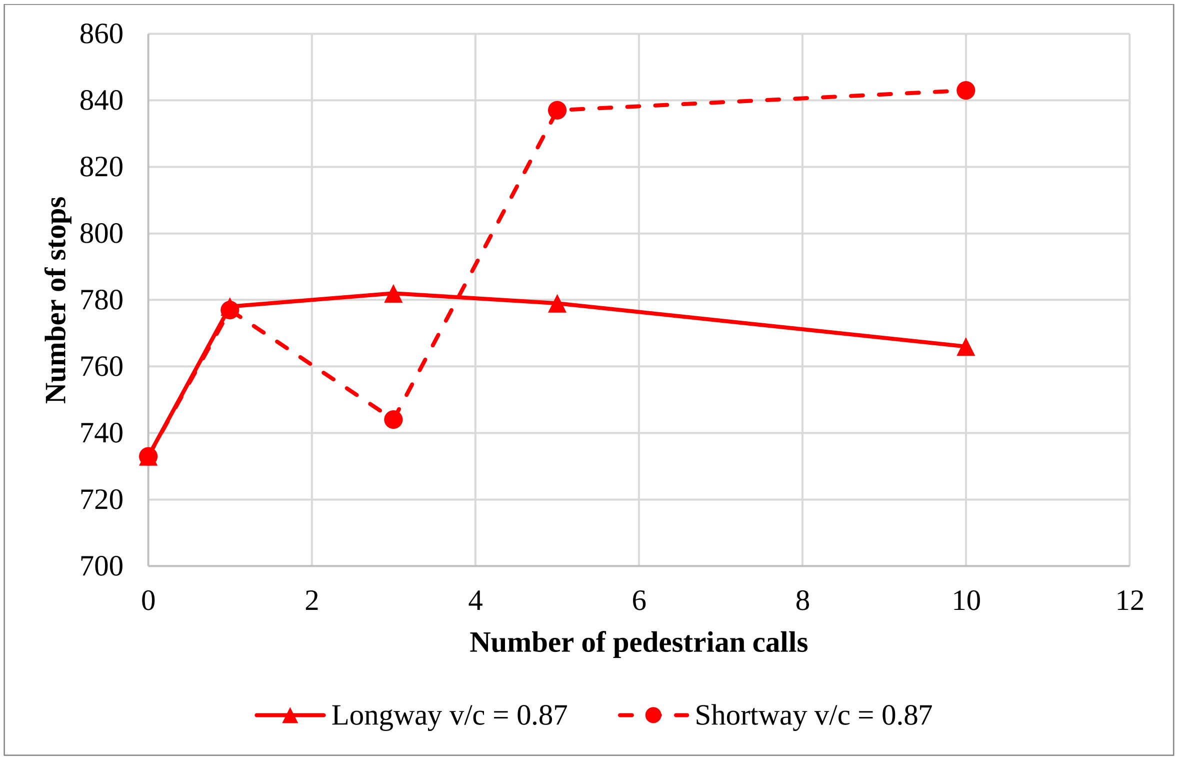


Figure 14. Number of stops for the intersection with V/C = 0.87.

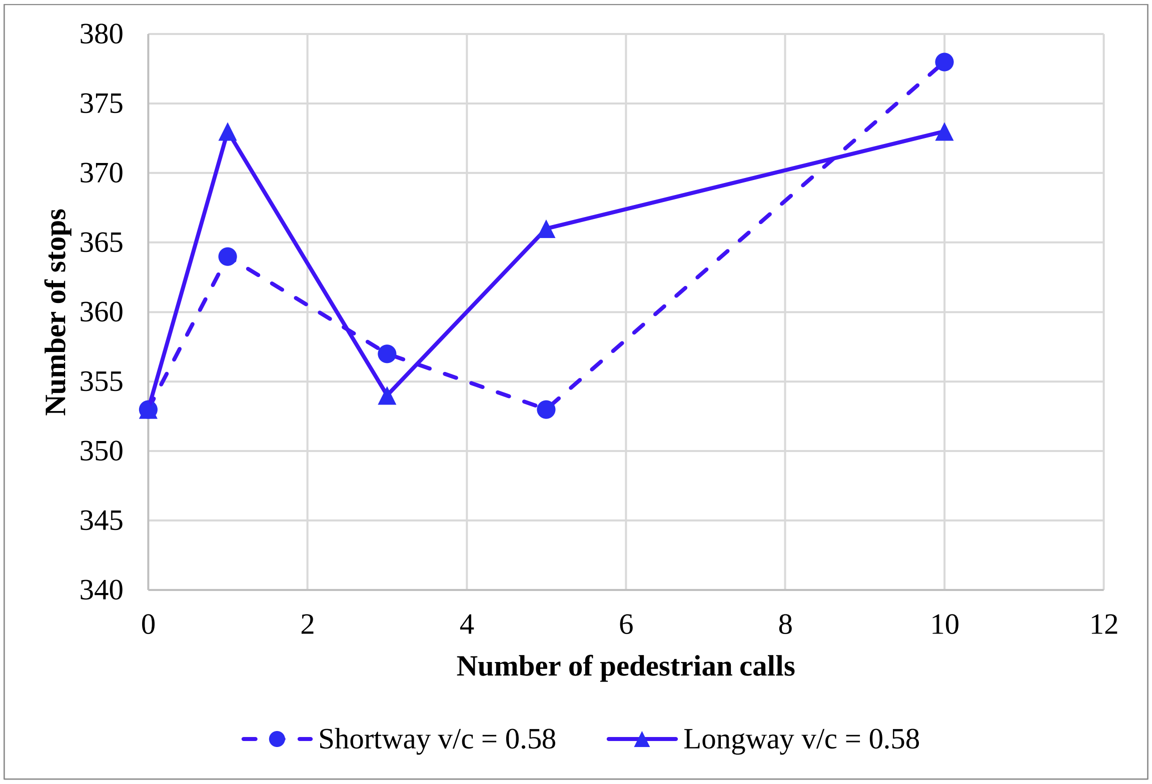


Figure 15. Number of stops for the intersection with V/C = 0.58.

4.4 Non-accommodated pedestrian time

Three different scenarios were simulated, where the non-accommodated times are 7.9 s, 9.9 s, and 11.9 s. For this analysis, a value of 10 % for Shortway and a value of 24 % for Longway were used. 1, 3, 5, and 10 pedestrian calls were served during the simulated period. Delay, number of total stops, and queue length were obtained from each simulation.

From Figure 16, delay results show that there is not a clear relationship between non-accommodated time and the total delay on the intersection. Simulation with the longest difference of non-accommodated time showed smaller delays compared to other scenarios. This outcome was observed for both Shortway and Longway. Therefore, this suggests that transition was done faster in comparison with the other cases.

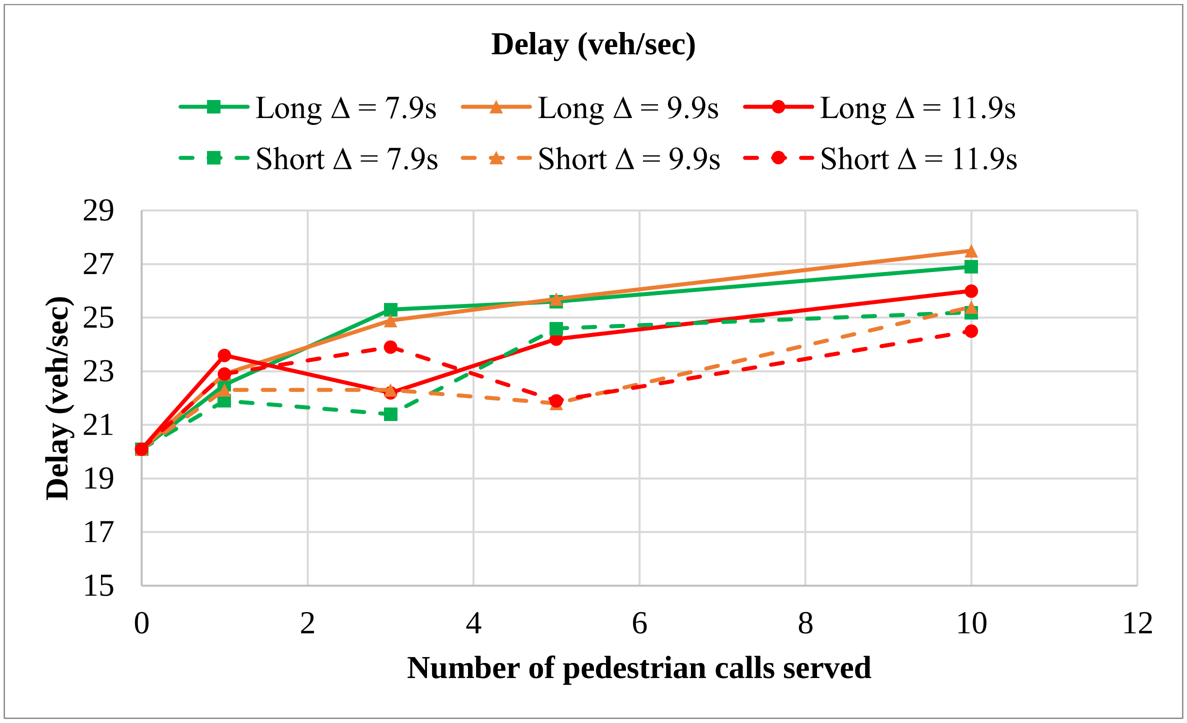


Figure 16. Total delay in the intersection according to number of pedestrian calls served and non-accommodated time.

Analyzing the number of total stops in the intersection, from Figure 17 it was observed that this latter does not show a relationship function of the non-accommodated time. When the non-accommodated pedestrian time is 11.9 s, the graph shows a fewer number of stops for both transition methods.

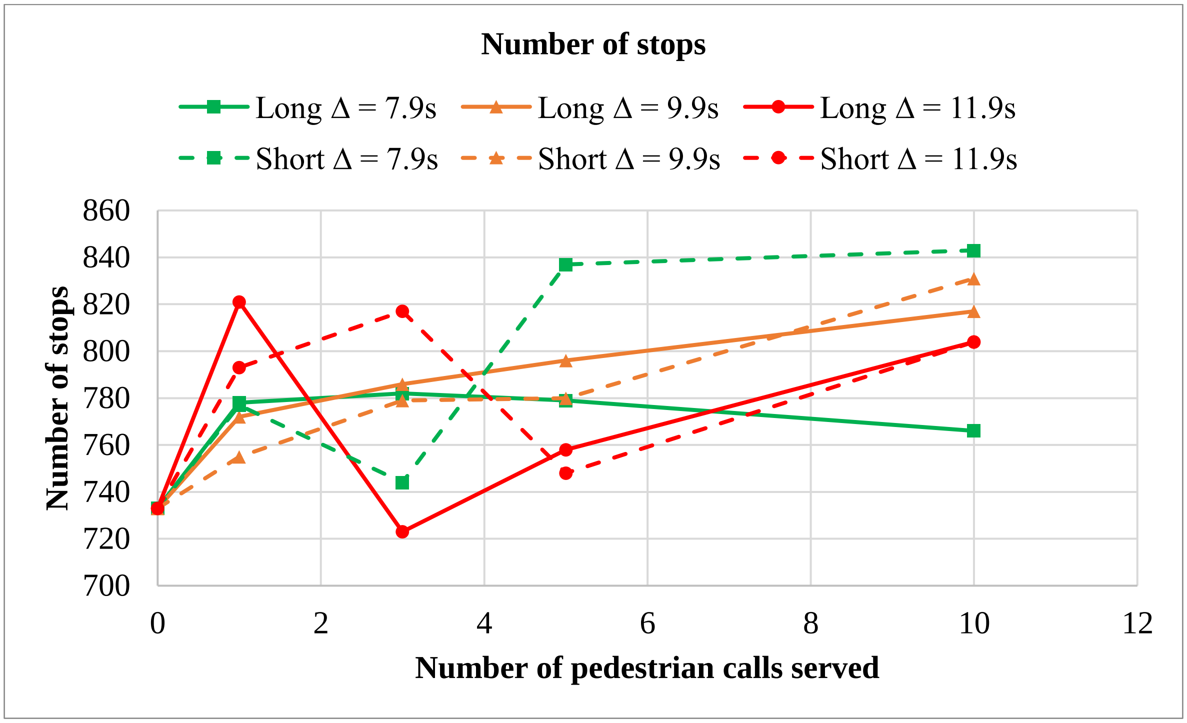


Figure 17. Total number of stops in the intersection according to number of pedestrian calls served and non-accommodated time.

Exploring the queue length on the main street, the results on the westbound remain constant.

However, eastbound results present fluctuations, where the eastbound is the main direction.

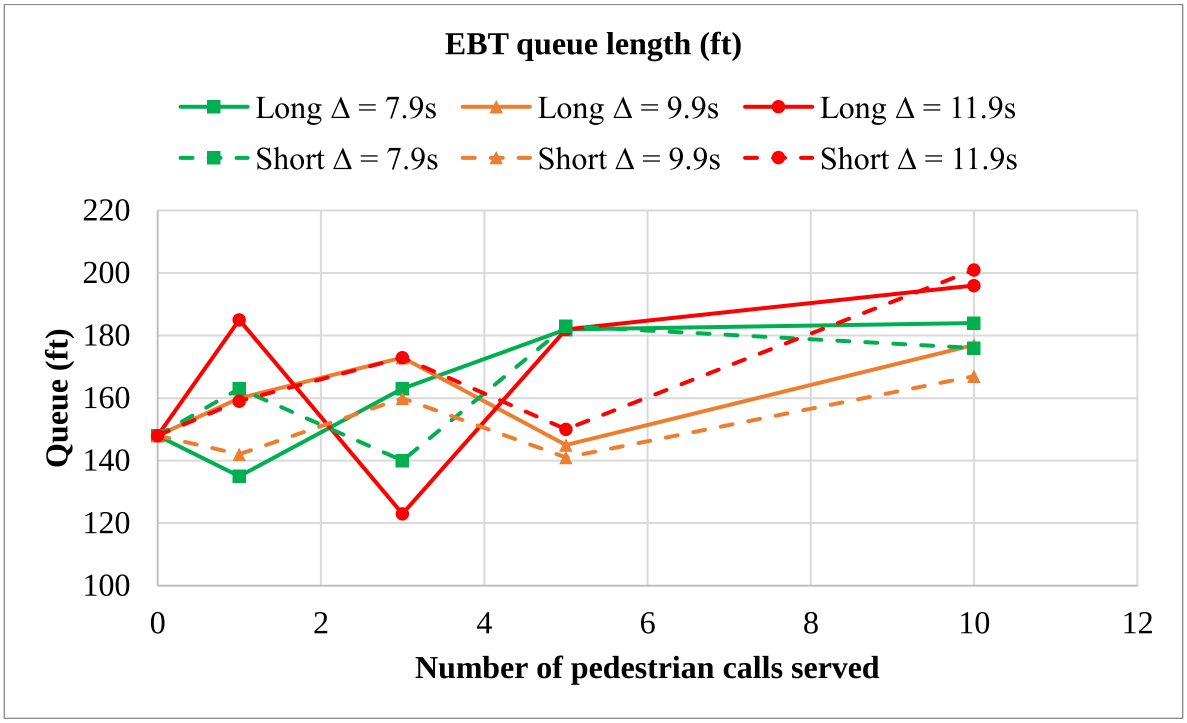


Figure 18. Eastbound through queue length in the intersection according to number of pedestrian calls served and non-accommodated time.

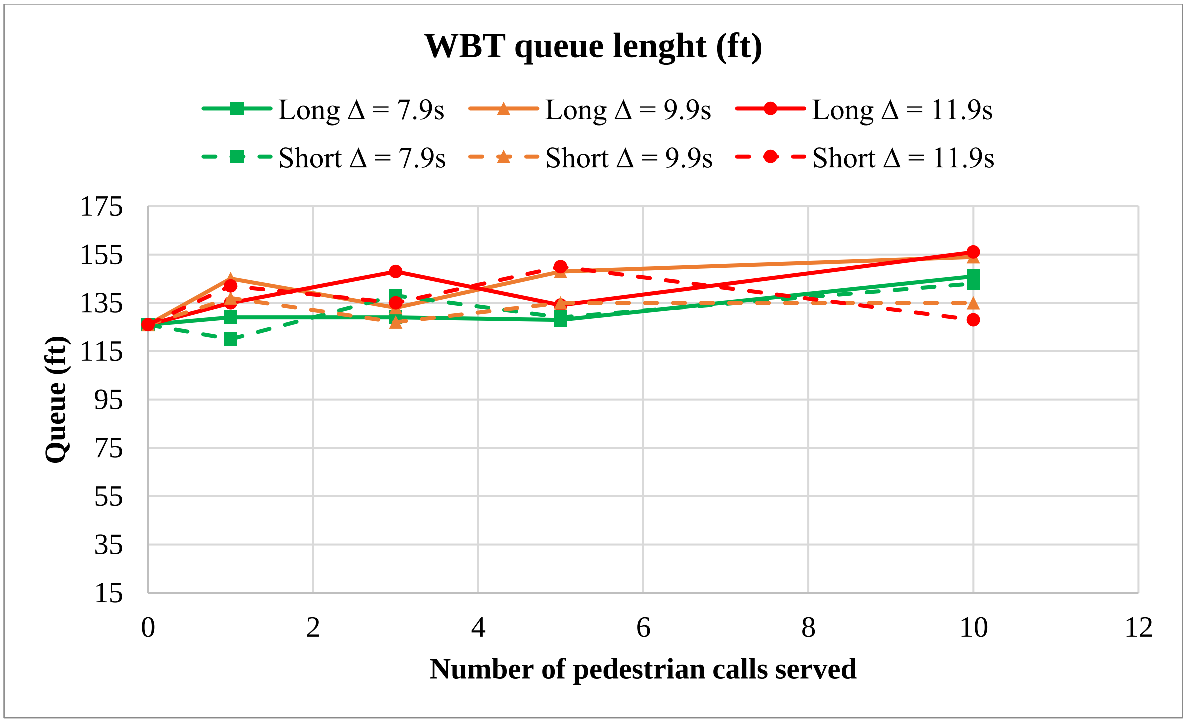


Figure 19. Westbound through queue length in the intersection according to number of pedestrian calls served and non-accommodated time.

In the case of the queue length in the southbound direction, when there are multiple pedestrian calls (in this case more than 3), the Longway method reduces the queue. This conclusion is expected since it extends the phase and potentially clears the queue.

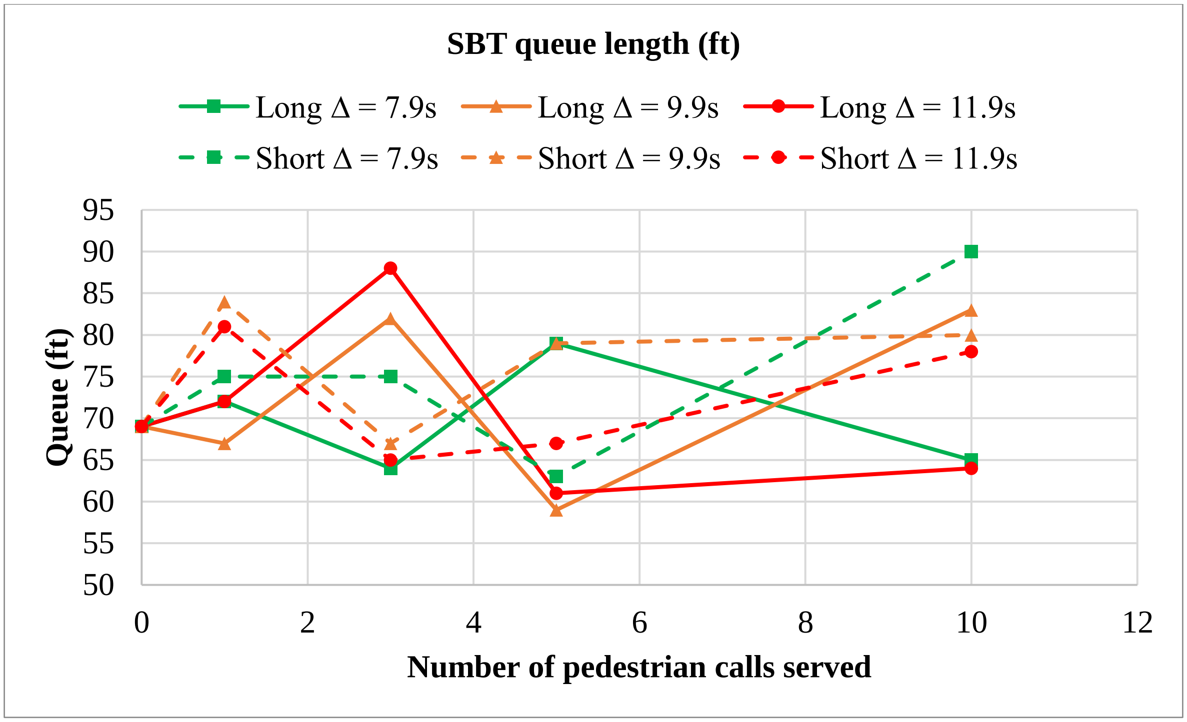


Figure 20. Southbound through queue length in the intersection according to number of pedestrian calls served and non-accommodated time.

After getting multiple results suggesting that longer non-accommodated time tends to have less impact on the intersection, a simulation with both methods at the same time running was performed. It was found that when there are multiple pedestrian calls in a row, the controller will eventually change from the Shortway method to the Longway method, as shown in Figure 21. In this case, after 6 pedestrian calls were placed in a row, around second 450 from Figure 21, the transition mode changes causing the error to be from 24 seconds (Shortway) to 76 seconds (Longway). This happens since the Shortway method accumulates the error (difference between offsets) every time there is a pedestrian call while in transition. Since the controller, while running Shortway, counts counterclockwise, the shortway method is better for sporadic transition.

In the case of Longway, the error is no accumulative, since the controller always counts counterclockwise. If multiple transitions are being triggered, the controller will reduce the error and potentially get back in sync faster.

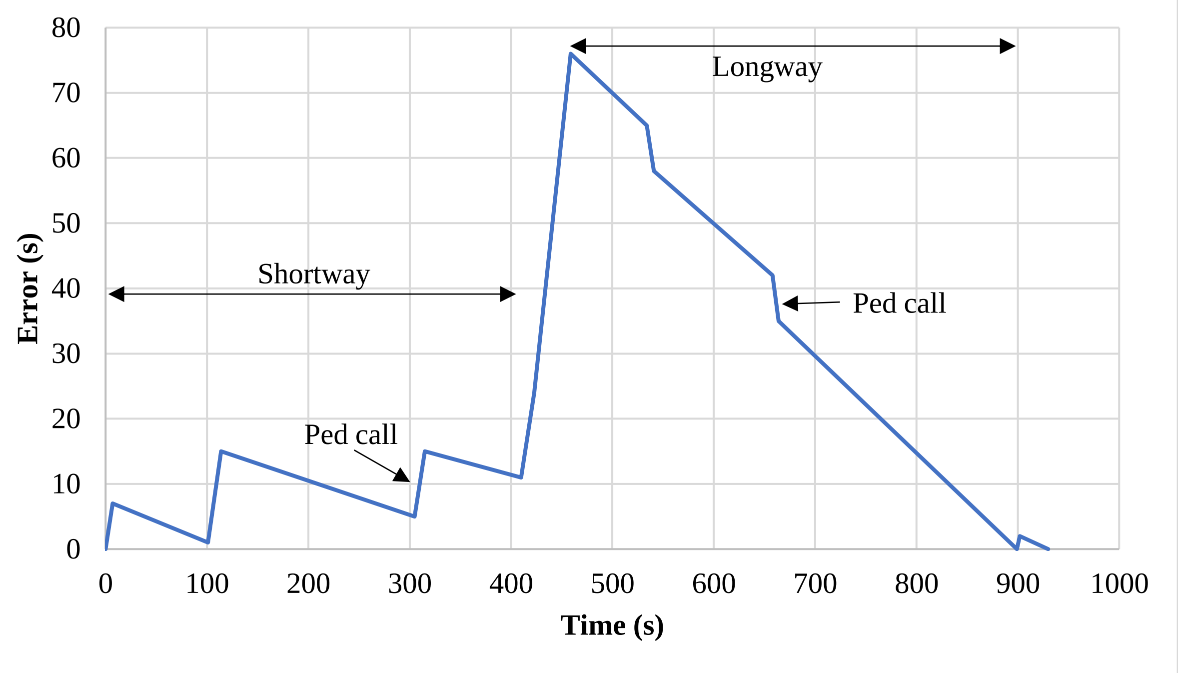


Figure 21. Simulation between Shortway and Longway while pedestrian calls are being generated in a row.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions were made from this study:

- This study investigated two transition algorithms used by Naztec Series 900 ATC controllers: Longway and Shortway. As well as the operational effect at intersections under different scenarios such as phasing sequence, recall modes, volume-to-capacity ratio, number of pedestrian calls served, and non-accommodated pedestrian time.
- Before performing the simulations, two different controller features were addressed for a functional setup. Stop-in-Walk featured was on through the entire simulation to allow transitions to happen without the controller running into failure. The feature minimum permissive window for pedestrians (MinPerm/P) had to be on since that is how the controller is usually programmed in the Reno-Sparks area. With the MinPerm/P feature on, the permissive window for serving a pedestrian call was reduced, resulting in a smaller difference of offsets between the local clock and the master clock. A controller software bug was discovered where the values of the permissive window shown on the controller screen were incorrect. Therefore, it is strongly recommended that the permissive window be calculated manually instead of using the controller values.
- Shortway has shown to have shorter transition times compared with Longway. The relationship between the transition time and the percent values of each method can be represented by a logarithmic function. Using medium-to-high percent values for each method is recommended since similar results compared to using the maximum percent value, which can avoid a drastic change of the phase splits.

- The phase sequence played an important role in the transition time. When the pedestrian phase was lagging, the transition time achieved was shorter. Also, recall modes affected the transition time but only with this particular condition for the phasing sequence. If the left-turn phases were skipped (none recall mode in these phases), the transition time was avoided. If side street usually operates with minimum recall instead of maximum recall, the transition time can reduce considerably.
- According to the manual, when there were infrequent pedestrian calls placed, a signal could get back in sync within one cycle as long as the offset difference was below 10 seconds; however, this study could not produce this outcome. As the early results have indicated that even with a higher Shortway percent value, it could still take up to three cycles to complete the transition.
- There was a difference between undersaturated and saturated intersections regarding signal performance based on the number of pedestrian calls. For undersaturated intersections, the delay and the number of stops were very similar for either Shortway or Longway. For saturated intersections, Longway tended to cause higher delays than Shortway, but Longway provided a fewer number of stops, thus Longway could be potentially better for saturated intersections.
- There was a positive correlation between the number of pedestrian calls and the delay, i.e., the more pedestrian calls, the higher the delay.
- In the case of queue length, there was not a clear relationship between this parameter and non-accommodated pedestrian time for the main street. There was a slight tendency that suggests that the queue length increases if there are multiple pedestrian calls in the main direction. However, this not necessarily occurs when the approach

is less saturated. For southbound, it has an opposite effect than the main street, the larger the non-accommodated time is and the more frequently pedestrian calls are, the smaller the queue length is.

- Using the Longway method is more convenient when there is a high number of pedestrian calls being served since the transition will occur faster and minimize the effects on the intersection.
- This study found out that modeling a network with three intersections using hardware-in-the-loop and SimTraffic 11 is not accurate at the moment when the analysis was conducted. After analyzing carefully of the network's simulation, it was discovered that SimTraffic's clock runs slower than the controller's clock or a regular clock. This resulted in an accumulative error in the offset between the intersections controlled by SimTraffic and by the Naztec controller over the simulation period. If the offsets between the intersections were not fixed and were changing constantly, then the coordination of the corridor would be affected, since the arrivals of the platoon through the intersection would be random. In this situation, the results from the simulation of a network using hardware-in-the-loop and SimTraffic 11 did not reflect a truly coordinated corridor.

5.2 Recommendations

From the present study, the following recommendations where obtained with the purpose to minimize transition impact at intersection.

- Since transition time versus percent value follows a logarithmic function, using medium percent values can obtain similar results instead of using maximum percent. Drastic changes of phase split can be avoided with this recommendation.

- Lagging the pedestrian phase can reduce the transition time. Especially in cases where the side street has low demand, and recall modes are either minimum recall and gap outs or phases are being skipped.
- For undersaturated intersections, either transition method is recommended. It was proven that either transition method provided similar results related to delay or number of vehicles stops, independently of the number of pedestrian calls.
- If an intersection is oversaturated, Longway is recommended to reduce the number of vehicles stops at the intersection.
- If multiple pedestrian calls are present in an intersection that is saturated, Longway method is highly recommended to reduce the transition time.

5.3 Further study

The following is a list of future activities to further enhance this research effort:

- Analyzing more scenarios including different volume-to-capacity ratios would be ideal to better understand the performance of an intersection involving transition.
- Using VISSIM instead of Synchro/SimTraffic in the hardware-in-the-loop simulation may be a better alternative to resolve the clock issues of Synchro/SimTraffic.
- Including cycle length in the analysis of transition impact will provide more insights on how to minimize pedestrian crossing impact in a coordinated system.

References

[1] Federal Highway Administration, Traffic Signal Timing Plan, 2008.

[2] National Transportation Operations Coalition, "National Traffic Signal Report Card," Institute of Transportation Engineers, Washington, DC, 2007.

[3] D. Schrank, B. Eisele and T. Lomax, "2019 Urban Mobility Report," Texas A&M Transportation Institute , Texas, 2019.

[4] S. Shelby, D. Bullock and D. Gettman, "Transition Methods in Traffic Signal Control," *Transportation Research Record: Journal of the Transportation Research Board,* pp. 130-140, 2006.

[5] Q. Xiaolin and K. Ata, "Control strategies of traffic signal timing transition for emergency," 2012.

[6] E. Nelson and D. Bullock, "Impact of Emergency Vehicle Preemption on Signalized Corridor Operation," Transportation Research Board, Washington, D.C., 2000.

[7] I. Yun, B. Park, C. Ki Lee and Y. Tae Oh, "Comparison of Emergency Vehicle Preemption Methods Using a Hardware-in-the-Loop Simulation," KSCE Journal of Civil Engineering, 2011.

[8] K. Balke, K. Rao and M. Husted, "Incorporating the Effects of signal Transition in the Selection of Timing Plans in Traffic Responsive Signal Systems," Texas A&M Transportation Institute, College Station, Texas, 1998.

[9] P. Ross, "An Evaluation of Network Signal Timing Transition Algorithms," *Institute of Transportation Engineers*, vol. 47, no. 9, pp. 17-21, 1977.

[10] R. Peñabaena-Nieble, V. Cantillo and J. Moura, "Impact of transition between signal timing plans in social cost based in delay, fuel consumption and air emissions," *Transportation Research Part D: Transport and Environment*, vol. 41, pp. 445-456, 2015.

[11] United States Federal Highway Administration (FHWA), Manual on Uniform Traffic Control Devices for Streets and Highways, Washington, DC, USA: Federal Highway Administration (FHWA), 2009.

[12] Z. Tian, T. Urbanik, K. Kacir, M. Vandehey and H. Long, "Pedestrian Timing Treatment for Coordinated Signal Systems," Institute of Transportation Engineers (ITE), Washington, DC, 1999.

[13] Trafficware, NTCIP Based TS2 Controllers, Texas, 2019.

APPENDIX A. TRANSITION TIME FOR SEQUENCE ONE UNDER SHORTWAY METHOD

Sequence 1 - Shortway 5 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	17	37	17	35	15	39	25	28	106	106
	2	16	27	17	35	14	29	24	27	95	95
	3	16	28	18	37	14	30	26	29	99	99
Max-Min	1	8	39	17	36	8	39	26	27	100	100
Max T-Min T	0	No transition									
Sequence 1 - Shortway 15 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	17	36	15	32	15	38	23	25	100	100
Max-Min	1	9	39	16	37	9	39	26	27	100	100
Max T-Min T	0	No transition									
Sequence 1 - Shortway 24 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	17	37	14	33	15	39	24	23	100	100
Max-Min	1	8	39	16	37	8	39	25	27	100	100
Max T-Min T	0	No transition									

APPENDIX B. TRANSITION TIME FOR SEQUENCE 1 FOR LONGWAY METHOD

Sequence 1 - Longway 10 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	17	37	20	41	15	39	29	32	114	114
	2	19	31	19	41	16	33	28	32	110	110
	3	19	31	20	40	17	33	28	32	110	110
	4	19	31	20	40	16	33	28	32	110	110
	5	19	31	20	41	17	33	28	32	110	110
	6	19	31	20	41	16	34	28	32	110	110
	7	19	31	20	40	16	33	29	32	110	110
	8	19	31	20	41	16	33	29	32	110	110
	9	19	31	20	41	16	33	28	32	110	110
	10	19	31	19	37	16	33	26	30	106	106
Max-Min	1	8	39	19	41	8	39	29	31	108	108
	2	9	11	50	41	9	11	28	62	110	110
	3	8	11	50	40	8	11	28	62	110	110
	4	8	11	50	40	8	11	28	62	110	110
	5	9	11	50	41	9	11	28	62	110	110
	6	9	11	50	40	9	11	28	62	110	110
	7	9	11	50	40	9	11	28	62	110	110
	8	9	8	53	41	9	8	29	65	110	110
	9	8	11	50	40	8	11	28	62	110	110
	10	9	11	50	41	9	11	29	62	110	110
	11	9	11	46	37	9	11	26	57	102	102
Max T-Min T	0	No transition									
Sequence 1 - Longway 25 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	17	37	22	46	15	39	32	36	122	122
	2	21	35	23	46	19	38	32	36	125	125
	3	21	35	22	46	19	38	33	36	125	125
	4	21	35	22	46	19	38	32	36	125	125
	5	20	28	18	37	18	31	26	29	103	103
Max-Min	1	9	39	22	46	9	39	32	36	116	116
	2	8	11	60	46	8	11	32	74	125	125
	3	8	11	60	46	8	11	32	73	125	125
	4	8	11	60	46	8	11	32	73	125	125
	5	9	11	53	37	9	11	25	65	109	109
Max T-Min T	0	No transition									
Sequence 1 - Longway 50 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	17	37	26	55	15	39	38	43	135	135
	2	26	42	27	55	23	45	39	43	150	150
	3	26	34	18	37	23	37	26	29	115	115
Max-Min	1	8	39	26	55	8	39	38	43	128	128
	2	9	11	76	55	9	11	39	92	150	150
	3	8	11	65	37	8	11	26	76	121	121
Max T-Min T	0	No transition									

APPENDIX C. TRANSITION TIME FOR SEQUENCE 2 FOR SHORTWAY METHOD

Sequence 2 - Shortway 5 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	17	38	17	35	16	39	24	27	106	106
	2	16	27	17	35	15	28	25	27	95	95
	3	16	28	17	37	16	28	26	29	99	99
Max-Min	1	8	39	24	35	9	39	25	34	106	106
	2	8	11	40	35	9	11	25	50	95	95
	3	9	11	42	37	9	11	26	53	99	99
Max T-Min T	1		39		67		39		67	105	105
	2		11		84		11		84	95	95
	3		11		88		11		88	99	99
Sequence 2 - Shortway 15 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	17	36	16	32	14	39	23	25	100	100
	2	17	28	18	37	16	29	26	29	100	100
Max-Min	1	9	39	20	32	9	39	23	29	100	100
Max T-Min T	1		39		62	39		62		101	101
	2		11		89	11		89		99	99
Sequence 2 - Shortway 24 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	17	35	14	35	13	39	26	23	100	100
	2	17	29	18	37	16	29	26	29	100	100
Max-Min	1	8	40	17	35	9	39	26	26	100	100
Max T-Min T	1		39		61	39		61		100	100

APPENDIX D. TRANSITION TIME FOR SEQUENCE 2 FOR LONGWAY METHOD

Sequence 2 - Longway 10 %

Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	17	40	20	41	18	39	29	32	117	117
	2	19	31	20	41	17	33	29	32	110	110
	3	19	31	20	40	18	32	29	32	110	110
	4	19	31	20	41	18	32	29	32	110	110
	5	19	31	20	41	18	32	29	31	110	110
	6	19	31	20	40	18	32	28	32	110	110
	7	19	31	20	40	18	33	28	32	110	110
	8	19	31	20	41	18	32	28	32	110	110
	9	19	31	19	41	18	32	29	31	110	110
	10	19	29	18	37	16	32	26	29	103	103
	11	17	28	18	37	16	29	25	29	100	100
Max-Min	1	8	40	29	41	9	39	29	41	117	117
	2	9	12	49	41	9	11	28	62	110	110
	3	8	11	50	40	9	11	28	62	110	110
	4	8	11	49	40	9	11	28	62	110	110
	5	9	11	50	40	9	11	28	62	110	110
	6	9	11	50	41	9	11	28	62	110	110
	7	8	11	50	41	9	11	29	62	110	110
	8	8	11	50	41	9	11	29	62	111	111
	9	8	11	50	41	9	10	29	62	109	109
	10	8	11	47	37	9	11	26	57	103	103
Max T-Min T	1		39		77	39		77		116	116
	2		11		99	11		99		110	110
	3		11		99	11		99		110	110
	4		11		99	11		99		110	110
	5		11		99	11		99		110	110
	6		11		99	11		99		110	110
	7		11		99	11		99		110	110
	8		11		99	11		99		110	110
	9		11		99	11		99		110	110
	10		11		94	11		94		104	104

Sequence 2 - Longway 25 %

Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	16	42	22	46	20	38	32	36	127	127
	2	21	35	23	46	20	37	32	36	125	125
	3	21	36	22	46	20	37	32	36	125	125
	4	21	35	22	43	20	37	30	36	123	123
	5	17	28	18	37	16	30	26	29	100	100
Max-Min	1	8	39	34	46	9	39	32	47	127	127
	2	9	11	59	46	9	11	32	73	125	125
	3	8	11	59	46	9	11	31	74	125	125
	4	9	11	59	43	9	11	30	73	122	122
Max T-Min T	1		39		87	39		87		126	126
	2		11		114	11		114		125	125

	3		11		114	11		114		125	125
	4		11		113	11		113		124	124
Sequence 2 - Longway 50 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	17	46	27	55	24	39	39	43	144	144
	2	26	42	27	55	24	44	39	43	150	150
	3	22	29	18	37	16	35	26	29	106	106
Max-Min	1	8	39	42	55	9	39	39	58	144	144
	2	9	11	75	55	9	11	38	92	150	150
	3	8	11	49	37	9	11	26	60	105	105
Max T-Min T	1		39		104		39		104	143	143
	2		11		139		11		139	150	150
	3		11		96		11		96	107	107

APPENDIX E. TRANSITION TIME FOR SEQUENCE 3 FOR SHORTWAY METHOD

Sequence 3 - Shortway 5 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	26	28	17	35	15	39	25	28	106	106
	2	17	26	17	38	15	28	28	27	98	98
Max-Min	1	36	11	24	35	8	39	25	34	107	107
	2	8	11	41	35	8	11	25	51	95	95
	3	8	11	42	37	8	11	26	53	99	99
Max T-Min T	1		39		67		39		67	105	105
	2		11		84		11		84	95	95
Sequence 3 - Shortway 15 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	25	27	16	32	14	39	23	25	100	100
Max-Min	1	36	11	21	32	8	39	23	30	100	100
Max T-Min T	1		39		61		39		61	100	100
Sequence 3 - Shortway 24 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	24	27	14	35	12	39	26	24	100	100
Max-Min	1	33	14	18	35	8	39	26	27	100	100
Max T-Min T	1		39		61		39		61	100	100

APPENDIX F. TRANSITION TIME FOR SEQUENCE 3 FOR LONGWAY METHOD

Sequence 3 - Longway 10 %

Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	29	27	20	41	17	39	29	32	117	117
	2	19	30	20	40	17	32	29	32	110	110
	3	19	30	20	40	17	32	29	32	110	110
	4	19	30	20	40	17	32	28	32	110	110
	5	19	30	21	40	17	32	29	32	110	110
	6	20	30	20	41	18	32	29	31	110	110
	7	19	30	20	40	17	32	29	32	110	110
	8	19	30	10	50	17	32	28	32	110	110
	9	19	30	20	40	17	33	28	32	110	110
	10	18	30	19	37	16	32	26	29	103	103
Max-Min	1	36	11	29	41	9	39	29	41	117	117
	2	9	11	50	41	9	11	28	62	110	110
	3	9	11	50	41	9	11	29	62	110	110
	4	8	11	50	41	8	11	29	62	110	110
	5	8	11	50	40	8	11	29	62	110	110
	6	8	11	50	41	8	11	29	62	110	110
	7	9	11	50	41	9	11	29	62	110	110
	8	8	11	50	41	8	11	28	62	110	110
	9	9	11	50	40	9	11	28	62	110	110
	10	8	11	47	37	8	11	26	58	103	103
Max T-Min T	1		39		76		39		76	116	116
	2		11		99		11		99	110	110
	3		11		99		11		99	110	110
	4		11		99		11		99	110	110
	5		11		99		11		99	110	110
	6		11		99		11		99	110	110
	7		11		99		11		99	110	110
	8		11		99		11		99	110	110
	9		11		99		11		99	110	110
	10		11		93		11		93	104	104

Sequence 3 - Longway 25 %

Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	33	25	23	46	20	39	33	36	128	128
	2	22	34	23	46	19	37	32	36	125	125
	3	22	34	23	46	20	37	32	37	125	125
	4	22	34	23	44	20	37	30	36	123	123
Max-Min	1	37	11	34	46	9	39	32	47	127	127
	2	9	11	60	46	9	11	32	73	125	125
	3	9	11	59	46	9	11	32	73	125	125
	4	8	11	60	44	8	11	30	73	123	123
Max T-Min T	1		39		86		39		86	126	126
	2		11		114		11		114	125	125
	3		11		114		11		114	125	125
	4		11		113		11		113	124	124

Sequence 3 - Longway 50 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	35	27	27	55	23	39	38	44	144	144
	2	27	41	27	55	24	44	38	44	150	150
	3	18	33	18	37	16	35	26	29	105	105
Max-Min	1	36	11	42	55	9	39	39	59	145	145
	2	9	11	76	55	9	11	38	92	150	150
	3	8	11	49	37	8	11	26	60	106	106
Max T-Min T	1		39		104		39		104	143	143
	2		11		139		11		139	150	150
	3		11		96		11		96	107	107

APPENDIX G. TRANSITION TIME FOR SEQUENCE 4 FOR SHORTWAY METHOD

Sequence 4 - Shortway 5 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	27	28	17	35	16	39	25	27	107	107
	2	17	26	17	35	14	29	25	27	95	95
	3	18	27	18	37	14	30	26	29	99	99
Max-Min	1	36	11	17	36	9	39	26	28	101	101
Max T-Min T	0	No transition									
Sequence 4 - Shortway 15 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	27	27	15	32	15	38	22	25	101	101
Max-Min	1	11	37	16	36	9	39	27	26	100	100
Max T-Min T	0	No transition									
Sequence 4 - Shortway 24 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	27	27	14	33	15	39	24	22	100	100
Max-Min	1	11	36	16	37	9	39	27	26	100	100
Max T-Min T	0	No transition									

APPENDIX H. TRANSITION TIME FOR SEQUENCE 4 FOR LONGWAY METHOD

Sequence 4 - Longway 10 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	26	28	20	41	18	36	29	32	114	114
	2	20	30	19	41	17	34	28	31	110	110
	3	20	30	20	41	16	33	28	32	110	110
	4	20	30	20	41	16	33	29	32	110	110
	5	20	30	20	41	16	33	29	32	110	110
	6	20	30	20	41	16	33	28	32	110	110
	7	20	31	19	41	17	33	29	31	110	110
	8	20	30	20	41	17	33	29	32	110	110
	9	20	30	19	41	16	34	29	31	110	110
	10	20	30	19	37	17	33	26	30	106	106
Max-Min	1	11	37	20	41	8	39	32	28	108	108
	2	11	9	50	40	8	12	61	29	110	110
	3	11	9	50	40	9	11	62	28	110	110
	4	11	9	50	40	9	11	62	29	110	110
	5	11	9	50	40	8	11	62	28	110	110
	6	11	9	50	40	9	11	62	29	110	110
	7	11	9	50	41	9	11	61	29	110	110
	8	11	9	50	40	9	11	62	28	110	110
	9	11	9	50	40	9	11	62	29	110	110
	10	11	9	50	41	9	11	62	28	110	110
	11	11	9	46	37	9	11	57	26	102	102
Max T-Min T	0	No transition									

Sequence 4 - Longway 25 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	27	27	22	46	15	39	32	36	122	122
	2	23	34	23	46	19	38	32	36	125	125
	3	23	34	22	46	19	38	32	36	125	125
	4	22	34	22	46	19	38	32	36	125	125
	5	18	30	18	37	18	31	26	29	103	103
Max-Min	1	11	37	22	46	9	39	36	32	116	116
	2	11	9	59	46	9	11	73	32	125	125
	3	11	9	59	46	9	11	73	32	125	125
	4	11	9	59	46	8	11	73	32	125	125
	5	11	9	53	37	8	11	64	26	109	109
Max T-Min T	0	No transition									

Sequence 4 - Longway 50 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1	27	27	27	56	15	39	39	43	136	136
	2	27	40	27	55	22	45	38	43	149	149
	3	19	42	18	37	23	37	26	29	115	115
Max-Min	1	36	11	27	55	8	39	39	43	129	129
	2	9	11	76	55	9	11	38	92	150	150
	3	9	11	64	37	8	11	26	75	121	121
Max T-Min T	0	No transition									

APPENDIX I. TRANSITION TIME FOR SEQUENCE 5 FOR SHORTWAY METHOD

<table>
<tr><td colspan="12">Sequence 5 - Shortway 5 %</td></tr>
<tr><td>Scenario</td><td>Cycle</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>Ring 1</td><td>Ring 2</td></tr>
<tr><td rowspan="3">Max-Max</td><td>1</td><td></td><td></td><td>17</td><td>35</td><td>15</td><td>39</td><td>24</td><td>29</td><td>106</td><td>106</td></tr>
<tr><td>2</td><td></td><td></td><td>17</td><td>34</td><td>14</td><td>29</td><td>24</td><td>27</td><td>94</td><td>94</td></tr>
<tr><td>3</td><td></td><td></td><td>18</td><td>37</td><td>16</td><td>30</td><td>24</td><td>30</td><td>100</td><td>100</td></tr>
<tr><td>Max-Min</td><td>1</td><td></td><td></td><td>17</td><td>36</td><td>8</td><td>39</td><td>24</td><td>29</td><td>100</td><td>100</td></tr>
<tr><td>Max T-Min T</td><td>1</td><td></td><td></td><td></td><td>53</td><td>8</td><td>39</td><td></td><td>53</td><td>100</td><td>100</td></tr>
<tr><td colspan="12">Sequence 5 - Shortway 15 %</td></tr>
<tr><td>Scenario</td><td>Cycle</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>Ring 1</td><td>Ring 2</td></tr>
<tr><td rowspan="2">Max-Max</td><td>1</td><td></td><td></td><td>15</td><td>31</td><td>15</td><td>39</td><td>21</td><td>26</td><td>101</td><td>101</td></tr>
<tr><td>2</td><td></td><td></td><td>18</td><td>37</td><td>14</td><td>30</td><td>25</td><td>30</td><td>99</td><td>99</td></tr>
<tr><td>Max-Min</td><td>1</td><td></td><td></td><td>16</td><td>36</td><td>8</td><td>39</td><td>23</td><td>30</td><td>100</td><td>100</td></tr>
<tr><td>Max T-Min T</td><td>1</td><td></td><td></td><td></td><td>53</td><td>9</td><td>39</td><td></td><td>53</td><td>100</td><td>100</td></tr>
<tr><td colspan="12">Sequence 5 - Shortway 24 %</td></tr>
<tr><td>Scenario</td><td>Cycle</td><td>5</td><td>6</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>Ring 1</td><td>Ring 2</td></tr>
<tr><td>Max-Max</td><td>1</td><td></td><td></td><td>14</td><td>33</td><td>15</td><td>38</td><td>19</td><td>27</td><td>100</td><td>100</td></tr>
<tr><td>Max-Min</td><td>1</td><td></td><td></td><td>16</td><td>37</td><td>9</td><td>39</td><td>23</td><td>30</td><td>100</td><td>100</td></tr>
<tr><td>Max T-Min T</td><td>1</td><td></td><td></td><td></td><td>53</td><td>8</td><td>39</td><td></td><td>53</td><td>100</td><td>100</td></tr>
</table>

APPENDIX J. TRANSITION TIME FOR SEQUENCE 5 FOR LONGWAY METHOD

Sequence 5 - Longway 10 %											
Scenario	Cycle	5	6	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1			20	40	15	39	28	32	114	114
	2			20	41	17	33	27	33	110	110
	3			20	40	16	33	27	33	110	110
	4			20	40	16	34	27	33	110	110
	5			20	41	16	33	28	33	110	110
	6			19	40	16	34	27	33	110	110
	7			20	40	16	33	27	33	110	110
	8			20	41	17	33	27	33	110	110
	9			20	41	16	33	27	33	110	110
	10			19	37	17	33	26	30	106	106
Max-Min	1			19	41	8	39	27	33	108	108
	2			50	41	8	11	58	33	110	110
	3			50	41	9	11	59	32	110	110
	4			50	41	8	11	58	33	110	110
	5			50	40	8	11	58	33	110	110
	6			50	40	9	11	58	33	110	110
	7			50	41	8	11	58	33	110	110
	8			50	40	8	11	58	33	110	110
	9			50	41	9	11	58	33	110	110
	10			50	40	8	11	58	33	110	110
	11			46	37	8	11	53	30	103	103
Max T-Min T	1				60	8	39		60	107	107
	2				91	8	11		91	110	110
	3				90	8	11		90	110	110
	4				91	19	1		91	111	111
	5				91	8	11		91	110	110
	6				91	8	11		91	110	110
	7				91	8	11		91	110	110
	8				91	9	11		91	110	110
	9				91	8	11		91	110	110
	10				90	9	11		90	110	110
	11				84	9	10		84	103	103

Sequence 5 - Longway 25 %											
Scenario	Cycle	5	6	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1			22	46	15	39	31	37	122	122
	2			22	46	19	38	31	37	125	125
	3			22	46	19	38	31	37	125	125
	4			22	46	19	38	31	37	125	125
	5			18	37	18	31	25	30	103	103
Max-Min	1			22	46	8	39	31	37	115	115
	2			59	46	8	11	68	37	125	125
	3			60	46	9	11	68	37	125	125
	4			60	46	9	11	69	37	125	125
	5			53	37	9	11	60	30	110	110

Max T-Min T	1				69	8	39		69	115	115
	2				106	8	11		106	124	124
	3				106	8	11		106	125	125
	4				106	8	11		106	125	125
	5				90	8	11		90	110	110
Sequence 5 - Longway 50 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1			26	55	15	39	37	44	135	135
	2			27	55	23	45	37	44	150	150
	3			18	37	23	37	25	30	115	115
Max-Min	1			26	55	9	39	37	44	129	129
	2			76	55	8	11	86	44	150	150
	3			65	37	8	11	72	30	121	121
Max T-Min T	1				81	8	39		81	129	129
	2				131	8	11		131	150	150
	3				102	9	11		102	121	121

APPENDIX K. TRANSITION TIME FOR SEQUENCE 6 FOR SHORTWAY METHOD

Sequence 6 - Shortway 5 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1			17	35	15	39	24	28	106	106
	2			17	35	14	28	24	28	95	95
	3			18	37	15	28	25	30	99	99
Max-Min	1			24	35	9	39	31	28	106	106
	2			41	35	8	11	47	29	95	95
	3			42	37	9	11	49	30	98	98
Max T-Min T	1				59	9	39		59	106	106
	2				76	9	11		76	95	95
	3				79	8	11		79	98	98
Sequence 6 - Shortway 15 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max				15	33	14	39	21	27	100	100
Max-Min				20	33	8	39	26	27	100	100
Max T-Min T					53	8	39		53	100	100
Sequence 6 - Shortway 24 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max				13	35	13	39	19	29	100	100
Max-Min				18	35	8	39	23	30	100	100
Max T-Min T					53	9	39		53	100	100

APPENDIX L. TRANSITION TIME FOR SEQUENCE 6 FOR LONGWAY METHOD

Sequence 6 - Longway 10 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1			20	40	17	39	28	33	117	117
	2			20	41	17	32	28	33	110	110
	3			20	41	17	32	28	33	110	110
	4			20	40	17	32	28	33	110	110
	5			20	41	17	32	28	33	110	110
	6			20	41	17	32	28	33	110	110
	7			20	41	17	32	28	33	110	110
	8			20	40	17	32	28	33	110	110
	9			20	41	17	32	28	33	110	110
	10			18	37	16	32	26	30	103	103
Max-Min	1			29	41	8	39	36	33	117	117
	2			50	40	8	11	58	33	110	110
	3			50	41	9	11	58	33	110	110
	4			50	40	8	11	58	33	110	110
	5			50	40	8	11	58	33	110	110
	6			50	40	9	11	58	33	110	110
	7			50	41	9	11	58	33	110	110
	8			51	40	9	11	58	33	110	110
	9			50	40	9	11	58	33	110	110
	10			47	37	9	11	54	30	103	103
Max T-Min T	1				69	9	39		69	117	117
	2				91	8	11		91	110	110
	3				91	9	11		91	110	110
	4				91	8	11		91	110	110
	5				91	8	11		91	110	110
	6				91	9	11		91	110	110
	7				90	9	11		90	110	110
	8				91	8	11		91	110	110
	9				91	8	11		91	110	110
	10				84	9	11		84	104	104
Sequence 6 - Longway 25 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1			23	46	20	39	31	37	127	127
	2			23	46	20	37	31	37	125	125
	3			23	46	20	37	31	37	125	125
	4			22	43	20	37	32	34	122	122
Max-Min	1			34	46	8	39	43	37	127	127
	2			60	46	8	11	69	37	125	125
	3			60	46	9	11	68	37	125	125
	4			60	44	8	11	69	35	123	123
Max T-Min T	1				80	9	39		80	127	127
	2				106	9	11		106	125	125
	3				106	9	11		106	125	125
	4				103	9	11		103	123	123

Sequence 6 - Longway 50 %											
Scenario	Cycle	1	2	3	4	5	6	7	8	Ring 1	Ring 2
Max-Max	1			27	55	23	39	38	44	144	144
	2			27	55	23	44	38	44	150	150
	3			18	37	16	35	25	30	106	106
Max-Min	1			42	55	9	39	53	44	144	144
	2			76	55	9	11	86	44	150	150
	3			50	37	8	11	57	30	106	106
Max T-Min T	1				97	9	39		97	144	144
	2				131	9	11		131	150	150
	3				86	8	11		86	106	106