University of Nevada, Reno

Minimizing Negative Impacts Caused by Emergency Vehicle Preemption on Arterial Signal Coordination

A thesis submitted in partial fulfillment of the
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by

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Abstract

Emergency vehicles are essential means of timely and urgent rescue. Emergency vehicle preemption (EVP), the most common form of traffic signal preemption in urban areas, is usually activated to grant emergency vehicles the right of way at signalized intersections by abruptly terminating the current signal timing plan. However, such mandatory signal changes can disrupt arterial signal coordination by terminating the current timing plan at each intersection and triggering unexpected transitions in traffic signal controllers at the end of the preemption. To comprehensively analyze and minimize such negative impacts caused by EVP, this research summarized optical-based EVP operations along with preemption modules in Trafficware 980 ATC V76 signal controllers to illustrate their negative impacts on arterial signal coordination. Hardware-In-the-Loop Simulation (HILS) was utilized to evaluate and compare five exit strategies of EVP in Trafficware 980 ATC V76 signal controllers: no exit phase, exit to fixed phases, exit to fixed phases (end dwell), Coord+Preempt and the dynamic threshold timer under defined five simulation scenarios with different numbers of preemptions. The evaluations were carried out using a signalized arterial, N. McCarran Blvd, which includes two intersections in Reno, Nevada.

It was found that the extent of negative impacts on arterial signal coordination was highly influenced by preemption activation points, routes of the emergency vehicle, the selection of an exit strategy and the number of preemptions. Average vehicle delay on the non-preempted arterial movements tended to rise with an increasing number of preemptions. Among those five exit strategies, no exit phase strategy delivered worse performance than others especially on the arterial through movements. End dwell and the dynamic threshold timer provided more flexibility of phase return than exiting to fixed phases only, which potentially enhances performance on the main-street and side-streets. Coord+Preempt was found to be the best exit strategy to be implemented due to its ability to proceed back to the background coordination without transition and produce the overall minimal delay for all turning movements under different numbers of preemptions.

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First and foremost, I would like to acknowledge my research advisor, Dr. Zong Tian. The door to his office was always open whenever I ran into a trouble spot or had a question about my research or writing. He consistently emboldens me and steers me in the right direction whenever he though I needed it for the past two years.

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Finally, I must express my profound gratitude to my family for their unceasing support and care during my ups and downs. I place on record, my sense of acknowledgement to one and all, who directly or indirectly, have lent their hand in this venture.

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1 Introduction

1.1 Problem Statement

In Manual on Uniform Traffic Control Devices (MUTCD), traffic signal preemption was defined as the transfer of normal operation to special control mode of operation by alternating the normal signal timing and phasing plans. EVP is one of the preemption controls to give the right way to emergency vehicles, such as firetrucks, law enforcement vehicles, ambulances and other official emergency vehicles by terminating current timing plans and activating preemption plans at intersections [1]. However, such mandatory signal changes directly affect normal phase operations and result in signal transitions in traffic signal controllers, which causes the controller to correct the offset and disrupts the entire arterial signal coordination when an emergency vehicle travels along a signalized arterial. Therefore, to analyze and minimize such negative impacts caused by EVP on arterial signal coordination is an essential area of study for researchers and practitioners.

1.2 Research Objective

To cope with the problem, this research summarized optical-based EVP operations along with preemption modules in Trafficware 980 ATC V76 signal controllers to analyze their negative impacts on the arterial signal coordination. Also, the selection of an exit strategy in traffic signal controllers of returning to normal operations at the end of EVP directly affects the performance of the disrupted traffic flows. Following that, performances of five exit strategies: no exit phase, exit to fixed phases, exit to fixed phases (end dwell), Coord+Preempt and the dynamic threshold timer after EVP in Trafficware 980 ATC V76 signal controllers were evaluated and compared using HILS under defined five simulation scenarios with different numbers of preemptions. Recommendations of use regarding the above exit strategies to mitigate EVP negative impacts were provided for agencies and practitioners.

The entire thesis is organized as follows: after this introduction, the second section covers literature review to unfold current EVP-related research. Optical-based EVP operations, including EVP components and preemption modules in Trafficware 980 ATC V76 signal controllers, are demonstrated in detail in the third section. In the fourth section, five exit strategies in Trafficware V76 signal controllers are introduced step by step and analyzed in detail. The fifth section illustrates negative impacts caused by EVP on arterial signal coordination. Following that, the operation mechanism of HILS and its set-up are included in the sixth section. A case study is conducted using HILS to evaluate and compare five exit strategies under five simulation scenarios with different numbers of preemptions in the seventh section. In the end, conclusions and recommendations are provided for engineering practice.

2 Literature Review

2.1 State-of-the-Practice EVP Applications

Federal Highway Administration (FHWA) (2006) conducted a cross-cutting study, which included benefits and learned lessons of EVP implementations in Fairfax County (Virginia), City of Plano (Texas) and St. Paul (Minnesota) [2]. The Centralized Emergency Vehicle Preemption (CEVP) was introduced in City of San José (2018) and proved to be effective in reducing average travel time for fire vehicles [3]. Maricopa Association of Government (MAG) (2016, 2018) summarized a report including operation challenges, current advanced technologies, state-of-the-practice case studies and future considerations regarding EVP [4] [5].

2.2 Signal Transition Caused by EVP

In Signal Timing Manual (STM), signal transition was described as the process of either entering into a coordinated timing plan or changing between two plan and triggered by a number of reasons, such as time-of-day schedule changes, manual operator selections, traffic coordination pattern changes, preemptions, unaccommodated pedestrian crossing and power loss and restoration [6]. During the transition, there were three common techniques to correct the offset: dwell, add and short. Shelby et al. (2006) investigated and compared transition methods in Eagle, Econolite, Nextphase and Naztec traffic signal controllers under the isolated intersection and arterial network environment [7]. They found that shortway transition method was the most effective transition method in general while add transition method performed better under congested conditions. Higher delay was produced using the dwell transition method. Signal transition caused by EVP attracted researchers' attentions and a number of researches centered on seeking the best transition method to exit from EVP to minimize its negative impacts on disrupted flows using Software-In-the-Loop (SILS) [8-9] and HILS [10-11]. They all reached the similar conclusions that the shortway (best way or smooth) transition method, which selected the quickest way by either lengthening or shortening phase splits to correct the offset, outperformed any other methods by producing enhanced measures of effectiveness (MOEs).

2.3 Hardware-In-the-Loop Simulation Studies of EVP

In order to better analyze and evaluate impacts of EVP, it is important to build connections between the simulation software and various brands of traffic signal controllers. Bullock et al. (1997) invented an interface called controller interface device (CID) to build real-time connections between the traffic signal controller and the simulation software, CORSIM [12]. Detector actuations were sent from CORSIM to the controller via CID and the controller transmitted signal indications back to the simulation package to set up the real-time communications. Based on the invention of CID, several researches were conducted to evaluate negative impacts of EVP on coordinated arterials through HILS. Bullock et al. (1998) studied impacts of EVP on three coordinated intersections in Virginia and proposed a general procedure to quantify impacts of EVP at a coordinated corridor [14]. In this study, they found that the impacts of preemption did not significantly influence arterial travel times on long-spacing intersections with long cycle length. Considering limitations of the previous study, such as long spacing between intersections, long cycle length and lack of evaluations on alternative transition strategies, Nelson and Bullock (2000) studied impacts of EVP on a coordinated arterial with closely-spaced intersections with a shorter cycle length and compared three transition strategies [15]. It was found that severe impacts were exerted on traffic operations with multiple EVP calls at closely-spaced intersections and smooth performed the best among other transition algorithms. Yun et al. (2011) utilized HILS to explore exit strategies in Econolite ASC/3-2100 controllers and included four coordinated intersections in Chantilly, Virginia [16]. They found that the dynamic exit phase control outweighed the fixed exit phase control to minimize EVP negative impacts and both of them produced reduced network delay than no exit phase control.

2.4 Other EVP-related Research

The remaining EVP-related studies mostly focused on proposing enhanced EVP systems [17-18] and optimized EVP control strategies with the purpose of minimizing travel times and maximizing average travel speeds for emergency vehicles [19-26]. Besides that, Teng et al. (2010) utilized GPS data from paratransit vehicles in City of Las Vegas to assess the impact of emergency vehicles on urban traffic speeds [27]. They found that the speed variance was significantly higher during the preemption and mean speeds were lower than normal conditions. Traffic on major arterials and in the opposite direction of the emergency vehicle tended to have higher speeds. In addition to that, signal preemption posed significantly negative impacts on traffic speeds during peak periods.

2.5 Contribution of This Research

The above pioneering studies mainly focused on: evaluating negative impacts caused by EVP, exploring the most efficient transition method to exit from EVP and proposing control strategies to minimize negative impacts caused by EVP. However, none of the previous research summarized EVP operations along with preemption modules in traffic signal controllers to address negative impacts caused by EVP on arterial signal coordination. Additionally, investigating the most effective transition method is only part of the countermeasures for minimizing such impacts and a large number of exit strategies of EVP released by traffic signal controller manufacturers remain to be discovered and evaluated. Therefore, this study summarized EVP operations integrated with preemption modules in Trafficware 980 ATC V76 signal controllers to analyze their negative impacts on arterial signal coordination. Five exit strategies in Trafficware 980 ATC V76 signal controllers were evaluated and compared using HILS under defined five simulation scenarios with different numbers of preemption calls. Recommendations of use were provided for engineering practice.

3 Optical-based Emergency Vehicle Preemption

In practice, there are three common types of EVP being used: optical-based EVP, radio-based EVP and GPS-based EVP. In this study, optical-based EVP is studied for further analysis due to existing optical emergency preemption systems in City of Reno, Nevada.

3.1 Optical-based EVP Components

The optical-based EVP commonly consists of four parts: optical emitters, optical detectors, confirmation lights and preemption detector cards.

3.1.1 Optical Emitter

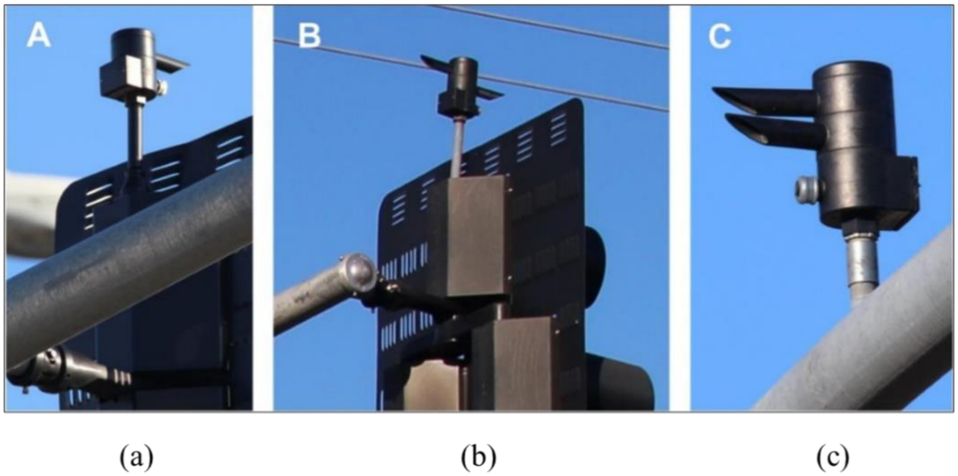
As shown in Figure 1, the optical emitter is usually mounted on the top of the emergency vehicle and transmits infrared strobe signal to the optical detector to activate traffic signal preemption. If the emergency vehicle is detected within the detection range of the optical detector, which is up to 2500 feet, the emergency signal will be forwarded to the optical detector then directly transmitted to the traffic signal cabinet for ID identifications.

Figure 1 Optical Emitter
Note. The figure is from *Emergency Vehicle Preemption State of the Practice Study*. 2016 [4]

3.1.2 Optical Detector

In practice, there are various types of optical detectors categorized as one-sight tube and two-sight tubes either for detecting two directions or the single direction. They are installed on the traffic signal arms and functioning by interacting with transmitted signals from emergency vehicles and delivering preemption request to the traffic signal cabinet. Figure 2 presents three typical kinds of optical detectors.

Compared with the one-sight tube detecting only one direction, two-sight tubes integrated into the same detector are more cost-effective in reducing the amount of wiring and underground conduits. In order to overcome sight limitations on curved roads, two-sight tubes with slightly different angles pointing at the same direction are implemented [4].



(a) (b) (c)

Figure 2 Optical Detectors: (a) one-sight tube detector, (b) two-sight tube detector pointing at two directions, (c) two-sight tube detector pointing at the same direction
Note. The figure is from *Emergency Vehicle Preemption State of the Practice Study*. 2016 [4]

3.1.3 Confirmation Light

The function of the confirmation light is to flash to provide EVP status feedback to emergency vehicles [4]. In addition to that, it delivers warnings to adjacent vehicles and pedestrians so that they can yield the right of way to the upcoming emergency vehicle in advance. The confirmation light is commonly installed next to the optical detector on the signal arm, which is shown in Figure 3.

Figure 3 Confirmation Light
Note. The figure is from *Emergency Vehicle Preemption State of the Practice Study*. 2016 [4]

3.1.4 Preemption Detector Card

Preemption detector cards are housed into the traffic signal cabinet to process preemption requests delivered from the optical detectors [4]. They activate corresponding preemption plans in the controller for the preempted direction after successful identifications of vehicle encoded ID. Eventually, EVP will be activated to prioritize the right of way to the emergency vehicle. Figure 4 displays the preemption detector card in the cabinet.

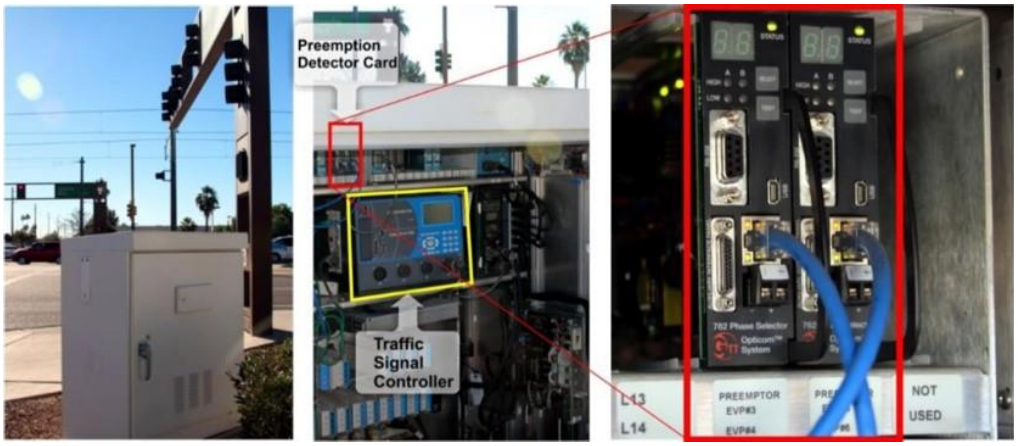
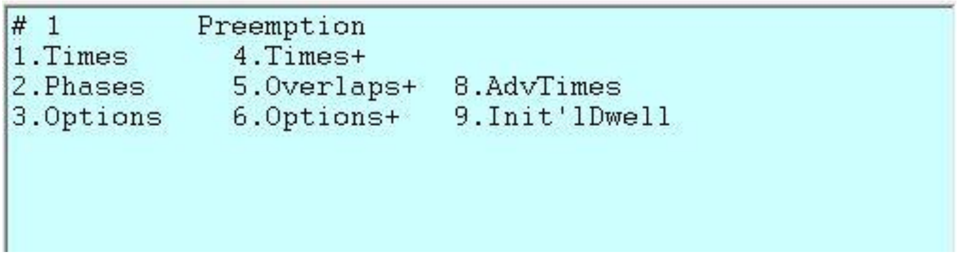


Figure 4 Preemption Detection Card in the Cabinet
Note. The figure is from *Emergency Vehicle Preemption State of the Practice Study*. 2016 [4]

3.2 Preemption Modules

In this research, preemption modules in Trafficware 980 ATC V76 controllers, one of the dominating signal controllers in the US market, are studied and introduced due to research projects sponsored by Regional Transportation Commission (RTC) of Washoe County, Nevada. There are 9 modules enclosed in each preemptor in the controller [28], which are illustrated in Figure 5. In this section, preemption times and preemption phases will be presented and explained in detail.

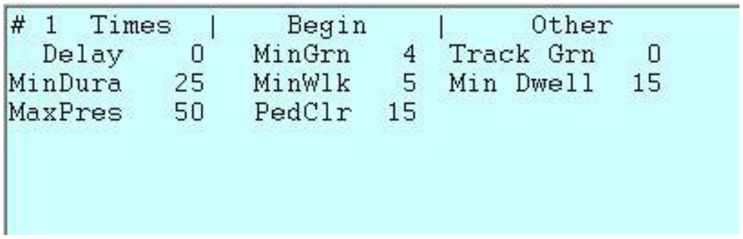


```
# 1         Preemption
1.Times       4.Times+
2.Phases      5.Overlaps+   8.AdvTimes
3.Options     6.Options+    9.Init'lDwell
```

Figure 5 Preemptor Modules

3.2.1 Preemption Times

In Figure 6, among all time parameters except for track green, which is especially used for railroad preemptions, they define how preemption terminates the current timing plan and active preemption periods.



```
# 1  Times   |    Begin     |     Other
  Delay    0   MinGrn   4  Track Grn   0
MinDura   25   MinWlk   5  Min Dwell  15
MaxPres   50   PedClr  15
```

Figure 6 Preemptor Times

3.2.1.1 Delay Time (Delay)

Delay time (0-600 sec) specifies a buffer period prior to running preempted phases. During this interval, the preemption call was received and will not come into effect until the end of the delay time. The preemption will be executed immediately if the delay time is set to 0.

3.2.1.2 Minimum Duration (MinDura)

The minimum duration (0-9999 sec) determines the shortest active preemption period and it begins to count down at the end of the delay timer.

3.2.1.3 Maximum Presence (MaxPres)

In contrast with the minimum duration, the maximum presence (0-9999 sec) limits the maximum active preemption period. Once the preemption call is holding over the programmed value, the controller will terminate the current preemption instantly and execute the programmed exit strategy.

3.2.1.4 Minimum Green (MinGrn)

The preemption minimum green (0-255 sec) guarantees the lesser of the preemption minimum green time or the programmed phase minimum green time for the current active phases when preemption is triggered during the phase minimum green period. More specifically, the minimum green timer will directly reduce from the phase minimum green time to preemption minimum green time if the former is greater than the latter.

3.2.1.5 Minimum Walk (MinWlk)

Functioning similarly to the minimum green, minimum walk (0-255 sec) insures the current active walk interval to be the lesser of minimum walk or the programmed phase walk time prior to running the preemption. This feature provides an option to end the currently conflicting pedestrian interval less violently before running the preemption.

3.2.1.6 Enter Pedestrian Clearance (PedClr)

Working in conjunction with the minimum walk, enter pedestrian clearance (0-255 sec) guarantees the lesser of the preemption pedestrian clearance time or the programmed pedestrian clearance time for the currently conflicting pedestrian phases before running the preemption.

3.2.1.7 Minimum Dwell (Min Dwell)

Minimum dwell (1-255 sec) determines the minimum active period of dwell phases and begins to count down at the end of the conflicting phase clearance period.

3.2.1.8 Preemption Times Summary

In practice, the entire preemption periods can be divided into not more than five periods: delay period, conflicting phase clearance period, min dwell period, min duration hold period and max presence hold period. As shown in Figure 7, preemption starts at the end of the delay period if the delay timer is not programmed as 0. If non-preempted vehicle or pedestrian phases are currently running, the preemptor will execute the conflicting phase clearance period by running the lesser of the preemption minimum time or the programmed phase minimum time. Then the preempted phases start to be served and held upon the expiration of the minimum duration timer (if the minimum duration time is programmed relatively long to cover the conflicting phase clearance period and the min dwell period). Once the emergency vehicle does not clear from the intersection after the min duration hold period, the max presence hold period extends the preemption until it clears. Max presence hold period may not exist if the emergency vehicle travels through the intersection by the end of the min duration hold period.

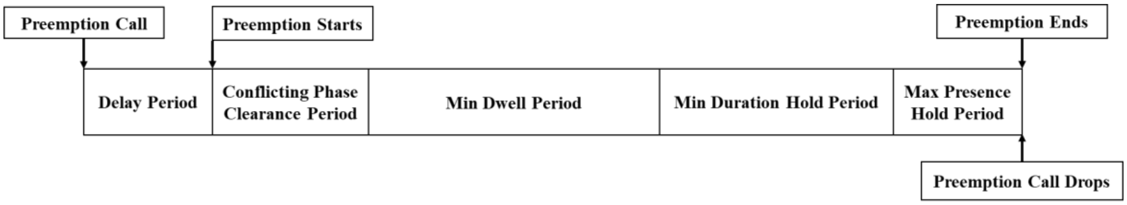
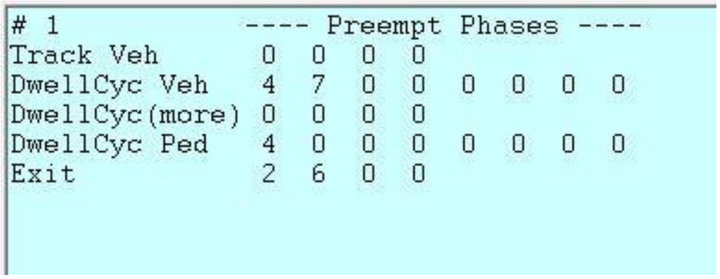


Figure 7 Preemption Times Summary

3.2.2 Preemption Phases

Under entries of preemption phases in Figure 8, a preemptor can define track vehicle phases, dwell vehicle phases, dwell pedestrian movements and exit phases. For the first row, track vehicle phase is especially used for the railroad preemption.



```
# 1           ---- Preempt Phases ----
Track Veh      0  0  0  0
DwellCyc Veh   4  7  0  0  0  0  0  0
DwellCyc(more) 0  0  0  0
DwellCyc Ped   4  0  0  0  0  0  0  0
Exit           2  6  0  0
```

Figure 8 Preemption Phases

3.2.2.1 Dwell Vehicle Phases (DwellCyc Veh)

Dwell vehicle phases determine which phases to be served in each ring during the preemption. It is possible to define multiple dwell phases in each ring (up to 12 in total) while they are required not to conflict with the preempted movement. In Figure 8, Ø4 and Ø7 are programmed as the dwell phases.

3.2.2.2 Dwell Pedestrian Movements (DwellCyc Ped)

Pedestrians can be served during the preemption when dwell pedestrian movements are programmed correspondingly. Dwell pedestrian phases must be set as dwell vehicle phases and the walk interval and pedestrian clearance interval during the preemption are determined by the programmed phase pedestrian crossing parameters. In Figure 8, the pedestrian movement associated with Ø4 is programmed and can be activated during the preemption.

3.2.2.3 Exit Phases (Exit)

Specifying fixed exit phases at the end of the preemption is one of the exit strategies. Exit phases determine which phases to be returned at the end of the preemption. It should be noticed that only one phase is allowed to be programmed in each ring and all exit phases are required to be concurrent. In Figure 8, Ø2 and Ø6 are programmed as the exit phases.

3.3 Optical-based EVP Operations

Based on the above introductions to preemption times and phase parameters, optical-based EVP operations are depicted as a flow chart in Figure 9.

Once the emergency vehicle is detected within the detection range, the signal captured by the optical detector will be delivered to the preemption detector card in the traffic signal cabinet for encoded ID identifications. If encoded, the signal controller will promptly execute the programmed preemption plan to initiate the delay timer, min duration timer and max presence timer or do nothing if not encoded. If currently active vehicle and pedestrian phases are conflicting with preempted phases, the preemptor will start to terminate them by running conflicting phase clearance period to transition to the preemption. Dwell phases start to be served and the min duration timer will continue to hold until it expires at the end of the min dwell period. Once the emergency vehicle clears from the intersection and is no longer detected, the programmed exit strategy will function to return to normal operations. It should be noted that the controller starts to check the max presence timer during the entire preemption period. Once it expires, the preemption ends and the controller runs the programmed exit strategy immediately.

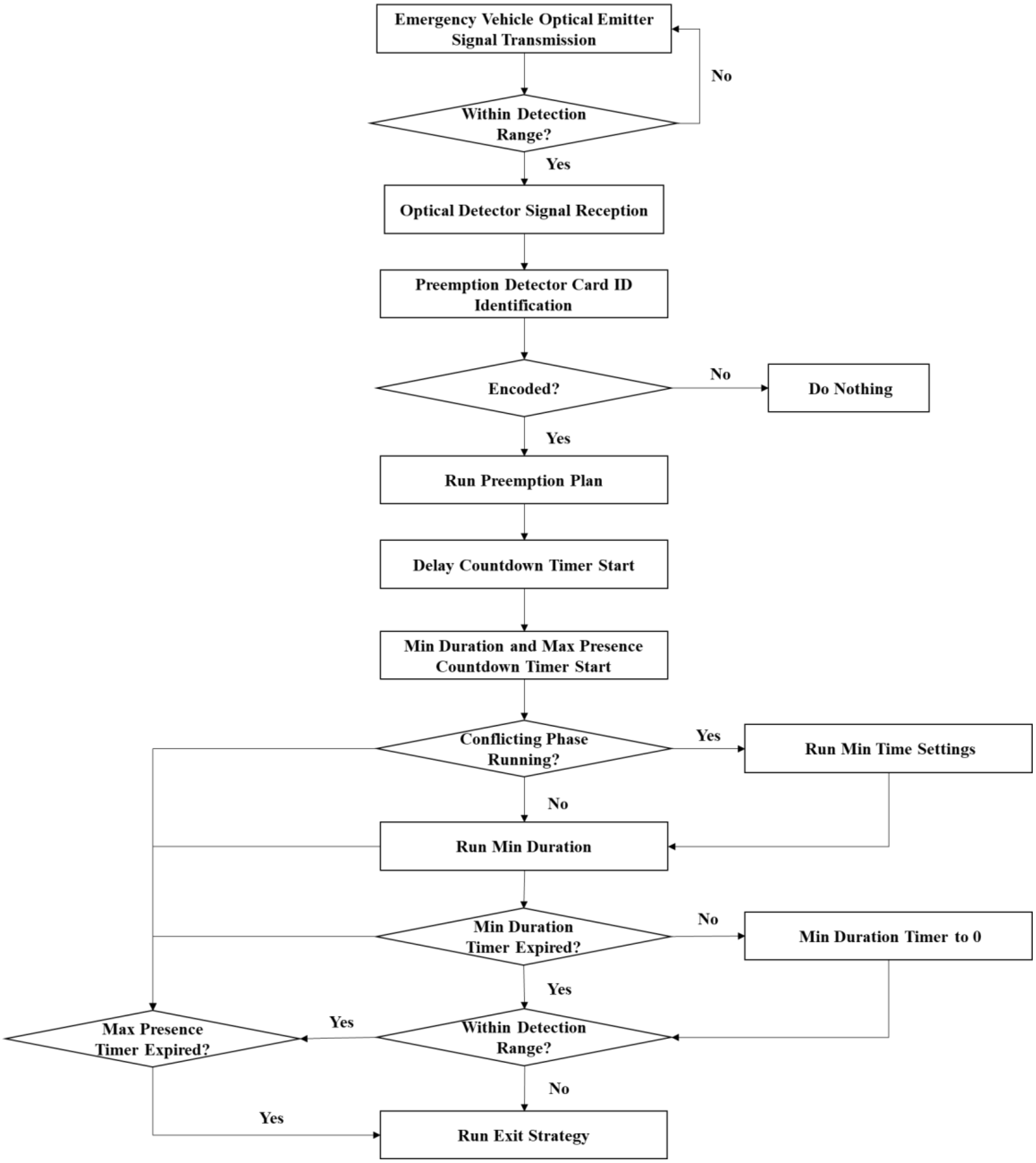


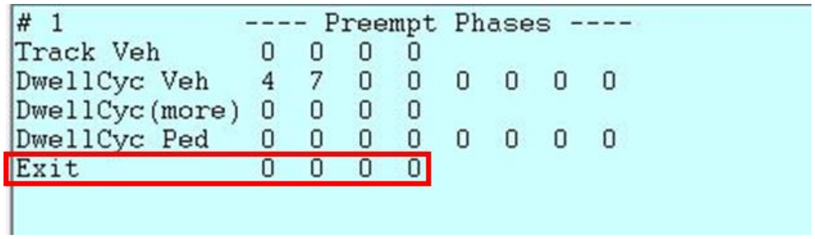
Figure 9 Optical-based EVP Operations

4 Exit Strategies of Emergency Vehicle Preemption

In this research, the following five exit strategies of EVP in Trafficware 980 ATC V76 signal controllers are included for further analysis and evaluations.

4.1 No Exit Phases

From the controller manual, it is recommended to program exit phases when Coord+Preempt is off. Otherwise, there is no certainty on which phases the controller will return to. In practice, some agencies ignore the importance of exit phases and leave them empty due to the lacking knowledge of EVP operations. In Figure 10, no exit phases are specified.

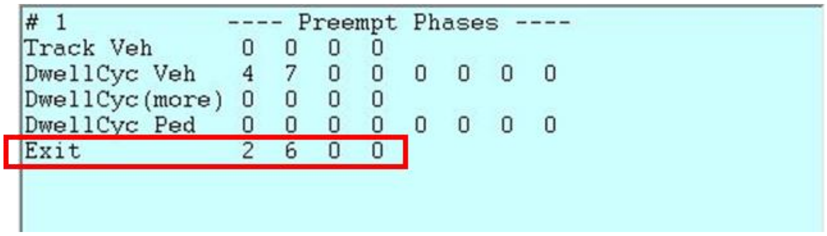


```
# 1            ---- Preempt Phases ----
Track Veh        0   0   0   0
DwellCyc Veh     4   7   0   0   0   0   0   0
DwellCyc(more)   0   0   0   0
DwellCyc Ped     0   0   0   0   0   0   0   0
Exit             0   0   0   0
```

Figure 10 No Exit Phases

4.2 Exit to Fixed Phases

Exit to fixed phase strategy unconditionally returns to programmed compatible phases at the end of the preemption. During the test, it was found that transition occurred when returning to programmed phases, which caused a resynchronization period for the controller to be back in sync. In Figure 11, Ø2 and Ø6 are programmed as the exit phases.

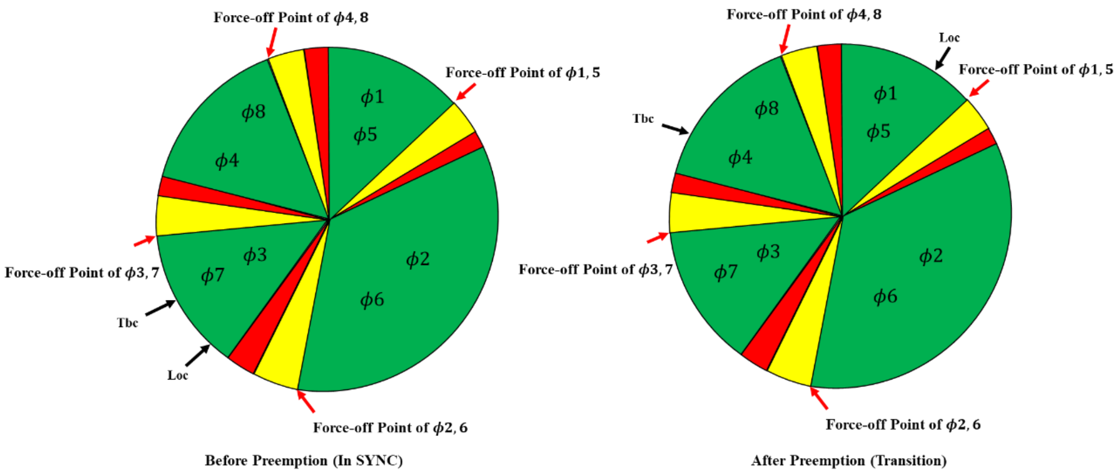


```
# 1           ---- Preempt Phases ----
Track Veh       0  0  0  0
DwellCyc Veh    4  7  0  0  0  0  0  0
DwellCyc(more)  0  0  0  0
DwellCyc Ped    0  0  0  0  0  0  0  0
Exit            2  6  0  0
```

Figure 11 Exit to Fixed Phases

As shown in Figure 12, the left part displays the permissive window of a signal timing plan with Ø2 as the coordinated phase. Force-off points of all phases are highlighted by red arrows and local clock (loc) and system clock (tbc) are depicted by black arrows. Suppose the timing plan is in sync and Ø3 and Ø7 are running at the moment. Main-street through phases, Ø2 and Ø6, are programmed as exit phases at the end of the preemption. One emergency vehicle suddenly activated the preemption with the dwell phase, Ø2, on the main street and it was found that the loc jumped to the point several seconds prior to the force-off point of preceding phases, Ø1 and Ø5, at the end of preemption. This resulted in signal transitions caused by the offset corrections between loc and tbc. It could be seen that Ø3 and Ø7 were partially served and Ø4 and Ø8 were skipped and starved to be served until the next cycle.

From the example, it is clear to know that exit to fixed phases strategy forces the controller to unconditionally return to programmed exit phases, which triggers signal transitions resulting in phase starving and phase skipping.



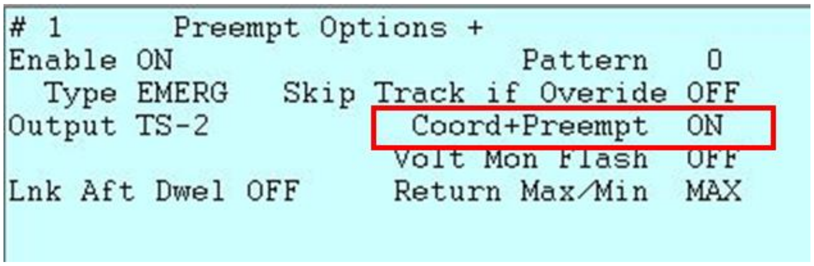
Before Preemption (In SYNC)

After Preemption (Transition)

Figure 12 Exit to Fixed Phases Illustrations

4.3 Coord+Preempt

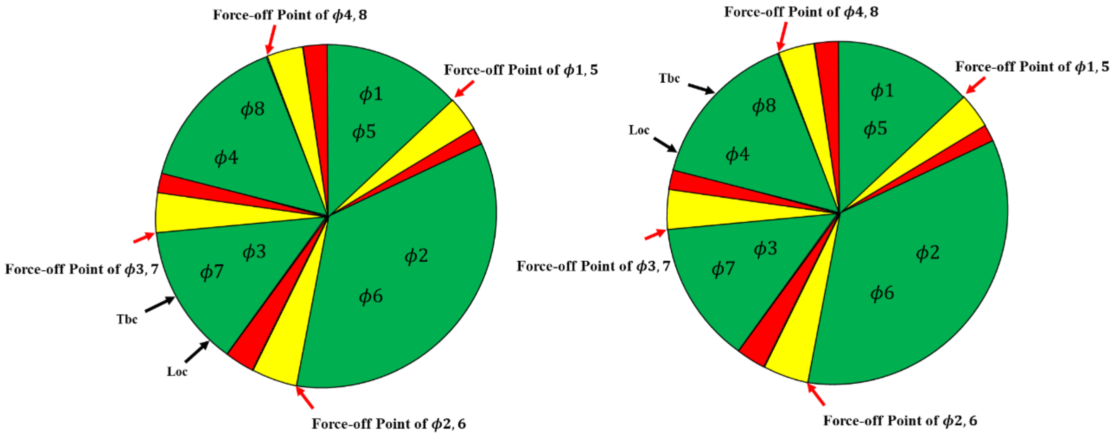
Different from the previous strategy, Coord+Preempt allows the coordination to proceed in the background when the preemption is running. The biggest advantage of this strategy is to maintain coordination without going through a transition period to correct the offset at the end of the preemption. It aims to disrupt current coordination as slightly as possible to eliminate negative impacts caused by EVP. From the controller manual, it is recommended not to use both exit to fixed phases and Coord+Preempt as exit strategies at the same time, which will confuse the controller to select exit phases appropriately. Coord+Preempt can be enabled under preemption options+ shown in Figure 13.



```
# 1       Preempt Options +
Enable ON                Pattern    0
  Type EMERG   Skip Track if Overide OFF
Output TS-2             Coord+Preempt   ON
                        Volt Mon Flash  OFF
Lnk Aft Dwel OFF        Return Max/Min  MAX
```

Figure 13 Coord+Preempt Option

The operation mechanism of this strategy is explained in detail in Figure 14. Suppose the timing plan is in sync and Ø3 and Ø7 are currently running with Coord+Preempt enabled as the exit strategy. A preemption call is activated at the moment and it was found that the time difference between loc and tbc remained unchanged when returning to coordination. Consequently, no signal transition occurred and the controller returned to Ø4 and Ø8 eventually. The exit phases are determined by where the loc is at the end of preemption. In this example, Ø4 and Ø8 were selected as exit phases since loc fell into the permissive window of Ø4 and Ø8 at the end of the preemption.



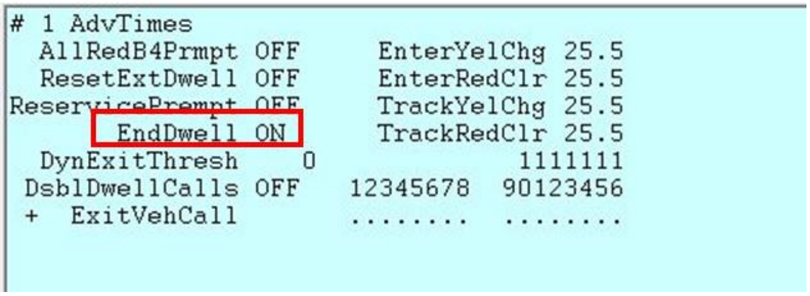
Before Preemption (In SYNC)

After Preemption (In SYNC)

Figure 14 Coord+Preempt Illustrations

4.4 End Dwell

When preemption comes into effect, non-preempted phases starve to be served during the dwell period until the termination of the preemption. End dwell provides an ancillary option for the controller to serve those non-preempted phases prior to running exit phases. This feature can be turned on or off under preemption advanced times illustrated in Figure 15. It functions by inserting a fully-actuated period to clear queues of non-preempted phases, which is demonstrated in Figure 16. During the test, this feature worked in conjunction with the exit to fixed phases strategy and played a vital role in serving overburdened non-preempted phases during the dwell period prior to returning to programmed exit phases. However, it was found that transition mostly occurred and the return point of loc became unpredictable based on starving phase demands, which may either benefit or worsen traffic operations when returning to normal operations.



```
# 1 AdvTimes
  AllRedB4Prmpt OFF     EnterYelChg 25.5
  ResetExtDwell OFF     EnterRedClr 25.5
ReservicePrempt OFF     TrackYelChg 25.5
       EndDwell ON      TrackRedClr 25.5
  DynExitThresh    0        1111111
 DsblDwellCalls OFF   12345678  90123456
 +  ExitVehCall        ........  ........
```

Figure 15 End Dwell Option

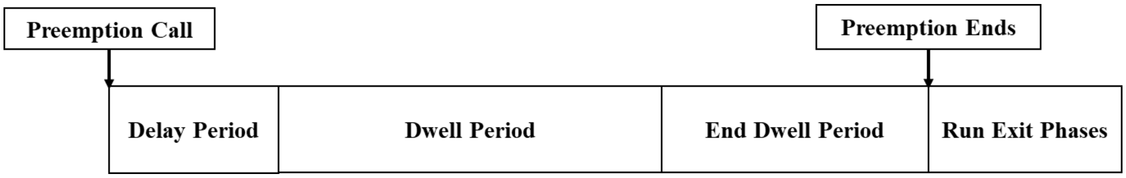
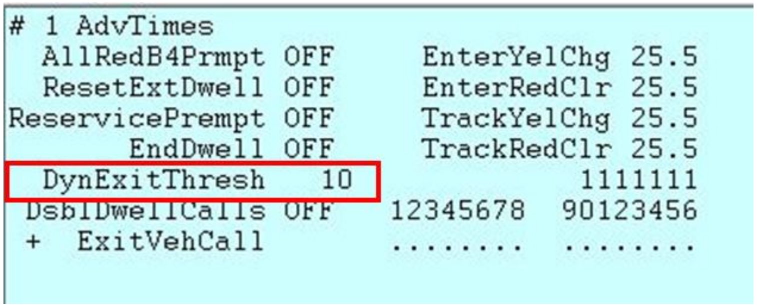


Figure 16 End Dwell Illustrations

4.5 Dynamic Threshold Timer (DynExitThresh)

The Dynamic threshold timer is the most dynamic of all exit strategies. The controller aims to select compatible phases, which have not been served for the longest time over the programmed threshold during the dwell period. It provides an option for the controller to dynamically select exit phases based on non-preempted phase waiting times. This strategy can be enabled by specifying a non-zero threshold under preemption advanced times indicated in Figure 17.

Shown in Figure 18, once the threshold is programmed to 0, programmed exit phases will be returned at the end of the preemption. If not, the controller checks waiting times of all unserved phases during the dwell period and compares them with the threshold. If no phase satisfies the requirement, programmed exit phases will be returned. If yes, the phase with the longest waiting time is going to be selected as the primary exit phase. Then the controller continues to seek the second compatible exit phase in other rings with the longest waiting time. Eventually, exit phases will be determined and returned to terminate the preemption. It should be addressed that physical vehicle inputs rather than recall modes will determine exit phase selections. During the test, this strategy cannot function concurrently with the Coord+Preempt and the end dwell option.



```
# 1 AdvTimes
  AllRedB4Prmpt OFF     EnterYelChg 25.5
  ResetExtDwell OFF     EnterRedClr 25.5
ReservicePrempt OFF     TrackYelChg 25.5
       EndDwell OFF     TrackRedClr 25.5
  DynExitThresh   10               1111111
 DsblDwellCalls OFF   12345678  90123456
 +  ExitVehCall       ........  ........
```

Figure 17 Dynamic Threshold Timer

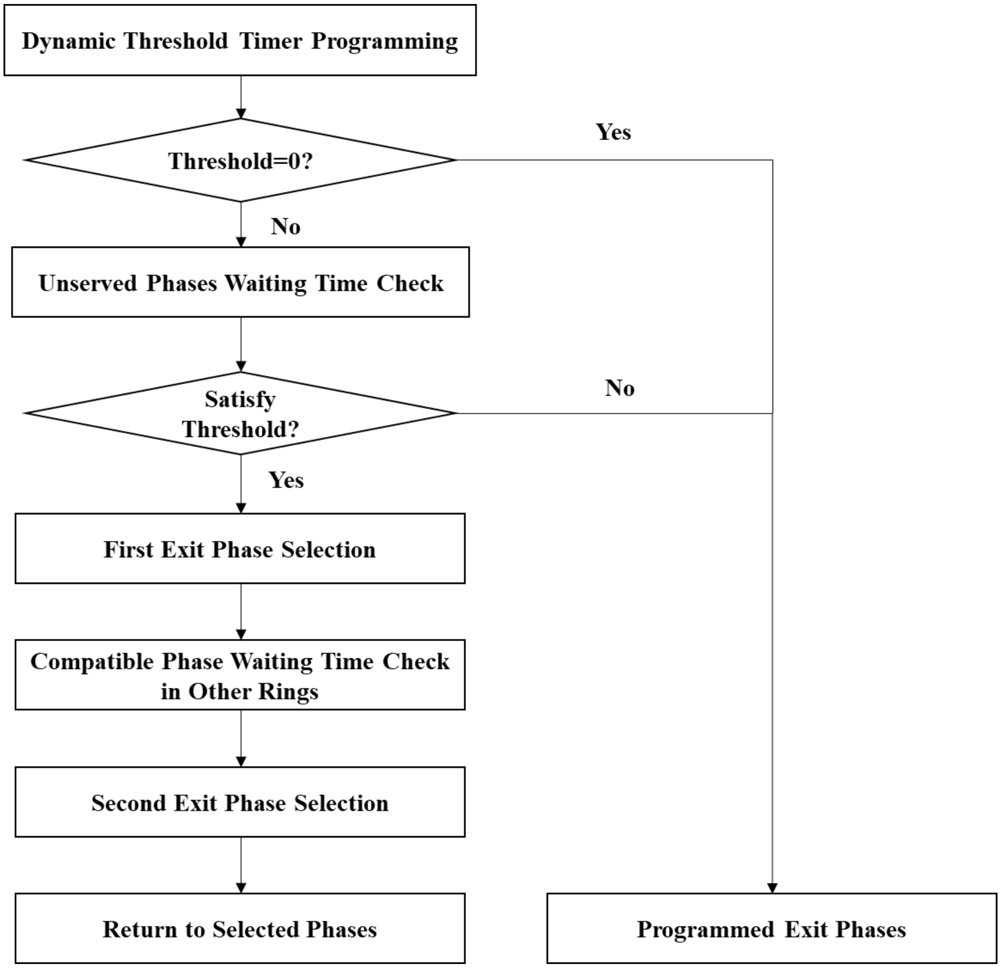


Figure 18 Dynamic Threshold Timer Operations

4.6 Exit Strategies Summary

Based on characteristics of the above exit strategies, analysis of advantages and disadvantages regarding them are presented in Table 1.

Table 1 Advantages and Disadvantages Analysis of Exit Strategies

	Advantages	Disadvantages
No Exit Phase		(1) There is no certainty on which phases to be returned to.
Exit to Fixed Phases	(1) The controller unconditionally returns to programmed exit phases.	(1) Signal transition occurs and disrupts arterial signal coordination. (2) Non-returned phases will be skipped and delayed due to programmed phases return.
Coord+Preempt	(1) The coordination proceeds in the background when preemption is running. (2) No transition occurs at the end of the preemption.	(1) Phases may be partially served or skipped when the controller returns to the following phases in sequence.
End Dwell	(1) It provides an ancillary option to serve non-preempted phases prior to running programmed exit phases.	(1) Signal transition mostly occurs and disrupts arterial signal coordination. (2) The return point of loc becomes unpredictable and signal transition time may increase due to unpredictable non-preempted phases serving.
Dynamic Threshold Timer	(1) Non-preempted phases with the longest waiting time can be automatically selected if satisfying the programmed threshold.	(1) Setting a relatively higher threshold timer will trigger the programmed exit phases to be returned rather than dynamic selections. (2) Signal transition occurs and disrupts arterial signal coordination.

On basis of exit to fixed phases strategy, end dwell inserts a fully actuated period to serve starving phases during the dwell period prior to running programmed exit phases. The dynamic threshold timer provides the flexibility to select exit phases dynamically once waiting times of non-preempted phases satisfy the threshold. In summary, there are five potential exit strategy options, displayed in Table 2, to be chosen in Trafficware 980 ATC V76 signal controllers.

Table 2 Potential Exit Strategy Options

	Potential Exit Strategy Options
1	No Exit Phase
2	Exit to Fixed Phases
3	Coord+Preempt
4	Exit to fixed phases + End Dwell
5	Dynamic Threshold Timer (Exit to Fixed Phases)

5 Negative Impacts Caused by EVP on Arterial Signal Coordination

It is not uncommon to see an emergency vehicle travel through a well-coordinated arterial by activating preemptions and terminating current timing plans at each intersection. Although the right of way is being preempted, negative impacts caused by EVP are exerted on arterial signal coordination. Such impacts vary based on the preemption activation point, routes of the emergency vehicle and the selection of an exit strategy. Two potential outcomes are illustrated as follows: Opponent through band cut-off and preemption band generation.

5.1 Opponent Link Band Cut-off

In order to clearly illustrate negative impacts caused by EVP on arterial signal coordination, the time-space diagram (TSD) is utilized for analysis. As shown in Figure 19, solid green and blue bars indicate eastbound (EB) and westbound (WB) through phases (∅4 and ∅8), respectively. Red bars display side-street phases. Green and blue parallelograms represent EB and WB link bands between two intersections. Downward green-hatched and upward blue-hatched bars indicate EB and WB left-turn phases (∅7 and ∅3), respectively.

Suppose one emergency vehicle is heading EB and activates preemptions at both intersections at certain distance (within the detection range) ahead of the first intersection. Vehicle trajectories are displayed as the black dashed line. At the beginning, WB through green at the first intersection terminates to give the right-of-way to preempted phases (∅4 and ∅7), which causes loss time of WB through movement during the preemption. Following the trajectory, the emergency vehicle eats up WB through green time at the second intersection and cuts off a portion of the WB link band, highlighted as downward blue-hatched parallelogram. Once the emergency vehicle exits from each intersection, programmed exit strategies begin to play an essential role in determining return phases. During the preemption, a large portion of the WB link band was disrupted, which resulted in undesired queues and delay for WB through movement. Such negative impacts could be extended to side-street movements if inappropriate exit strategy was selected. Also, it could be imagined that designed arterial signal coordination will be completely disrupted if the emergency vehicle travels through and activates preemptions at each intersection on an arterial. At this point, the appropriate selection of an exit strategy can be used to minimize such negative impacts.

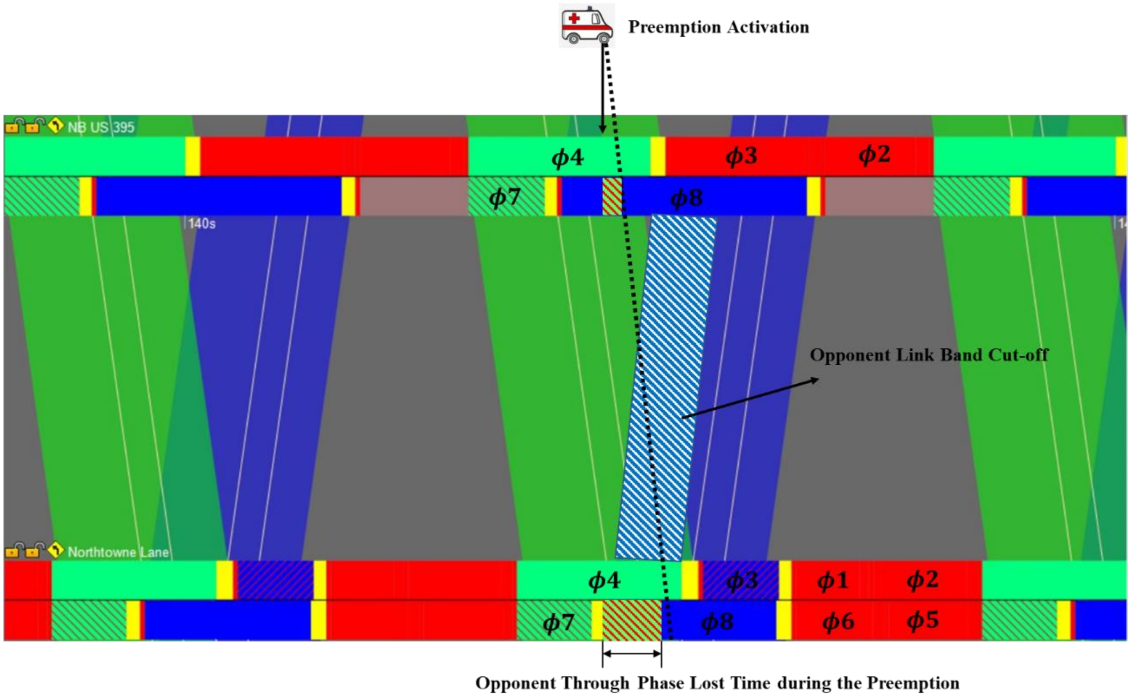


Figure 19 Opponent Link Band Cut-off

5.2 Preemption Band Generation

Another potential outcome caused by EVP is the generation of the preemption band to disrupt side-street operations if the emergency vehicle activates preemption at certain points within the side-street permissive window. Shown in Figure 20, suppose an emergency vehicle is heading EB and a new EB link band is generated between two intersections, which disrupts side-street traffic operations by terminating side-street phases at both intersections. For the worst scenario, side-street phases may be skipped and will not get served until the next cycle if exit phases are programmed as main-street through phases.

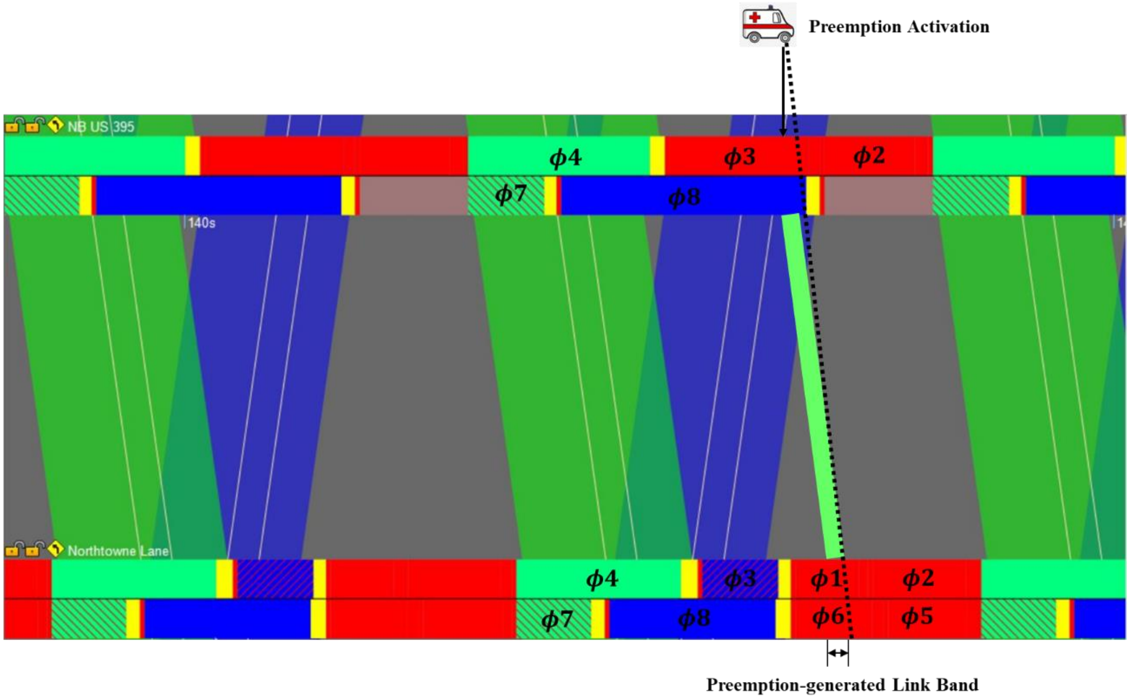


Figure 20 Preemption Band Generation

6 Hardware-In-the-Loop Simulation (HILS)

6.1 HILS Concept

HILS was innovated as an approach to achieve evaluations of various traffic signal systems. In practice, traffic signal controller manufacturers do not release details of control algorithms in their controllers, which makes it difficult for traffic simulation software to include all features comprehensively from different manufacturers into the program. Additionally, increasingly new features released in different traffic signal controllers are supposed to be fully tested and evaluated due to safety concerns, such as inappropriate and conflicting settings, before deployment in the field. To bridge the gap, it is of essence to produce an interface to build connections between different brands of traffic signal controllers and simulation software. The simulation software is able to simulate traffic flows and provide MOEs to quantify the performance.

Illustrated in Figure 21, a closed loop system is set up for HILS: real-time detector actuations are sent from the simulation program to the traffic signal controller via CID and simultaneously, phase indications from the controller are sent back to the software to control vehicle movements.

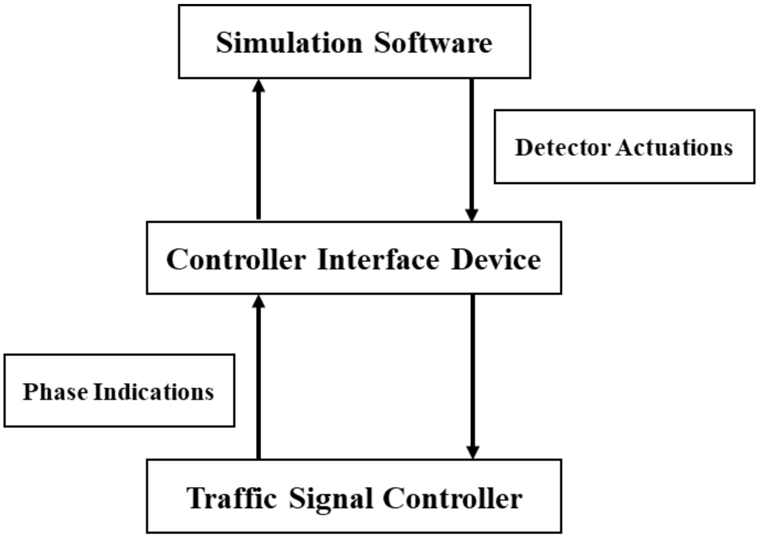


Figure 21 HILS Operation Mechanism

6.2 HILS Set-up

In this study, HILS was the only approach to evaluating and comparing five exit strategies of EVP in Trafficware 980 ATC V76 signal controllers as no current simulation software include exactly the same preemption module. In Figure 22, PM timing plans of two intersections were coded into two real controllers accordingly. A, B and C connectors of two controllers were linked to controller interface devices, which function by providing power supply to controllers. To build connections between the controller and the simulation package, two NEMA TS2 testboxes released by Trafficware, were used as the CIDs. Two SDLC cables were linked from P-1/SP5 ports of two controllers to TS-2 ports of testboxes. The laptop was connected to testboxes via two USB cables. Synchro 10 was utilized to code the simulation model including two intersections and CI options in SimTraffic were used to match intersections with correct USB ports [29], which is shown in Figure 22. During the simulation, detector actuations in SimTraffic were transmitted to controllers via testboxes and phase indications were sent back to SimTraffic to achieve real-time communications.

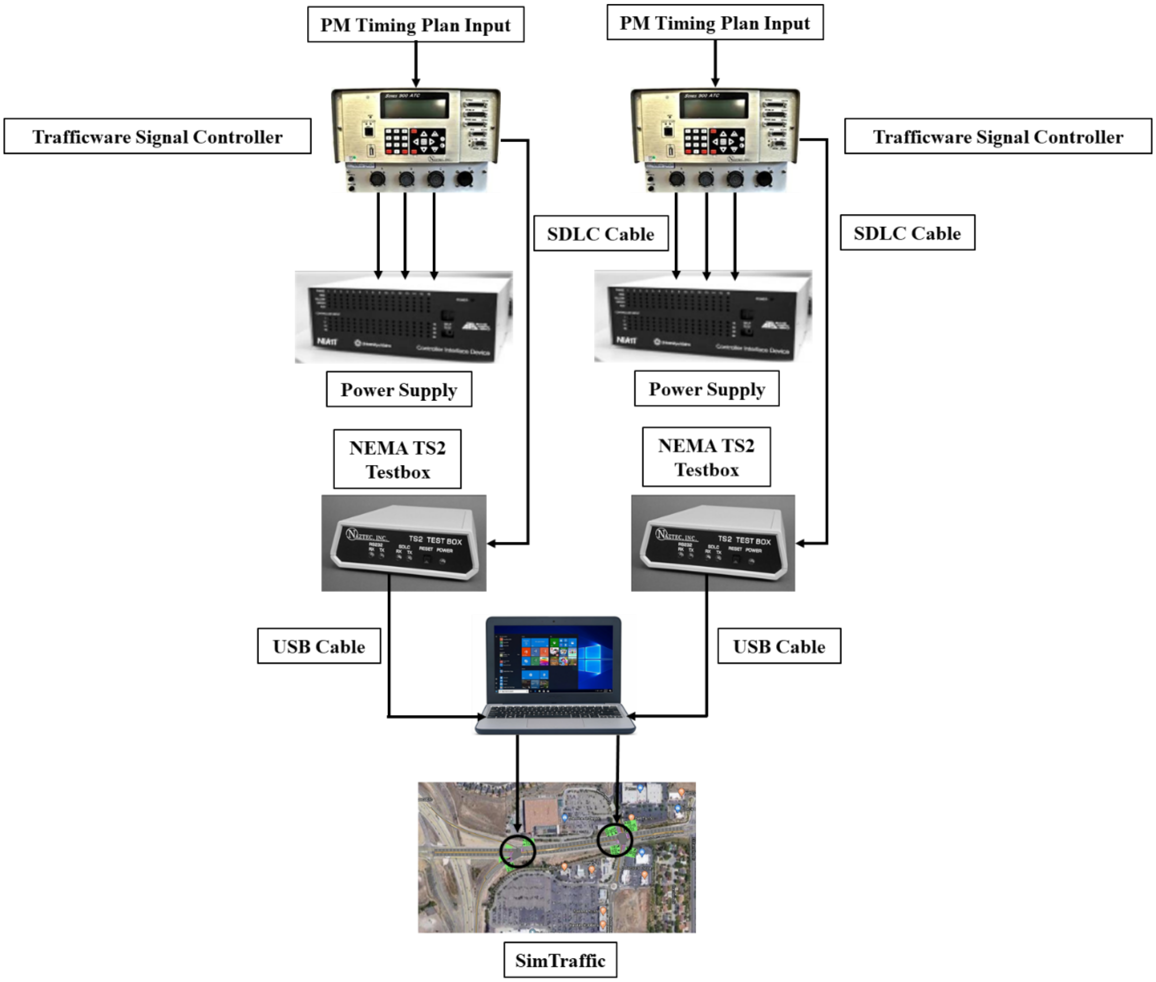
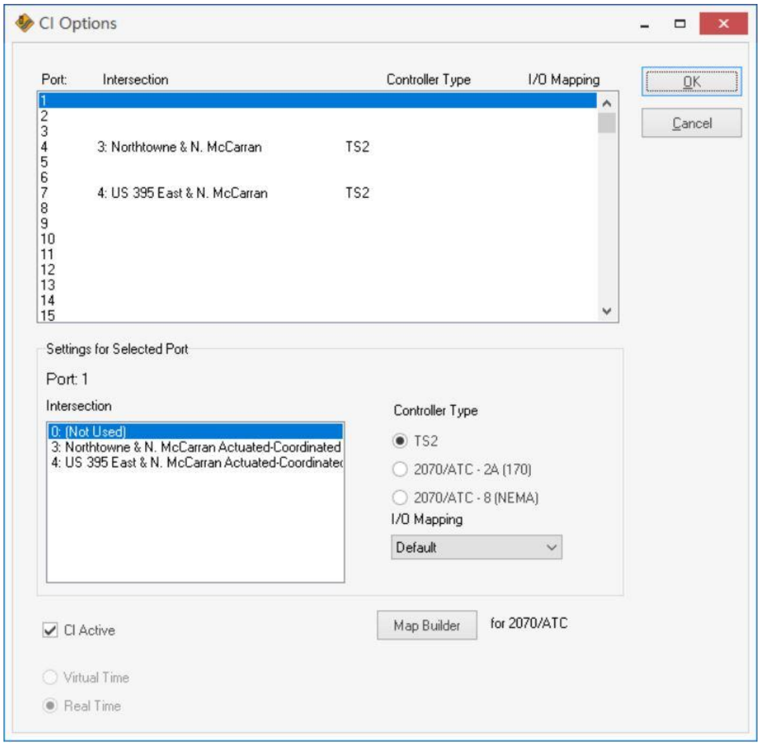


Figure 22 HILS Setup



Port:	Intersection	Controller Type	I/O Mapping
1			
2			
3			
4	3: Northtowne & N. McCarran	TS2	
5			
6			
7	4: US 395 East & N. McCarran	TS2	
8			
9			
10			
11			
12			
13			
14			
15			

Settings for Selected Port

Port: 1

Intersection

- 0: (Not Used)
- 3: Northtowne & N. McCarran Actuated-Coordinated
- 4: US 395 East & N. McCarran Actuated-Coordinate

Controller Type

● TS2
○ 2070/ATC - 2A (170)
○ 2070/ATC - 8 (NEMA)

I/O Mapping: Default

☑ CI Active

Map Builder for 2070/ATC

○ Virtual Time
● Real Time

Figure 23 CI Options in SimTraffic

7 Case Study

In this study, two well-coordinated intersections with their PM timing plan of 150s-cycle length on N. McCarran Blvd in Reno, Nevada were chosen and analyzed. They were N. McCarran & NB US 395 and N. McCarran & Northtowne Lane. The reasons for selecting this arterial were based on available hourly traffic volume counts collected by RTC and major commuting traffic flows on N. McCarran Blvd.

Five simulation scenarios based on different preemption activation points and routes of the emergency vehicle were defined to evaluate and compare five exit strategies in Trafficware 980 ATC V76 signal controllers under different numbers of preemption calls.

7.1 Basic Information of Intersections

7.1.1 Distance Information

According to Figure 24, the distance information between intersections is displayed and the preemption call is assumed to be triggered at both intersections simultaneously once the emergency vehicle activates the preemption. Speed limits for both directions are 45 mph.

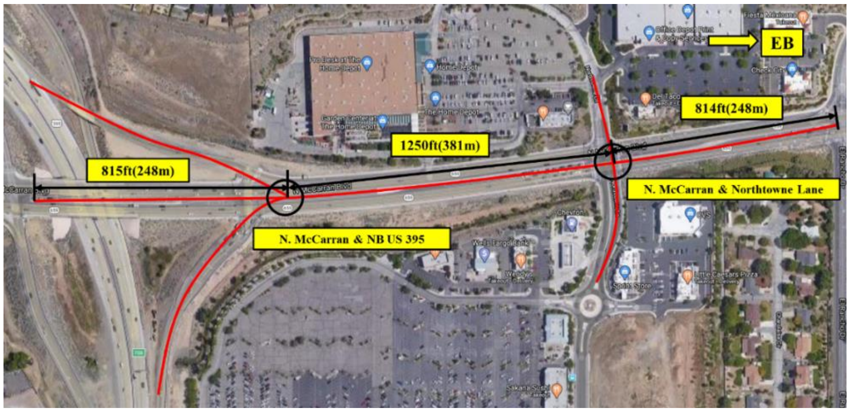
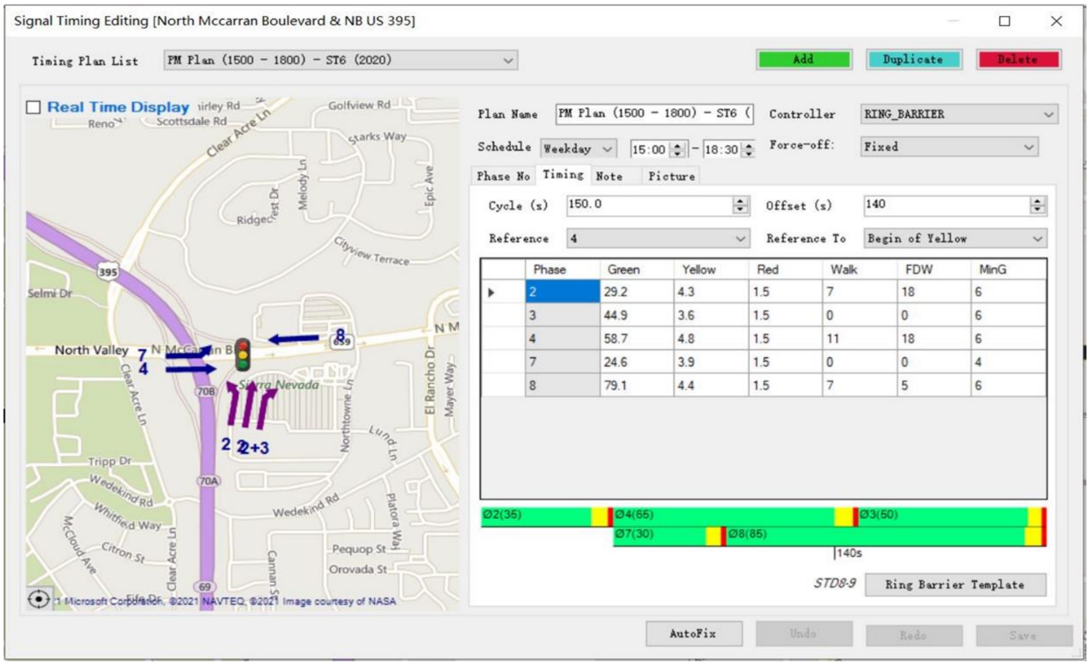


Figure 24 Distance Information of Intersections

7.1.2 Signal Timing Information

PM signal timing plan of two intersections was studied and timing information, including cycle, offset, reference phase, reference point and phase splits, of two intersections was programmed in TranSync [30], a traffic signal timing optimization tool, which is depicted in Figure 25. Designed progression speed limits were 45 mph for both directions. To better visualize signal progression between them, TSD of PM timing plan is presented in Figure 26.


Signal Timing Editing [North Mccarran Boulevard & NB US 395]

Timing Plan List: PM Plan (1500 - 1800) - ST6 (2020)

Plan Name: PM Plan (1500 - 1800) - ST6 (

Controller: RING_BARRIER

Schedule: Weekday 15:00 - 18:30

Force-off: Fixed

Cycle (s): 150.0

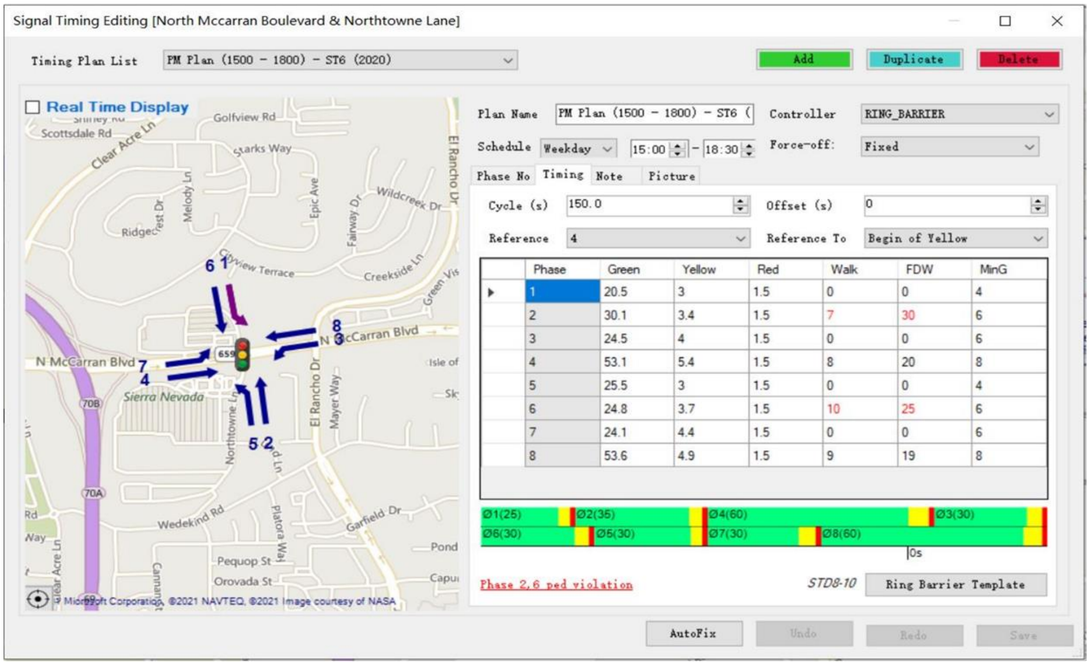
Offset (s): 140

Reference: 4

Reference To: Begin of Yellow

Phase	Green	Yellow	Red	Walk	FDW	MinG
2	29.2	4.3	1.5	7	18	6
3	44.9	3.6	1.5	0	0	6
4	58.7	4.8	1.5	11	18	6
7	24.6	3.9	1.5	0	0	4
8	79.1	4.4	1.5	7	5	6

(a)


Signal Timing Editing [North Mccarran Boulevard & Northtowne Lane]

Timing Plan List: PM Plan (1500 - 1800) - ST6 (2020)

Plan Name: PM Plan (1500 - 1800) - ST6 (

Controller: RING_BARRIER

Schedule: Weekday 15:00 - 18:30

Force-off: Fixed

Cycle (s): 150.0

Offset (s): 0

Reference: 4

Reference To: Begin of Yellow

Phase	Green	Yellow	Red	Walk	FDW	MinG
1	20.5	3	1.5	0	0	4
2	30.1	3.4	1.5	7	30	6
3	24.5	4	1.5	0	0	6
4	53.1	5.4	1.5	8	20	8
5	25.5	3	1.5	0	0	4
6	24.8	3.7	1.5	10	25	6
7	24.1	4.4	1.5	0	0	6
8	53.6	4.9	1.5	9	19	8

Phase 2,6 ped violation

(b)

Figure 25 PM Signal Timing Information of Intersections: (a) N. McCarran & NB US 395, (b) N. McCarran & Northtown Lane

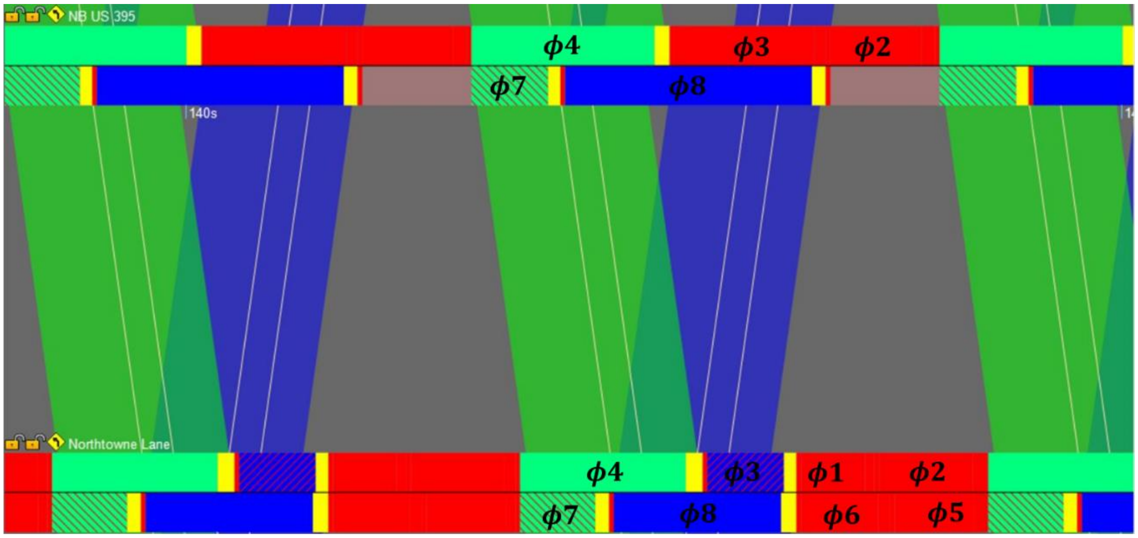


Figure 26 TSD of PM Timing Plan

7.1.3 Traffic Turning Volumes

Available traffic turning volumes at two intersections during PM period were collected from 16:00-17:00 on December 10th, 2019, which are demonstrated in Figure 27.

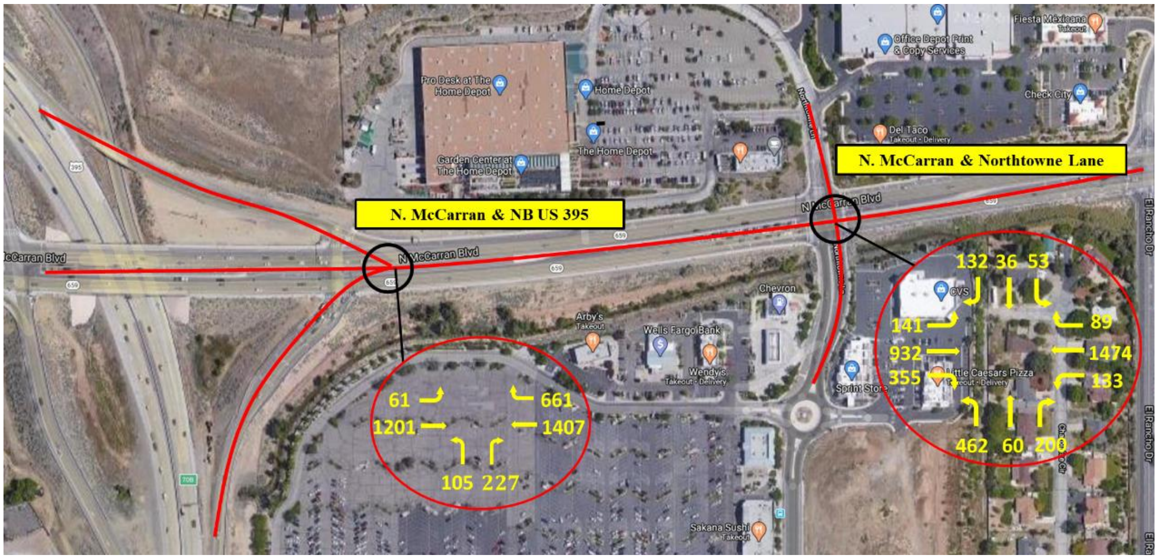
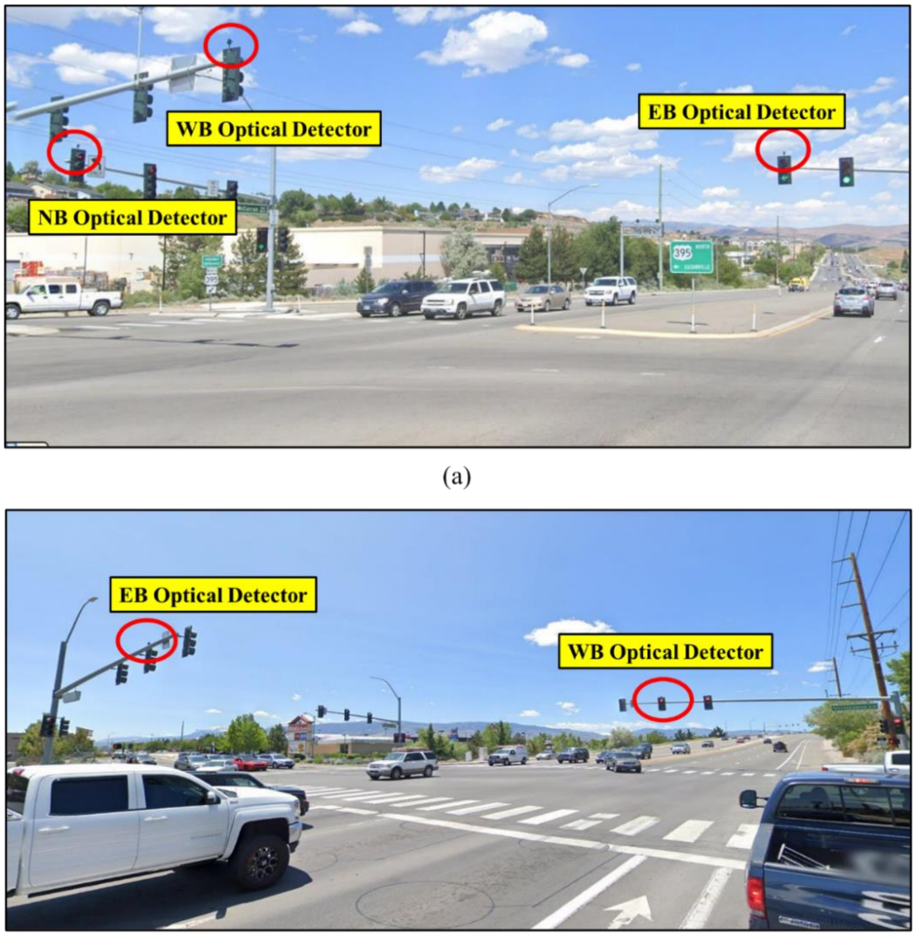


Figure 27 PM Traffic Turning Volumes of Intersections

7.1.4 Field Optical Detectors of EVP

In the field, one-sight tube optical detectors are implemented for each direction at two intersections shown in Figure 28. At N. McCarran & NB US 395, three EVP optical detectors are installed for EB, WB and NB. At N. McCarran & Northtowne Lane, there are only two optical detectors for detecting EB and WB. According to the detector configuration, dwell phases of each direction are programmed as through and left-turn phases.



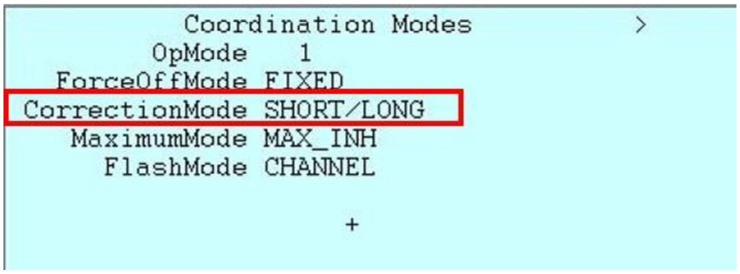
(a)

(b)

Figure 28 EVP Optical Detector at Intersections: (a) N. McCarran & NB US 395, (b) N. McCarran & Northtowne Lane

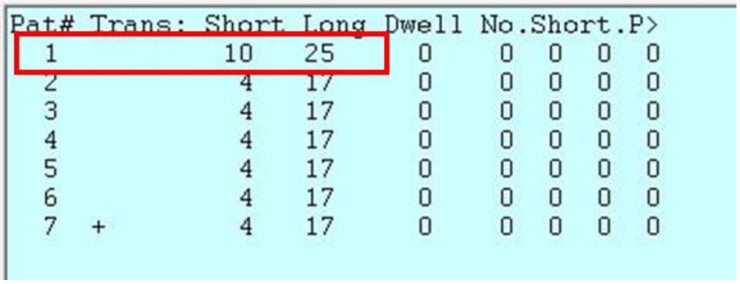
7.1.5 Transition Parameter Settings in Controllers

Following conclusions drawn from the previous studies regarding investigating the best transition method to exit from EVP [9-11], short/long was programmed as the transition method in both controllers, which is shown in Figure 29. As illustrated in Figure 30, phase reduction and extension percent values during the transition were set to 10% and 25%, respectively in two controllers. Dynamic shortway (DynShortway) was enabled to assist in speeding up transitions [28], which is displayed in Figure 31.



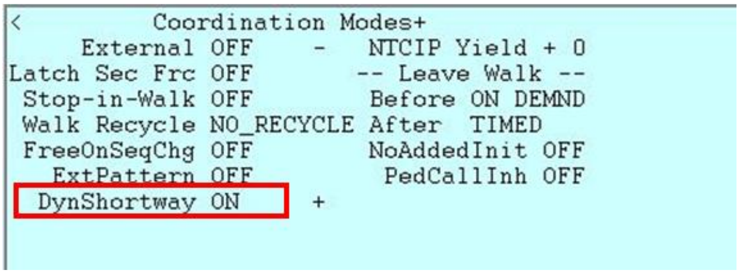
```
           Coordination Modes          >
        OpMode    1
  ForceOffMode FIXED
CorrectionMode SHORT/LONG
   MaximumMode MAX_INH
     FlashMode CHANNEL

                    +
```

Figure 29 Transition Methods in Controllers



```
Pat# Trans: Short Long Dwell No.Short.P>
  1            10   25    0    0  0  0  0
  2             4   17    0    0  0  0  0
  3             4   17    0    0  0  0  0
  4             4   17    0    0  0  0  0
  5             4   17    0    0  0  0  0
  6             4   17    0    0  0  0  0
  7  +          4   17    0    0  0  0  0
```

Figure 30 Phase Reduction and Extension Percentages in Transition



```
<        Coordination Modes+
     External OFF     -   NTCIP Yield + 0
Latch Sec Frc OFF        -- Leave Walk --
 Stop-in-Walk OFF         Before ON DEMND
 Walk Recycle NO_RECYCLE After  TIMED
 FreeOnSeqChg OFF         NoAddedInit OFF
   ExtPattern OFF           PedCallInh OFF
  DynShortway ON       +
```

Figure 31 Dynamic Shortway under Coordination Modes+

7.1.6 Preemption Time Settings

Following programmed preemption time settings in Advanced Traffic Management System (ATMS) of Reno, they are presented in Table 3.

Table 3 Preemption Time Settings of Intersections

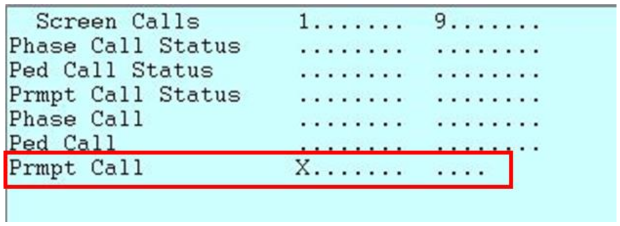
	N. McCarran & NB US 395	N. McCarran & Northtowne Lane
Delay Time (second)	0	0
Minimum Duration (second)	15	15
Maximum Presence (second)	50	50
Minimum Green (second)	4	4
Minimum Walk (second)	5	5
Enter Pedestrian Clearance (second)	15	15
Minimum Dwell (second)	15	15

7.2 Simulation Scenarios

Based on different preemption activation points and routes of the emergency vehicle, countless scenarios can be created to trigger the preemption [14]. Due to the time-consuming limitation of HILS, it is impossible to simulate each of them and five representative simulation scenarios were defined in this research to evaluate and compare five exit strategies demonstrated in Table 4. In order to minimize disruptions on the mainline signal progression after the preemption, fixed exit phases were programmed to be main-street through phases, $\phi4$ and $\phi8$. The dynamic threshold timer was set to 10s once enabled.

Suppose the emergency vehicle was traveling on the arterial with the speed of 55 mph and it took 25s to go through the farthest optical detectors (both for EB and WB) to terminate the preemption. Preemption calls were triggered using the screen calls in controllers shown in Figure 32 once and twice, separately in each simulation scenario to compare results under different number of preemptions.

SimTraffic was used to obtain MOEs and each simulation run was conducted for 35 minutes in real time with the seeding interval of 5 minutes and the simulation interval of 30 minutes. 10 runs were executed for each exit strategy under different simulation scenarios with different numbers of preemptions.



```
  Screen Calls        1.......  9.......
Phase Call Status     ........  ........
Ped Call Status       ........  ........
Prmpt Call Status     ........  ........
Phase Call            ........  ........
Ped Call              ........  ........
Prmpt Call            X.......  ....
```

Figure 32 Screen Calls in Trafficware Controllers

Table 4 Exit Strategies

	Exit Strategies
1	No exit phase
2	Exit to main-street through phases ($\phi4$ and $\phi8$)
3	Coord+Preempt
4	Exit to main-street through phases + End dwell ($\phi4$ and $\phi8$)
5	Dynamic threshold timer=10s ($\phi4$ and $\phi8$)

7.2.1 Scenario 1

In the first scenario, the EB preemption call was activated at both intersections when the loc of N. McCarran & NB US 395 was 121s, which is depicted in Figure 33. The activation points corresponded to the simulation time of 10:25 and 21:44 after the simulation begun. Dwell phases were $\phi4$ and $\phi7$ at both intersections.

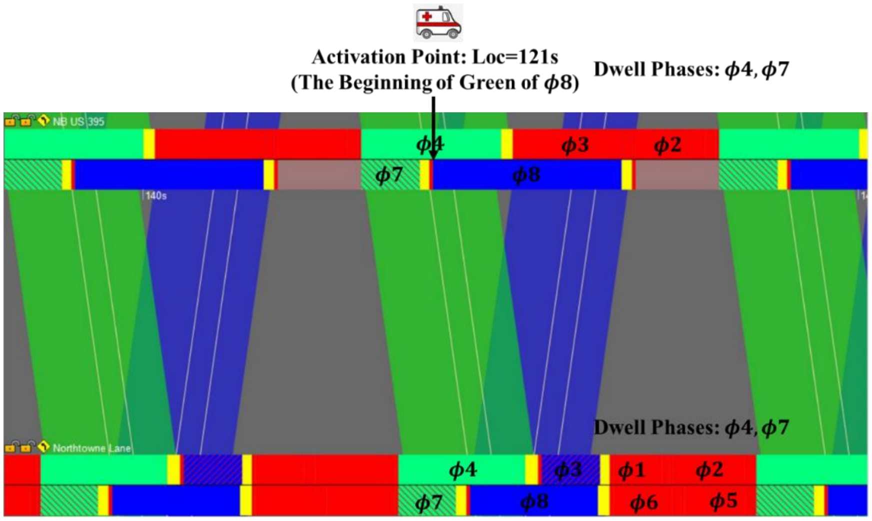
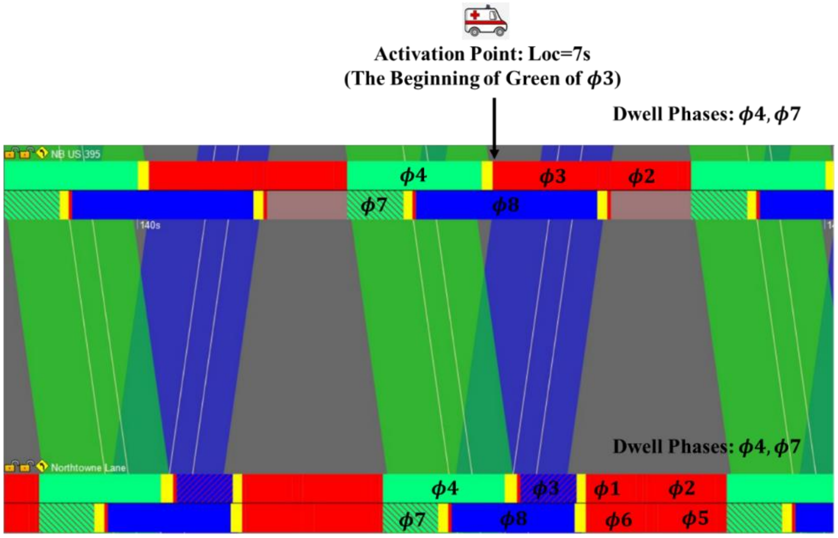


Figure 33 TSD of the Simulation Scenario 1

7.2.2 Scenario 2

In the second scenario, the EB preemption call was activated at both intersections when the loc of N. McCarran & NB US 395 was 7s, which is depicted in Figure 34. The activation points corresponded to the simulation time of 10:51 and 22:13 after the simulation begun. Dwell phases were $\phi4$ and $\phi7$ at both intersections.



Activation Point: Loc=7s
(The Beginning of Green of $\phi 3$)

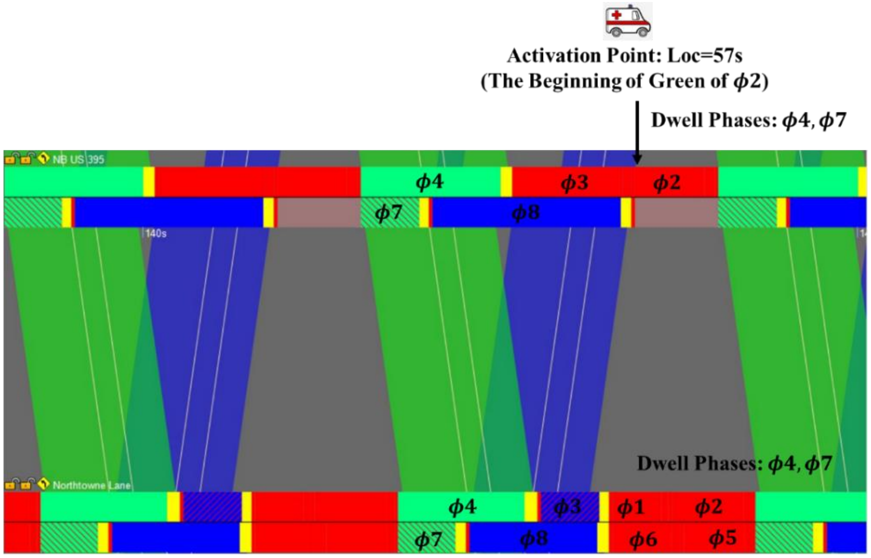
Dwell Phases: $\phi 4, \phi 7$

Dwell Phases: $\phi 4, \phi 7$

Figure 34 TSD of the Simulation Scenario 2

7.2.3 Scenario 3

In the third scenario, the EB preemption call was activated at both intersections when the loc of N. McCarran & NB US 395 was 57s, which is depicted in Figure 35. The activation points corresponded to the simulation time of 11:43 and 22:50 after the simulation begun. Dwell phases were $\phi 4$ and $\phi 7$ at both intersections.



Activation Point: Loc=57s
(The Beginning of Green of $\phi 2$)

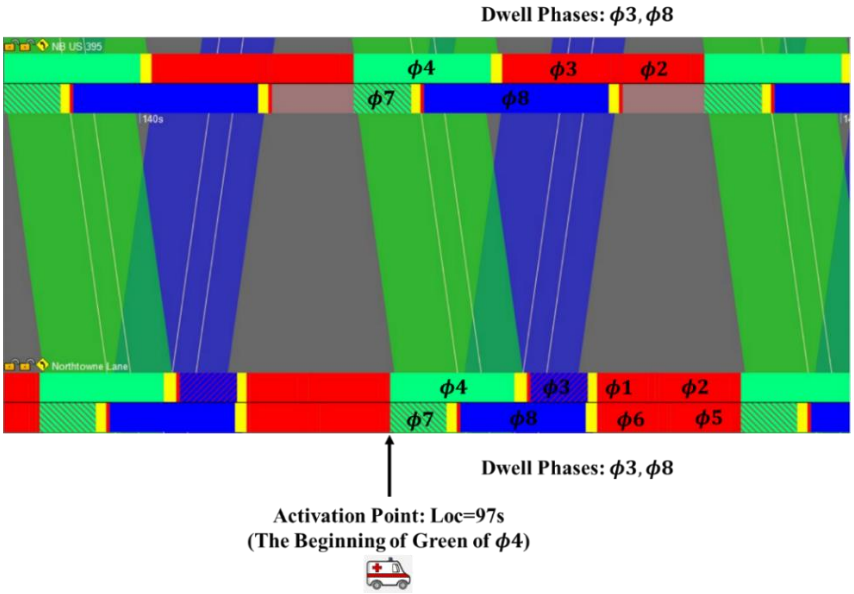
Dwell Phases: $\phi 4, \phi 7$

Dwell Phases: $\phi 4, \phi 7$

Figure 35 TSD of the Simulation Scenario 3

7.2.4 Scenario 4

In the scenario 4, the WB preemption call was activated at both intersections when the loc of N. McCarran & Northtowne Lane was 97s, which is depicted in Figure 36. The activation points corresponded to the simulation time of 12:29 and 23:51 after the simulation begun. Dwell phases were $\phi3$ and $\phi8$ at both intersections.



Dwell Phases: $\phi3, \phi8$

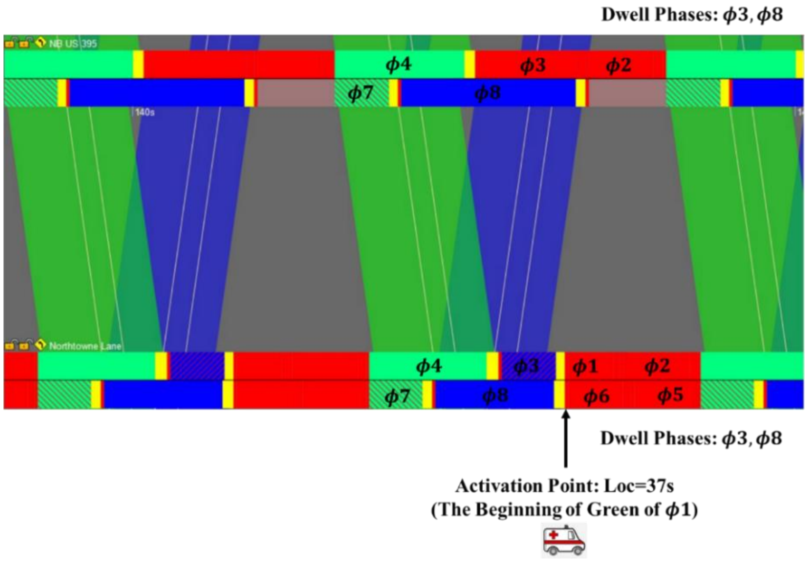
Dwell Phases: $\phi3, \phi8$

Activation Point: Loc=97s
(The Beginning of Green of $\phi4$)

Figure 36 TSD of the Simulation Scenario 4

7.2.5 Scenario 5

In the scenario 5, the WB preemption call was activated at both intersections when the loc of N. McCarran & Northtowne Lane was 37s, which is depicted in Figure 37. The activation points corresponded to the simulation time of 11:34 and 22:52 after the simulation begun. Dwell phases were $\phi3$ and $\phi8$ at both intersections.



Dwell Phases: $\phi3, \phi8$

Dwell Phases: $\phi3, \phi8$

Activation Point: Loc=37s
(The Beginning of Green of $\phi1$)

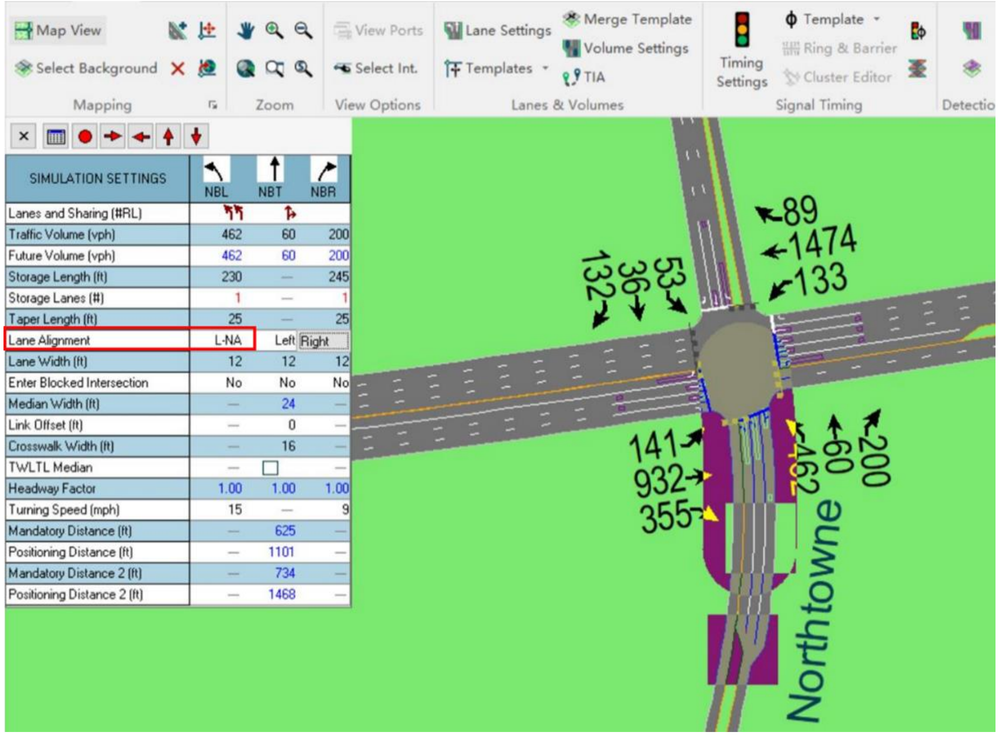
Figure 37 TSD of the Simulation Scenario 5

7.3 Simulation Results

7.3.1 Model Calibration

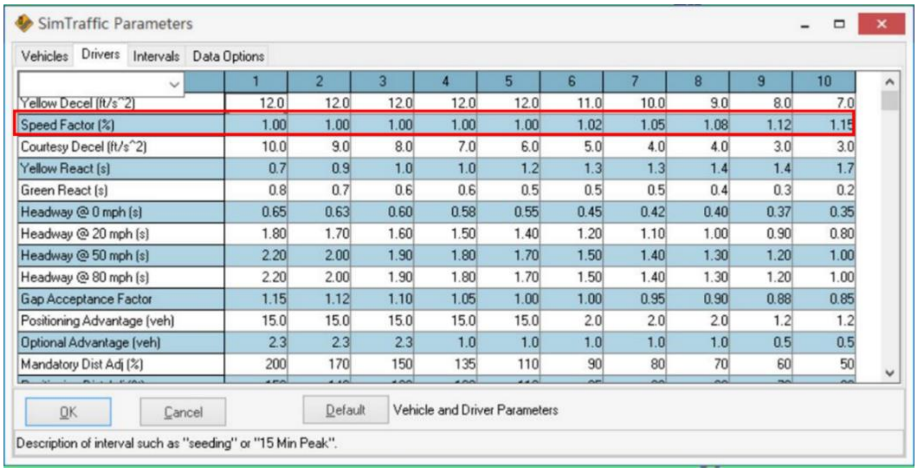
In order to better calibrate the simulation model to match the traffic operations in the field, the following two changes were made. Firstly, the lane alignment of NB left-turn at N. McCarran & Northtowne Lane was changed from Left to L-NA, which is indicated in Figure 38, to avoid left-turn queues concentrating only on the outside left-turn lane [29]. Secondly, to model the driver behavior in the field as accurately as possible, the least speed factor in driver parameters was modified to be 1.0 rather than default settings in SimTraffic, which is demonstrated in Figure 39.

Average travel times and speeds were selected to compare the operational performance after the model calibration. It could be seen from Figure 40 that EB and WB average travel times decreased by 6.1% and 4.4%, respectively at N. McCarran & NB US 395, and 7% and 6.6%, respectively at N. McCarran & Northtowne Lane. As for average travel speeds, they increased by 7% and 5.4% for EB and WB, respectively at N. McCarran & NB US 395 and 7.8% and 7.5% for EB and WB at N. McCarran & Northtowne Lane. The comparison of average vehicle delay of each turning movement at two intersections was presented (see Appendix A-1). The MOEs in the following five simulation scenarios were obtained on basis of the calibrated model.



SIMULATION SETTINGS	NBL	NBT	NBR
Lanes and Sharing (#RL)	↰↰	↱	
Traffic Volume (vph)	462	60	200
Future Volume (vph)	462	60	200
Storage Length (ft)	230	—	245
Storage Lanes (#)	1	—	1
Taper Length (ft)	25	—	25
Lane Alignment	L-NA	Left	Right
Lane Width (ft)	12	12	12
Enter Blocked Intersection	No	No	No
Median Width (ft)	—	24	—
Link Offset (ft)	—	0	—
Crosswalk Width (ft)	—	16	—
TWLTL Median	—	☐	—
Headway Factor	1.00	1.00	1.00
Turning Speed (mph)	15	—	9
Mandatory Distance (ft)	—	625	—
Positioning Distance (ft)	—	1101	—
Mandatory Distance 2 (ft)	—	734	—
Positioning Distance 2 (ft)	—	1468	—

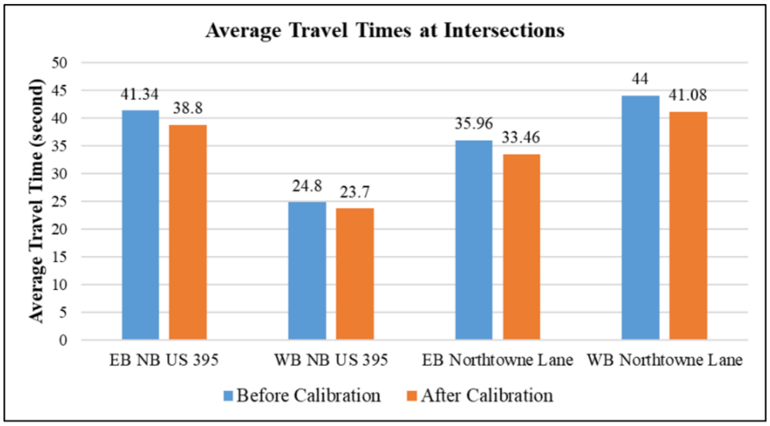
Figure 38 Lane Alignment Changes at N. McCarran & Northtowne Lane



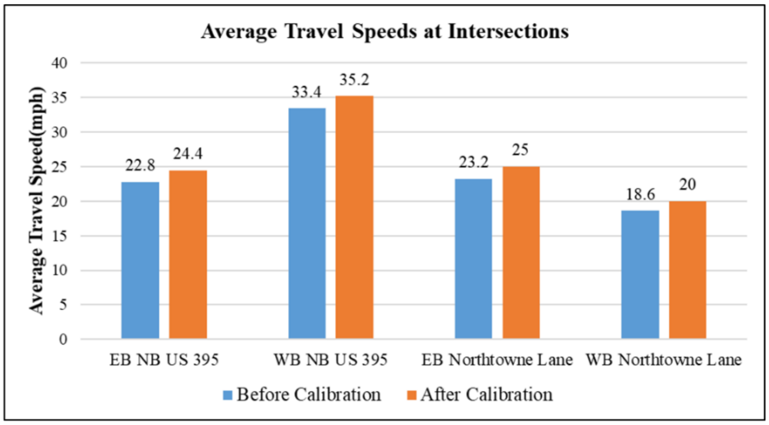
	1	2	3	4	5	6	7	8	9	10
Yellow Decel (ft/s^2)	12.0	12.0	12.0	12.0	12.0	11.0	10.0	9.0	8.0	7.0
Speed Factor (%)	1.00	1.00	1.00	1.00	1.00	1.02	1.05	1.08	1.12	1.15
Courtesy Decel (ft/s^2)	10.0	9.0	8.0	7.0	6.0	5.0	4.0	4.0	3.0	3.0
Yellow React (s)	0.7	0.9	1.0	1.0	1.2	1.3	1.3	1.4	1.4	1.7
Green React (s)	0.8	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.3	0.2
Headway @ 0 mph (s)	0.65	0.63	0.60	0.58	0.55	0.45	0.42	0.40	0.37	0.35
Headway @ 20 mph (s)	1.80	1.70	1.60	1.50	1.40	1.20	1.10	1.00	0.90	0.80
Headway @ 50 mph (s)	2.20	2.00	1.90	1.80	1.70	1.50	1.40	1.30	1.20	1.00
Headway @ 80 mph (s)	2.20	2.00	1.90	1.80	1.70	1.50	1.40	1.30	1.20	1.00
Gap Acceptance Factor	1.15	1.12	1.10	1.05	1.00	1.00	0.95	0.90	0.88	0.85
Positioning Advantage (veh)	15.0	15.0	15.0	15.0	15.0	2.0	2.0	2.0	1.2	1.2
Optional Advantage (veh)	2.3	2.3	2.3	1.0	1.0	1.0	1.0	1.0	0.5	0.5
Mandatory Dist Adj (%)	200	170	150	135	110	90	80	70	60	50

Description of interval such as "seeding" or "15 Min Peak".

Figure 39 Calibrated Speed Factors in Driver Parameters



(a)



(b)

Figure 40 Before-and-after Performance Comparison: (a) average travel time at intersections, (b) average travel speeds at Intersections

7.3.2 Scenario 1

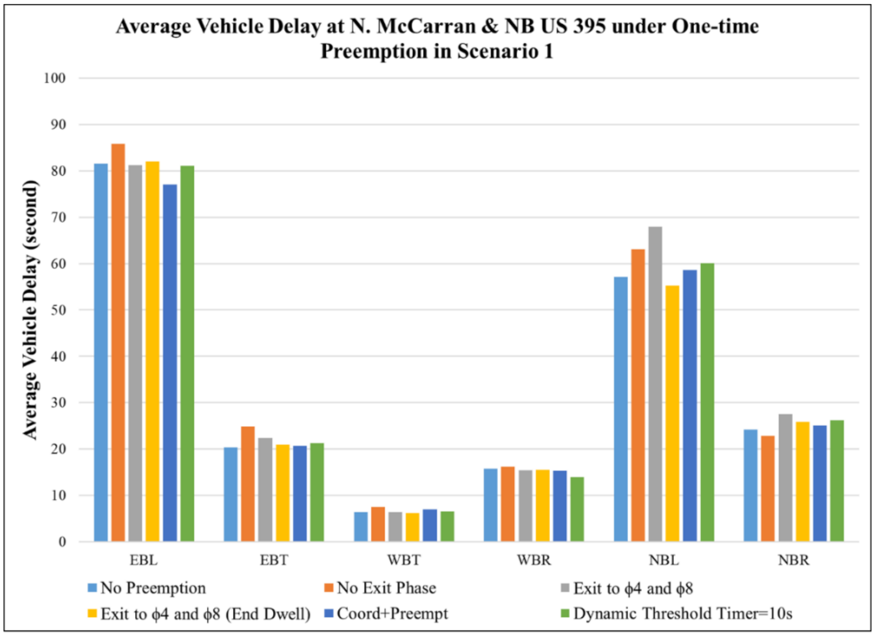
7.3.2.1 Average Vehicle Delay under One-time Preemption

During the simulation, it was found out that $\phi3$ and $\phi8$ were selected as the exit phases at both intersections when no exit phases were implemented. As for the dynamic exit phase selections, all occurred exit phases were: $\phi2$, or $\phi4$ and $\phi8$ were returned at N. McCarran & NB US 395. $\phi2$ and $\phi5$, $\phi1$ and $\phi6$ or $\phi4$ and $\phi8$ were selected at N. McCarran & Northtowne Lane.

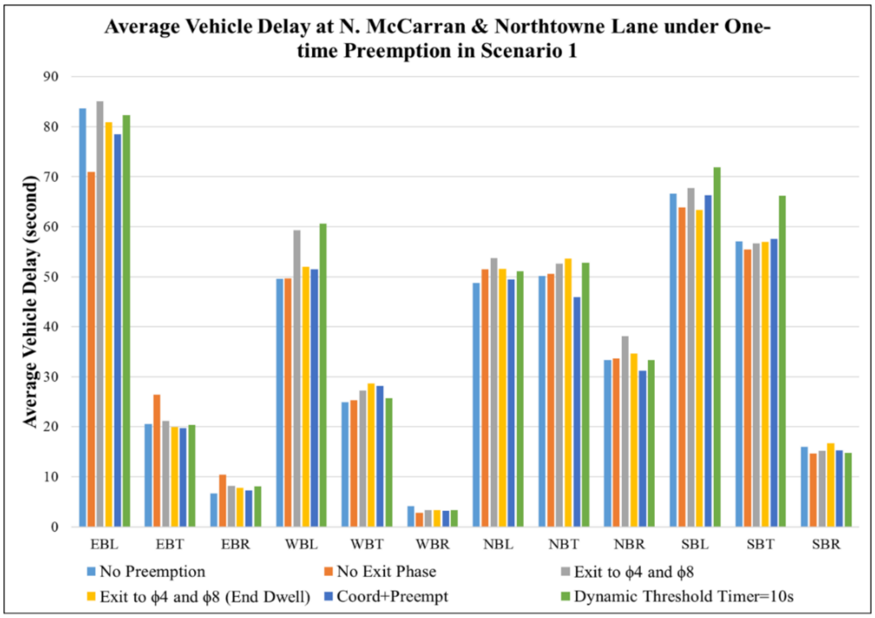
From the average vehicle delay shown in Appendix A-2, it was evident to see that no exit phase strategy produced the greatest delay of main-street through movements at N. McCarran & NB US 395 due to the phase return to $\phi3$ and $\phi8$. Compared with exit to $\phi4$ and $\phi8$ only, end dwell benefited movements of non-return phases, such as EBT, NBL and NBR. Also, it outperformed the dynamic threshold timer by benefiting all turning movements except for EBL at N. McCarran & NB US 395. With regard to Coord+Preempt, it produced the overall minimal delay of each turning movement except at WBT and NBL.

At N. McCarran & Northtowne Lane, EBT suffered the greatest delay under no exit phase strategy among other exit strategies. In comparison with exit to $\phi4$ and $\phi8$ only, end dwell greatly reduced movement delay of non-return phases, such as EBL, WBL, NBL and SBL, while it produced slightly greater WBT delay due to cycling to non-preempted phases prior to exiting to $\phi8$. Compared with end dwell, the dynamic threshold timer generated reduced delay of WBT but increased it at EBL, EBT and WBL. As for Coord+Preempt, it outperformed the others by producing the overall minimal delay of each movement.

Average vehicle delay under one-time preemption in simulation 1 is plotted in Figure 41 for better visualization.



(a)



(b)

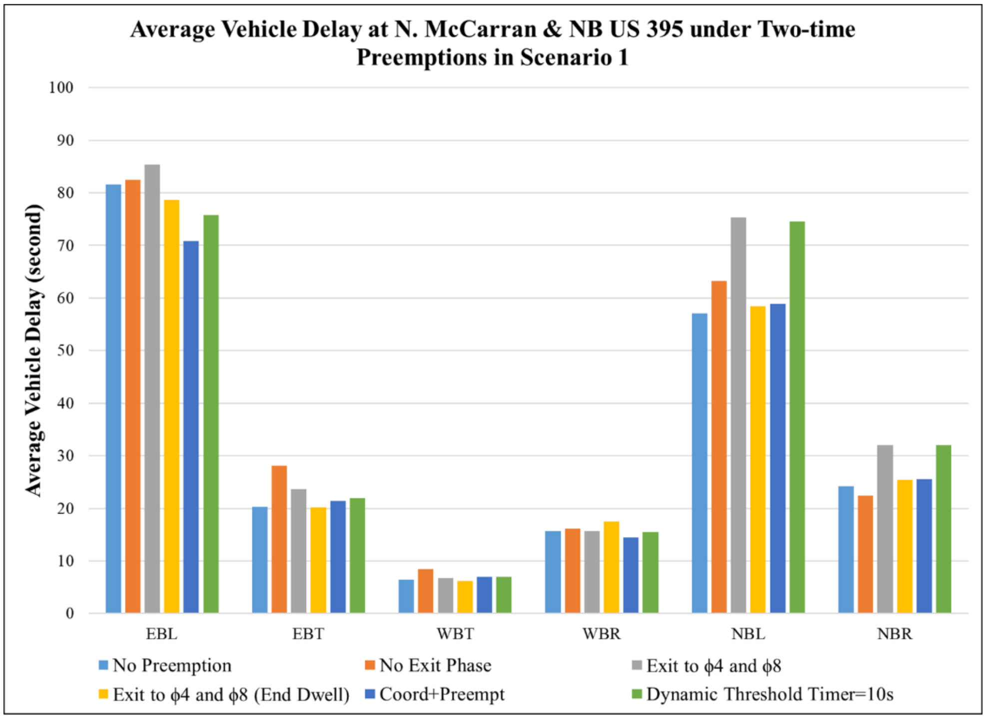
Figure 41 Comparison of Average Vehicle Delay under One-time Preemption in Scenario 1: (a) N. McCarran & NB US 395, (b) N. McCarran & Northtowne Lane

7.3.2.2 Average Vehicle Delay under Two-time Preemptions

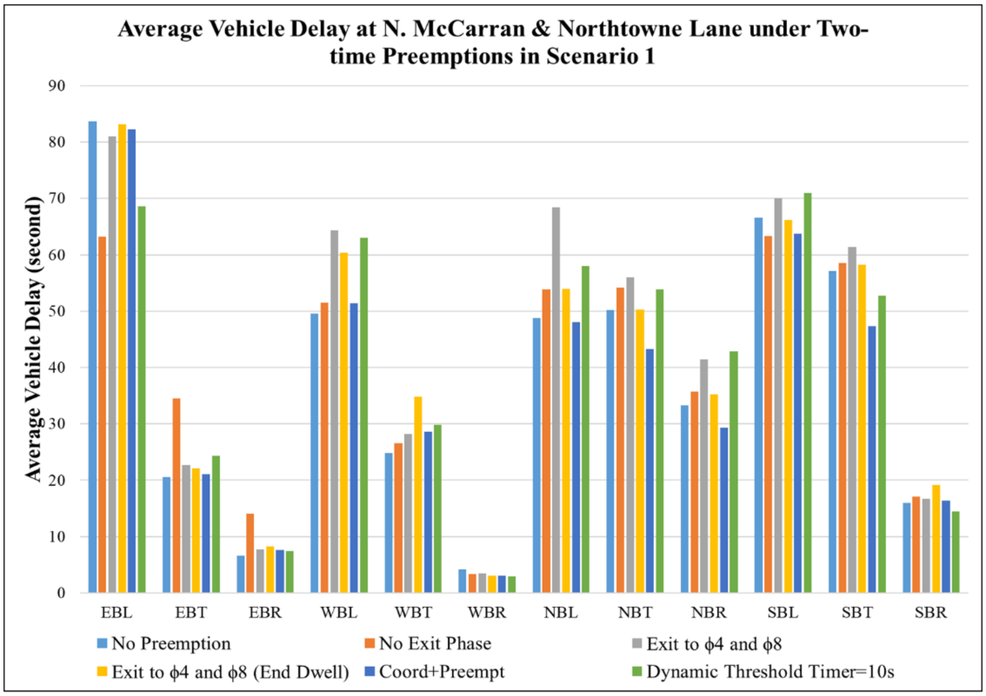
From Appendix A-3, it could be figured out that no exit phase strategy produced the greatest delay for main-street through movements as the same as the one-time preemption at N. McCarran & NB US 395. Compared with exit to $\phi 4$ and $\phi 8$ only, end dwell benefited movements of non-return phases, such as EBL, NBL and NBR. Under two-time preemptions, exit to $\phi 4$ and $\phi 8$ (end dwell) outweighed the dynamic threshold timer especially for side-street movements, NBL and NBR. With regard to Coord+Preempt, it only produced less delay at EBL when compared with exit to $\phi 4$ and $\phi 8$ (end dwell).

At N. McCarran & Northtowne Lane, EBT suffered the greatest delay as well under the no exit phase strategy. In comparison with exit to $\phi 4$ and $\phi 8$ only, end dwell greatly reduced movement delay of non-return phases, such as EBL, WBL, NBL, NBT, SBL and SBT while it produced the greatest WBT delay due to cycling to starving phases prior to exiting to $\phi 8$. Compared with end dwell, the dynamic thresholder timer cut down delay of EBL and WBT but increased it at EBT, WBL, NBL and NBT. As for Coord+Preempt, it outperformed the others by producing the overall minimal delay of each movement and there were little changes in delay under different numbers of preemptions to minimize negative impacts.

Average vehicle delay under two-time preemptions in scenario 1 is plotted in Figure 42 for better visualization. Performance comparison of each exit strategy in scenario 1 under different numbers of preemptions is illustrated from Figure 43 to Figure 47.



(a)



(b)

Figure 42 Comparison of Average Vehicle Delay under Two-time Preemptions in Scenario 1: (a) N. McCarran & NB US 395, (b) N. McCarran & Northtowne Lane

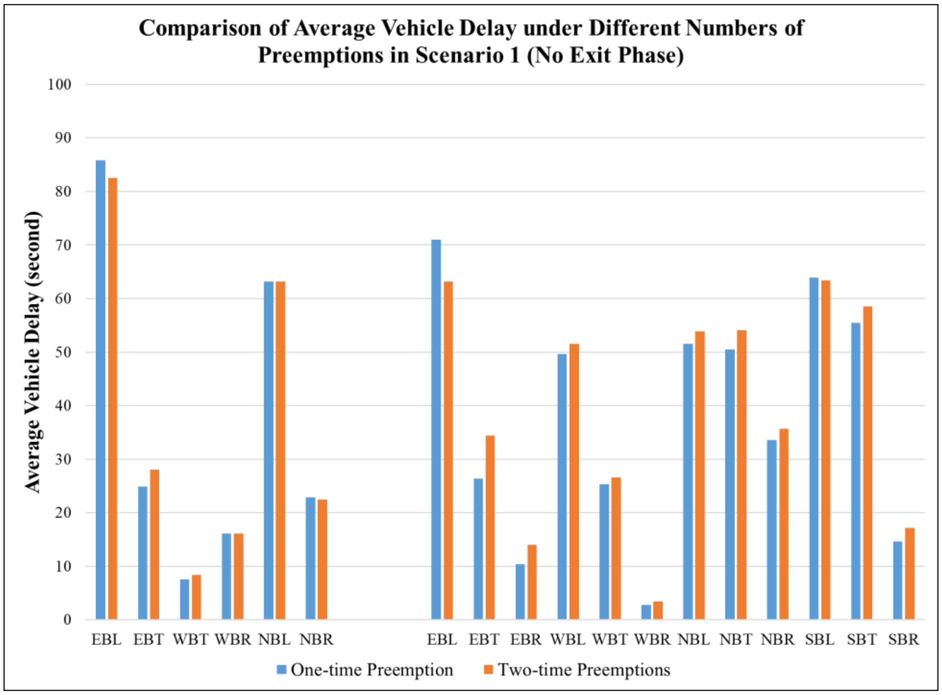


Figure 43 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 1 (No Exit Phase)

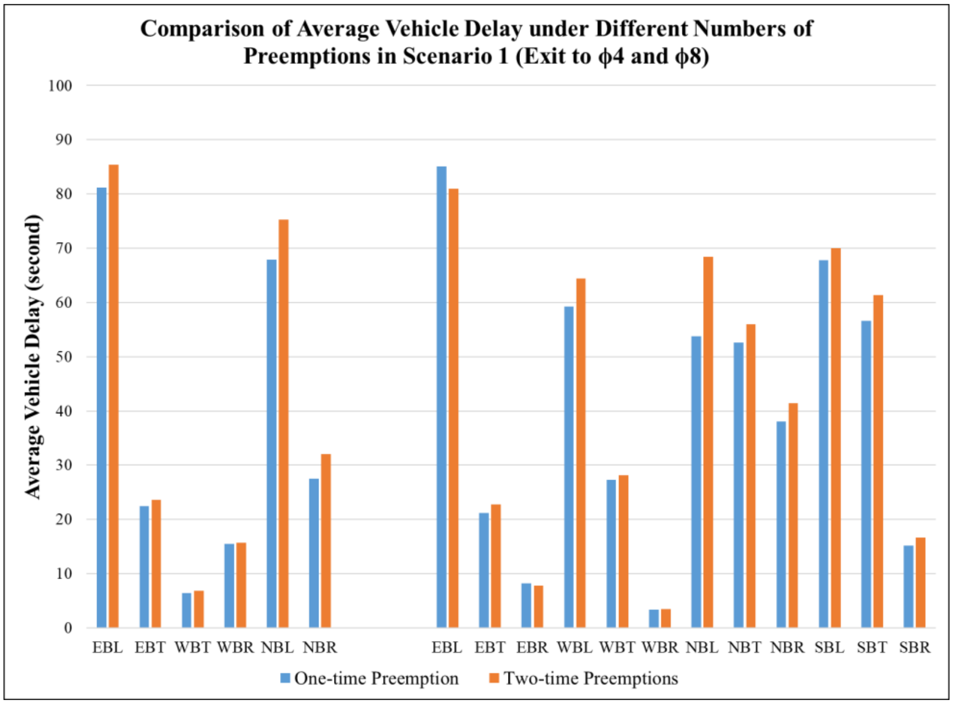


Figure 44 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 1 (Exit to $\phi 4$ and $\phi 8$)

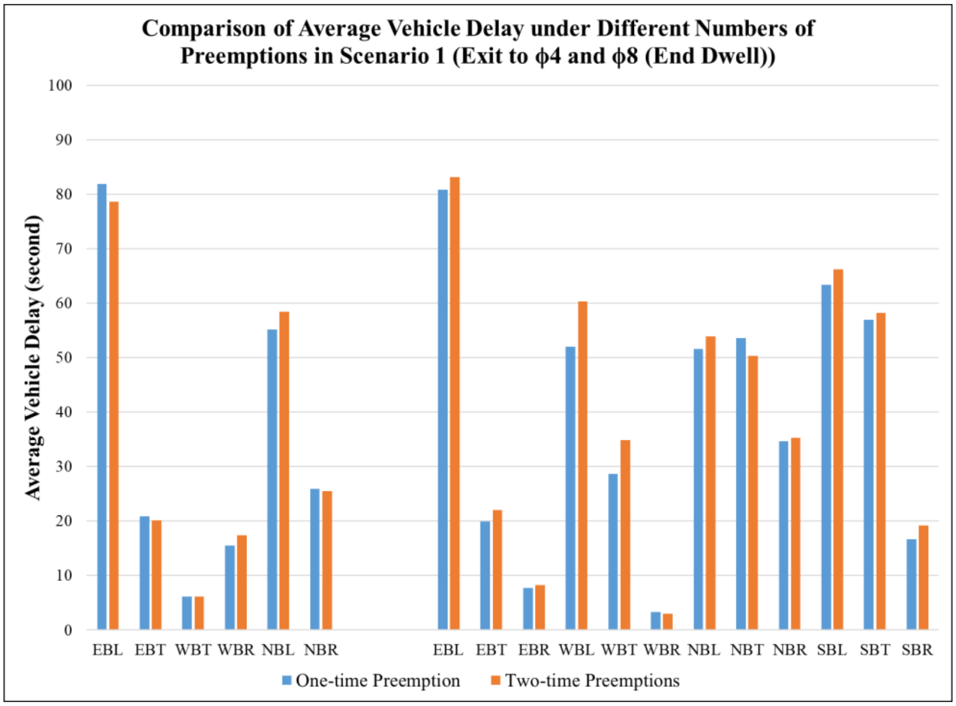


Figure 45 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 1 (Exit to $\phi4$ and $\phi8$ (End Dwell))

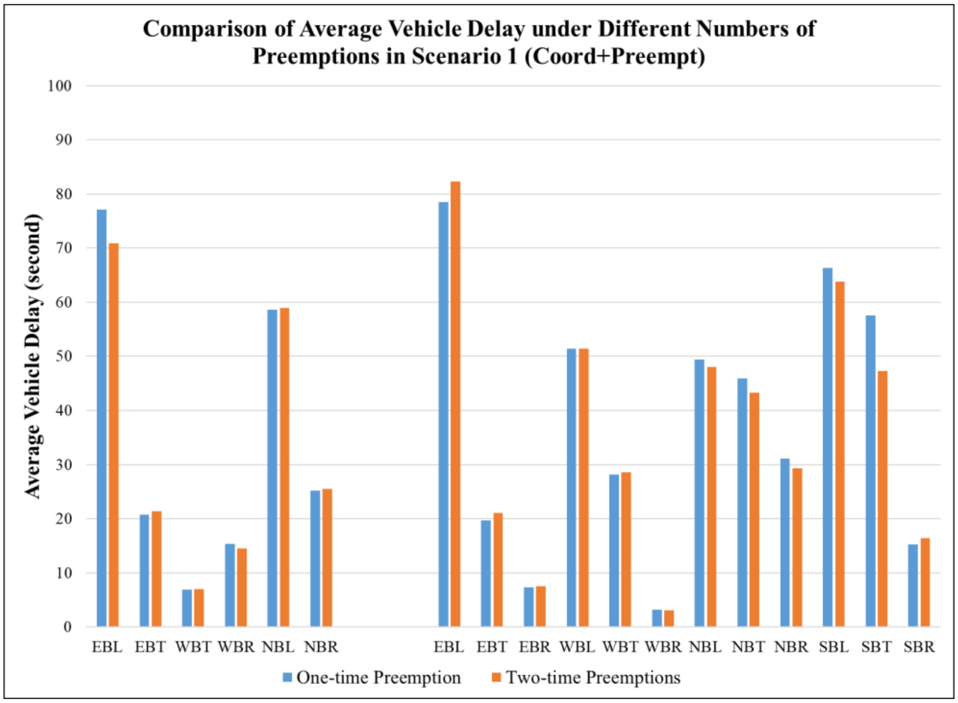


Figure 46 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 1 (Coord+Preempt)

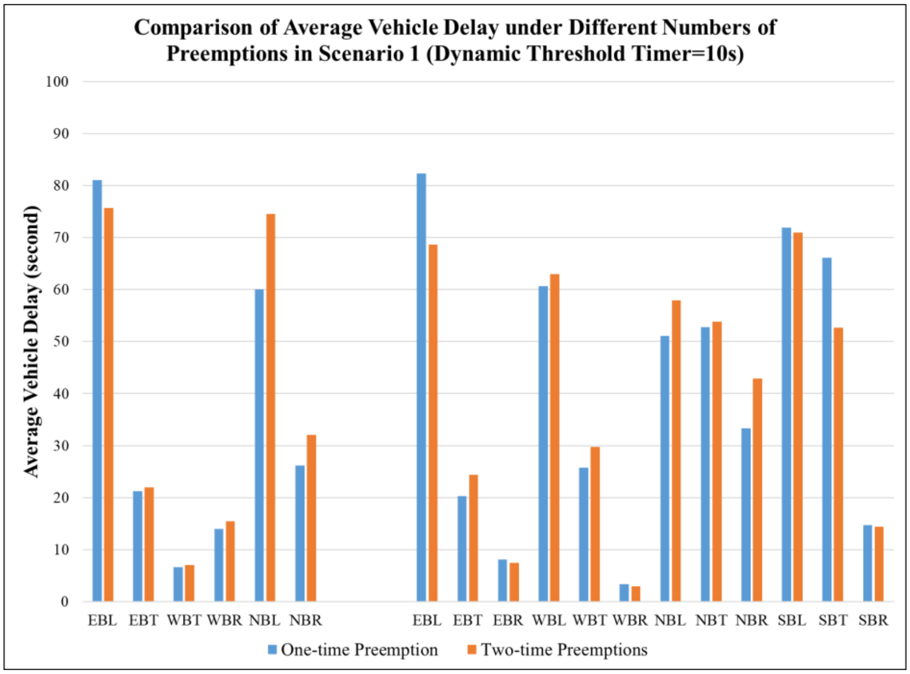


Figure 47 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 1 (Dynamic Threshold Timer=10s)

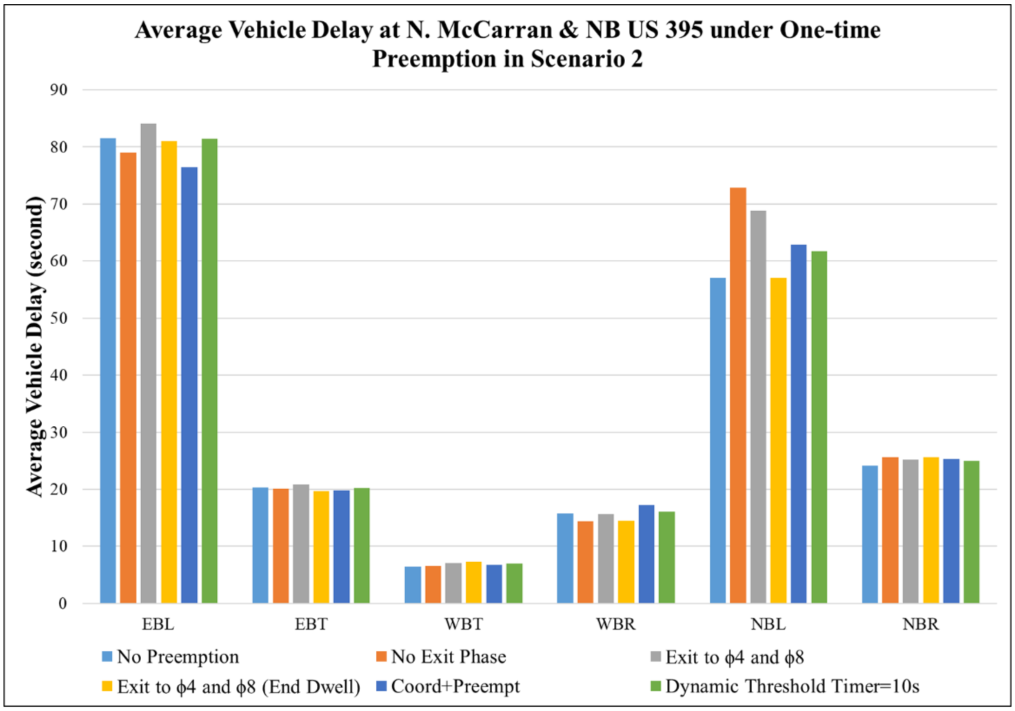
7.3.3 Scenario 2

7.3.3.1 Average Vehicle Delay under One-time Preemption

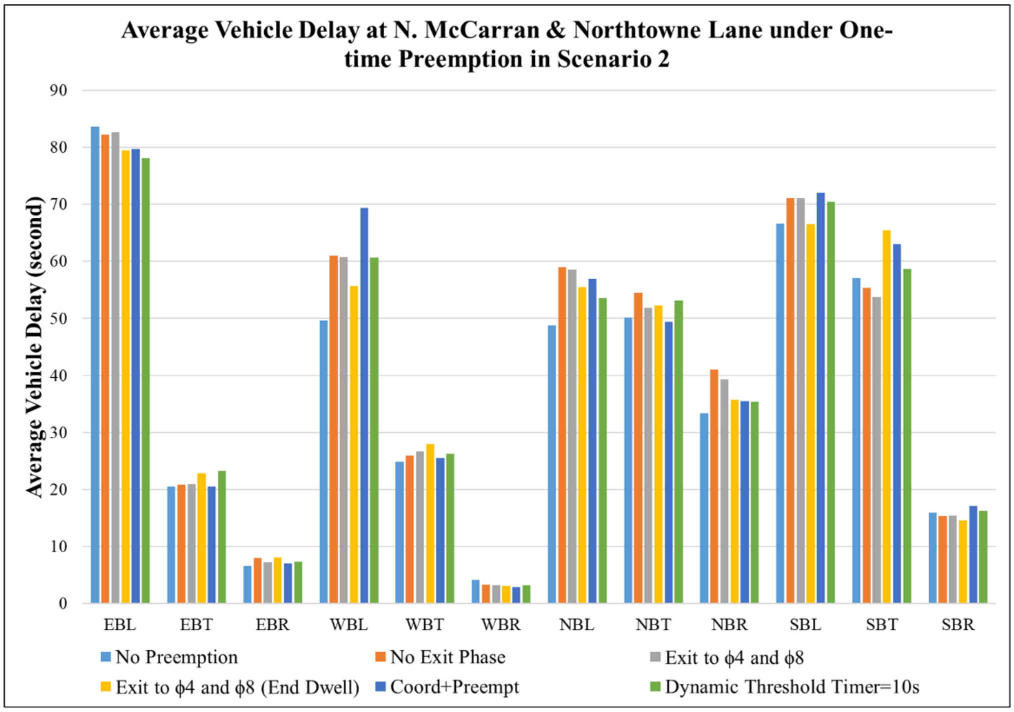
During the simulation, it was observed that $\phi 4$ and $\phi 8$ were selected as the exit phases at N. McCarran & NB US 395 and $\phi 3$ or $\phi 4$ and $\phi 8$ were returned at N. McCarran & Northtowne Lane when no exit phases were programmed. As for the dynamic exit phase selections, all occurred exit phases were: $\phi 2$ or $\phi 4$ and $\phi 8$ were returned at N. McCarran & NB US 395. $\phi 2$ and $\phi 6$ or $\phi 3$ and $\phi 8$ were selected at N. McCarran & Northtowne Lane.

From the average vehicle delay unfolded in Appendix A-4, it was obvious to see that no exit phase strategy produced the greatest delay of NBL at N. McCarran & NB US 395. Compared with exit to $\phi 4$ and $\phi 8$ only, end dwell greatly benefited movement of non-return phases, such as EBL and NBL and it produced less delay at EBL, EBT and NBL than the dynamic threshold timer while WBT performed worse at N. McCarran & NB US 395. With regard to Coord+Preempt, it produced the overall minimal delay for each turning movement except at NBL and NBR.

At N. McCarran & Northtowne Lane, no exit phase and exit to $\phi4$ and $\phi8$ generated the similar performance due to nearly the same phase return. In comparison with exit to $\phi4$ and $\phi8$ only, although end dwell greatly reduced movement delay of non-return phase, such as EBL, WBL, and SBL, it produced greater delay on the main-street through movements. Compared with end dwell, the dynamic thresholder timer generated reduced delay at EBL, WBT and NBL but increased it at EBT and WBL. As for Coord+Preempt, delay of the main-street through movements were minimal. Average vehicle delay under one-time preemption in scenario 2 is plotted in Figure 48 for better visualizations.



(a)



(b)

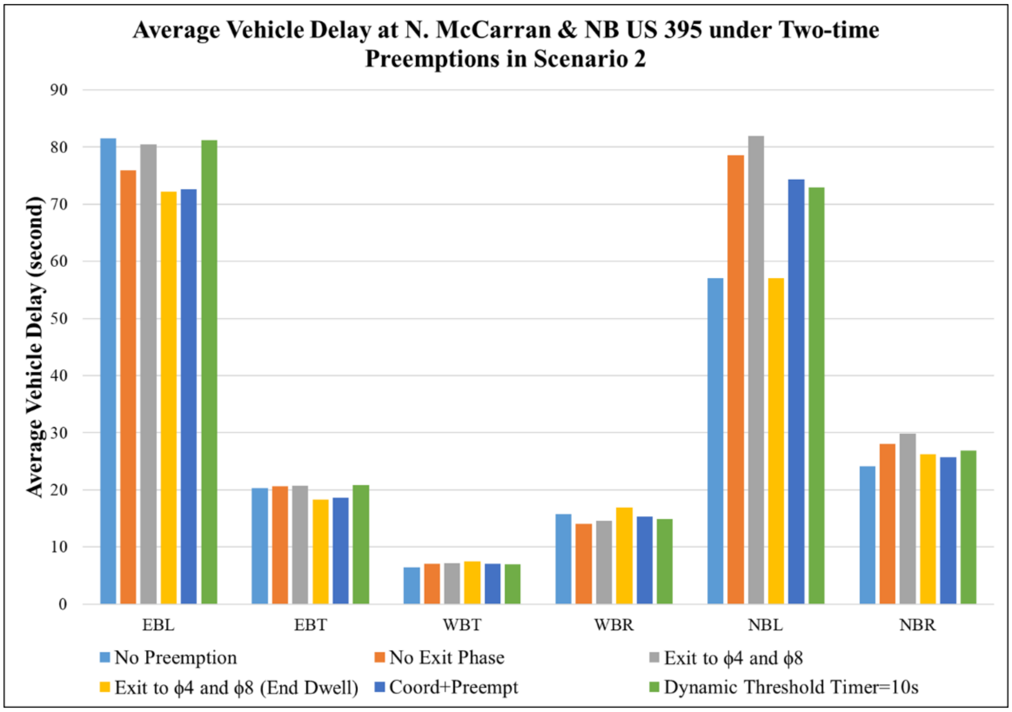
Figure 48 Comparison of Average Vehicle Delay under One-time Preemption in Scenario 2: (a) N. McCarran & NB US 395, (b) N. McCarran & Northtowne Lane

7.3.3.2 Average Vehicle Delay under Two-time Preemptions

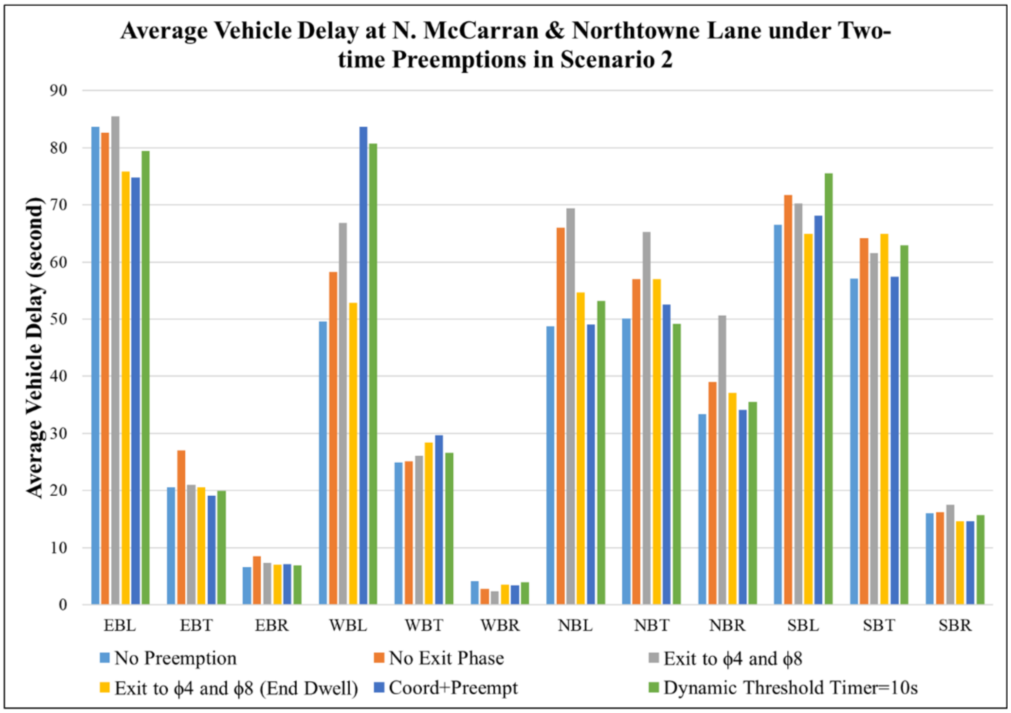
From Appendix A-5, it could be figured out that exit to $\phi 4$ and $\phi 8$ performed worse than the no exit phase under two-time preemptions at N. McCarran & NB US 395. Compared with exit to $\phi 4$ and $\phi 8$ only, end dwell benefited all turning movements except at WBT due to cycling to non-preempted phases prior to exit phases. Under two-time preemptions, exit to $\phi 4$ and $\phi 8$ (end dwell) outperformed the dynamic threshold timer except at WBT. With regard to Coord+Preempt, it produced the lowest delay on the main-street through movements.

At N. McCarran & Northtowne Lane, EBT suffered the greatest delay under no exit phase among other exit strategies. In comparison with exit to $\phi 4$ and $\phi 8$ only, end dwell greatly reduced movement delay of non-return phase, such as EBL, WBL, NBL, NBT and SBL while it produced greater WBT delay due to cycling to non-preempted phases prior to exiting to $\phi 8$. Compared with end dwell, the dynamic thresholder timer lowered down delay of main-street through movements but increased it at main-street left-turn movements, EBL and WBL. As for Coord+Preempt, although it generated the worst performance on WB approach, it minimized delay of other turning movements and there were little changes in delay under different numbers of preemptions to minimize negative impacts.

Average vehicle delay under two-time preemptions in scenario 2 is plotted in Figure 49 for better visualization. Performance comparison of each exit strategy in scenario 2 under different numbers of preemptions is illustrated from Figure 50 to Figure 54.



(a)



(b)

Figure 49 Comparison of Average Vehicle Delay under Two-time Preemptions in Scenario 2: (a) N. McCarran & NB US 395, (b) N. McCarran & Northtowne Lane

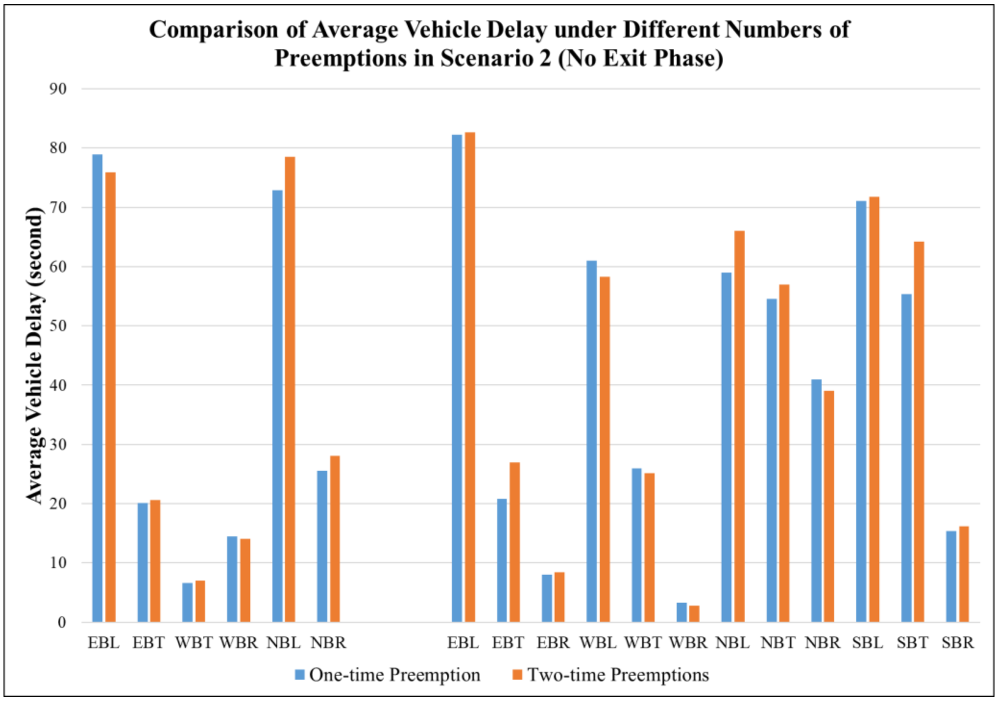


Figure 50 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 2 (No Exit Phase)

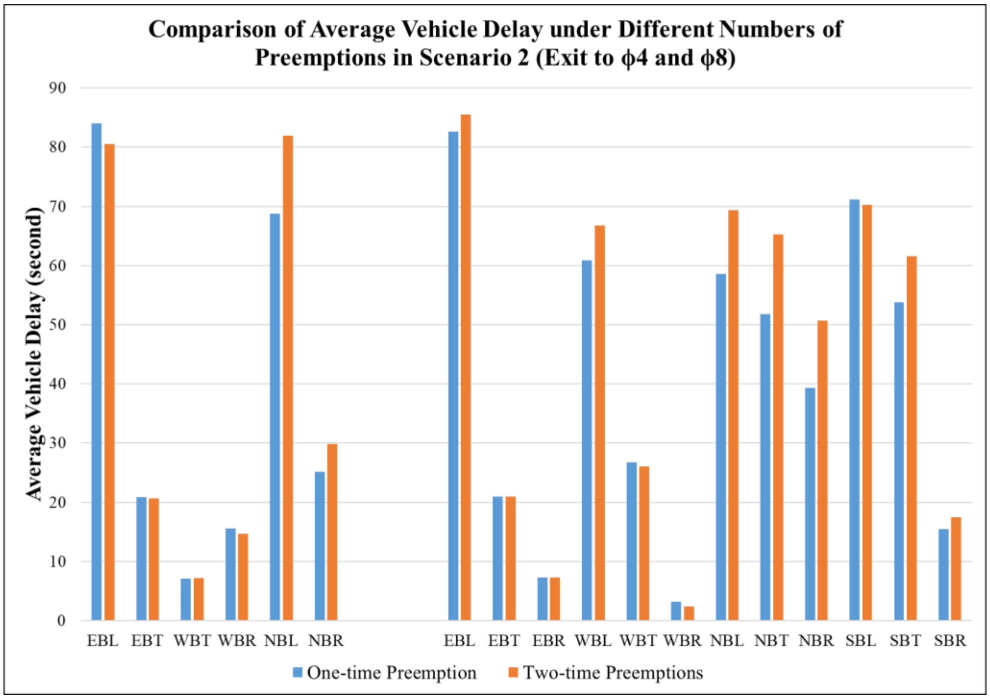


Figure 51 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 2 (Exit to $\phi 4$ and $\phi 8$)

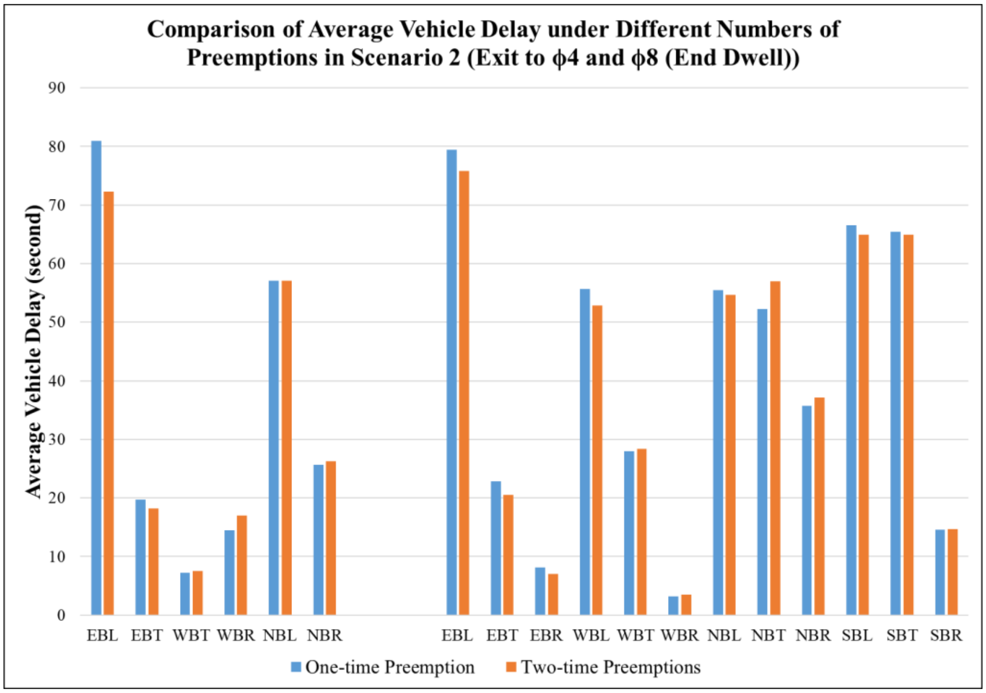


Figure 52 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 2 (Exit to $\phi 4$ and $\phi 8$ (End Dwell))

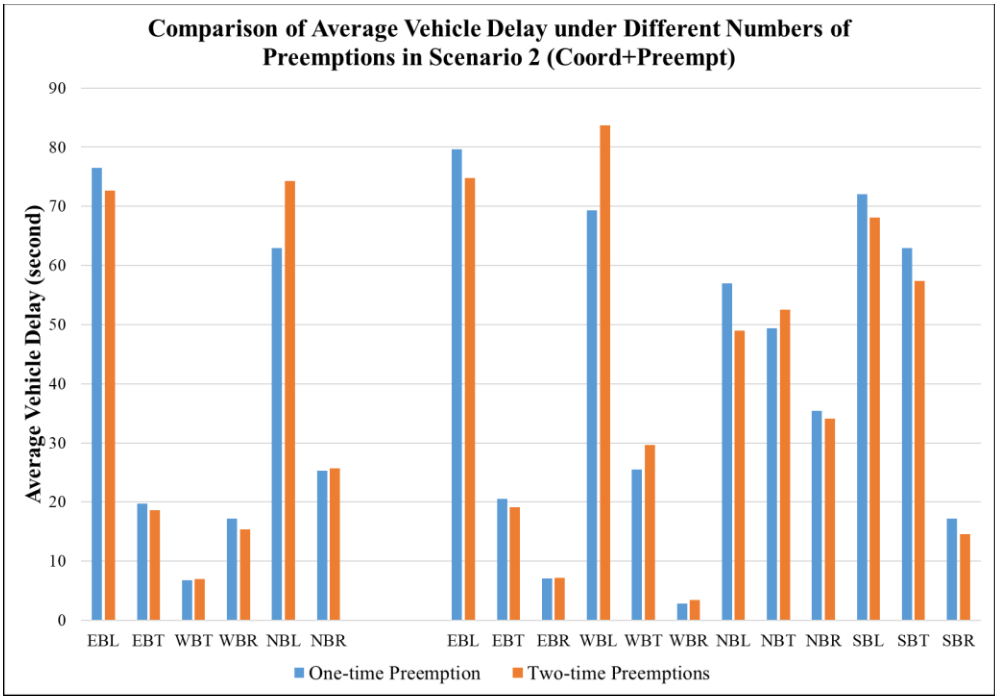


Figure 53 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 2 (Coord+Preempt)

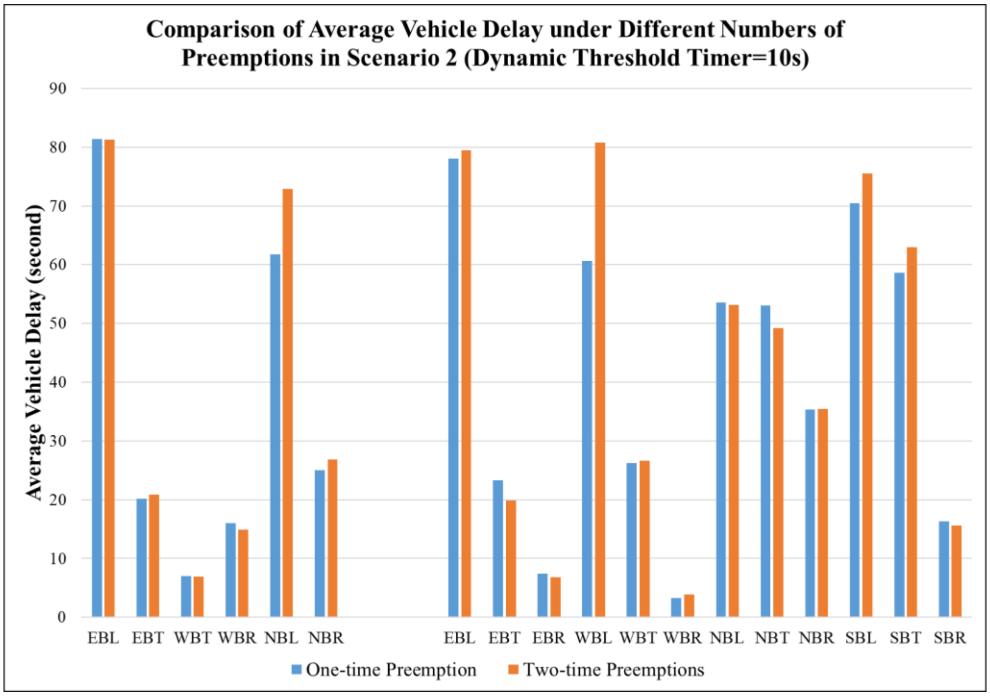


Figure 54 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 2 (Dynamic Threshold Timer=10s)

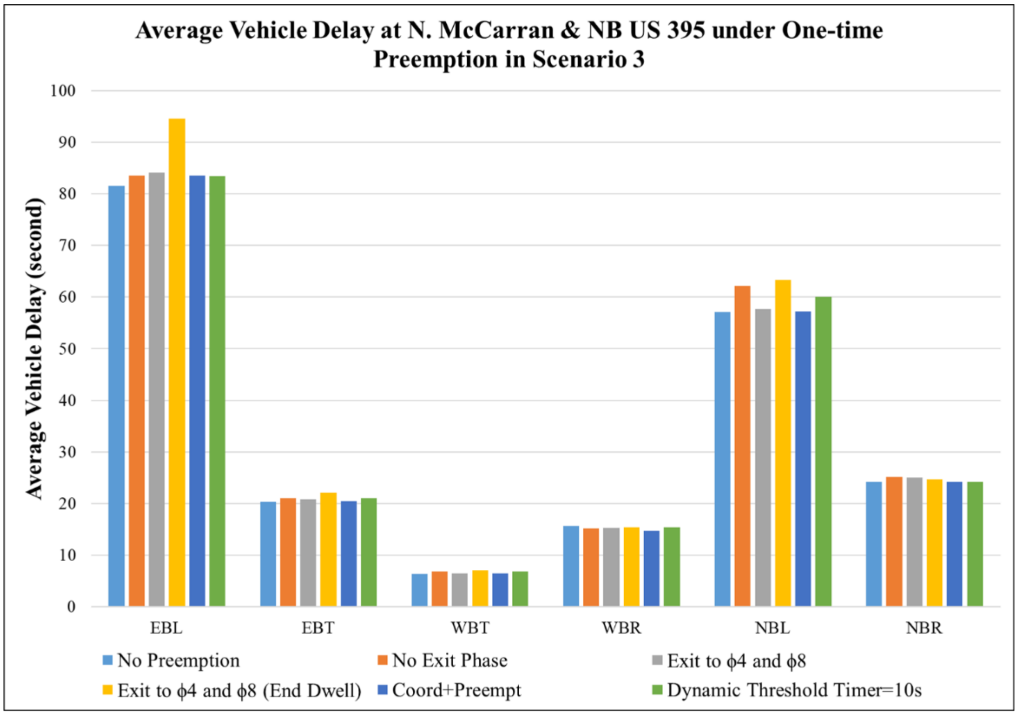
7.3.4 Scenario 3

7.3.4.1 Average Vehicle Delay under One-time Preemption

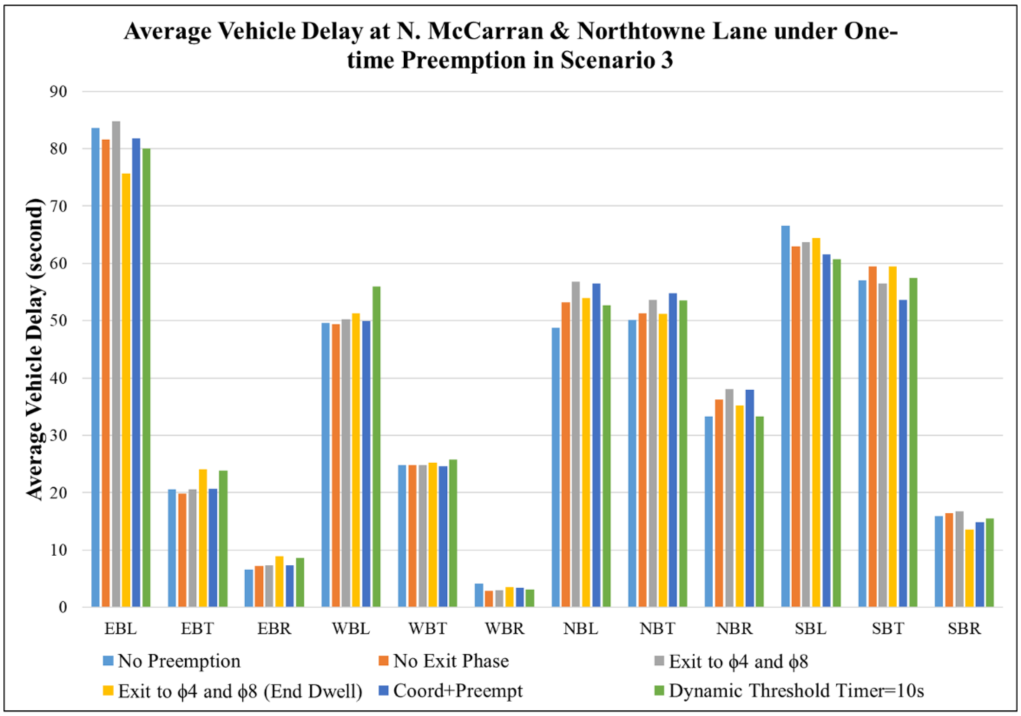
During the simulation, it was found out that $\phi4$ and $\phi8$ were selected as the exit phases at both intersections when no exit phases were programmed. As for the dynamic exit phase selections, all occurred exit phases were: $\phi4$ and $\phi8$ were returned at N. McCarran & NB US 395. $\phi2$ and $\phi6$ were selected at N. McCarran & Northtowne Lane.

From the average vehicle delay unfolded in Appendix A-6, it was figured out that no exit phase strategy produced the similar performance to exit to $\phi4$ and $\phi8$ due to the same phase return at N. McCarran & NB US 395. Compared with exit to $\phi4$ and $\phi8$ only, end dwell benefited side-street movements, such as NBL and NBR. In this scenario, dynamic threshold timer outperformed exit to $\phi4$ and $\phi8$ (end dwell) on all turning movements at N. McCarran & NB US 395. With regard to Coord+Preempt, it produced the overall minimal delay for each turning movement.

At N. McCarran & Northtowne Lane, no exit phase and exit to $\phi 4$ and $\phi 8$ generated the similar performance due to the same phase return. In comparison with exit to $\phi 4$ and $\phi 8$ only, although end dwell reduced movement delay of non-return phases, such as EBL and NBL, it produced greater delay on the main-street through movements. Compared with end dwell, the dynamic thresholder timer generated reduced delay at EBT and NBL. As for Coord+Preempt, it lowered delay of the main-street through movements and maintained minimal delay for other movement as always. Average vehicle delay under one-time preemption in scenario 3 is plotted in Figure 55 for better visualization.



(a)



(b)

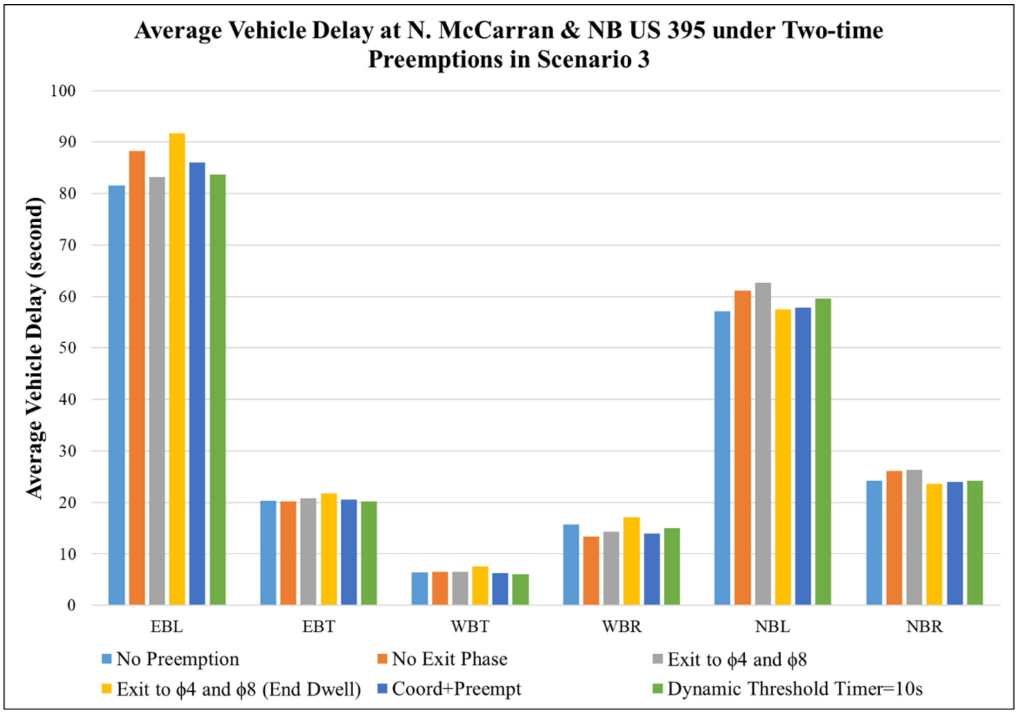
Figure 55 Comparison of Average Vehicle Delay under One-time Preemption in Scenario 3: (a) N. McCarran & NB US 395, (b) N. McCarran & Northtowne Lane

7.3.4.2 Average Vehicle Delay under Two-time Preemptions

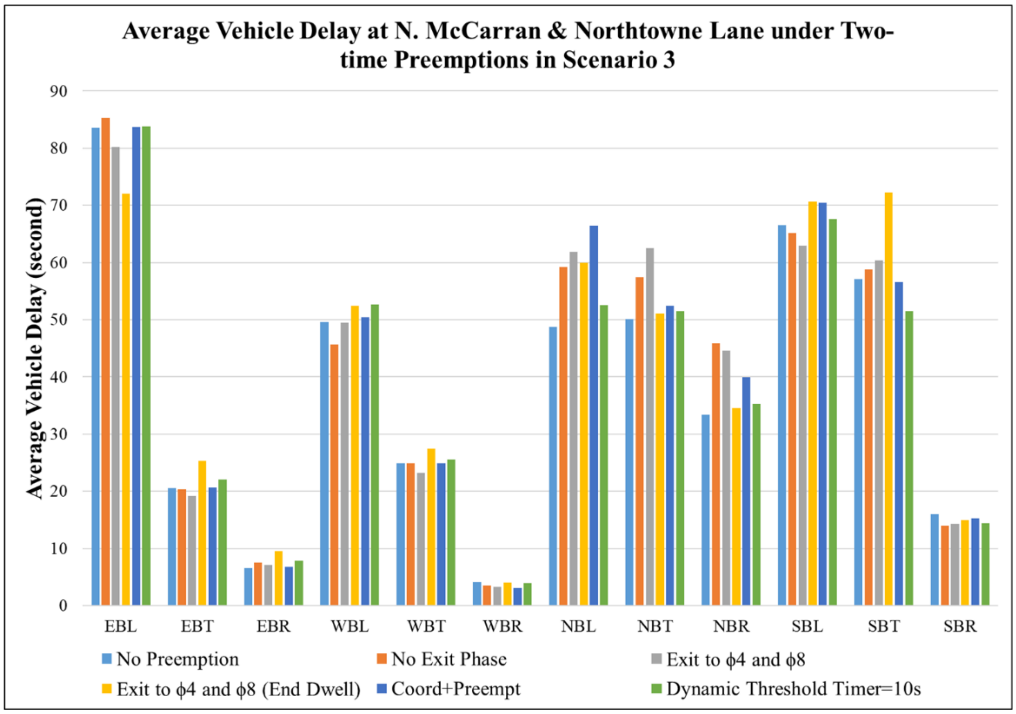
From Appendix A-7, it is clear that exit to $\phi 4$ and $\phi 8$ performed similarly to the no exit phase under two-time preemptions at N. McCarran & NB US 395. Compared with exit to $\phi 4$ and $\phi 8$ only, end dwell greatly benefited the side-street movements, NBL and NBT but produced the worse performance on the main-street movements. Under two-time preemptions, the dynamic threshold timer outperformed exit to $\phi 4$ and $\phi 8$ (end dwell) on the main-street movements. With regard to Coord+Preempt, it produced the lowest delay on the main-street through movements and balanced side-street delay.

At N. McCarran & Northtowne Lane, the performance between no exit phase and exit to $\phi 4$ and $\phi 8$ were similar due to the same phase return. In comparison with exit to $\phi 4$ and $\phi 8$ only, end dwell reduced movement delay of non-return phase, such as EBL and NBL while it produced greater delay on the main-street through movements due to cycling to starving phases prior to exiting to $\phi 8$. Compared with end dwell, the dynamic thresholder timer cut down delay of main-street through movements. As for Coord+Preempt, although it generated the worst performance at NBL, it minimized delay of the main-street through movements and there were little changes in delay under different numbers of preemptions to minimize negative impacts.

Average vehicle delay under two-time preemptions in scenario 3 is plotted in Figure 56 for better visualization. Performance comparison of each exit strategy in scenario 3 under different numbers of preemptions is illustrated from Figure 57 to Figure 61.



(a)



(b)

Figure 56 Comparison of Average Vehicle Delay under Two-time Preemptions in Scenario 3: (a) N. McCarran & NB US 395, (b) N. McCarran & Northtowne Lane

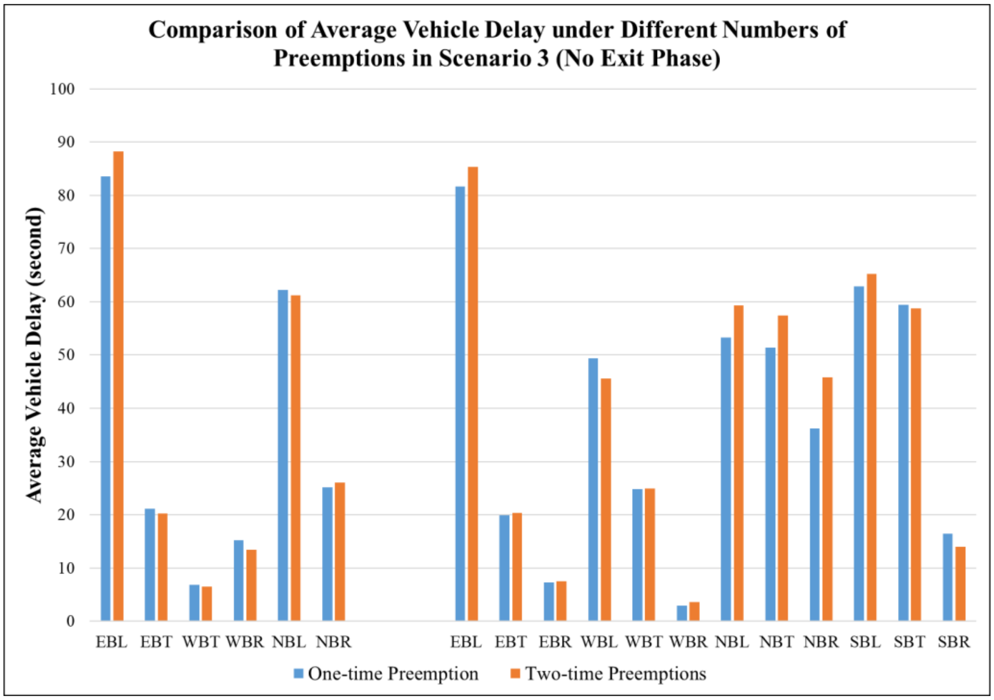


Figure 57 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 3 (No Exit Phase)

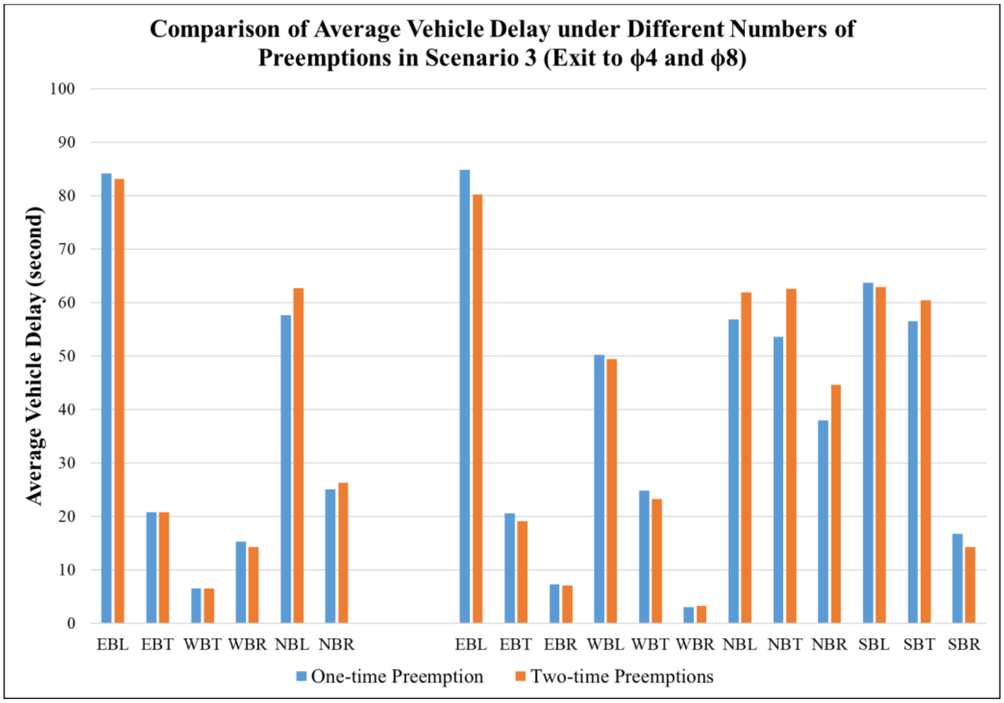


Figure 58 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 3 (Exit to $\phi4$ and $\phi8$)

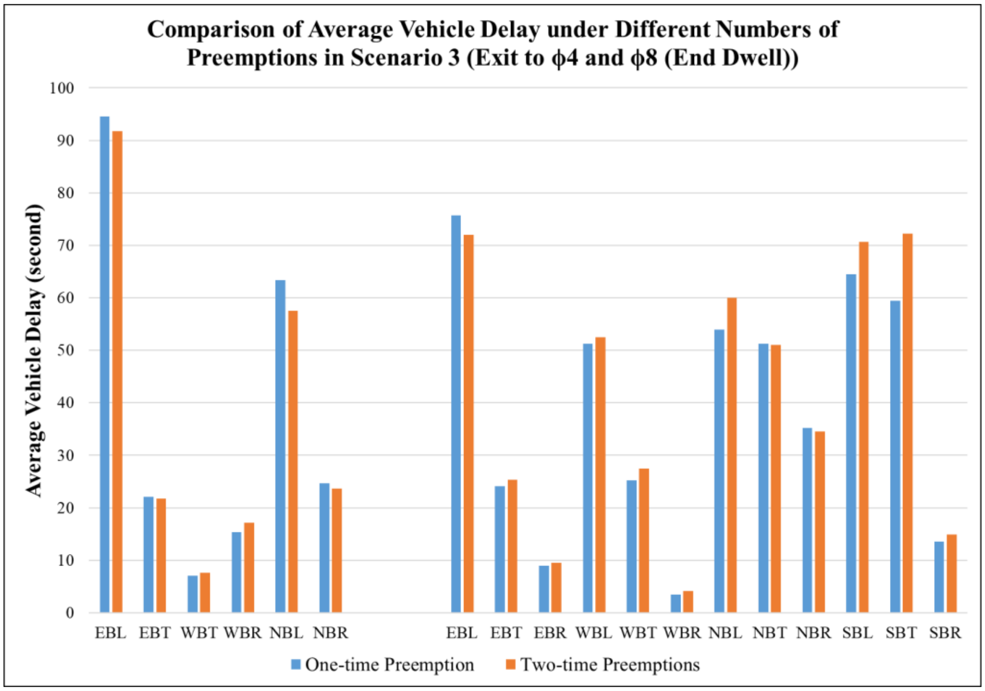


Figure 59 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 3 (Exit to $\phi 4$ and $\phi 8$ (End Dwell))

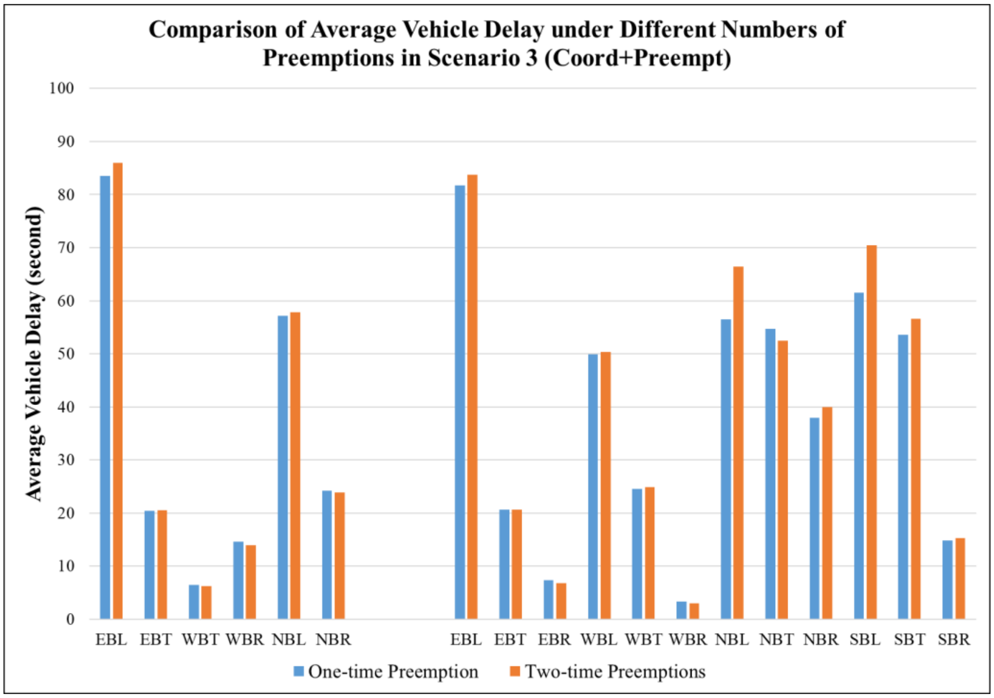


Figure 60 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 3 (Coord+Preempt)

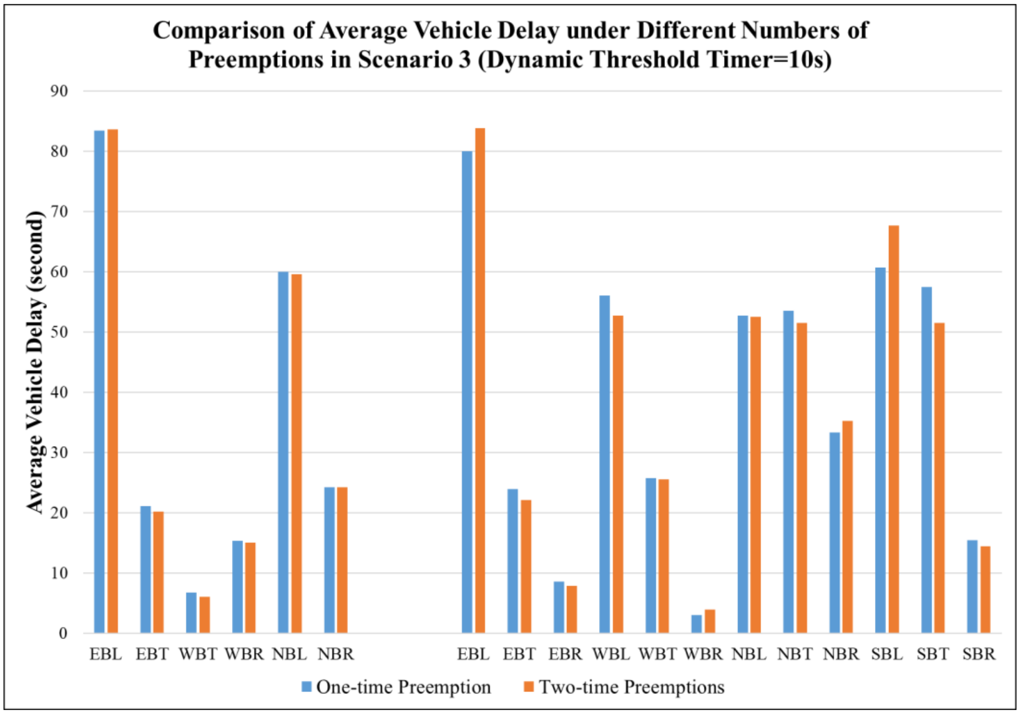


Figure 61 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 3 (Dynamic Threshold Timer=10s)

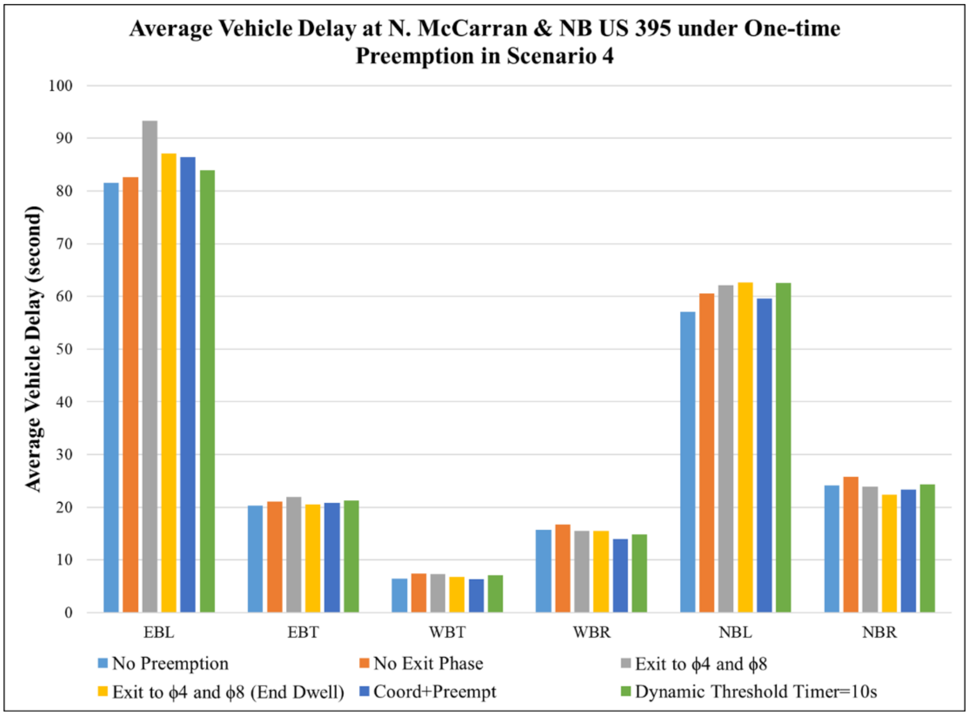
7.3.5 Scenario 4

7.3.5.1 Average Vehicle Delay under One-time Preemption

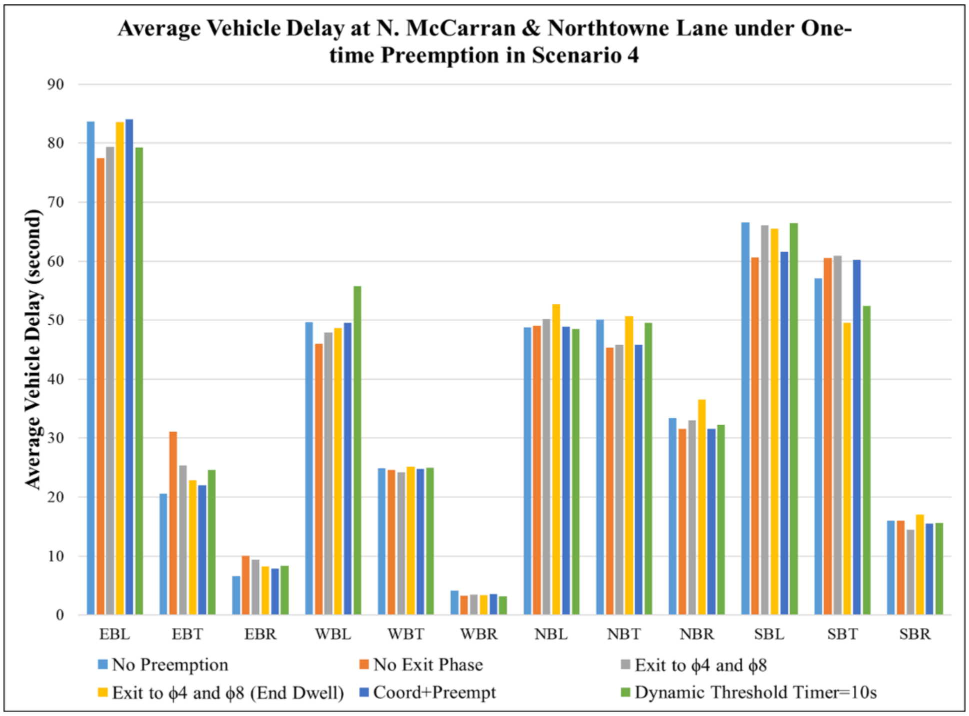
During the simulation, it was found out that $\phi 2$, or $\phi 3$ or $\phi 4$ and $\phi 8$ were returned as the exit phases at N. McCarran & NB US 395 and $\phi 3$ and $\phi 8$ were selected at N. McCarran & Northtowne Lane when no exit phases were programmed. As for the dynamic exit phase selections, all occurred exit phases were: $\phi 4$ and $\phi 8$ were returned at N. McCarran & NB US 395. $\phi 2$ and $\phi 6$ were selected at N. McCarran & Northtowne Lane.

From the average vehicle delay unfolded in Appendix A-7, it was figured out that exit to $\phi 4$ and $\phi 8$ produced the greatest delay of EBL and EBT at N. McCarran & NB US 395. Compared with exit to $\phi 4$ and $\phi 8$ only, end dwell benefited EBL, EBT, WBT and NBR. In this scenario, exit to $\phi 4$ and $\phi 8$ (end dwell) outperformed the dynamic thresholder timer especially at main-street through movements at N. McCarran & NB US 395. With regard to Coord+Preempt, it produced the overall minimal delay for each turning movement.

At N. McCarran & Northtowne Lane, no exit phase generated the worst performance on EBT due to the phase return to $\phi3$ and $\phi8$. In comparison with exit to $\phi4$ and $\phi8$ only, end dwell failed to improve movement delay of non-return phases, such as EBL, WBL and NBL in this scenario. Compared with end dwell, although the dynamic thresholder timer generated reduced delay of EBL and WBT, it did not produce better performance on EBT. As for Coord+Preempt, it performed well by lowering delay of the main-street through movements and balancing reduced delay of other movement as always. Average vehicle delay under one-time preemption in scenario 4 is plotted in Figure 62 for better visualization.



(a)



(b)

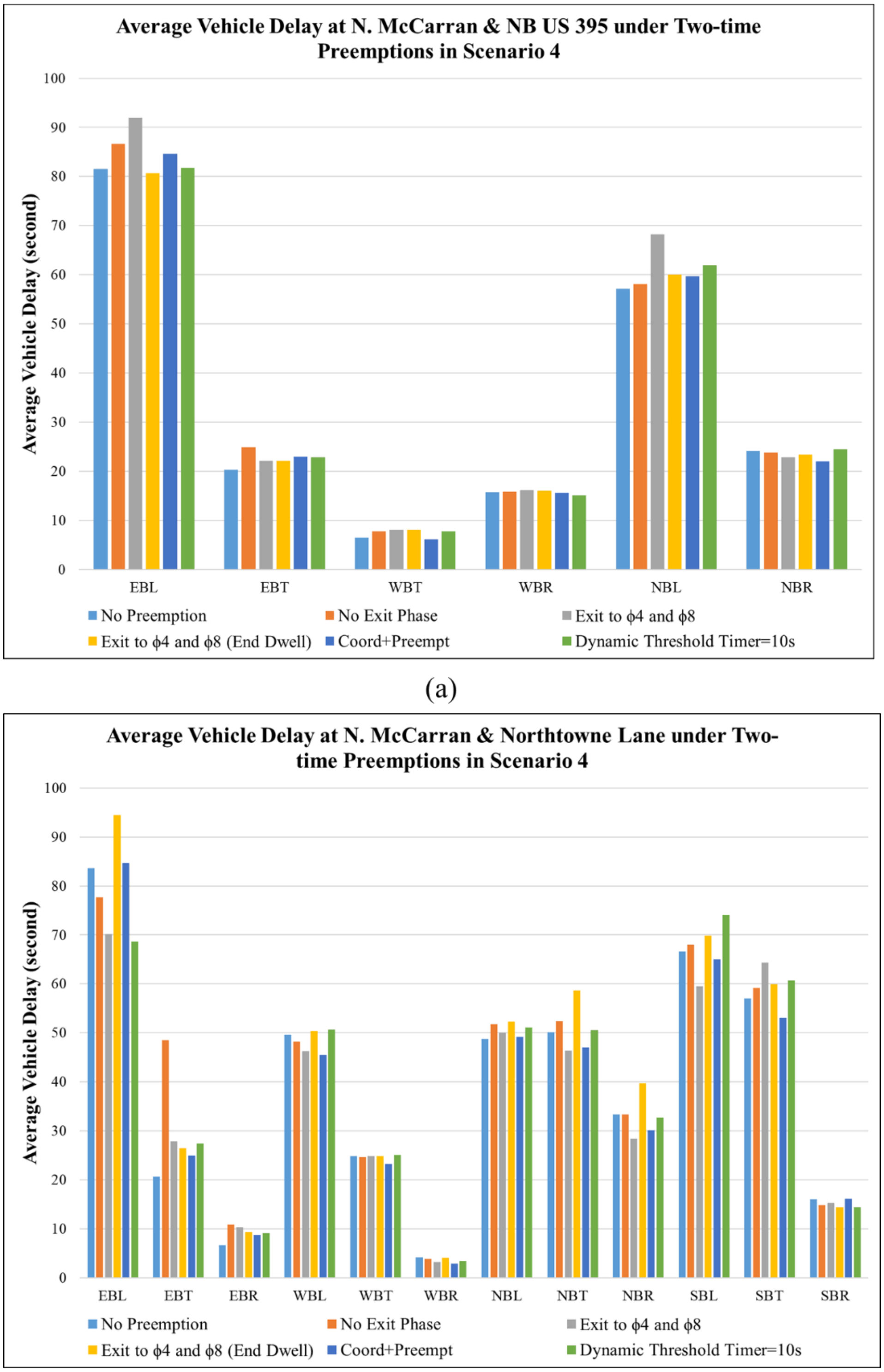
Figure 62 Comparison of Average Vehicle Delay under One-time Preemption in Scenario 4: (a) N. McCarran & NB US 395, (b) N. McCarran & Northtowne Lane

7.3.5.2 Average Vehicle Delay under Two-time Preemptions

From Appendix A-8, it was observed that no exit phase generated the greatest delay of EBT under two-time preemptions at N. McCarran & NB US 395. Compared with exit to $\phi 4$ and $\phi 8$ only, end dwell greatly benefited EBL and NBL. Under two-time preemptions, exit to $\phi 4$ and $\phi 8$ (end dwell) outperformed the dynamic threshold timer except at the WBT. With regard to Coord+Preempt, although it produced the worst performance for EBT, average vehicle delay at WBT, NBL and NBR were the lowest.

At N. McCarran & Northtowne Lane, the phase return to $\phi 3$ and $\phi 8$ greatly ruined the EBT progression under no exit phase strategy. In comparison with exit to $\phi 4$ and $\phi 8$ only, end dwell performed worse without benefiting non-preempted phases. Compared with end dwell, the dynamic thresholder timer cut down delay at EBL, NBL and NBT while it did not demonstrate better performance on the main-street through movements. As for Coord+Preempt, it produced the lowest delay at the main-street through movements and there were little changes in delay under different numbers of preemptions to minimize negative impacts.

Average vehicle delay under two-time preemptions in scenario 4 is plotted in Figure 63 for better visualization. Performance comparison of each exit strategy in scenario 4 under different numbers of preemptions is illustrated from Figure 64 to Figure 68.



(a)

(b)

Figure 63 Comparison of Average Vehicle Delay under Two-time Preemptions in Scenario 4: (a) N. McCarran & NB US 395, (b) N. McCarran & Northtowne Lane

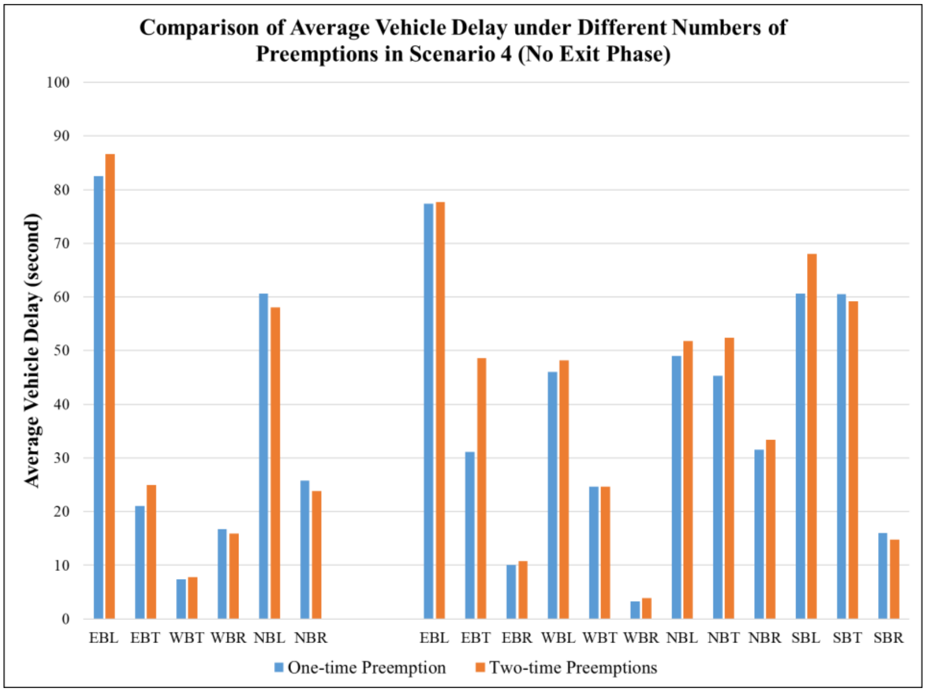


Figure 64 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 4 (No Exit Phase)

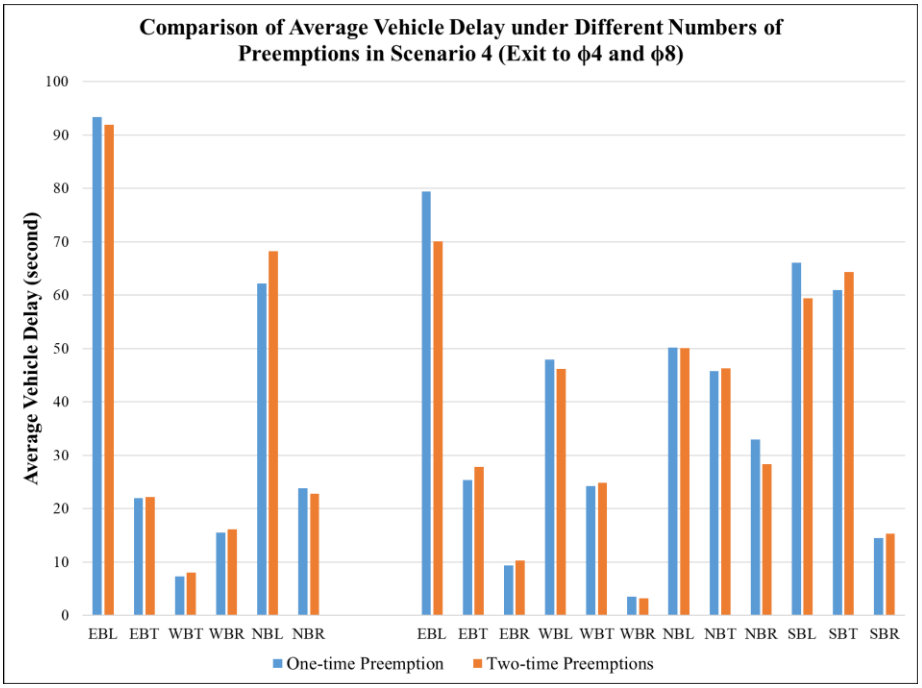


Figure 65 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 4 (Exit to $\phi 4$ and $\phi 8$)

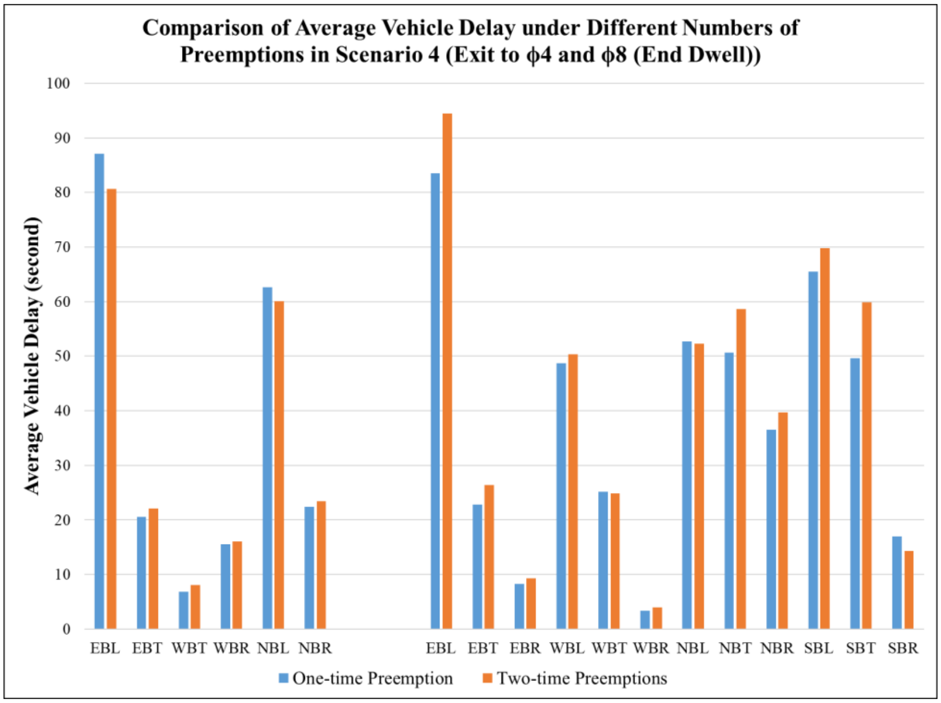


Figure 66 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 4 (Exit to ϕ4 and ϕ8 (End Dwell))

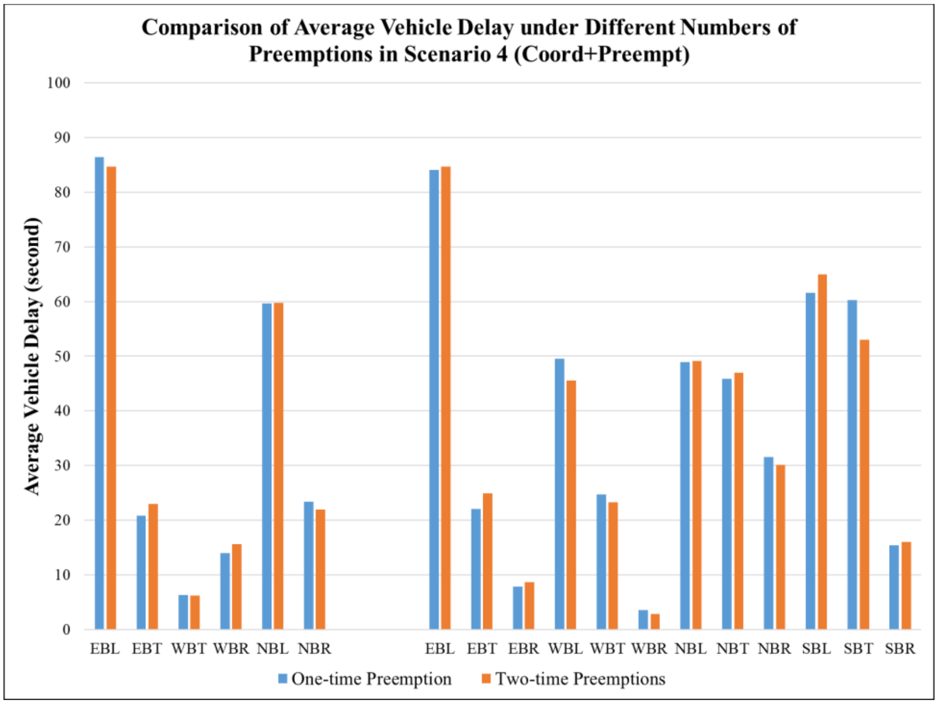


Figure 67 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 4 (Coord+Preempt)

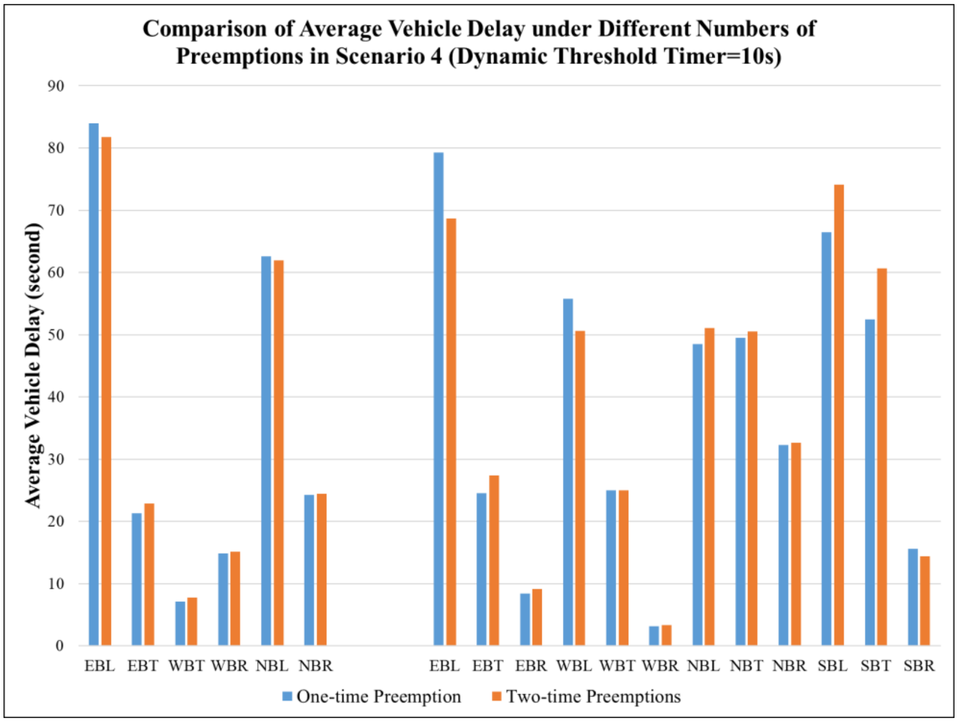


Figure 68 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 4 (Dynamic Threshold Timer=10s)

7.3.6 Scenario 5

7.3.6.1 Average Vehicle Delay under One-time Preemption

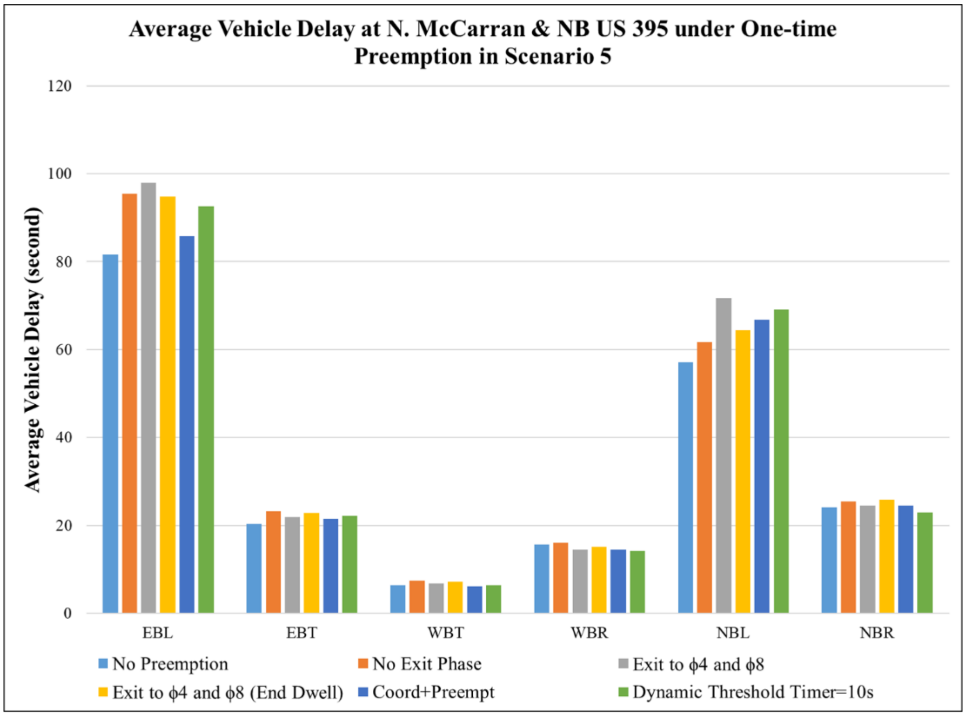
During the simulation, it was observed that $\phi 2$ was selected as the exit phases at N. McCarran & NB US 395 and $\phi 3$ and $\phi 8$ were returned at N. McCarran & Northtowne Lane when no exit phases were programmed. As for the dynamic exit phase selections, all occurred exit phases were: $\phi 4$ and $\phi 8$ were returned at N. McCarran & NB US 395. $\phi 2$ and $\phi 5$ or $\phi 6$ were selected at N. McCarran & Northtowne Lane.

From the average vehicle delay unfolded in Appendix A-10, it was figured out that no exit phase produced the greatest delay of main-street through movements at N. McCarran & NB US 395. Compared with exit to $\phi 4$ and $\phi 8$ only, end dwell benefited EBL and NBL. In this scenario, the dynamic threshold timer outperformed exit to $\phi 4$ and $\phi 8$

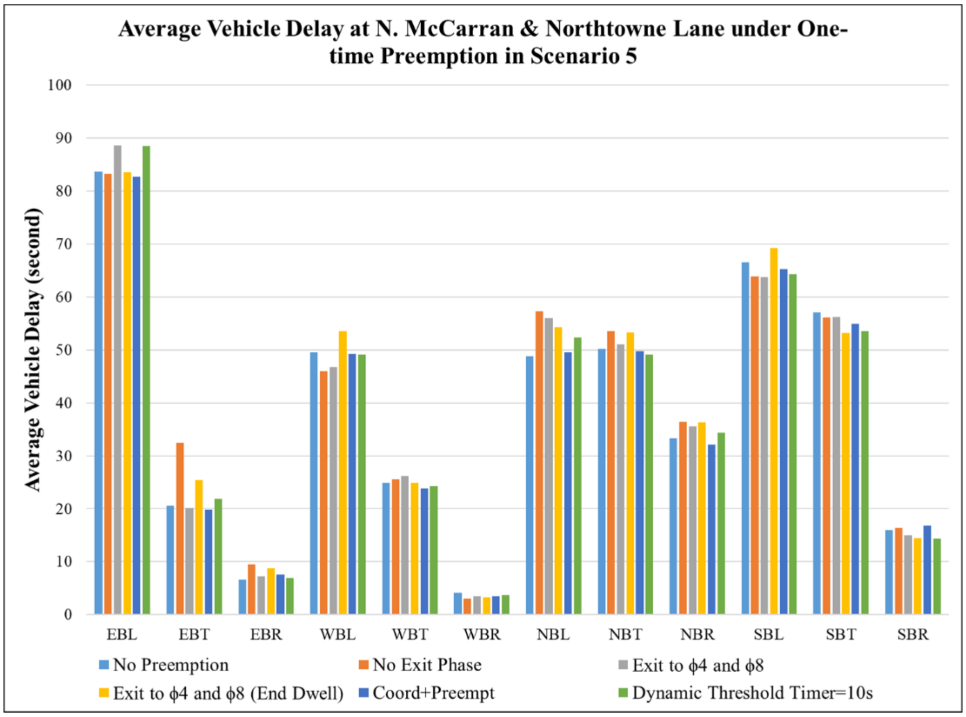
(end dwell) on the main-street through movements. With regard to Coord+Preempt, it produced the best performance on the main-street movements and overall balanced delay of side-street movements.

At N. McCarran & Northtowne Lane, no exit phase generated the worst performance on EBT due to the phase return to $\phi 3$ and $\phi 8$. In comparison with exit to $\phi 4$ and $\phi 8$ only, although the end dwell reduced movement delay of EBL and NBL, it unexpectedly worsened EBT progression. Compared with end dwell, the dynamic thresholder timer generated reduced delay of the main-street through movements. As for Coord+Preempt, it performed solidly by resulting in the lowest delay of the main-street through movements and balancing reduced delay of other movement as always.

Average vehicle delay under one-time preemption in scenario 5 is plotted in Figure 69 for better visualization.



(a)



(b)

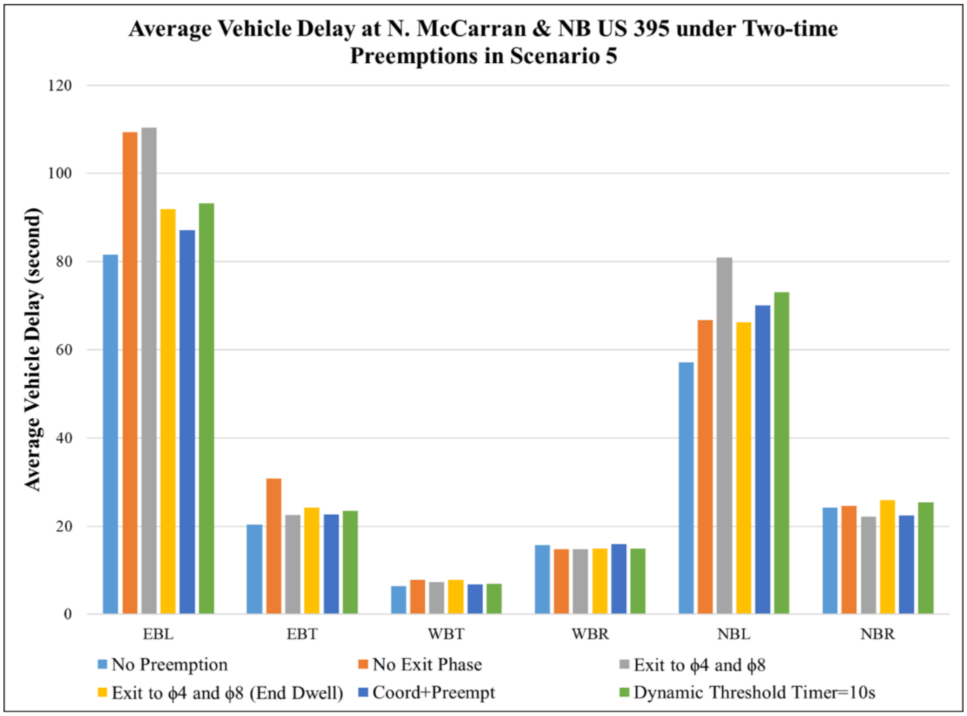
Figure 69 Comparison of Average Vehicle Delay under One-time Preemption in Scenario 5: (a) N. McCarran & NB US 395, (b) N. McCarran & Northtowne Lane

7.3.6.2 Average Vehicle Delay under Two-time Preemptions

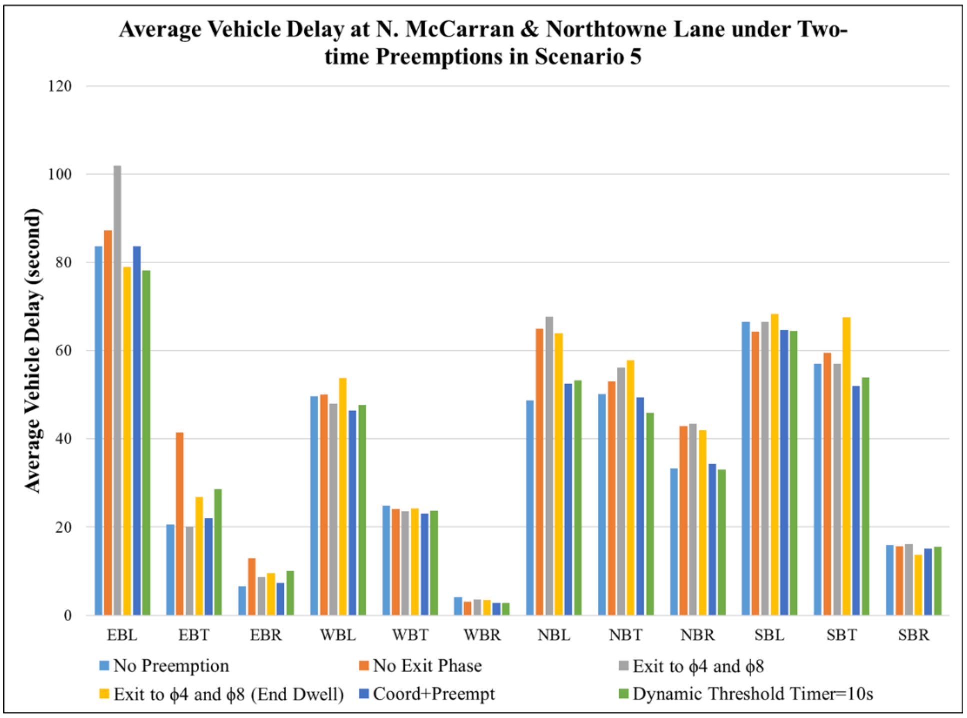
From Appendix A-11, results suggested that no exit phase generated the greatest delay at EBT under two-time preemptions at N. McCarran & NB US 395. Compared with exit to $\phi 4$ and $\phi 8$ only, although the end dwell benefited EBL and NBL, it produced greater delay of the main-street through movements. Under two-time preemptions, the dynamic threshold timer outperformed exit to $\phi 4$ and $\phi 8$ (end dwell) by reducing the delay of main-street through movements. With regard to Coord+Preempt, it produced the lowest delay of the main-street movements and balanced performance on the side-streets.

At N. McCarran & Northtowne Lane, the phase return to $\phi 3$ and $\phi 8$ unexpectely disrupted the EBT progression under no exit phase strategy. In comparison with exit to $\phi 4$ and $\phi 8$ only, end dwell only benefited EBL and NBL while it failed to enhance the performance on the main-street through movements. Compared with end dwell, the dynamic thresholder timer cut down delay at EBL, WBL, WBT, NBL and NBT. As for Coord+Preempt, it produced the overall minimal delay for each turning movement and there were little changes in delay under different numbers of preemptions to minimize negative impacts.

Average vehicle delay under two-time preemptions in scenario 5 is plotted in Figure 70 for better visualization. Performance comparison of each exit strategy in scenario 5 under different numbers of preemptions is illustrated from Figure 71 to Figure 75.



(a)



(b)

Figure 70 Comparison of Average Vehicle Delay under Two-time Preemptions in Scenario 5: (a) N. McCarran & NB US 395, (b) N. McCarran & Northtowne Lane

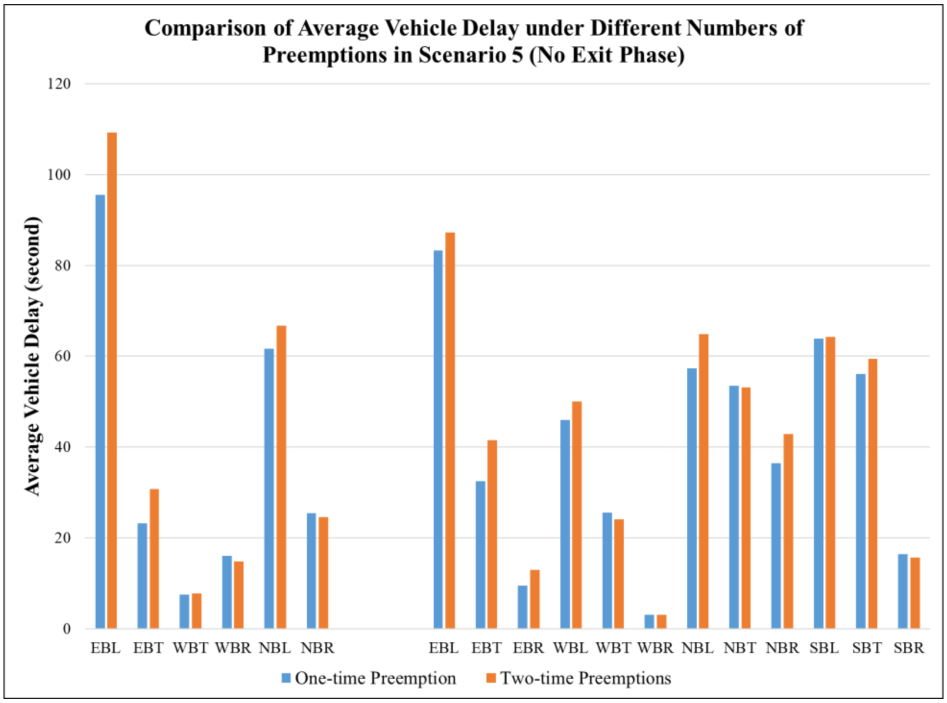


Figure 71 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 5 (No Exit Phase)

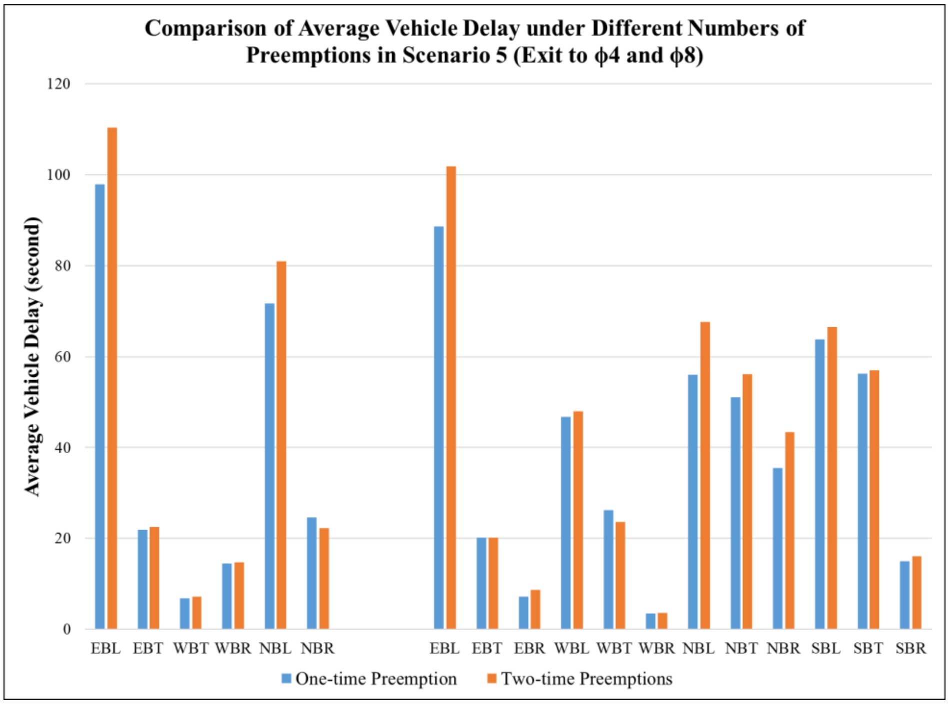


Figure 72 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 5 (Exit to $\phi 4$ and $\phi 8$)

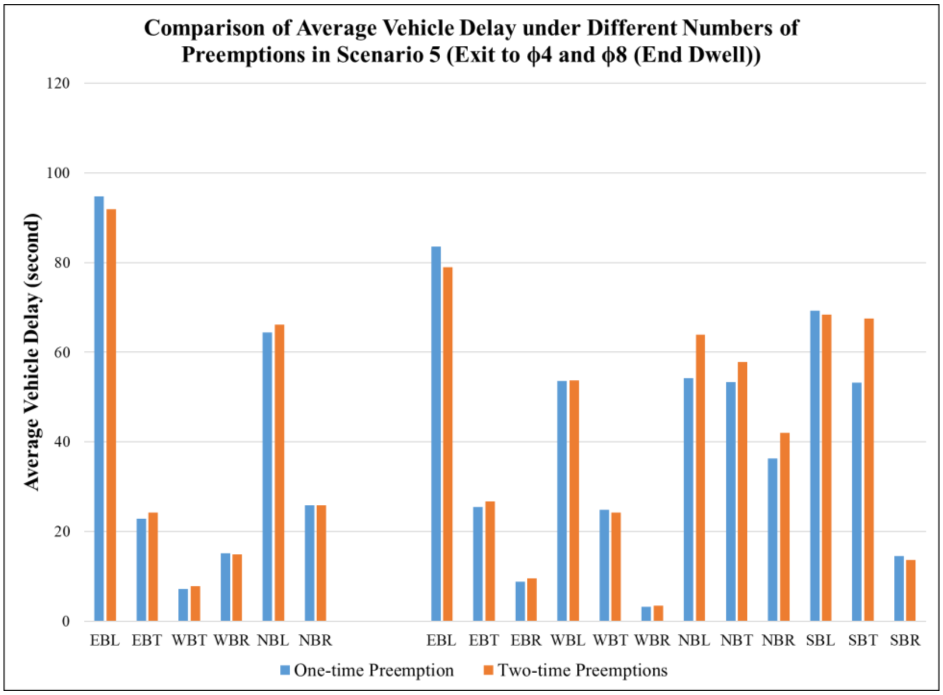


Figure 73 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 5 (Exit to $\phi 4$ and $\phi 8$ (End Dwell))

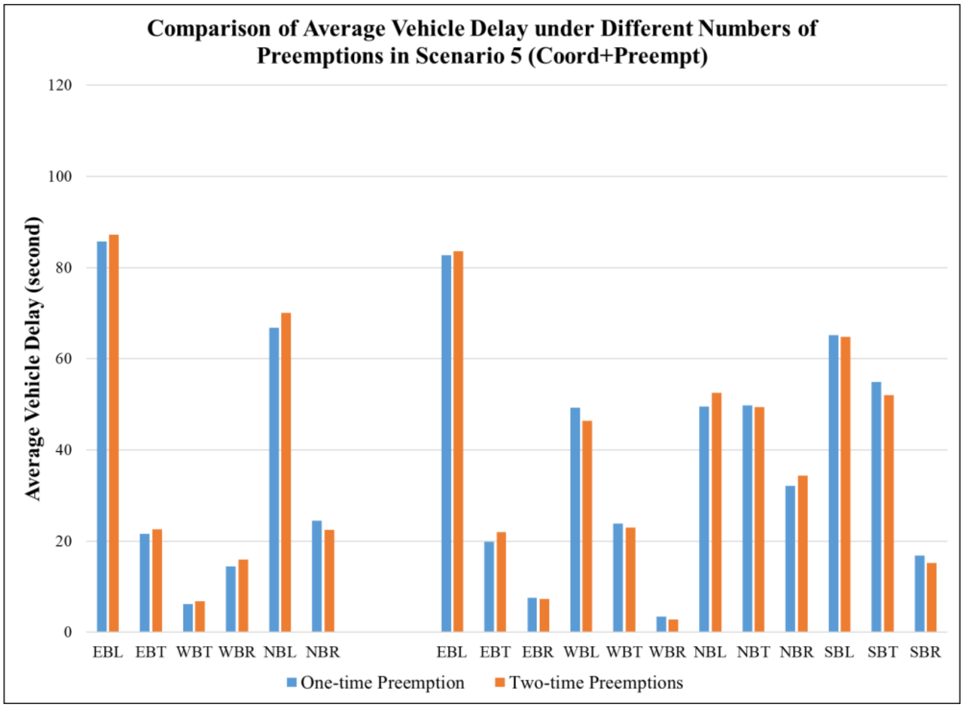


Figure 74 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 5 (Coord+Preempt)

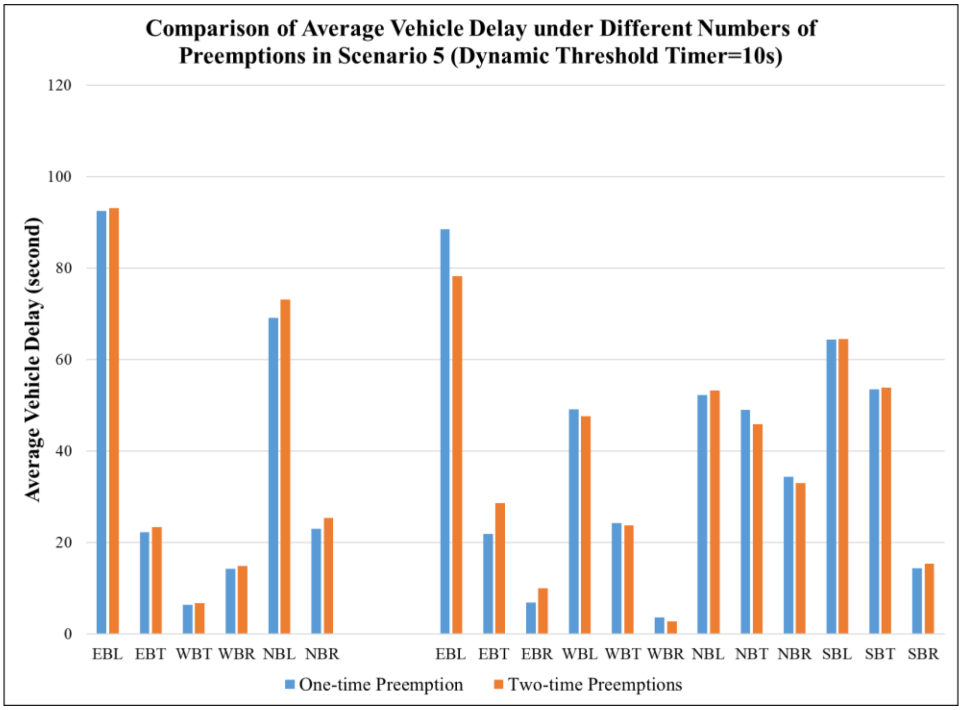


Figure 75 Comparison of Average Vehicle Delay under Different Numbers of Preemptions in Scenario 5 (Dynamic Threshold Timer=10s)

7.3.7 Simulation Results Summary

Based on the simulation results from the above five scenarios, it could be concluded that the extent of negative impacts on all turning movements was related to preemption activation points, routes of the emergency vehicle, the selections of an exit strategy and the number of preemptions. Additionally, average vehicle delay on the non-preempted main-street movements was accumulated under two-time preemptions in comparison with the one-time preemption in all scenarios.

Among all exit strategies, the no exit phase strategy tended to worsen the performance on the main-street through movements due to its uncertain phase return. Compared with exit to main-street through movements only, end dwell and the dynamic threshold timer provided more flexibility of phase return rather than unconditionally returning to the programmed exit phases, which potentially enhances performance on the main-street and side-streets. Comparing end dwell with the dynamic threshold timer, end dwell performed better in minimizing vehicle delay of non-returned phases by cycling to them prior to running exit phases. Nevertheless, it usually produced increased delay on the non-preempted exit phases when serving other phases. The dynamic threshold timer was complementary to the end dwell by directly returning to non-preempted phases with the longest waiting time and generating better performance on the main-street through movements. As for Coord+Preempt, it minimized the negative impacts by proceeding back to the background coordination without transition and generating the overall minimal delay on all turning movements under different numbers of preemptions.

8 Conclusions and Recommendations

This research conducted a comprehensive analysis of optical-based EVP operations by introducing preemption modules in Trafficware 980 ATC V76 signal controllers to analyze the negative impacts caused by EVP on arterial signal coordination. To minimize such impacts, five exit strategies: no exit phase, exit to fixed phases, exit to fixed phases (end dwell), Coord+Preempt and the dynamic threshold timer, in Trafficware 980 ATC V76 signal controllers were evaluated and compared using HILS in five simulation scenarios on basis of various preemption activation points and routes of the emergency vehicle with different numbers of preemptions.

The conclusions were drawn as follows：

- The extent of negative impacts caused by EVP on arterial signal coordination was highly influenced by preemption activation points, routes of the emergency vehicle, the selection of an exit strategy and the number of preemptions.
- Average vehicle delay on the non-preempted arterial movements tended to rise with an increasing number of preemptions for all exit strategies.
- The no exit phase strategy unexpectedly produced worse performance on the arterial through movements than other exit strategies due to its uncertain phase return at the end of the preemption.
- End dwell and the dynamic threshold timer provided more flexibility of phase return than unconditionally returning to the programmed exit phases, which potentially enhances performance on the main-street and side-streets. End dwell performed better in minimizing vehicle delay of non-returned phases by cycling to them prior to running

exit phases. However, it usually produced increased delay on the non-preempted exit phases. The dynamic threshold timer took precedence by producing reduced delay on the arterial through movements.

- Among all the exit strategies, Coord+Preempt performed the best since it minimized the negative impacts to the maximum extent by proceeding back to the background coordination without transition and generating the overall minimal delay on all turning movements under different numbers of preemptions.

In practice, Coord+Preempt was recommended to be implemented as the exit strategy to minimize disruptions caused by EVP on arterial signal coordination.

As for further research, it is suggested that Trafficware enhances the logic processor by adding local clock and numerical operators (> and <) to customized input in controllers for flexibly selecting an exit strategy based on preemption activation points and routes of the emergency vehicle. More signalized intersections could be considered into HILS to comprehensively evaluate and compare existing exit strategies in more scenarios. Additionally, how to refine and balance both vehicle and pedestrian performance after EVP remains to be explored for further research.

REFERENCES

1. United States Department of Transportation (USDOT), FHWA. (2009). Manual on Uniform Traffic Devices for Streets and Highways (MUTCD).
2. FHWA, NHTSA. (2006). Traffic Signal Preemption for Emergency Vehicles: A Cross-Cutting Study.
3. Gehami, A. (2019). San José Fire Department CEVP Data Story: Studying the Impact of San José Fire Department's Centralized Emergency Vehicle Preemption System on Fire Vehicle Travel Time.
4. Maricopa Association of Governments (MAG). (2016). Emergency Vehicle Preemption State of the Practice Study.
5. Maricopa Association of Governments (MAG). (2018). Emergency Vehicle Preemption Regional Coordination for Unified Operations Project Report.
6. National Academies of Sciences, Engineering, and Medicine. (2015). Signal Timing Manual - Second Edition. Washington, DC: The National Academies Press. https://doi.org/10.17226/22097
7. Shelby, S. G., Bullock, D. M., & Gettman, D. (2006). Transition Methods in Traffic Signal Control. Transportation Research Record, 1978(1), 130–140. https://doi.org/10.1177/0361198106197800117
8. Obenberger, J., & Collura, J. (2001). Transition Strategies to Exit Preemption Control: State-of-the-Practice Assessment. Transportation Research Record, 1748(1), 72–79. https://doi.org/10.3141/1748-09

9. Obenberger, J., & Collura, J. (2007). Methodology to Assess Traffic Signal Transition Strategies for Exit Preemption Control. Transportation Research Record, 2035(1), 158–168. https://doi.org/10.3141/2035-18
10. Yun, I., Best, M., & Park, B. B. (2008). Evaluation of Transition Methods of the 170E and 2070 ATC Traffic Controllers after Emergency Vehicle Preemption. Journal of Transportation Engineering-ASCE, 134, 423-431.
11. Yun, I., Park, B. B., Lee, C., & Oh, Y. (2012). Comparison of Emergency Vehicle Preemption methods using a Hardware-In-The-Loop simulation. KSCE Journal of Civil Engineering, 16, 1057-1063.
12. Bullock, D. M. (2001). Controller Interface Device. United States Patent and Trademark Office. US 6172617 B1.
13. Bullock, D. M., & Catarella, A. (1998). A Real-Time Simulation Environment for Evaluating Traffic Signal Systems. Transportation Research Record, 1634(1), 130–135. https://doi.org/10.3141/1634-17
14. Bullock, D. M., Morales, J. M. & Sanderson, B. (1999). Evaluation of Emergency Vehicle Signal Preemption on the Route 7 Virginia Corridor. FHWA-RD-99-070. URL: https://rosap.ntl.bts.gov/view/dot/35851
15. Nelson, E. J., & Bullock, D. (2000). Impact of Emergency Vehicle Preemption on Signalized Corridor Operation: An Evaluation. Transportation Research Record, 1727(1), 1–11. https://doi.org/10.3141/1727-01
16. Yun, I., Park, B. B., Lee, C. K., & Oh, Y. T. (2011). Investigation on the exit phase controls for emergency vehicle preemption. KSCE Journal of Civil Engineering, 15(8), 1419-1426. http://dx.doi.org/10.1007/s12205-011-1326-2

17. Shibuya, S., Yoshida, T., Yamashiro, Z., & Miyawaki, M. (2000). Fast Emergency Vehicle Preemption Systems. Transportation Research Record, 1739(1), 44–50. https://doi.org/10.3141/1739-06
18. Wang, Y., Wu, Z., Yang, X., & Huang, L. (2013). Design and Implementation of an Emergency Vehicle Signal Preemption System Based on Cooperative Vehicle-Infrastructure Technology. Beyond Behavior, 85–96. https://doi.org/10.1177/10742956211020666
19. Kwon, E., & Kim, S. (2003). Development of Dynamic Route Clearance Strategies for Emergency Vehicle Operations, Phase I.
20. Kamalanathsharma, R.K., & Hancock, K.L. (2010). Congestion-Based Emergency Vehicle Preemption.
21. Qin, X. & Khan, A. M. (2012). Control Strategies of Traffic Signal Timing Transition for Emergency Vehicle Preemption. Transportation Research Part C: Emerging Technologies, 25(1), 1-17. https://doi.org/10.1016/j.trc.2012.04.004
22. Wang, J., Ma, W., & Yang, X. (2013). Development of Degree-of-Priority Based Control Strategy for Emergency Vehicle Preemption Operation. Discrete Dynamics in Nature and Society, 2013, 1-10.
23. Zhang, Z., He, Q., Gou, J. & Li, X. (2016). Performance Measure for Reliable Travel Time of Emergency Vehicles. Transportation Research Part C: Emerging Technologies, 65(1), 97-110. http://dx.doi.org/10.1016/j.trc.2016.01.015
24. Shaaban, K., Khan, M. A., Hamila, R. & Ghanim, Mohammad. (2019). A Strategy for Emergency Vehicle Preemption and Route Selection. Arabian Journal for

Science and Engineering, 44(1), 8905–8913. https://doi.org/10.1007/s13369-019-03913-8

25. Mu, H., Song, Y., & Liu, L. (2018). Route-Based Signal Preemption Control of Emergency Vehicle. Journal of Control Science and Engineering, 2018(1), 1024382:1-1024382:11. https://doi.org/10.1155/2018/1024382
26. Mu, H., Liu, L., Song, Y., & Wang, N. (2020). Control Strategy of Signal Transition after Emergency Vehicle Signal Preemption. Discrete Dynamics in Nature and Society, 2020, 1-11.
27. Teng, H., Valerian, K., Xie, G., Mohamed, K. & Gibby, A.R. (2010). The Impacts of Emergency Vehicle Signal Preemption on Urban Traffic Speed. Journal of the Transportation Research Forum, 49(1), 69-79.
28. Cubic. (2020). Training Manual for NTCIP Based Advanced Transportation Controllers (ATC) Version 76.x – Cubic Trafficware ATC Controllers.
29. Trafficware. (2017). Synchro Studio 10: Synchro plus SimTraffic and 3D Viewer Traffic Signal Optimization and Simulation Modeling Software User Guide.
30. Yue, R., Yang, G., Lin, D., Wang, A. & Tian, Z. (2021). Traffic Signal Retiming to Improve Corridor Performance. Journal of Transportation Engineering, Part A: Systems, 147(1). https://ascelibrary.org/doi/10.1061/JTEPBS.0000482

Appendix A

A-1

Before-and-after Comparison of Average Vehicle Delay at Intersections

Movement	Before Calibration	After Calibration
N. McCarran & NB US 395		
EBL	87.54	81.57
EBT	21.84	20.33
WBT	6.40	6.44
WBR	14.94	15.71
NBL	56.88	57.10
NBR	25.42	24.17
N. McCarran & Northtowne Lane		
EBL	82.26	83.63
EBT	21.90	20.58
EBR	7.32	6.62
WBL	48.7	49.59
WBT	26.18	24.86
WBR	3.22	4.14
NBL	50.42	48.76
NBT	46.50	50.14
NBR	33.50	33.33
SBL	57.94	66.57
SBT	49.36	57.06
SBR	18.40	15.96

A-2

Comparison of Average Vehicle Delay under One-time Preemption in Scenario 1

Movement	No Preemption	No Exit Phase	Exit to $\phi 4$ and $\phi 8$	Exit to $\phi 4, \phi 8$ (End Dwell)	Coord+Preempt	Dynamic Thresholder Timer=10s
N. McCarran & NB US 395						
EBL	81.57	85.81	81.15	81.93	77.09	81.12
EBT	20.33	24.90	22.42	20.88	20.74	21.24
WBT	6.44	7.53	6.38	6.15	6.94	6.55
WBR	15.71	16.16	15.48	15.50	15.32	13.96
NBL	57.10	63.12	67.88	55.19	60.07	58.56
NBR	24.17	22.88	27.53	25.92	25.14	26.20
N. McCarran & Northtowne Lane						
EBL	83.63	71.00	85.09	80.86	78.46	82.30
EBT	20.58	26.39	21.19	19.91	19.74	20.32
EBR	6.62	10.38	8.20	7.76	7.30	8.11
WBL	49.59	49.61	59.29	51.99	51.44	60.62
WBT	24.86	25.36	27.25	28.64	28.13	25.72
WBR	4.14	2.75	3.34	3.28	3.16	3.29
NBL	48.76	51.52	53.73	51.57	49.41	51.05
NBT	50.14	50.53	52.59	53.62	45.91	52.76
NBR	33.33	33.59	38.06	34.64	31.16	33.33
SBL	66.57	63.86	67.74	63.38	66.28	71.91
SBT	57.06	55.47	56.65	56.97	57.53	66.18
SBR	15.96	14.67	15.16	16.69	15.29	14.73

A-3

Comparison of Average Vehicle Delay under Two-time Preemptions in Scenario 1

Movement	No Preemption	No Exit Phase	Exit to $\phi4, \phi8$	Exit to $\phi4, \phi8$ (End Dwell)	Coord+Preempt	Dynamic Thresholder Timer=10s
N. McCarran & NB US 395						
EBL	81.57	82.48	85.36	78.62	70.86	75.76
EBT	20.33	28.08	23.62	20.16	21.38	21.92
WBT	6.44	8.38	6.8	6.18	6.98	7.02
WBR	15.71	16.10	15.74	17.44	14.46	15.44
NBL	57.10	63.22	75.30	58.44	58.90	74.56
NBR	24.17	22.46	32.08	25.46	25.52	32.04
N. McCarran & Northtowne Lane						
EBL	83.63	63.18	80.98	83.14	82.28	66.64
EBT	20.58	34.46	22.72	22.04	21.06	24.34
EBR	6.62	14.0	7.78	8.26	7.58	7.46
WBL	49.59	51.52	64.36	60.32	51.38	62.96
WBT	24.86	26.54	28.16	34.82	28.60	29.78
WBR	4.14	3.38	3.46	3.02	3.06	2.90
NBL	48.76	53.82	68.44	53.92	48.08	57.98
NBT	50.14	54.12	56.02	50.3	43.26	53.84
NBR	33.33	35.68	41.46	35.24	29.28	42.90
SBL	66.57	63.34	70	66.18	63.74	70.94
SBT	57.06	58.52	61.40	58.18	47.34	52.70
SBR	15.96	17.12	16.66	19.18	16.42	14.40

A-4

Comparison of Average Vehicle Delay under One-time Preemption in Scenario 2

Movement	No Preemption	No Exit Phase	Exit to $\phi 4, \phi 8$	Exit to $\phi 4, \phi 8$ (End Dwell)	Coord+Preempt	Dynamic Thresholder Timer=10s
N. McCarran & NB US 395						
EBL	81.57	78.96	84.04	80.96	76.48	81.40
EBT	20.33	20.06	20.87	19.70	19.77	20.17
WBT	6.44	6.57	7.06	7.25	6.74	7.01
WBR	15.71	14.42	15.61	14.44	17.21	16.03
NBL	57.1	72.9	68.8	57.11	62.92	61.73
NBR	24.17	25.58	25.17	25.65	25.31	25.02
N. McCarran & Northtowne Lane						
EBL	83.63	82.25	82.62	79.45	79.67	78.1
EBT	20.58	20.85	20.96	22.82	20.56	23.28
EBR	6.6	8.01	7.26	8.10	7.06	7.40
WBL	49.59	61.02	60.82	55.64	69.33	60.62
WBT	24.86	25.93	26.70	28.01	25.54	26.23
WBR	4.14	3.33	3.20	3.15	2.87	3.23
NBL	48.76	58.97	58.57	55.44	56.94	53.57
NBT	50.14	54.51	51.81	52.29	49.37	53.08
NBR	33.33	40.99	39.28	35.72	35.45	35.39
SBL	66.57	71.04	71.11	66.52	72.01	70.48
SBT	57.06	55.37	53.79	65.47	62.99	58.64
SBR	15.96	15.37	15.45	14.58	17.16	16.32

A-5

Comparison of Average Vehicle Delay under Two-time Preemptions in Scenario 2

Movement	No Preemption	No Exit Phase	Exit to $\phi4, \phi8$	Exit to $\phi4, \phi8$ (End Dwell)	Coord+Preempt	Dynamic Thresholder Timer=10s
N. McCarran & NB US 395						
EBL	81.57	75.93	80.5	72.24	72.68	81.26
EBT	20.33	20.63	20.68	18.24	18.58	20.88
WBT	6.44	7.03	7.14	7.54	7.02	6.96
WBR	15.71	14.05	14.662	16.96	15.36	14.94
NBL	57.10	78.52	81.92	57.06	74.30	72.94
NBR	24.17	28.03	29.86	26.24	25.68	26.82
N. McCarran & Northtowne Lane						
EBL	83.63	82.63	85.5	75.84	74.82	79.44
EBT	20.58	27	20.96	20.5	19.1	19.9
EBR	6.62	8.47	7.30	6.98	7.14	6.84
WBL	49.59	58.28	66.80	52.84	83.68	80.74
WBT	24.86	25.15	26.04	28.34	29.7	26.64
WBR	4.14	2.75	2.38	3.46	3.44	3.90
NBL	48.76	66.02	69.36	54.62	49.02	53.16
NBT	50.14	56.95	65.22	56.98	52.5	49.18
NBR	33.33	39.02	50.66	37.12	34.08	35.44
SBL	66.57	71.73	70.20	64.94	68.12	75.54
SBT	57.06	64.23	61.52	64.90	57.38	62.96
SBR	15.96	16.18	17.46	14.66	14.60	15.66

A-6

Comparison of Average Vehicle Delay under One-time Preemption in Scenario 3

Movement	No Preemption	No Exit Phase	Exit to $\phi4, \phi8$	Exit to $\phi4, \phi8$ (End Dwell)	Coord+Preempt	Dynamic Thresholder Timer=10s
N. McCarran & NB US 395						
EBL	81.57	83.53	84.13	94.56	83.52	83.42
EBT	20.33	21.08	20.80	22.11	20.44	21.06
WBT	6.44	6.82	6.49	7.05	6.45	6.80
WBR	15.71	15.20	15.31	15.40	14.66	15.38
NBL	57.10	62.19	57.68	63.35	57.18	59.99
NBR	24.17	25.14	25.08	24.67	24.21	24.20
N. McCarran & Northtowne Lane						
EBL	83.63	81.64	84.80	75.66	81.78	79.96
EBT	20.58	19.85	20.53	24.12	20.69	23.89
EBR	6.62	7.25	7.30	8.93	7.32	8.60
WBL	49.59	49.37	50.28	51.27	49.95	55.99
WBT	24.86	24.79	24.85	25.28	24.57	25.74
WBR	4.14	2.90	3.02	3.51	3.37	3.07
NBL	48.76	59.26	61.88	59.98	66.42	52.54
NBT	50.14	57.38	62.54	51.02	52.42	51.46
NBR	33.33	45.84	44.64	34.56	39.92	35.26
SBL	66.57	65.20	62.94	70.70	70.50	67.62
SBT	57.06	58.76	60.40	72.22	56.62	51.48
SBR	15.96	13.98	14.32	14.90	15.30	14.42

A-7

Comparison of Average Vehicle Delay under Two-time Preemptions in Scenario 3

Movement	No Preemption	No Exit Phase	Exit to $\phi 4, \phi 8$	Exit to $\phi 4, \phi 8$ (End Dwell)	Coord+Preempt	Dynamic Thresholder Timer=10s
N. McCarran & NB US 395						
EBL	81.57	88.28	83.18	91.72	86.00	83.62
EBT	20.33	20.18	20.82	21.72	20.54	20.22
WBT	6.44	6.50	6.50	7.58	6.28	6.06
WBR	15.71	13.38	14.28	17.12	13.96	15.02
NBL	57.10	61.18	62.70	57.52	57.78	59.62
NBR	24.17	26.06	26.32	23.60	23.94	24.22
N. McCarran & Northtowne Lane						
EBL	83.63	85.28	80.18	72.00	83.70	83.82
EBT	20.58	20.30	19.14	25.34	20.70	22.08
EBR	6.62	7.52	7.12	9.50	6.82	7.84
WBL	49.59	45.62	49.44	52.44	50.38	52.70
WBT	24.86	24.88	23.24	27.44	24.86	25.50
WBR	4.14	3.54	3.32	4.08	3.06	3.90
NBL	48.76	59.26	61.88	59.98	66.42	52.54
NBT	50.14	57.38	62.54	51.02	52.42	51.46
NBR	33.33	45.84	44.64	34.56	39.92	35.56
SBL	66.57	65.20	62.94	70.70	70.50	67.62
SBT	57.06	58.76	60.40	72.22	56.62	51.48
SBR	15.96	13.95	14.32	14.90	15.30	14.42

A-8

Comparison of Average Vehicle Delay under One-time Preemption in Scenario 4

Movement	No Preemption	No Exit Phase	Exit to $\phi 4, \phi 8$	Exit to $\phi 4, \phi 8$ (End Dwell)	Coord+Preempt	Dynamic Thresholder Timer=10s
N. McCarran & NB US 395						
EBL	81.57	82.57	93.32	87.12	86.46	83.97
EBT	20.33	21.06	21.93	20.54	20.85	21.29
WBT	6.44	7.38	7.31	6.82	6.32	7.09
WBR	15.71	16.70	15.51	15.55	14.00	14.84
NBL	57.10	60.58	62.14	62.63	59.63	62.57
NBR	24.17	25.80	23.86	22.38	23.39	24.29
N. McCarran & Northtowne Lane						
EBL	83.63	77.42	79.41	83.54	84.04	79.27
EBT	20.58	31.07	25.30	22.84	22.02	24.56
EBR	6.62	10.07	9.35	8.25	7.81	8.37
WBL	49.59	46.01	47.90	48.68	49.58	55.75
WBT	24.86	24.62	24.19	25.12	24.76	24.99
WBR	4.14	3.25	3.49	3.34	3.55	3.17
NBL	48.76	49.01	50.22	52.70	48.89	48.49
NBT	50.14	45.30	45.79	50.64	45.81	49.53
NBR	33.33	31.53	32.95	36.51	31.55	32.23
SBL	66.57	60.59	66.09	65.50	61.56	66.49
SBT	57.06	60.51	60.95	49.58	60.29	52.42
SBR	15.96	16.00	14.45	17.02	15.46	15.59

A-9

Comparison of Average Vehicle Delay under Two-time Preemptions in Scenario 4

Movement	No Preemption	No Exit Phase	Exit to $\phi 4, \phi 8$	Exit to $\phi 4, \phi 8$ (End Dwell)	Coord+Preempt	Dynamic Thresholder Timer=10s
N. McCarran & NB US 395						
EBL	81.57	86.68	91.92	80.64	84.64	81.74
EBT	20.33	24.90	22.12	22.08	22.94	22.86
WBT	6.44	7.74	8.02	8.08	6.18	7.76
WBR	15.71	15.88	16.16	16.02	15.64	15.12
NBL	57.10	58.10	68.26	60.06	59.72	61.98
NBR	24.17	23.86	22.82	23.38	21.98	24.48
N. McCarran & Northtowne Lane						
EBL	83.63	77.64	70.10	94.48	84.64	68.66
EBT	20.58	48.56	27.80	26.44	24.92	27.38
EBR	6.62	10.80	10.28	9.30	8.64	9.14
WBL	49.59	48.20	46.22	50.30	45.54	50.64
WBT	24.86	24.62	24.84	24.84	23.26	25.02
WBR	4.14	3.86	3.22	4.02	2.82	3.36
NBL	48.76	51.74	50.04	52.30	49.18	51.10
NBT	50.14	52.38	46.32	58.68	47.00	50.54
NBR	33.33	33.36	28.34	39.70	30.10	32.64
SBL	66.57	67.98	59.46	69.84	64.96	74.06
SBT	57.06	59.16	64.30	59.90	53.02	60.68
SBR	15.96	14.82	15.26	14.36	16.08	14.40

A-10

Comparison of Average Vehicle Delay under One-time Preemption in Scenario 5

Movement	No Preemption	No Exit Phase	Exit to $\phi 4, \phi 8$	Exit to $\phi 4, \phi 8$ (End Dwell)	Coord+Preempt	Dynamic Thresholder Timer=10s
N. McCarran & NB US 395						
EBL	81.57	95.50	97.93	94.78	85.73	92.52
EBT	20.33	23.24	21.89	22.79	21.55	22.22
WBT	6.44	7.51	6.76	7.20	6.14	6.44
WBR	15.71	16.04	14.48	15.18	14.43	14.22
NBL	57.10	61.65	71.76	64.69	66.80	69.15
NBR	24.17	25.40	24.55	25.89	24.50	23.00
N. McCarran & Northtowne Lane						
EBL	83.63	83.29	88.60	83.58	82.68	88.53
EBT	20.58	32.44	20.17	25.42	19.84	21.85
EBR	6.62	9.47	7.20	8.79	7.51	6.93
WBL	49.59	46.01	46.72	53.54	49.24	49.08
WBT	24.86	25.56	26.21	24.90	23.81	24.26
WBR	4.14	3.07	3.47	3.22	3.46	3.70
NBL	48.76	57.31	56.05	54.24	49.50	52.31
NBT	50.14	53.50	51.03	53.31	49.76	49.07
NBR	33.33	36.38	35.51	36.30	32.06	34.36
SBL	66.57	63.88	63.75	69.26	65.21	64.33
SBT	57.06	56.15	56.26	53.18	54.91	53.52
SBR	15.96	16.39	14.94	14.45	16.83	14.36

A-11

Comparison of Average Vehicle Delay under Two-time Preemptions in Scenario 5

Movement	No Preemption	No Exit Phase	Exit to $\phi 4, \phi 8$	Exit to $\phi 4, \phi 8$ (End Dwell)	Coord+Preempt	Dynamic Thresholder Timer=10s
N. McCarran & NB US 395						
EBL	81.57	109.28	110.34	91.90	87.15	93.17
EBT	20.33	30.80	22.54	24.25	22.62	23.43
WBT	6.44	7.78	7.22	7.85	6.78	6.83
WBR	15.71	14.82	14.72	14.88	15.98	14.90
NBL	57.10	66.67	80.98	66.20	70.05	73.10
NBR	24.17	24.62	22.20	25.83	22.40	25.40
N. McCarran & Northtowne Lane						
EBL	83.63	87.27	101.92	78.98	83.58	78.23
EBT	20.58	41.50	20.10	26.77	21.97	28.67
EBR	6.62	12.92	8.64	9.48	7.33	10.02
WBL	49.59	50.08	47.98	53.75	46.33	47.63
WBT	24.86	24.10	23.56	24.22	23.02	23.75
WBR	4.14	3.05	3.60	3.47	2.83	2.73
NBL	48.76	64.90	67.62	63.93	52.47	53.23
NBT	50.14	53.07	56.12	57.87	49.33	45.88
NBR	33.33	42.90	43.38	42.02	34.32	32.98
SBL	66.57	64.25	66.48	68.38	64.75	64.50
SBT	57.06	59.45	57.00	67.57	51.97	53.87
SBR	15.96	15.67	16.10	13.67	15.15	15.45