University of Nevada, Reno

Pedestrian Crossing Caused Signal Transition Study

A thesis submitted in partial fulfillment
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by

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ABSTRACT

Traffic signal coordination is generally applied to improve traffic efficiency on arterial roads. In traditionally coordinated signal systems, signal transition may reduce traffic operational efficiency, causing extra number of stops on the main-street and extra delay for both the main-street and side-street. One of the most common events that cause signal transition is a signal timing plan without accommodating pedestrian crossing. When a traffic signal timing strategy does not accommodate pedestrian crossing, it allows shorter phase splits than the minimum green time for pedestrians crossing the main street. The crossing street green time is extended to meet the requirement of minimum green for pedestrian when a pedestrian pushes the crossing button. In this case, the signal coordination will be interrupted. It generally takes 1-3 cycles for the signal to go back to coordination after the pedestrian interruption. Previous studies have been focusing on the fundamentals of transition algorithms associated with time-of-day transition and emergency vehicle preemption. However, the transition impact due to un-accommodated pedestrian crossing, which can be minimized by using appropriate transition algorithms, has not been explored thoroughly.

This research first reviews the transition algorithms and summarizes them into three categories. Qualitative analyses are then conducted on how coordination bandwidth and main-street delay are affected by pedestrians under three categories of transition algorithms. The analyses are conducted using the HILS tool based on a real-world arterial. Two types of controllers – Eagle EPAC300 controller and Naztec 981 TS2 controller – are tested in the analyses. The study compares the main-street number of stops and delay under various scenarios, with a wide range of affecting factors, including pedestrian call frequency, V/C ratio, transition algorithm, and phase split difference. The results indicate that the Subtract and Add algorithms perform most efficiently for under-saturated and over-saturated conditions, respectively. The benefit of Subtract transition algorithm is more significant with lower degree of saturation. However, when split difference increased, it was necessary to consider more factors such as traffic volume when choosing an appropriate transition algorithm.

Keywords: Traffic signal transition, Pedestrian crossing, Traffic operations, Hardware-in-the-Loop simulation

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1.1 Background

Traffic signal transition is the process of changing the phasing, timing, offsets or the combinations such factors in a coordinated signal system towards the object signal timing plan. Signal transition may occur after an event such as pedestrian crossing, preemption and time of day (TOD) change. Signal coordination will be disrupted during signal transition period and negative impacts may be imposed on signal system operations. This thesis focuses on the signal transition caused by pedestrian crossing.

Minimum pedestrian crossing time at side-street can be either accommodated or unaccommodated by vehicle green time. Accommodated pedestrian crossing means that side-street split time will be greater than pedestrian-minimum-crossing time no matter how much the side-street demand is. Un-accommodated pedestrian crossing is a signal timing strategy which allows traffic signals to run a shorter split time than pedestrian-minimum-crossing time on side-street due to low traffic demand. The pedestrian-minimum-crossing time will be given only when a pedestrian pushes the crossing button. For accommodated pedestrian crossing, signal transition can be avoided. However, it potentially makes signal operation inefficient when both vehicle and pedestrian volumes on side-street are low. Drivers who stop on main-street may feel frustrated and complain about the traffic operation when they wait for a long time seeing neither pedestrians nor vehicles crossing side-street. This strategy should only be applied at intersections which pedestrians are sufficiently highly.

Un-accommodated pedestrian crossing is a common signal timing strategy at coordinated intersections. Side-street green times are assigned based on traffic demand instead of pedestrian crossing time. Traffic runs smoothly when no pedestrian appears. Only when a pedestrian pushes the crossing button, the minimum pedestrian crossing time will be provided for pedestrians' safety, and this causes traffic signal out of coordination. With appropriate configurations in the controller, the signal can get back to coordination in about two cycles. However, selecting inappropriate transition algorithms and parameters may cause traffic signal to run in transition all the time. For different agencies, different default settings may be applied based on engineer judgement. Due to limited existing study, it's difficult to evaluate which transition algorithm operates most efficiently for pedestrian caused signal transition.

In different cities in North America, pedestrian volume varies a lot from intersection to intersection. Pedestrian crossing caused signal transition is a typical problem in both metropolitan and rural areas. The signal transition study based on pedestrian crossing is necessary in order to address the most efficient algorithm and parameters for different controllers.

1.2 Literature Review

The pedestrian crossing time implemented at signalized intersections in the U.S. has become longer due to the decrease of assumed pedestrian crossing speed in Manual on Uniform Traffic Control Devices (MUTCD). The assumed pedestrian walking speed used to be 4 feet per second[1]; however, the speed was reduced to 3.5 feet per second in the latest MUTCD version[2]. Un-accommodated pedestrian crossing is a common practice at intersections where pedestrian volumes are low. However, this practice will lead to the event of pedestrian caused signal transition.

The problem of pedestrian crossing caused signal transition was first mentioned by Tian et al[3]. The paper demonstrated the advantages and disadvantages of the two signal timing alternatives: timing to accommodate pedestrians and timing based on vehicle demands. The two alternatives could impact coordination as described by the two phenomena: early phase release and signal going out-of-coordination. Early phase release results in more stops, while signal-going-out-of-coordination disrupts normal progression. The advantages and disadvantages of these two timing strategies were investigated through a real world signal-timing project in Vancouver, Washington. However, more detailed cases and parameters need to be tested in order to find out how pedestrian crossing affects signal coordination.

Signal Transition Algorithms

There are five general signal transition algorithms, which are Dwell, Max Dwell, Add, Subtract and Shortway[4,5]. Dwell transition algorithm, which is also referred to as *Longway* by some manufactures, will cause the controller to rest in the coordinated phases until the new coordination plan is reached by increasing the cycle length. Max Dwell transition algorithm allocates green time to coordinated phase for a specific amount of time every cycle to make transition smoother than Dwell. The Add transition algorithm allows signal controller to change the offset through lengthening the cycle by increasing all phases proportionally to their splits. The amount of time added to the cycle length is typically constrained to a specified percentage of the cycle length of the next signal timing plan. Conversely, the Subtract transition algorithm corrects the offset by shortening all phases, subject to minimum green time and a specified percentage of the cycle length of the new pattern. The Shortway transition algorithm selects either the Add or Subtract algorithm based on which can achieve the transition over a shorter transition period. Some controller manufactures refer to this algorithm as *Smooth*, *Bestway*, and *Minimax*.

Different transition algorithms were tested by former researchers under a variety of situations. Hamilton[6] tested three different transition algorithms including *Shortway*, *Shortway Add Only* and *Infinite Dwell* algorithms in Eagle EPAC300 controller with CORSIM simulation. Offset corrections were tested varying from 10 seconds to 90 seconds. The traffic volume is based on constant volume at 85% capacity at the coordinated phase. *Shortway* algorithm was concluded as the best under for all offset corrections situations. Shelby et al[5] studied different transition algorithms in Eagle, Econolite, NextPhase, and Naztec controller. Their study confirmed *Shortway* algorithm was the most effective in general, but also showed that under congested conditions, *Add* algorithm performed as well or better. Lee and Williams[7] examined two operational situations, i.e. transition into peak and out of peak traffic demands. Although the *Shortway* algorithm showed the best performance for most simulation scenarios, *Max Dwell* and *Dwell* algorithms also had a good performance in terms of average delay of the entire intersection.

While some researchers tried to find the most efficient transition algorithm among existing transition algorithms, other researchers tried to find a more efficient transition algorithm by developing mathematical models. Selekwa and Chiteshe[8] developed a transition procedure based on the quadratic optimization method. The procedure aimed to reduce disutility measures to motorists during the transition period. Optimal control techniques were used to determine the step size and minimum number of stops necessary to complete the transition with minimum disruption to traffic flow. The proposed transition algorithm reduced the queue delay for minor streets in one scenario by an average of 5.88%, compared to the immediate transition algorithm embedded in CORSIM. However, the algorithm slightly increased delay on the main-street by approximately 1.43% compared to CORSIM's immediate algorithm. Lee and Williams[9] presented a non-linear mathematical model that provides constrained delay minimization through incremental and simultaneous adjustments in offset and cycle length during plan transitions. According to the simulation results, the proposed transition algorithm showed overall approximately 18.7% decrease in delay compared to *Shortway* algorithm without pedestrian effect. The proposed transition algorithm showed a notable overall improvement compared to traditional *Shortway* algorithm, however, a thorough test is still needed and the pedestrian effect cannot be neglected. Lu et al[10] proposed two transition algorithms, which were the single-cycle symmetrical adjustment transition algorithm and the N-cycle weighted adjustment transition algorithm.

Compared with traditional transition algorithms, the proposed algorithm better satisfies the control demands of different signal intersections.

Previous studies have been focusing on fundamentals of transition algorithms associated with TOD transition and preemption. Signal transition impact due to un-accommodated pedestrian crossing has not been explored thoroughly in exsiting literature. TOD transitions generally occur as a small number of scheduled events in a day when the signal timing plan changes, and will interrupt signal coordination along the entire arterial. Besides the research on transition algorithms, previous studies of TOD transition has been focused on how to minimize the impact by determining an appropriate time point to start signal transition.

Preemption, as a random event, may interrupt signal coordination at an intersection from any approach and at any time point of a cycle. Existing studies on the impact of preemption are generally based on a single event, and analyzed how different transition algorithms would affect intersection operation. Obenberger and Collura[11] provided a state-of-the-practice assessment of different transition strategies used to exit a preemption control plan and return to the coordinated operation of a signal timing plan. The study shows time required to exit a preemption control plan will vary on the basis of the exit transition strategy selected, when this plan terminates, and where the normal signal timing plan would have been if it had not been preempted. It also pointed out that the availability of transition strategies after preemption control are typically restricted according to different controller manufactures. Obenberger and Collura[12] continue their research using Software-in-the-loop simulation and tested *Dwell*, *Subtract*, *Add* and *Shortway* algorithms after preemption. The research concludes that for the base traffic volume and a 40% increase in traffic volume, the most effective transition strategies are *Shortway* and *Add* or *Dwell* alternatives. The *Shortway* was the most effective transition strategy for a 20% increase in traffic volume. Yun et al[13] on the other hand using Hardware-in-the-loop simulation evaluated preemption caused traffic signal transition on 170E and 2070 ATC traffic controllers. The case study result indicated that: (1) the performance measures varied significantly depending on the preemption transition algorithms; (2) *Shortway* in 170E controller and *Smooth* in the 2070 ATC controller generally outperformed the other transition algorithms; and (3) the use of exit phases-available in the 2070 ATC controller-provided significant benefits over the 170Econtroller. Mussa and Selekwa[14] proposed an algorithm to optimize traffic flow during signal transition period between time-of-day timing changes. The preliminary simulation results that compared the proposed algorithm to transition algorithm embedded in CORSIM showed that it has the potential of reducing queue delay, particularly on side-street approaches.

Compared to TOD and preemption, un-accommodated pedestrian crossings are random but frequent events that can interrupt signal coordination with predictable pattern associated with pedestrian volume. Studies on TOD transitions cannot address the stochastic nature of un-accommodated pedestrian crossing, and research on preemption does not account for the accumulative effect of repeatedly occurred random events. The methods used in previous research are primarily based on software simulation, but hardware controllers in the field may function differently than software. It is of interest to investigate how the characteristics and frequency of pedestrian crossing would impact traffic operation, and how the adverse impact of un-accommodated pedestrian crossing on signal coordination can be minimized by adopting the appropriate transition algorithm in signal controllers operated in the field.

The existing research on traffic signal transition focused on fundamentals of transition algorithms associated with either Time-of-day (TOD) transition or emergency vehicle preemption. To the author’s best knowledge, there has been no research that directly addresses the impact of un-accommodated pedestrian crossing. Thus further study is necessary on pedestrian related signal transition, especially under situations of un-accommodated pedestrian crossing.

Traffic Simulation

As a way of evaluating algorithm performance in the signal operations perspective, simulation can be an alternative especially when a field evaluation is unpredictable and potentially unsafe. The stochastic nature of a pedestrian crossing makes the occurrence time of traffic signal transition unpredictable and difficult to conduct afield evaluation. In this case, traffic simulation can serve as an efficient means to evaluate the impact of signal transition caused by pedestrian crossing.

Existing simulation methodologies can be classified as software-in-the-loop simulation and hardware-in-the-loop simulation. The signal timing embedded in software-in-the-loop simulation is designed by commercial software companies and is not necessarily consistent with real controller algorithms. The flexibility to modify specific controller parameters is also limited. However, hardware-in-the-loop simulation is a way to solve this problem. It makes use of an actual traffic controller to control signal lights in road network and traffic is simulated by software such as CORSIM and VISSIM. In order to build the connection between real controller and simulation software, a controller interface device (CID) is needed. Wells et al[15] at the National Institute for Advanced Transportation Technology (NIATT) in the University of Idaho developed a CID based on a universal serial bus (USB) interface and distributed implementation. This NIATT-CID has discrete interface connectors allowing it to be connected to any controller with a discrete interface such as NEMA TS1, NEMA TS-2, 170, and 2070 controllers.

The methods used in previous research related to traffic signal transition are were based on software-in-the-loop simulation, but hardware controllers in the field may function differently than software. It is of interest to investigate how the characteristics and frequency of pedestrian crossing would impact traffic operation, and how the adverse impact of un-accommodated pedestrian crossing on signal coordination can be minimized by adopting the appropriate transition algorithm in signal controllers operated in the field.

1.3 Research Objectives

The previous research either focused on general signal transition algorithms, emergency vehicle preemption or time of day transition. Pedestrian crossing caused signal transition was documented but few tests were conducted. This research aims to address the signal transition problem caused by un-accommodated pedestrian crossing. It focuses on two aspects: 1) how pedestrian crossing impacts existing coordination; and 2) what is the most efficient transition algorithm and what parameters should be used for the algorithm to allow the signal to get back to coordination.

Different signal transition algorithms and parameters will be tested for Naztec controller and Eagle controller, which are mainly used in Reno-Sparks area. A case study intersection was adopted at ClearAcre Ln/ N McCarran Blvd in Reno, Nevada. National Institute for Advanced Transportation Technology (NIATT) controller interface device (CID) hardware-in-the-loop simulation was used in order to build the connection between Naztec 980 controller and VISSIM simulation.

The organization of this thesis is described as follows. The first chapter introduces the background of the study problem, literature review and research objectives. Chapter 2 summarizes three categories of signal transition algorithms and illustrates how coordination bandwidth and main-street delay will be affected under each category when the transition is caused by un-accommodated pedestrian crossing.. Performances of signal transition algorithms in Naztec and Eagle controllers are tested and summarized in Chapter 3. Some transition issues observed in Naztec controller during the test are also documented. With a case study, Chapter 4 compares main-street number of stops and delay under various scenarios, with a wide range of affecting factors, including pedestrian call frequency, V/C ratio, transition algorithm, and split difference.. Conclusions and recommendations are provided in Chapter 5.

2 Impact of Transition Algorithms on Traffic Signal Coordination

2.1 Categories of Transition Algorithms

Five general transition algorithms are documented in the Traffic Signal Timing Manual (STM): Dwell, Max Dwell, Add, Subtract, and Shortway. These algorithms can be classified into the following three categories:

- **Lengthening the cycle**

The algorithms change the signal timing back to coordination by adding time to a specific split. This category includes Dwell, Max Dwell and Add.

- **Shortening the cycle**

Subtract is the algorithm that changes the signal timing back to coordination by subtracting time from a specific split.

- **Shortway**

Shortway is a combination of the two above mentioned categories. It automatically chooses lengthening or shortening strategy by instantly calculating which way is faster.

2.2 Impact of Transition Algorithms on Coordination Bandwidth and Delay

The following example illustrates how different transition algorithms affect traffic progression. Figure 1 shows a time-space diagram of a normal traffic progression the southbound direction when the signals are coordinated without signal transition.

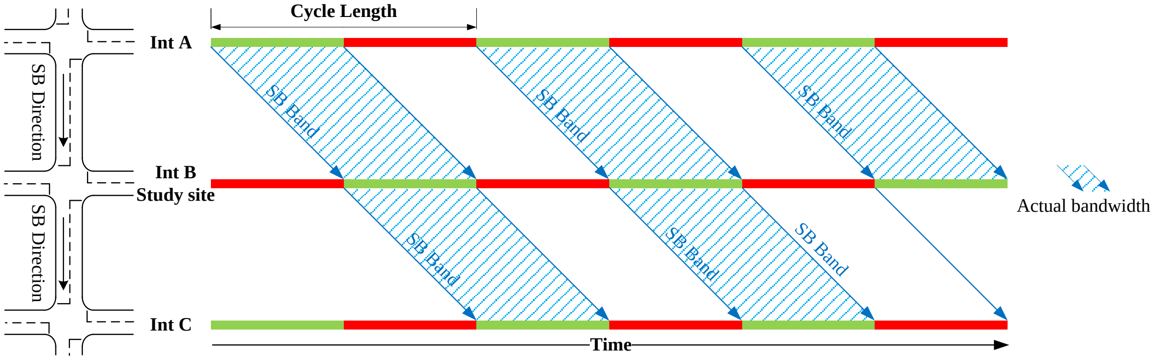

Figure 1 Normal Traffic Progression with Signal Coordination

Intersection B is the study site where the side-street phase split does not accommodate the pedestrian crossing time. When the side-street has a pedestrian demand and the push button is pressed, the side-street green time will be enlarged to ensure the pedestrian(s) having sufficient time to cross the street, as shown in Figure 2.

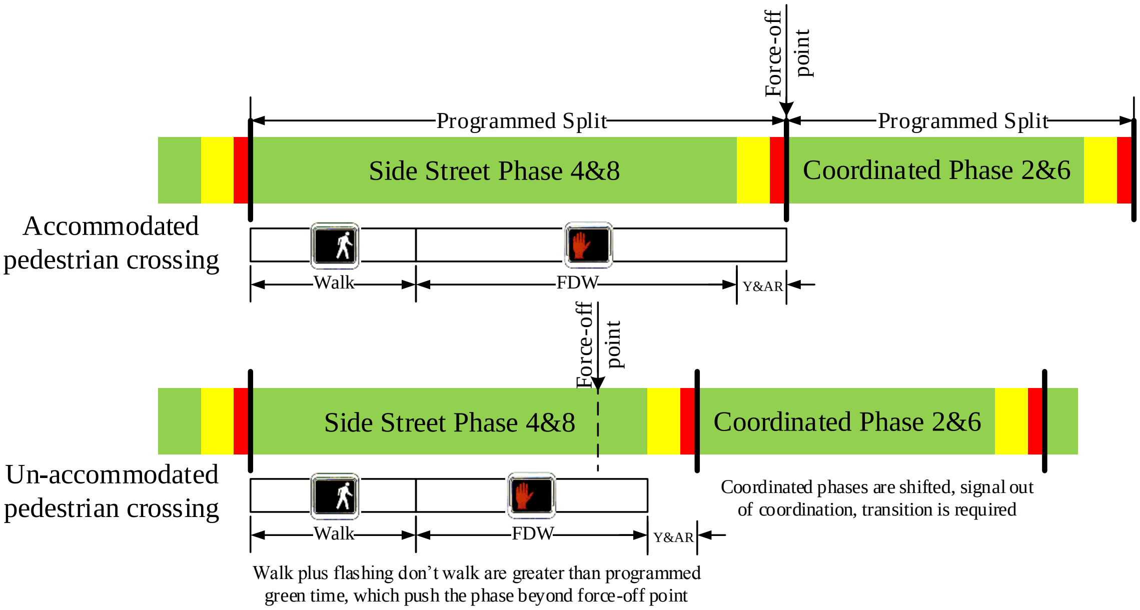

Figure 2 Accommodated and Un-accommodated Pedestrian Crossing

The pedestrian crossing event will push the force-off point behind, causing signal out of coordination. The progression of the arterial will be affected. The closed areas in Figure 3 indicated the total delay for through movement of the arterial. When the signal is running coordination, the delay for through movement is low; however, when a pedestrian crossing event pushes then side-street split R_1 seconds beyond force-off point, the efficiency of coordinated system will be reduced, causing extra delay.

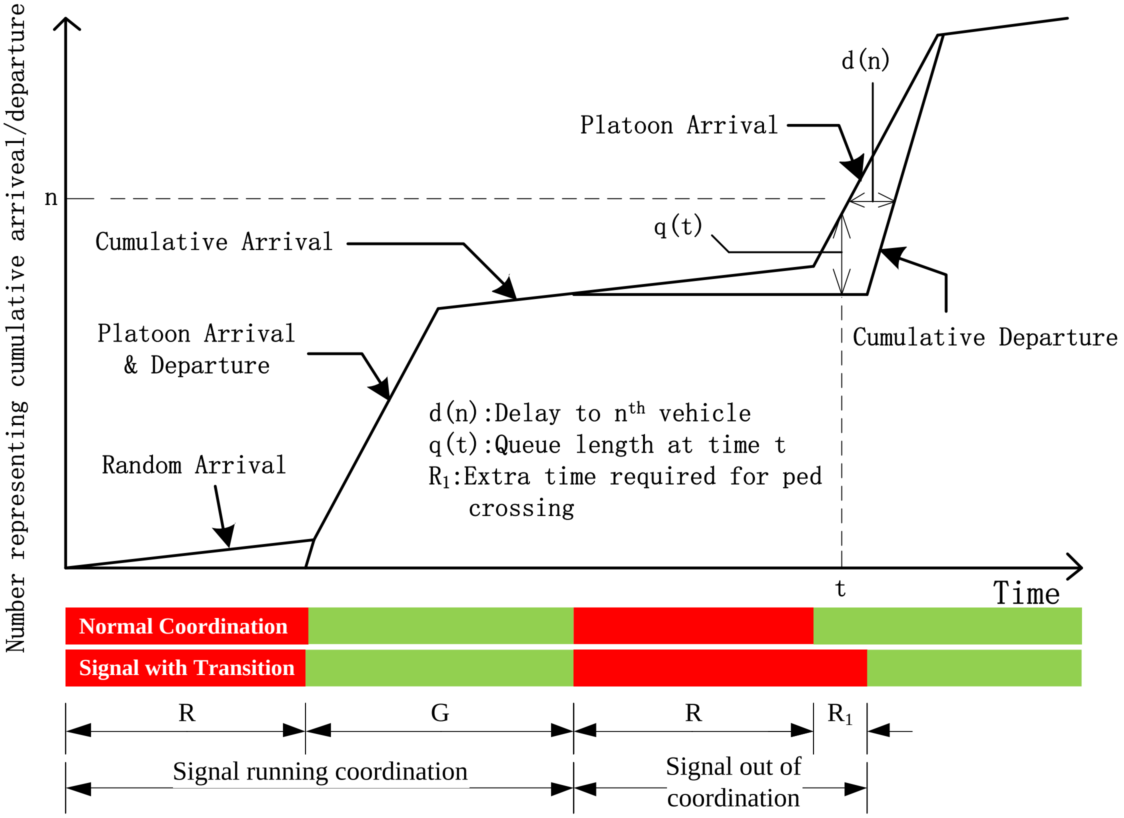

Figure 3 Signal Coordination Inefficiency Caused by Pedestrian Crossing

In addition, more inefficiency will be caused during the transition period because normal traffic progression is interrupted. It generally takes 1-2 cycles before the signal comes back to coordination. The next section will provide detailed description of how each transition algorithm impacts the timing-space diagram and arterial vehicle delay.

2.2.1 The Lengthening Transition Algorithms

- **Dwell**

Dwell is the most common transition algorithm in all types of controllers but seldom applied in the field. This algorithm corrects offset by resting in the coordinated phases until the new coordination plan is reached. This transition algorithm can make a signal controller get back to coordination in just one cycle and it has the least impact on the main-street bandwidth. However, it will cause considerable delay to the side-street vehicles. Figure 4 shows the change of the southbound bandwidth under the Dwell transition algorithm. Figure 5 shows the cumulative arrival/departure of through movement of the arterial during the Dwell transition algorithm.

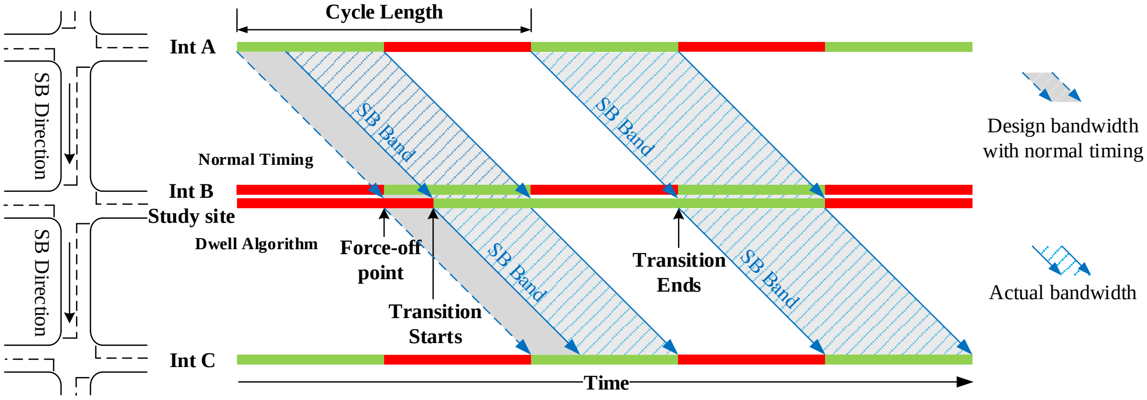

Figure 4 Traffic Progression with Dwell Transition Algorithm

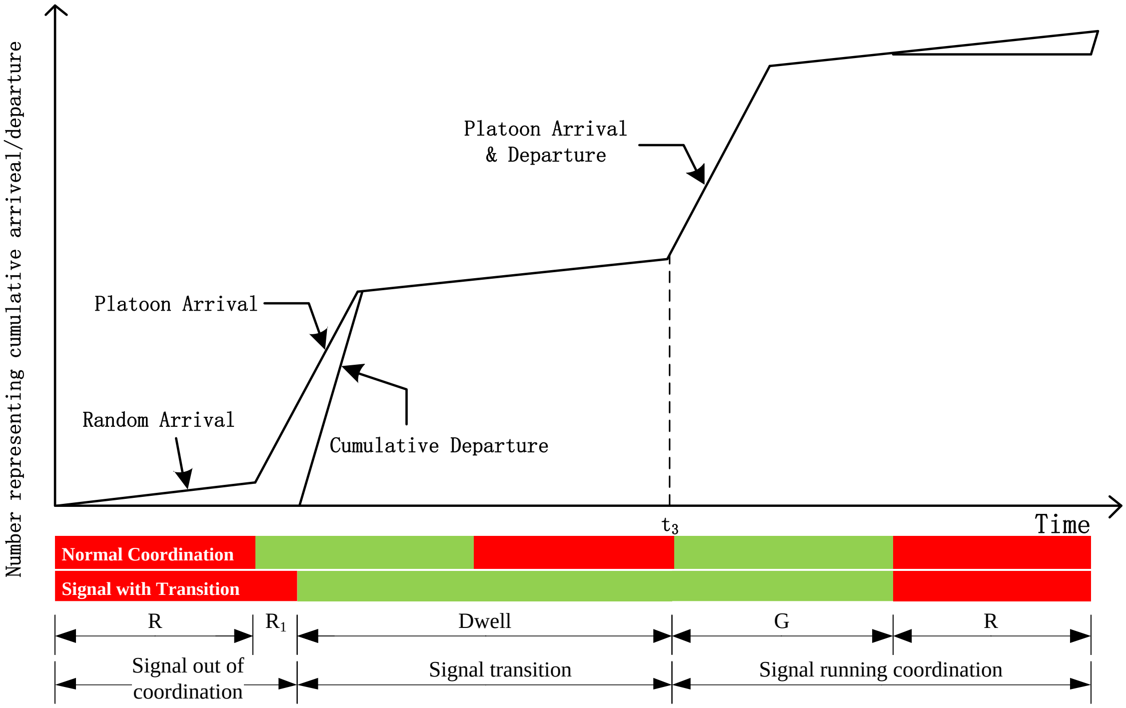

Figure 5 Cumulative Arrival/Departure with Dwell Transition Algorithm

It can be seen from the figures that there is no extra delay caused for arterial through movement during the Dwell transition. However, the side-street vehicles need to wait for a long time and may complain for the signal timing due to few random vehicles arrival on the main-street.

- **Max Dwell**

Max Dwell is a similar transition algorithm as Dwell. It smoothens the Dwell algorithm by enlarging the main-street split for more than cycles. Figure 6 shows an example of the Max Dwell algorithm by transiting back in two cycles. Compared with the Dwell algorithm, the southbound bandwidth is reduced during transition.

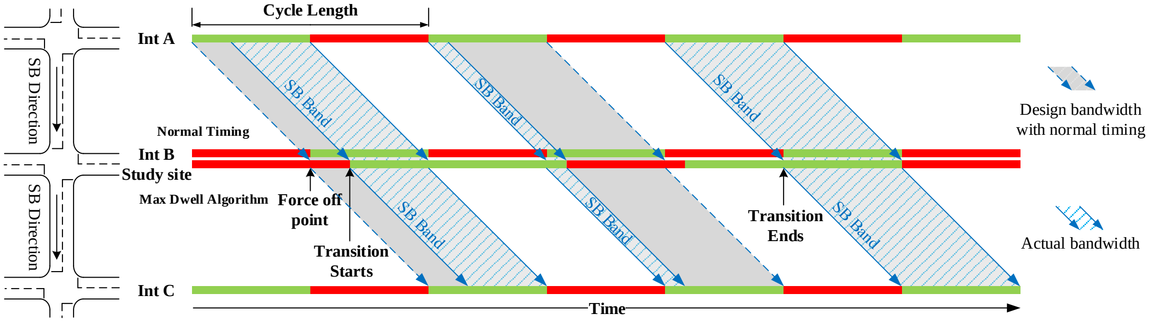

Figure 6 Traffic Progression with Max Dwell Transition Algorithm

Figure 7 shows that the Max Dwell transition algorithm interrupts normal traffic progression between t_1 and t_2. However, this algorithm provides side-street with more green time during transition period, which reduces side-street delay compared to the Dwell algorithm.

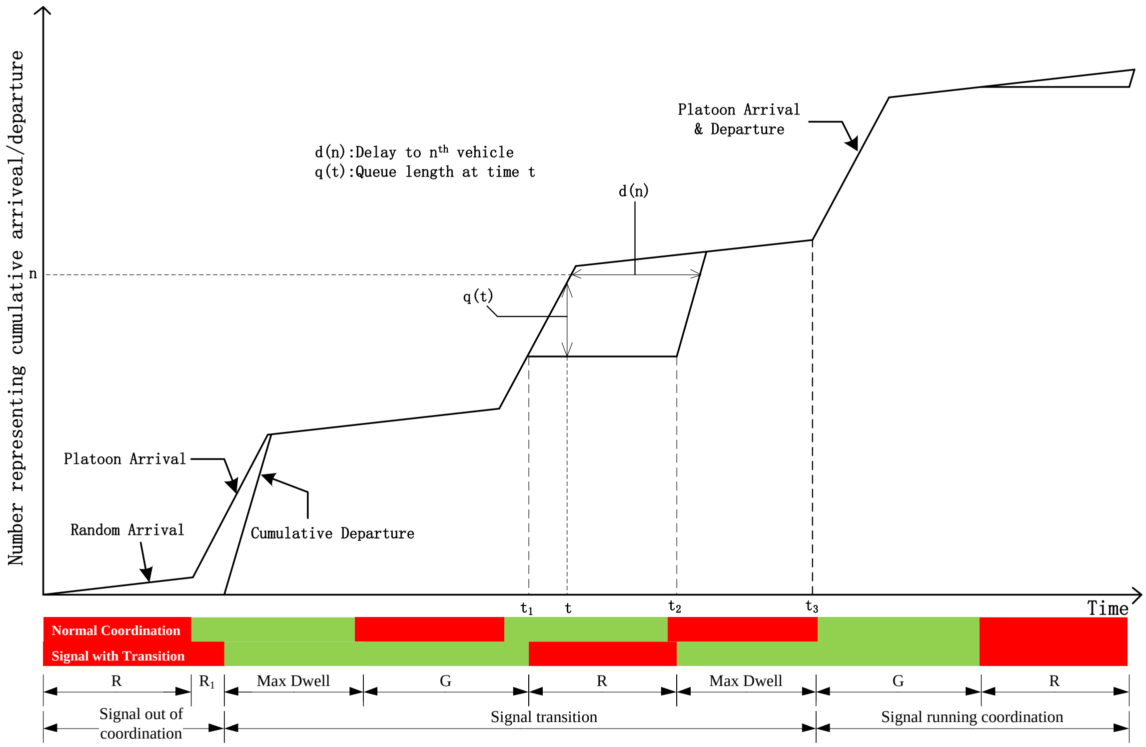

Figure 7 Cumulative Arrival/Departure with Max Dwell Transition Algorithm

- **Add**

The Add transition algorithm increases time for all splits. Figure 8 shows an example of Add transition algorithm by transiting back in two cycles. Compared to the Max Dwell algorithm, the side-street of intersection B has more green time with the Add transition algorithm.

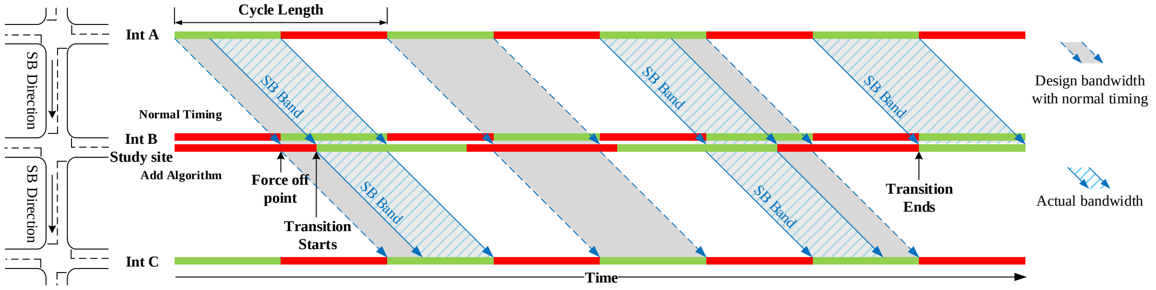

Figure 8 Traffic Progression with Add Transition Algorithm

Figure 9 shows the progression disturbance during Add transition. Because this algorithm gives more time to the side-street, it stopped the whole platoon during transition.

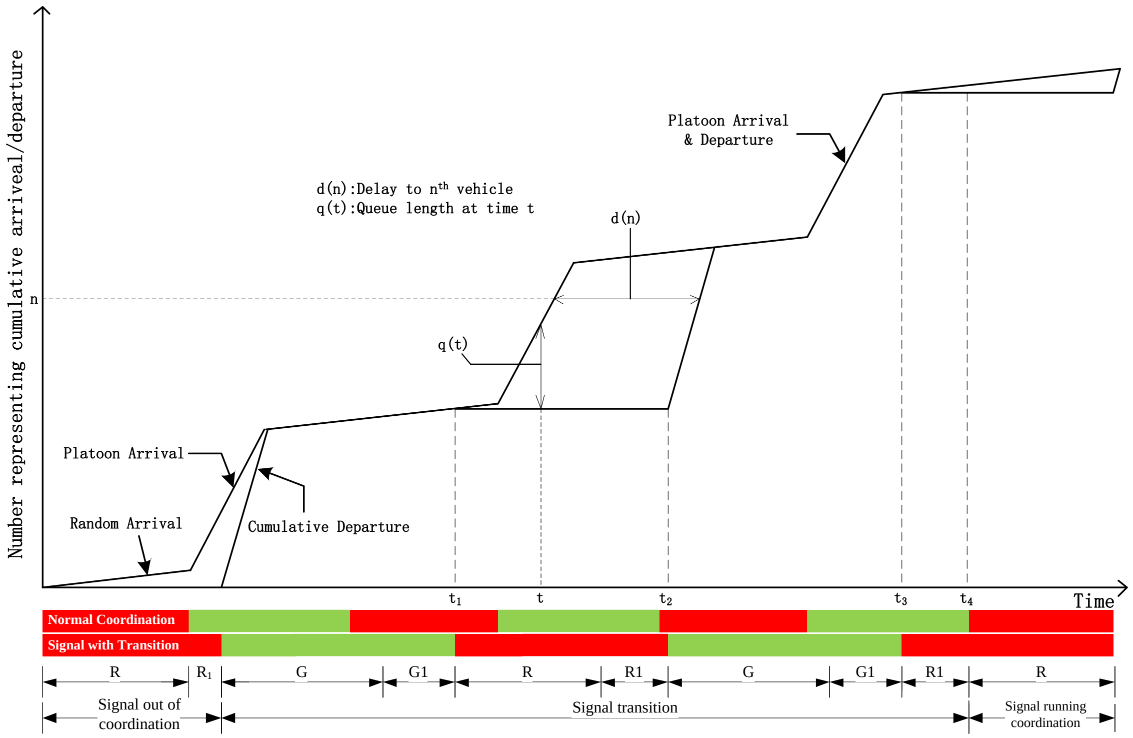

Figure 9 Cumulative Arrival/Departure with Add Transition Algorithm

2.2.2 The Shortening Transition Algorithms

- **Subtract**

The Subtract transition algorithm is a widely used major transition algorithm. This transition algorithm achieves the target offset by shortening the times of each split. Figure 10 shows an example of Subtract transition algorithm by transiting back in two cycles.

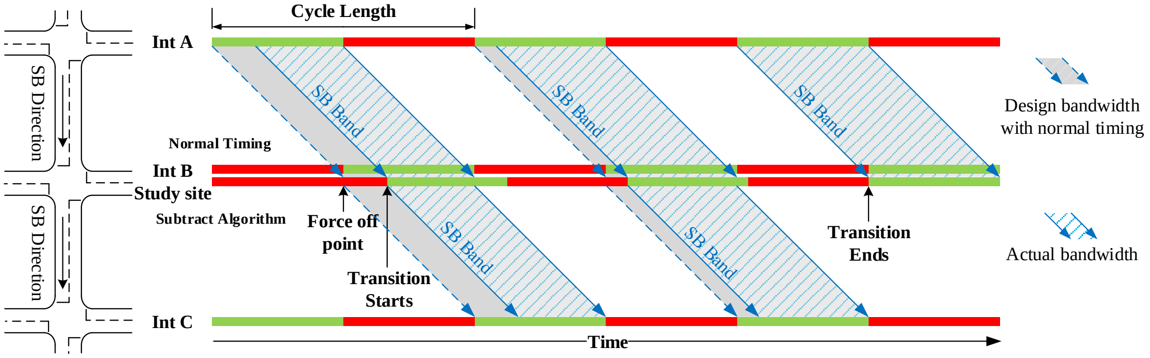

Figure 10 Traffic Progression with Subtract Transition Algorithm

Compared to the other transition algorithms, the Subtract algorithm has the minimum impact on the existing coordination and the side-street green time, shown in Figure 11. Subtract algorithm also takes less time during transition compare to other algorithms. Because lengthening algorithms need to enlarge split time to meet the target offset, getting back in two cycles actually takes three normal cycle time. However, the downside of the Subtract algorithm is the shortened split time sometimes cannot meet minimum green time for each phase. Shortening split time also means reducing capacity. Queue may form when the traffic volume is high.

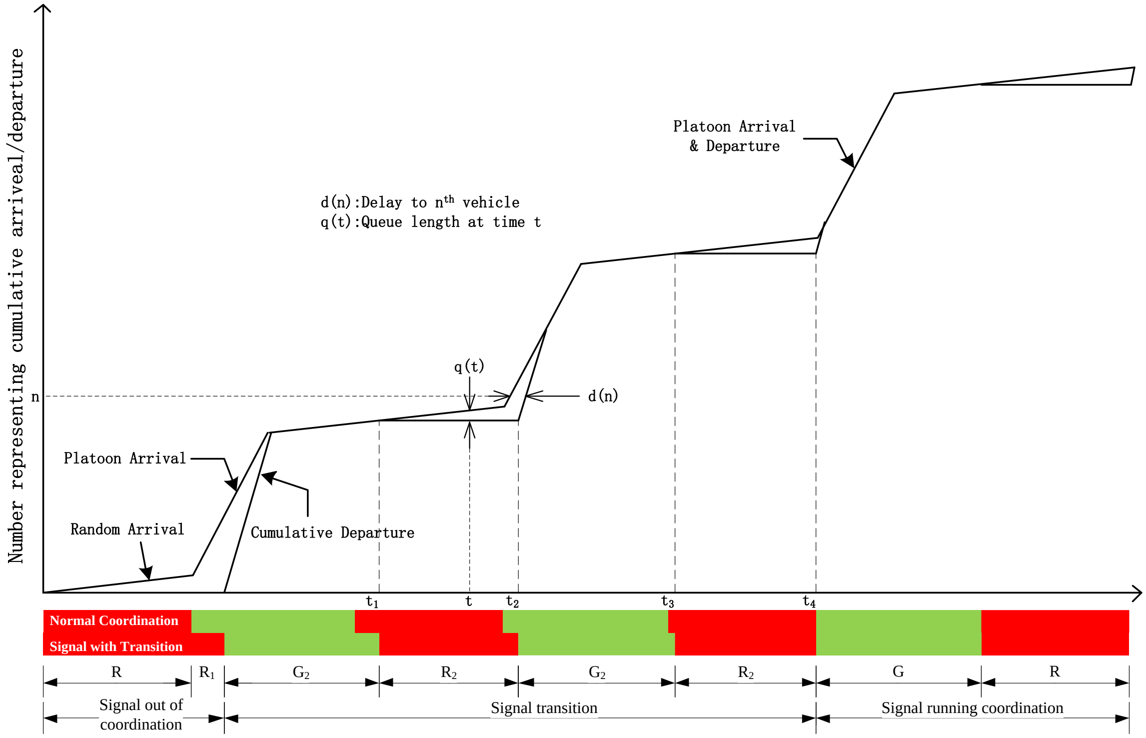

Figure 11 Cumulative Arrival/Departure with Subtract Transition Algorithm

2.2.3 The Shortway Transition Algorithm

- **Shortway**

For the Shortway transition, controllers made by different manufactures may implement the algorithm differently. The general principle is to select the faster approach between the Add transition algorithm and the Subtract transition algorithm. Some controllers may choose between

Max Dwell and Subtract.

2.3 Advantages and Disadvantages of Different Transition Algorithms

According to above analyses, the advantages and disadvantages of different transition algorithms are summarized in Table 1.

Table 1 Summary of Transition Algorithms

Transition Algorithm	Pros	Cons	Recommendations
Dwell	Increases main-street capacity; Least impact on main-street coordination	Significantly reduces side-street capacity; Longer delay on side-street	Heavy vehicle demand on main-street; Light vehicle demand on side-street
Max Dwell	Increases main-street capacity	Reduces side-street capacity; interrupts coordination progression	Heavy vehicle demand on main-street; Light vehicle demand on side-street
Add	Increases capacity for both main-street and side-street	Adversely interrupts coordination progression	High vehicle demand at both main-street and side-street
Subtract	Least impact on intersection overall efficiency	Reduce capacity for both main-street and side-street	Under-saturated at both main-street and side-street
Shortway	Chooses the faster way between lengthening and shortening strategy	Does not consider different traffic conditions	Applicable on most intersections

The lengthening strategy enlarges cycle length. Fewer cycles are expected during transition period, which reduces the lost time during phase switching. The capacity for specific directions will be generally increased depending on green time assignment during transition. These algorithms can be applied at commonly congested intersections, in order to reduce the queue length and improve progression after signal transition. However, it should be noted that downstream intersection might become congested when a lengthening transition algorithm is applied.

On the contrary, the shortening strategy shortens the cycle length, and the capacity will be generally reduced during transition. However, less impact on existing coordination and side-street delay time makes shortening strategy a preferable choice among all the transition algorithms. Therefore, when an intersection is mostly under-saturated, a shortening algorithm will have the best performance.

The Shortway algorithm is more advanced compared with other algorithms. The strategy selection of Shortway algorithm is based on split difference. When split difference varies for each transition event (like change of time-of-day plan), Shortway is the most efficient algorithm. However, the split difference is usually fixed for pedestrian-caused signal transition. It does not benefit from the flexibility of Shortway algorithm.

In terms of arterial bandwidth and delay of coordinated phase, Dwell and Subtract algorithms both have the least impact on existing coordination plans and their differences are minimal. However, considering their impact on approach capacity and side-street delay, Subtract significantly outperforms Dwell algorithm. Based on the qualitative analysis so far, it can be concluded that Subtract is the most efficient transition algorithm with under-saturated traffic condition. But it is inconclusive which transition algorithm would least affect coordination with over-saturated conditions. More analyses need to be conducted through case study to further evaluate the impact of different algorithms.

3 Performance of Signal Transition Algorithms in Controllers

This section specifically discusses the transition algorithms in the NEMA controllers manufactured by Naztec and Eagle, which are the two controller types currently deployed in the Reno-Sparks area. Transition algorithms are given different names in the two controllers (represented in *italic* in Table 2. In general there are five transition algorithms which are Dwell, Max Dwell, Add, Subtract and Shortway. According to the controller user's manuals, the transition algorithms implemented in Naztec and Eagle controllers are summarized in Table 2. For each algorithm, every controller can have its own options. The table lists the name and the configurations to realize the general transition algorithm.

Table 2 Transition Algorithms Implemented in Naztec and Eagle Controllers

Algorithm	Naztec 981 TS2	Eagle EPAC300
Dwell	*Dwell* holds until synchronized.	*Dwell* holds until synchronized.
Max Dwell	*Max Dwell* holds to sync or set limit per cycle, ranging from 1 to 99s. Set limits per plan. Set Long and Short to zero.	*Max Dwell* holds to sync of set limit per cycle, ranging from 1 to 999s. *Shortway+* holds to sync or fixed limit per cycle of 18.75%.
Add	*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.	*Shortway+* adds to sync phases only, as needed, up to fixed limit per cycle of 18.75%.
Subtract	*Short* 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.	Subtract is not a directly available option, but this approach is selectable by the *Shortway* algorithm. Subtract up to 18.75% of a cycle, from all phases.
Shortway	*Short/Long* with both limits set to non-zero, will choose the faster of the two algorithms, which operates as described above.	*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.

The User's Manual of each controller provides a general description of how each transition algorithm works. For example, it shows in how many cycles each algorithm can get the signal back to coordination. But it lacks a more detailed description regarding the split changes during transition. To further understand each algorithm, a test case was conducted to document how splits change during the transition period. The same case was tested against all four algorithms. The results of the evaluation are presented next.

3.1 Hardware-in-the-Loop Simulation (HILS) Environment

The hardware-in-the-loop simulation (HILS) was used in this study in order to accurately reflect the actual controller operations. HILS system consists of a controller interface device (CID). A CID permits a computer to communicate with traffic control hardware, such as Eagle and Naztec controller.

Figure 12 shows the workflow of HILS. The controller is connected with micro simulation software VISSIM 6.0 by controller interface device (CID). Naztec TS-2 test box is used to trigger pedestrian calls in Naztec controller. During the simulation, VISSIM provides vehicle input and the traffic controller provides signal control. In order to synchronize the software and the hardware system, the software simulation time step needs to be set as real time.

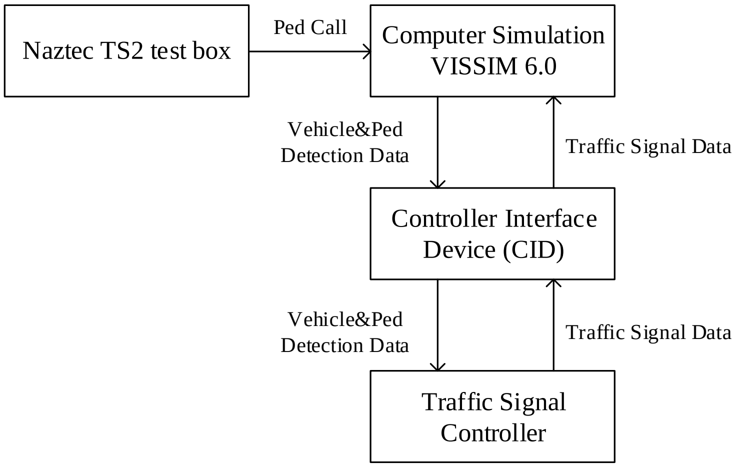

Figure 12 Hardware-in-the-Loop Simulation Workflow

However, it should be noted that the log time from HILS may lag the real controller time by up 10 seconds per hour in the tests that the author has conducted, due to the communication issue between the hardware and software. This time lag presents negligible impact for the purpose of the study.

3.2 Evaluation of the Transition Algorithms in Naztec Controllers

The test case for Naztec controller is based on a real signal timing running at the intersection of ClearAcre Ln/McCarran Blvd in Reno, Nevada. As shown in Figure 13, McCarran Blvd is the main street and ClearAcre Ln is the side street.

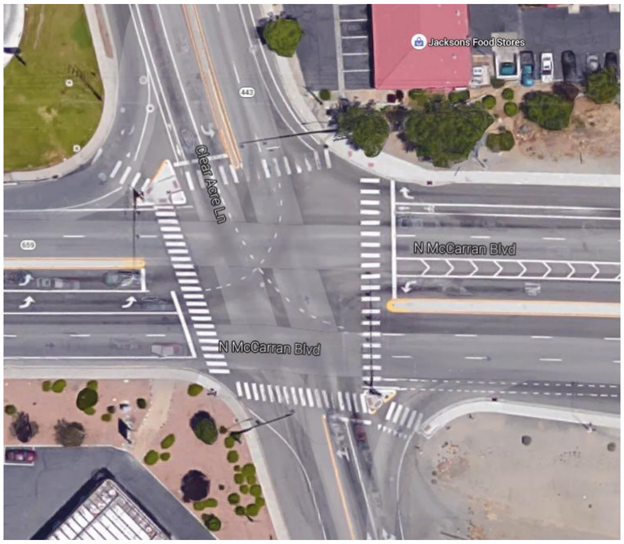

Figure 13 The Intersection of ClearAcre Ln and McCarran

The signal is running a six-phase operation with a cycle length of 120 seconds where the side-street signal is operating split phasing. The phase entries are listed in Table 3. Max Recall is placed for each phase in order to minimize the impact of other factors and observe how the split time changes during transition.

Table 3 Phase Entries for Test Case in Naztec Controller

Timing Parameters	Phase 1	Phase 2	Phase 3	Phase 4	Phase 7	Phase 8
Min Green, sec	4	4	4	4	4	4
Yellow, sec	4	4	3	4.3	3	4.3
All-Red, sec	2	2	0.5	1	0.5	1
WALK, sec	-	7	-	-	-	-
FDW, sec	-	36	-	-	-	-
Split, sec	30	29	15	46	14	47

A pedestrian call is triggered in phase 2 and it causes a 20-second split difference. Split difference is defined as the difference between the phase split and the minimum split to accommodate pedestrian crossing. It indicates the amount of offset correction during transition, and is calculated by:

$$\text{Split difference} = \text{Pedestrian crossing time} - \text{Phase split} \tag{1}$$

where

$$\text{Pedestrian crossing time} = \text{WALK} + \text{FDW} + \text{Yellow} + \text{AR}. \tag{2}$$

Using Phase 2 as an example, the calculation of the parameters is listed below.

$$\text{Pedestrian crossing time} = 7 + 36 + 4 + 2 = 49\text{s}, \tag{3}$$

$$\text{Phase split} = 29\text{s},$$

(4)

$$\text{Split difference} = 49 - 29 = 20\text{s}. \tag{5}$$

HILS was used in this study in order to accurately reflect the actual controller operations. To test different transition algorithms, the split of Phase 2 is enlarged by 20 seconds when a pedestrian call is placed. The transition begins with phases 3 and 7.

The following sub-sections will specifically document how the Naztec controller performs with each transition algorithm by comparing the split time of every phase during the transition period.

3.2.1 Dwell

For the *Dwell* algorithm, the split difference is assigned to the coordinated phases, as shown in Table 4. Design Split in the table shows the split time of each phase when the signal runs in coordination. Calculated split in transition shows the calculated split of each phase during the transition period according to the algorithm configurations. Observed split in transition documents the actual controller output observed in the signal transition period.

Table 4 Phase Splits in Naztec Controller during Transition with *Dwell*

Split	Phase 1	Phase 2	Phase 3	Phase 4	Phase 7	Phase 8
Design split, sec	30	29	15	46	14	47
Calculated split in transition, sec	30	29	15	146	14	147
Observed split in transition, sec	30.6	28.0	13.4	142.1	14.3	141.3

3.2.2 Max Dwell

The *Max Dwell* algorithm assigns the split difference to the coordinated phases up to a limited amount per cycle. In this case, the limit is set at 50 seconds, which means the coordinated phase will be enlarged up to 50 seconds more than its original split. In this way, the offset will be corrected in 2 cycles, as shown in Table 5.

Table 5 Phase Splits in Naztec Controller during Transition with *Max Dwell*

Split/Phase	Phase 1	Phase 2	Phase 3	Phase 4	Phase 7	Phase 8
Design Split, sec	30	29	15	46	14	47
Calculated split in transition, sec (First cycle)	30	29	15	96	14	97
Observed split in transition, sec (First cycle)	30.4	29.2	13.5	95.9	14.4	94.9

Calculated split in transition, sec (Second cycle)	30	29	15	96	14	97
Observed split in transition, sec (Second cycle)	30.4	28.8	13.5	95.1	14.4	94.1

3.2.3 Longway

Longway algorithm moves the offset "forward in time" by increasing split times the Long-way%. The split calculation is listed below. The Long-way% is set as 42%, so the controller will correct a maximum of 50.4 second per cycle. In this way, the signal will transit back in two cycles, as shown in Table 6.

$$\text{Longway Split}=\frac{\text{Split}\times(100+\text{Long-way\%})}{100} \tag{6}$$

Table 6 Phase Splits in Naztec Controller during Transition with *Longway*

Split/Phase	Phase 1	Phase 2	Phase 3	Phase 4	Phase 7	Phase 8
Design Split, sec	30	29	15	46	14	47
Calculated split in transition, sec (First cycle)	42.6	41.2	21.3	65.3	19.9	66.7
Observed split in transition, sec (First cycle)	38.6	39.8	19.9	65.9	21.3	64.5
Calculated split in transition, sec (Second cycle)	42.6	40.4	21.3	65.3	19.9	66.7
Observed split in transition, sec (Second cycle)	41.2	40.8	21.9	64.9	23.5	63.5

3.2.4 Short/Long

The *Short/Long* algorithm in Naztec controller moves the offset "back in time" by decreasing split times the Shortway%. The Shortway% is set as 17%. In Naztec controller, before Shortway algorithm is applied, Shortway Split needs to be validated. If Shortway Split is less than the minimum vehicle split, the controller will run free pattern instead of coordination.

$$\text{Shortway Split} = \frac{\text{Split}\times(100-\text{Shortway\%})}{100} \tag{7}$$

$$\text{Minimum Vehicle Split} = \text{Min Green} + \text{Yellow} + \text{All Red} \tag{8}$$

Table 7 Phase Splits in Naztec Controller during Transition with *Short/Long*

Split/Phase	Phase 1	Phase 2	Phase 3	Phase 4	Phase 7	Phase 8
Design split, sec	30	29	15	46	14	47
Minimum vehicle split, sec	10	10	9.5	11.3	9.5	11.3
Calculated split in transition, sec	24.9	24.4	12.5	38.2	11.6	39.0
Observed split in transition, sec	25.0	24.2	10.7	39.5	11.5	38.5

In *Short/Long* algorithm, the calculated split in transition usually isn’t integer. When the calculated split is very close to minimum vehicle split, the controller doesn’t always run coordination as it is supposed to be. Several tests were conducted to see how Naztec controller compares these two numbers, and the results are listed in Table 8.

Table 8 Coordination Issue in Naztec Controller with *Short/Long*

Calculated split, sec	30	30	30.6	30.6
Minimum vehicle split, sec	29.7	30	30.1	30
Controller runs coordination?	Yes	No	No	Yes

3.3 Evaluation of the Transition Algorithms in Eagle Controllers

The author tested the transition algorithms implemented in Eagle controller with a signal timing implemented at the intersection of McCarran Blvd/Greenbrae Dr in Sparks, Nevada. The test signal timing is a standard 8-phase operation, but with a cycle length of 80 seconds. The phase entries and phasing sequences are listed in Table 9. Phase 4 and 8 are defined as coordinated phases. Max Recall is placed for every phase. A pedestrian call is triggered at phase 2 and it causes a 20 second split difference. Although the cycle lengths used for the two controllers are different, the comparison of the transition performance will be based on percentage changes and not affected by the different cycle lengths.

Table 9 Phase Entries for Test Case In Eagle Controller

Timing Parameters	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8
Direction	SBL	NBT	EBL	WBT	NBL	SBT	WBL	EBT
Min Green, sec	5	5	5	5	5	5	5	5
Yellow, sec	3	3	3	3	3	3	3	3
AR, sec	1	1	1	1	1	1	1	1
Walk, sec	-	7	-	7	-	7	-	7
FDW, sec	-	29	-	8	-	8	-	8
Split, sec	10	20	15	35	10	20	15	35

3.3.1 Dwell

Dwell transition algorithm in Eagle controller changes offset by dwelling in the coordinated phase green until the correction is made. The test result from Eagle controller is consistent with the result from Naztec controller despite some minor variance in observed split time.

3.3.2 Max Dwell

Max Dwell algorithm in Eagle controller changes offset by dwelling in the coordinated phase green with a limited time every cycle, until the correction is made. The test result from Eagle controller is also consistent with the result from Naztec controller.

3.3.3 Shortway

With *Shortway* algorithm, Eagle controller will compare the faster way between *Subtract* and *Max Dwell* at the beginning of first coordinated phase.

Subtract

The maximum time that can be shortened for each cycle is equal to 18.75% of the cycle length. This time will be assigned for each phase based on adjustable split time. Adjustable split time is the difference between split time and minimum split time, as shown below.

$$\text{Min Split} = \text{Min Green} + \text{Yellow} + \text{AR} \tag{9}$$

$$\text{Adjustable Split Time} = \text{Split time} - \text{Min Split} \tag{10}$$

According to the case study, the adjustable split time for each phase is calculated in Table 10. The total adjustable split time for both ring 1 and ring 2 is 44 sec. So the percentage of adjustable split time can be calculated by adjustable split time for each phase divided by 44 sec. For subtract algorithm in Eagle controller, the maximum value can be changed per cycle is 18.75%. The cycle length of this case intersection is 80 sec. So the maximum seconds that can be changed for each cycle is 80sec * 18.75% = 15 sec. The theoretical adjustable time can be calculated by multiplying percentage of adjustable split time by 15 sec. The actual adjust time is read from the controller.

Table 10 Adjustable Split Time in *Shortway* Transition for Case Study

Phase/Split	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8
Design Split, sec	10	20	15	35	10	20	15	35
Min split, sec	9	9	9	9	9	9	9	9
Adjustable split time, sec	1	11	6	26	1	11	6	26
% of adjustable split time	2.3%	25.0%	13.6%	59.1%	2.3%	25.0%	13.6%	59.1%
Theoretical adjustable time, sec	-0.34	-3.75	-2.05	-8.86	-0.34	-3.75	-2.05	-8.86
Actual adjustable time, sec	0	-4	-2	-7	0	-4	-2	-7
Recall type	Max	Max	Max	Coord	Max	Max	Max	Coord

Max Dwell

The controller will add 18.75% of the cycle length to coordinated phase until coronation is achieved. In this case, the split phase will add 80sec * 18.75% = 15sec to phase 4 and phase 8.

3.3.4 Shortway+

This transition algorithm changes offset similarly as *Max Dwell* algorithm in the Eagle controller. However there is a maximum dwell limit for every cycle, which 18.75% of the cycle length for the study case.

3.3.5 Shortway2

This transition algorithm operates the same as *Shortway* mode except when going long will add to all phases proportionally to their split time.

3.4 Transition Issues Encountered in Naztec Controller

In some cases, the controller acts less efficiently than expected. Several issues encountered during the tests are documented below.

3.4.1 Skipped Left Turn Not Shortening Transition Time

The test case is standard 8-phase mode. The split of side-street through movement is 13 sec shorter than the sum of Walk+FDW+Y+AR of phase 2. On the main-street, the left-turn split is 15s. Max recall is placed on all phases except for the main-street left-turn which has no recall. So the two left-turn phases skip each cycle in the test because there is no left-turn demand. A pedestrian call is placed on the side-street to allow the signal to go into transition. We would expect the signal should never go into transition since the skipped main-street LT phase is longer than the time loss due to pedestrian on the side-street. But the signal still goes into transition.

3.4.2 Issue with Longway Algorithm

For *Longway* transition algorithm, a second pedestrian call is triggered during the test. After the first pedestrian call, the signal will go into transition for the following two cycles and get back to sync at the end of the second cycle. Then the second pedestrian call is triggered during the second transition cycle. The controller setting is the same as described in section 3.1.3. Table 11 lists the split changes shown in the controller from the first to the third cycle.

Table 11 Test Results of *Longway* Algorithm

Phase 2	Split difference, sec
First cycle end of green	-100
Second cycle end of green	-50
Third cycle end of green	-112

After the first pedestrian call, the signal should sync back at the middle of phase 2 in the second transition cycle. The second pedestrian call is triggered before phase 2 to implement the second 20s split difference. At the end of phase 2 the controller is supposed to show -100s split difference (equal to +20s split difference) on the panel, but instead, it shows -112s (equal to +8s split difference). This problem causes Long-way algorithm less efficient because it takes more time in transition for the second cycle.

3.4.3 Short/Long Decision Problem

The Short/Long algorithm should be the most efficient transition algorithm. According to the user manual, it says the controller will automatically decide the faster way between *Shortway* algorithm and *Longway* algorithm. The problem is that the user manual doesn’t clearly provide the decision point when the controller will make this decision.

In order to test it, the author set the Shortway% as 6% and Long-way% as 50%. The split difference is 20s. The calculation is as follows.

$$\text{Cycles needs for Shortway algorithm} = \frac{\text{Split difference}}{\text{Cycle length} \times \text{Shortway\%}} = 2.8 \text{ cycles} \qquad (11)$$

$$\text{Cycles needs for Longway algorithm} = \frac{\text{Cycle length} - \text{Split difference}}{\text{Cycle length} \times \text{Longway\%}} = 1.7 \text{ cycles} \qquad (12)$$

From the above calculation, the faster way should be *Longway* algorithm. But in the test, the controller automatically chooses *Shortway* algorithm until end of green at phase 4 and phase 8. Figure 14 shows the actual decision point observed from the controller.

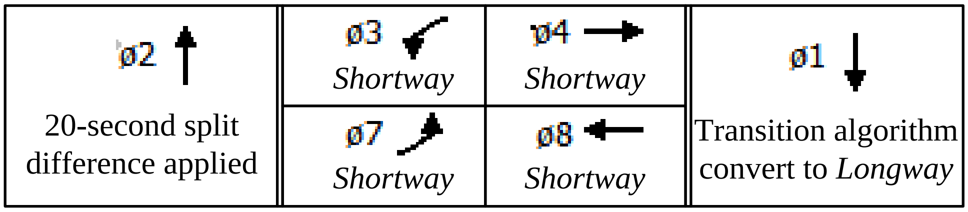

Figure 14 Short/Long Algorithm Decision Changing Point (Ring-Barrier Diagram)

This decision making algorithm will make transition less efficient because it puts signal into transition back and forth. The transition algorithm should be determined as soon as the signal is in transition.

3.4.4 Shortway Transition Decision Point Problem

When using dual-leading left turns for main-street, transition decision will skip main-street leading left turn phase and begin from main-street through movement. This may cause transition certain seconds longer than expected.

4 Pedestrian Effect on Signal Transition by Case Study

In order to study the impact of pedestrian crossing caused signal transition on coordination, an arterial consisting of three intersections was applied in the case study and hardware-in-the-loop simulation (HILS) was used to test different scenarios. The middle of the three intersections was controlled by Naztec controller. Its upstream and downstream intersections were controlled by Econolite and Eagle controller, respectively. The controllers were connected with micro-simulation software VISSIM 6.0 by controller interface device (CID). Naztec TS-2 test box was used to trigger pedestrian calls in Naztec controller.

The first step to conduct pedestrian effect study was to set up evaluation factors related to traffic and geometric conditions in order to examine the impact on algorithm performance during the transition, as shown in Figure 15. Then existing coordination timing plans were gathered from City of Reno engineer and input into the three controllers. Simulation scenarios were configured and calibrated to evaluate delay performance of transition algorithms. Finally, statistical analysis was conducted with the simulation results from various simulation scenarios.

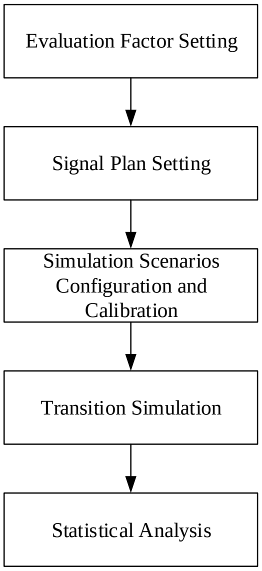

Figure 15 Evaluation Procedures for Naztec Controller Transition Algorithms

The study evaluates four main factors including frequency of pedestrian call, split difference, V/C ratio and transition method. Frequency of pedestrian call is interpreted as percent of cycles that have pedestrian calls. Split difference equals pedestrian crossing time minus split time. V/C ratio is the ratio of volume to capacity for subject movement. For this study, vehicle volumes are changed simultaneously for each approach. Transition algorithm represents the mode used in Naztec controller during transition. Naztec controller implements four transition algorithms: Dwell (DWELL), Max Dwell (MAX DWELL), Short (SUBTRACT) and Long (ADD). For Dwell algorithm, the split time will be assigned for coordinated phase. Max Dwell algorithm assigns the split time to coordinated phase with a maximum limit per cycle. Longway algorithm moves the offset "forward in time" by increasing split times the Longway%. Shortway algorithm moves the offset "back in time" by decreasing split times the Shortway%. The values to be tested for each factor are shown in Table 12. The study is to analyze delay and stop times of the middle intersection under these factors.

Table 12 Factors and Values to Be Tested in the Study

Factor	**Values to be tested**
V/C ratio	60%, 80%, 100%, 110%
Frequency of pedestrian call	10%, 20%, 30%
Transition algorithm	Dwell, Max Dwell, Add, Subtract
Split difference (seconds)	5, 10, 15, 20, 25, 30

4.1 Results and Analysis with Fixed Split Difference of 5 Seconds

To analyze the transition performance, a period of 10 cycles was used in each test to simulate the traffic operation. Given a 5-second split difference, delay and stop times were get under different combinations of V/C ratio and pedestrian frequency, using each transition algorithm. Table 13 shows intersection delay time of each transition algorithm at the study intersection. From the table it can be concluded that when split difference was 5 seconds, *Subtract* had the best performance with under saturated scenarios, and *Longway* had the best performance with over saturated scenarios.

Table 13 Intersection Delay with 5s Split Difference

Ped Call	V/C ratio	Intersection delay (sec)				
		No Transition	Subtract	Dwell	Max Dwell	Add
10%	60%	34.68	34.56	37.73	38.50	39.40
	80%	40.47	41.47	49.32	48.53	46.83
	100%	50.56	49.67	63.30	58.94	49.85
	110%	54.78	58.76	64.84	63.82	54.76
20%	60%	34.68	35.36	42.53	43.05	45.29
	80%	40.47	39.67	54.88	53.57	49.54
	100%	50.56	46.75	63.68	58.97	52.93
	110%	54.78	58.50	66.36	67.26	57.67
30%	60%	34.68	34.88	51.04	50.45	44.73
	80%	40.47	39.85	57.25	60.29	49.50
	100%	50.56	48.30	61.80	67.59	51.65
	110%	54.78	57.13	72.63	67.03	56.06

Figure 16 to Figure 18 show the performances of different transition algorithms when traffic volume is at under-saturated conditions. Figure 19 shows the performance at over-saturated condition. *Short* transition algorithm has a better performance when traffic flow is relatively low and *Add* transition algorithm has a better performance when traffic is over-saturated.

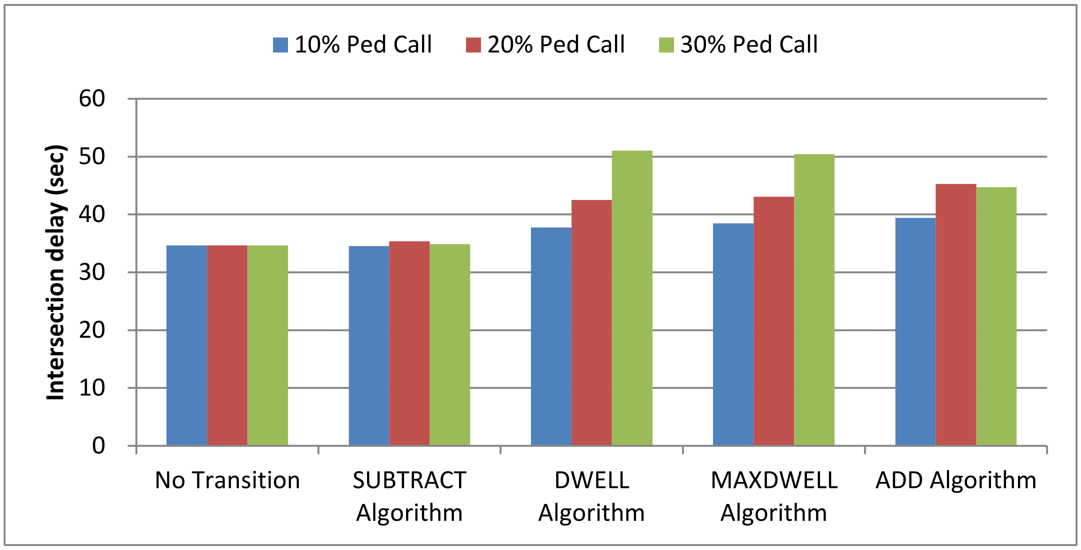

Figure 16 Intersection Delay with 5s Split Diffrence at 60% V/C Ratio

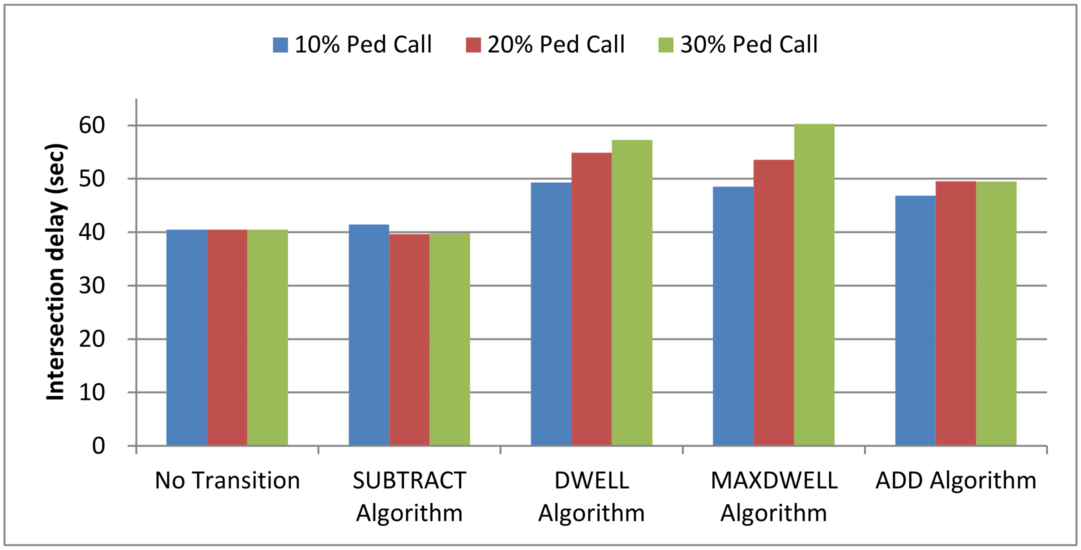

Figure 17 Intersection Delay with 5s Split Different at 80% V/C Ratio

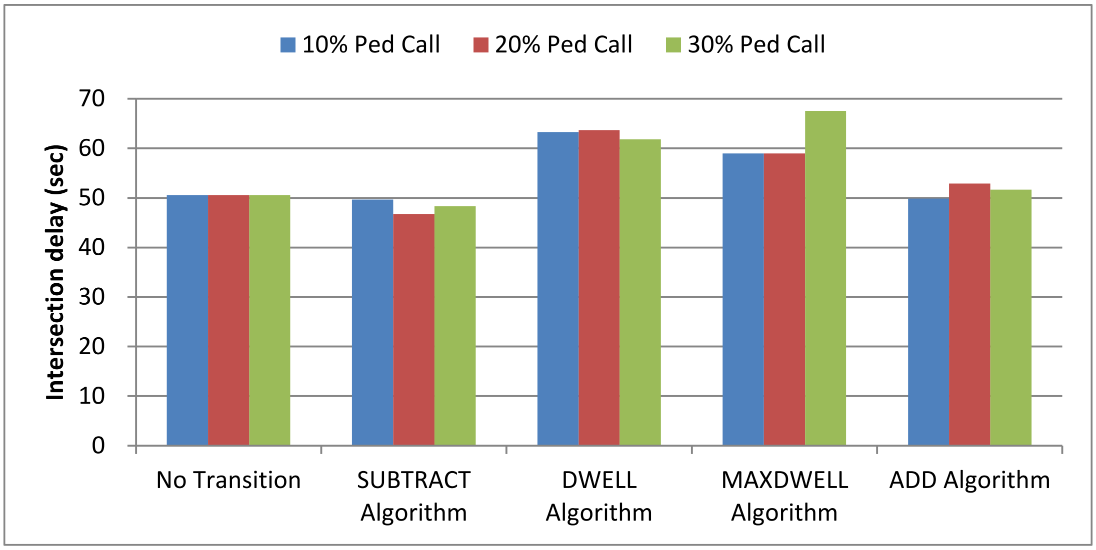

Figure 18 Intersection Delay with 5s Split Different at 100% V/C Ratio

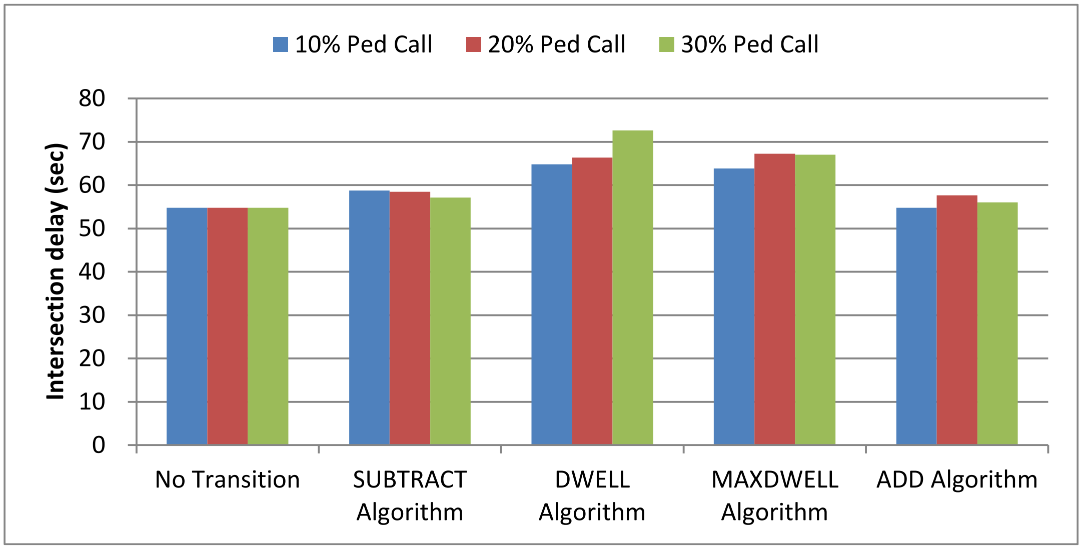

Figure 19 Intersection Delay with 5s Split Different at 110% V/C Ratio

Table 14 shows the delay of EBT movement at the study intersection. Compared to the delay of existing coordinated signal plan (without transition), *Subtract* transition algorithm has the lowest percentage change in delay for EBT movements.

Table 14 EBT Movement Delay with 5s Split Difference

Ped Call	V/C ratio	No Transition	Subtract		Dwell		Max Dwell		Add	
		Delay	Delay	Percentage change	Delay	Percentage change	Delay	Percentage change	Delay	Percentage change
10%	60%	20.00	15.37	23.13%	13.83	30.84%	19.49	2.55%	19.53	2.36%
	80%	22.32	21.45	3.87%	20.60	7.71%	22.05	1.18%	35.85	60.66%
	100%	32.11	34.32	6.90%	34.93	8.79%	27.81	13.39%	34.17	6.43%
	110%	37.87	47.30	24.91%	36.64	3.24%	35.06	7.41%	45.53	20.25%
20%	60%	20.00	22.96	14.78%	13.03	34.84%	19.48	2.59%	36.92	84.60%
	80%	22.32	21.77	2.45%	19.79	11.34%	18.96	15.06%	43.98	97.07%
	100%	32.11	25.03	22.04%	29.29	8.77%	28.55	11.06%	47.34	47.44%
	110%	37.87	39.57	4.50%	31.06	17.99%	34.19	9.70%	44.98	18.77%
30%	60%	20.00	18.45	7.75%	16.29	18.54%	21.56	7.79%	34.13	70.64%
	80%	22.32	20.88	6.44%	15.96	28.47%	25.25	13.16%	41.81	87.33%
	100%	32.11	32.67	1.75%	23.25	27.59%	24.42	23.94%	45.40	41.42%
	110%	37.87	42.31	11.73%	24.16	36.19%	27.95	26.20%	47.65	25.83%
Average			-	10.85%	-	19.52%	-	11.17%	-	46.90%

Similarly, the performance of each transition algorithm was tested using the measurement of stop times.

Table 15 shows the stop times of EBT movement at the study intersection. Compared to the stop times of existing coordinated signal plan (without transition), *Subtract* transition algorithm has the lowest percentage change of stop times for EBT movement.

Table 15 EBT Movement Stop Times with 5s Split Difference

Ped Call	V/C ratio	No Transition	Subtract		Dwell		Max Dwell		Add	
		Stop Times	Stop Times	Percentage change	Stop Times	Percentage change	Stop Times	Percentage change	Stop Times	Percentage change
10%	60%	0.31	0.24	22.76%	0.22	30.78%	0.32	2.89%	0.29	6.22%
	80%	0.33	0.32	4.64%	0.29	12.46%	0.36	8.33%	0.54	62.14%
	100%	0.47	0.48	2.26%	0.50	5.46%	0.43	9.12%	0.50	5.67%
	110%	0.55	0.71	29.64%	0.52	5.05%	0.53	2.98%	0.66	20.37%
20%	60%	0.31	0.34	10.24%	0.20	36.75%	0.35	11.57%	0.55	75.43%
	80%	0.33	0.32	3.41%	0.28	15.22%	0.34	1.66%	0.61	85.62%
	100%	0.47	0.36	23.79%	0.41	11.67%	0.48	2.03%	0.70	49.64%
	110%	0.55	0.58	7.33%	0.46	15.57%	0.58	5.95%	0.66	20.48%
30%	60%	0.31	0.27	12.20%	0.23	26.19%	0.40	28.92%	0.53	68.40%
	80%	0.33	0.30	8.92%	0.22	33.50%	0.48	43.96%	0.58	75.89%
	100%	0.47	0.47	0.89%	0.31	33.11%	0.41	12.41%	0.67	41.91%
	110%	0.55	0.61	11.14%	0.33	38.69%	0.47	13.19%	0.74	35.93%
Average			-	7.11%	-	11.13%	-	8.47%	-	23.88%

From the above analysis, it can be concluded that *Subtract* transition algorithm has the least impact on coordination when the intersection is under saturated, because the delay and stop times of arterial through movement is closest to the existing coordinated plan, and it has the lowest intersection delay.

4.2 Results and Analysis with Fixed Split Difference of 20 Seconds

From previous tests, the conclusion can be reached that *Subtract* transition algorithm has the best performance with a short split difference. However the impact with a longer split difference needs to be studied. A further study with 20-second split difference is conducted.

Table 16 shows the intersection delay under each scenario. From the results it can be seen that when split difference was 20 seconds, *Subtract* had the best performance with under saturated condition, and *Add* had the best performance with over saturated condition.

Table 16 Intersection Delay with 20s Split Difference

Ped Call	V/C ratio	No Transition	Subtract	Dwell	Max Dwell	Add
10%	60%	34.68	36.04	39.88	38.84	40.61
	80%	40.47	41.61	49.56	49.74	44.03
	100%	50.56	51.87	59.31	63.26	48.83
	110%	54.78	60.25	66.10	64.63	59.50
20%	60%	34.68	35.29	45.13	42.14	46.79
	80%	40.47	42.14	55.02	56.91	47.85
	100%	50.56	53.87	68.07	64.62	56.38
	110%	54.78	63.47	68.64	67.96	56.49
30%	60%	34.68	37.09	53.90	48.98	45.04
	80%	40.47	40.81	59.33	63.76	49.10
	100%	50.56	53.00	70.80	69.86	55.48
	110%	54.78	65.88	72.44	74.11	62.20

Figure 20 to Figure 22 show the performance of different transition algorithms when traffic volume is at under-saturated conditions. Figure 23 shows the performance of different transition algorithms when traffic volume is at over-saturated condition. *Short* transition algorithm has a better performance when traffic flow is relatively low and *Add* transition algorithm has a better performance when traffic is over saturated. The testing result with 20-second split difference is similar with 5-second split difference test.

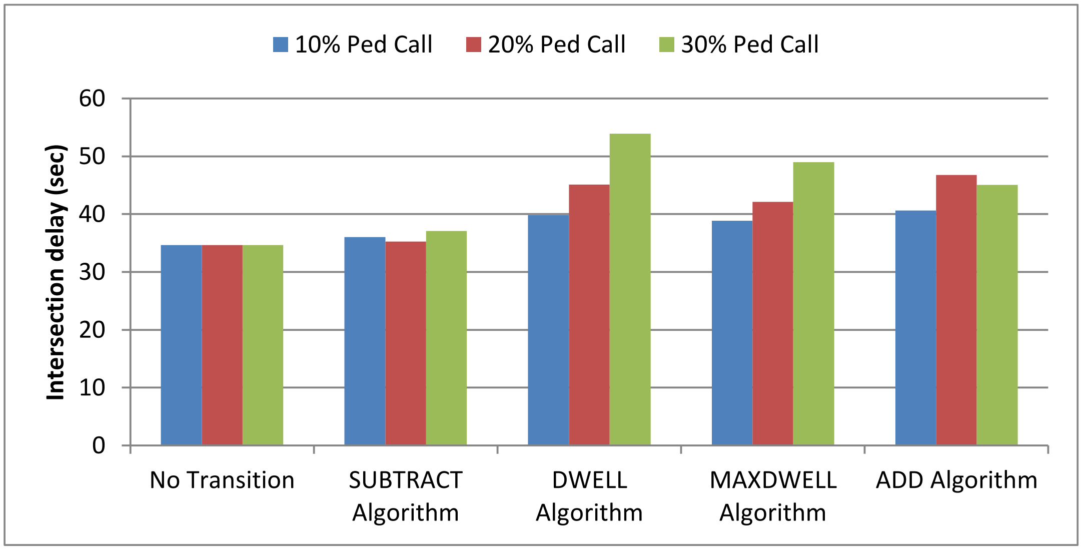

Figure 20 Intersection Delay with 20s Split Different at 60% V/C Ratio

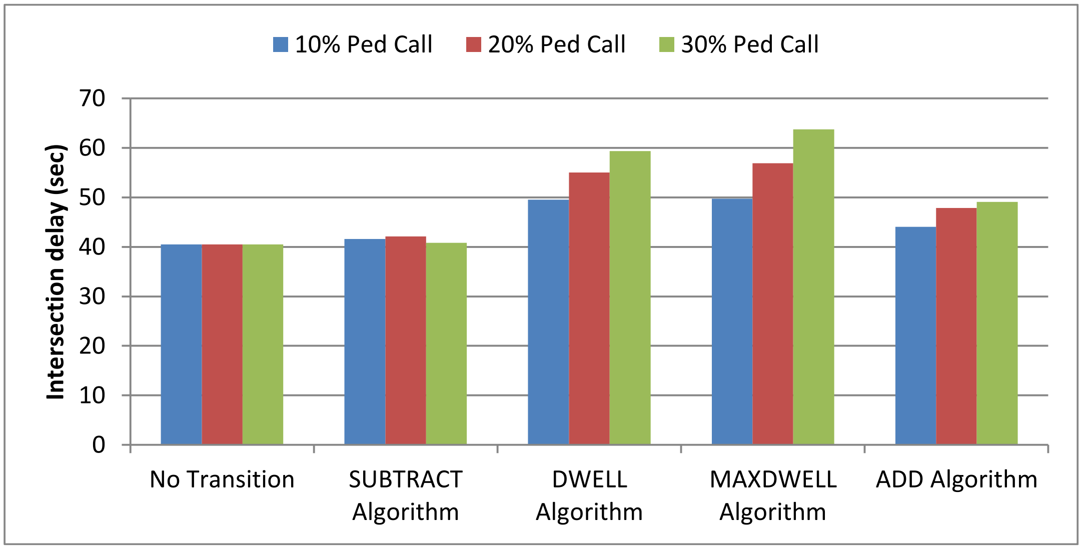

Figure 21 Intersection Delay with 20s Split Different at 80% V/C Ratio

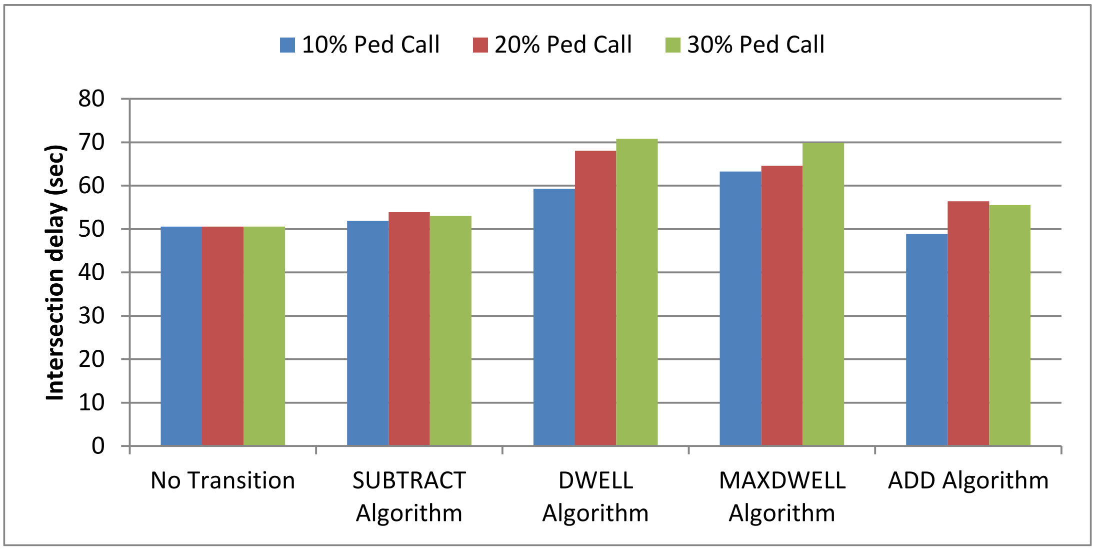

Figure 22 Intersection Delay with 20s Split Different at 100% V/C Ratio

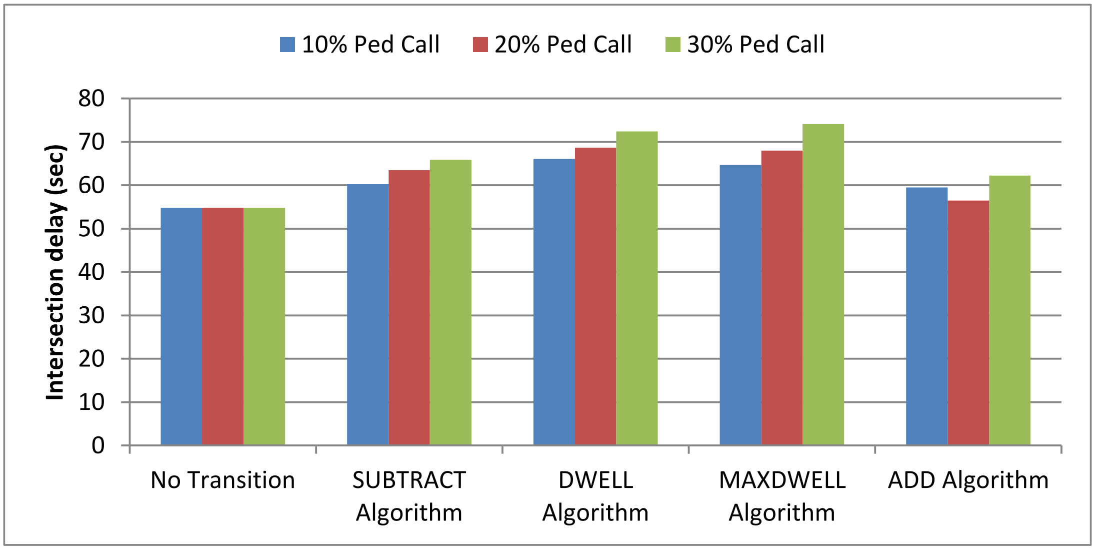

Figure 23 Intersection Delay with 20s Split Different at 110% V/C Ratio

Table 17 lists the delay of EBT movement at the study intersection. Compared to delay of existing coordinated signal plan (without transition), *Subtract* transition algorithm has the lowest percentage change in delay for EBT movement.

Table 17 EBT Movement Delay with 20s Split Difference

Ped Call	V/C ratio	No Transition	Subtract		Dwell		Max Dwell		Add	
		Delay	Delay	Percentage change	Delay	Percentage change	Delay	Percentage change	Delay	Percentage change
10%	60%	20.00	22.09	10.44%	18.99	5.03%	21.70	8.49%	24.67	23.34%
	80%	22.32	22.26	0.24%	20.84	6.62%	20.71	7.19%	30.76	37.83%
	100%	32.11	30.03	6.46%	32.89	2.44%	37.48	16.75%	32.08	0.09%
	110%	37.87	41.24	8.91%	43.70	15.41%	35.94	5.09%	49.23	30.02%
20%	60%	20.00	18.25	8.77%	18.12	9.42%	16.52	17.39%	39.07	95.37%
	80%	22.32	21.03	5.79%	17.12	23.31%	30.93	38.60%	40.88	83.20%
	100%	32.11	34.12	6.28%	36.65	14.15%	32.17	0.19%	55.90	74.10%
	110%	37.87	45.44	19.99%	31.45	16.95%	40.03	5.70%	48.25	27.42%
30%	60%	20.00	23.65	18.24%	20.38	1.89%	26.17	30.84%	40.70	103.50%
	80%	22.32	20.67	7.39%	19.22	13.86%	26.10	16.95%	42.69	91.27%
	100%	32.11	30.42	5.26%	28.51	11.21%	37.23	15.97%	46.86	45.94%
	110%	37.87	50.16	32.46%	33.04	12.74%	33.54	11.42%	57.77	52.56%
Average			-	10.85%	-	11.08%	-	14.55%	-	55.39%

Table 18 shows the performance of each transition algorithm using the measurement of stop times. Compared to stop times of existing coordinated signal plan (without transition), *Subtract* transition algorithm has the lowest percentage change in stop times for EBT movements.

Table 18 EBT Movement Stop Times with 20s Split Difference

Ped Call	V/C ratio	No Transition	SUBTRACT		DWELL		MAX DWELL		ADD	
		Stop Times	Stop Times	Percentage change	Stop Times	Percentage change	Stop Times	Percentage change	Stop Times	Percentage change
10%	60%	0.31	0.33	5.37%	0.30	5.37%	0.35	12.37%	0.37	19.47%
	80%	0.33	0.33	1.62%	0.32	4.09%	0.34	4.25%	0.45	35.27%
	100%	0.47	0.44	6.30%	0.47	0.06%	0.53	13.40%	0.47	0.76%
	110%	0.55	0.61	11.38%	0.61	11.54%	0.55	0.43%	0.70	28.08%
20%	60%	0.31	0.27	13.80%	0.27	13.12%	0.32	2.15%	0.64	103.42%
	80%	0.33	0.33	0.05%	0.25	25.49%	0.50	49.86%	0.62	87.64%
	100%	0.47	0.49	4.75%	0.55	16.34%	0.53	12.88%	0.76	62.14%
	110%	0.55	0.68	25.15%	0.49	10.32%	0.65	18.86%	0.67	23.45%
30%	60%	0.31	0.39	24.31%	0.35	11.51%	0.49	57.43%	0.61	94.78%
	80%	0.33	0.32	4.59%	0.29	13.21%	0.51	53.88%	0.57	71.52%
	100%	0.47	0.47	0.08%	0.44	5.94%	0.61	28.96%	0.70	48.64%
	110%	0.55	0.73	34.30%	0.50	8.94%	0.58	5.83%	0.70	28.84%
Average			-	7.11%	-	10.49%	-	21.69%	-	50.33%

From the above analysis, it can be concluded that *Subtract* transition algorithm has the least impact on coordination when the intersection is under saturated, because the delay and stop times of arterial through movement is closest to the existing coordinated plan, and it has the lowest intersection delay.

4.3 Impact of Subtract Algorithm

In previous tests, *Subtract* proved to be the most efficient transition algorithm when split difference was equal to 5 and 20 seconds. However, the previous analysis was based on a single intersection with a fixed split difference. The split difference at other locations may vary due to the difference in intersection geometry and/or side-street vehicle demand. It is necessary to study the performance of *Subtract* when split difference is different. Therefore in the following tests, a list of split differences was applied to analyze the efficiency of *Subtract*. Test variables included are shown in Table 19.

Table 19 Factors and Values to Be Tested for *Subtract*

Factor	**Values to be tested**
V/C ratio	100%
Frequency of pedestrian call	10%, 20%, 30%
Transition algorithm	Subtract
Split difference (seconds)	5, 10, 15, 20, 25, 30

The test scenario is based on 100% V/C ratio due to two reasons. First, *Subtract* has the best performance only when the intersection V/C ratio is no more than 100%. To test the impact of *Subtract*, over saturated condition is no longer considered. Second, SUBTRACT has similar performance patterns with the V/C ratio of 60% to 100%. When split difference increases, intersection with 100% V/C ratio will have more significant changes in delay and stop times. Therefore, 100% V/C ratio has been chosen in the test. Besides, 30 cycles are used instead of 10 cycles in order to obtain more stable results.

Table 20 and Figure 24 show that split difference and pedestrian volume both have effect on coordination. When pedestrian volume is under 10% and split difference under 20, the average intersection delay will not increase significantly (less than 6%). The factors are more sensitive when one of them exceeds the limit.

Table 20 Intersection Delay with *Subtract* at 100% V/C Ratio

Ped Call Split Diff	0%	10%	20%	30%	0% (Isolated control)	Average
0	50.3	50.3	50.3	50.3	50.0	50.3
5	50.3	50.1	48.7	48.1	50.0	49.0
10	50.3	50.4	52.1	52.8	50.0	51.8
15	50.3	51.7	53.7	53.4	50.0	53.0
20	50.3	51.8	52.7	54.7	50.0	53.1
25	50.3	53.0	59.3	61.4	50.0	57.9
30	50.3	53.8	66.2	74.1	50.0	64.7
Average	50.3	51.6	54.7	56.4	50.0	

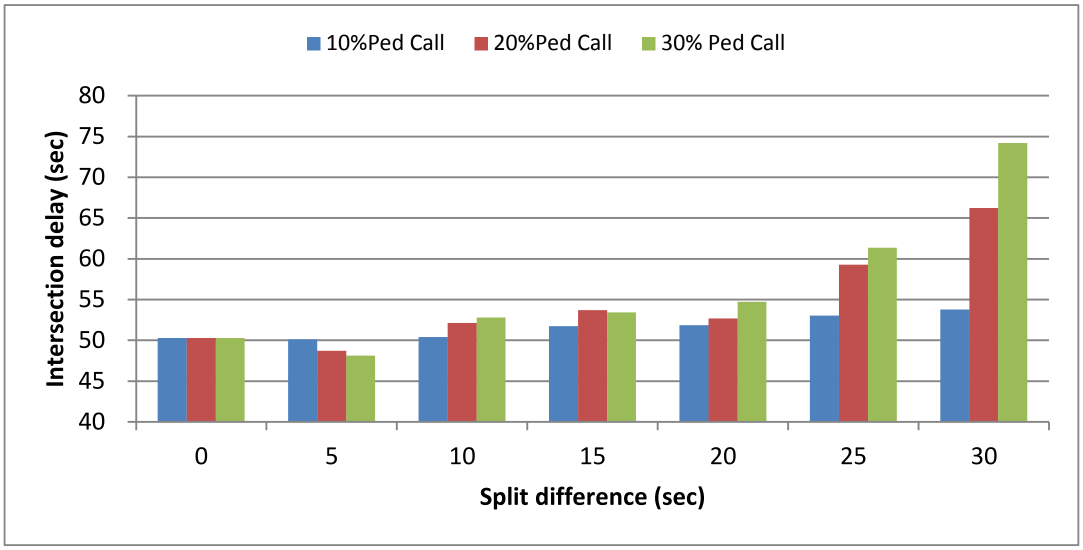

Figure 24 Intersection Delay at 100% V/C Ratio with Subtract Algorithm

Table 21 EBT Movement Delay with *Subtract* at 100% V/C Ratio

Ped Call Split Diff	0%	10%	20%	30%	0% (Isolated control)	Average
0	30.8	30.8	30.8	30.8	33.6	30.8
5	30.8	26.2	29.6	27.8	33.6	27.9
10	30.8	29.8	33.0	32.4	33.6	31.8
15	30.8	29.3	29.8	27.7	33.6	29.0
20	30.8	30.0	31.3	33.6	33.6	31.6
25	30.8	32.9	31.6	37.0	33.6	33.8
30	30.8	32.8	44.3	44.1	33.6	40.4
Average	30.8	30.3	32.9	33.4	33.6	

Table 22 EBT Movement Stop Times with *Subtract* at 100% V/C Ratio

Ped Call Split Diff	0%	10%	20%	30%	0% (Isolated control)	Average
0	0.44	0.44	0.44	0.44	0.72	0.44
5	0.44	0.38	0.43	0.40	0.72	0.40
10	0.44	0.43	0.47	0.46	0.72	0.45
15	0.44	0.42	0.43	0.40	0.72	0.42
20	0.44	0.44	0.46	0.50	0.72	0.47
25	0.44	0.48	0.47	0.57	0.72	0.51
30	0.44	0.49	0.65	0.68	0.72	0.61
Average	0.44	0.44	0.48	0.49	0.72	

Table 21 and Table 22 show a similar impact on delay and stop times of EBT movement with *Subtract* transition. When split difference is under 20 seconds, pedestrian volume will not have a significant impact on delay and stop times of EBT movement. When split difference exceeds 20 seconds, delay and stop times of EBT movement will increase significantly with the increase of pedestrian volume.

5 Conclusions and Recommendations

In this research, the general transition algorithms as well as their impact on signal coordination were firstly reviewed. The transition algorithms were summarized into three categories: lengthening, shortening, and shortway. The impacts of the algorithms on signal coordination were evaluated through a case study using the hardware-in-the-loop simulation. The following conclusions were reached:

- Generally, the Subtract transition algorithm has the least interruptions on signal coordination when the traffic condition is under-saturated. The benefit of the Subtract transition algorithm is more significant with a lower degree of saturation. However, when the split difference increases (e.g. more than 20 seconds), it is necessary to take more factors (e.g. traffic volume) into consideration when choosing the best transition algorithm.

- The Add transition algorithm has the minimum impact on signal coordination when the traffic condition is over saturated.

- The existing Shortway transition algorithm makes a transition decision only based on the split difference, instead of traffic volume conditions. It is not recommended to use this algorithm when traffic flow fluctuates significantly at an intersection.

- When a signal transition is caused by un-accommodated pedestrian crossing, none of the transition algorithms can reduce the interruption of coordination progression to an acceptable level if the split difference is large (e.g. more than 20 seconds) or the pedestrian call frequency is high (e.g. larger than 20%). Engineering judgements are necessary and other solutions for handling pedestrian crossing may be considered. For example, accommodating minimum pedestrian crossing time in the phase split may be used when pedestrian volume is relatively high. Overpasses and underpasses may also provide safe pedestrian crossing environment and avoid interruption of signal coordination.

The summary of the different controllers' configuration performance with regards to different transition algorithms can help traffic engineers expect the controller performance. The results from case studies can provide traffic engineers with quantitative evidence on how un-accommodated pedestrian crossing affects signal coordination. Depending on the traffic condition and pedestrian crossing time at each specific intersection, traffic engineers can choose the most efficient transition algorithm based on the conclusions and recommendations reached in this study.

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