Revising Concept of Resonant Cycle Length and Investigation of Resonant Signal Timing Plans

by

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The most difficult part of designing optimal traffic signal timings is selection of an appropriate cycle length. In recent years, a new concept called “resonant cycle” has been introduced by several researchers referring to a particular cycle length that provides good performance on two-way arterial streets for a wide range of traffic flows. However, an attempt to define a resonant cycle length is a difficult task on its own as it has ambiguous connotation and inconsistent meaning to various scholars. Two major schools of thought are: resonant cycles serve either to provide good progression only for coordinated movements or they provide good conditions for all movements (equally prioritizing traffic on main street and side street). This research addresses inconsistencies in definitions and ambiguity of the meaning of resonant cycle length by introducing a new concept called Resonant Signal Timing Plan (RSTP) that , besides cycle length, considers that the entire set of signal timings (splits, offsets, etc.) needs to be “resonant”, or work well with a range of traffic volumes. To investigate the existence of such an RSTP, a methodology was developed to test a number of signal timing optimization scenarios. Each of the tested signal timing plans was evaluated on overall network level (all movements) and main-corridor level (coordinated movements only). The results of evaluations on network level reveal no existence of the RSTP; each candidate RSTP could provide decent performance only for a few hours of similar traffic demands. Similarly, the corridor-level evaluation did not find any RSTP either as conditions differ significantly for traffic in inbound and outbound directions.

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1.0 Introduction

1.1 Background

Signal coordination is one of the most important and complex procedures of arterial and corridor management. With increasing numbers of cars on the road, it has played a crucial role in reducing congestion, both by handling problems between consecutive traffic signals to minimize delay and stops in order to shorten travel time and by providing adequate green time to guarantee that traffic flows in each direction will travel with least number of stops. The most critical procedure for designing coordinated traffic signal timing plans is the selection of an appropriate cycle length. Cycle length refers to the time it takes to complete one full cycle of indications. The optimal cycle length of a corridor or an arterial system along with appropriate offsets between each intersection will keep the progression quality at a high level. Webster's formula [1], which takes the lost time and volume-to-saturation ratios of the critical intersection into consideration, offers a strategy to select the optimal cycle length for fixed-time signals. However, traffic flows keep fluctuating in most situations and one or two specific signal timing plans cannot satisfy the demand of the changing volume. Nowadays, actuated-time signals are gradually replacing fixed-time signals because they are more efficient and flexible with the fluctuation of traffic. When it comes to arterials that experience highly variable or unpredictable traffic demand, adaptive signal control can provide multiple signal timing solutions and handle congestion problems [2]. Among all signal control types, the cycle length which decides the time interval of each signal period is undoubtedly one of the most important parameters. Although the Highway Capacity Manual (HCM) [3] does not provide a specific methodology for selecting the optimal cycle length for a network of signalized intersections, there are five models that are commonly used as cycle length selection strategies: TRANSYT model, Synchro model, 90% rule, Largest rule and Comparing model according to Lu et al [4]. Each model has its special characteristics and none of them is much better than the others, which makes the cycle length decision hard.

In recent years, a new concept named “resonant cycle” has been proposed as a strategy for network cycle length selection. Shelby et al. [5] defined the resonant cycle as a particular cycle length which can keep providing good progression for a two-way arterial over a range of traffic volumes. This principle has been regarded as a potential strategy to solve the cycle length selection problem. Previous work focused on various conditions where resonant cycles might exist and demonstrated the benefits of using resonant cycles to replace other kinds of cycle length selection methods. However, based on the relevant literature review there is still a number of questions that remained unaddressed in the concept of the resonant cycle. First, the definition of resonant cycle is not consistently understood among researchers [5 - 8]. Second, the term “good progression” associated with the main purpose of the resonant cycle is not defined clearly. In other words, different studies rely on performance estimation based on different sets of performance measures (not necessarily related to progression measurement) [5, 6, 9, 10]. Third, signal timing plans developed to support good progression are essentially developed with other objectives (reduce overall network performance (by making the same priority for all movements on a network) and similar [5 - 7, 9, 10]. This study aims to define the concept of resonant cycle, through the extensive signal timings optimization and evaluation on the conditions of real world-like arterial network simulated in microsimulation.

1.2 Problem Description

It is necessary to review the different definitions of the resonant cycle before describing the problems. According to Shelby et al. [5], “Resonant cycles are cycle lengths that result in good arterial progression over a range of traffic flows. The notion of resonant cycle times contrasts with the prevalent adaptive control practice of setting the arterial cycle length in proportion to flow levels at the most congested intersection on the arterial”. He also pointed out that resonant cycles naturally arise on arterials which have given value of parameters like intersection spacing, vehicle speeds, volume levels, saturation flow rates, platoon dispersion, and phase sequencing as a specific cycle length to provide good two-way progression. Guevara [6, 10] gave a similar definition which said, “we define resonant cycles as cycle lengths for two-way arterials that are robust over a range of traffic volume.” However, Li et al. [7] and Henry [8] described the resonant cycle as a cycle length equals to integer multiples of twice the travel time between neighboring intersections. So far, there is no widely accepted definition for the resonant cycle.

The concept of resonant cycle is usually followed by the provision of good progression. In order to estimate the quality of progression, Shelby [5], Day [9] and Guevara [6, 10] evaluated the network performance through Performance Index (PI), which is a combination of total delay and stops for all movements (coordinated – progressed, or non-coordinated – those from side streets). In most cases, the PI is calculated by the equation:

$$\mathrm{PI} = \mathrm{Delay} + \mathrm{n} * \mathrm{Stops} \tag{1.1}$$

Where n is an integer number representing the penalty of stops. Such PI, which considering side street situation lacks to provide a clear picture of the performance of coordinated movements. Several stops on the main street may slightly affect the total PI value but will significantly deteriorate the progression, in other words, the fluency of the major road is more likely to represent intersection efficiency. Thus, there is no evidence to illustrate that a low PI is equal to a good progression, and based on this fact, it is necessary to explore if the “resonant cycle” really exists on networks.

In addition, only finding out the value of cycle length is meaningless for a real network as there are many parameters highly relevant to coordinated signal control, e.g. split, which represents the distribution of the cycle length into each phase; offsets, which means the time interval of signal heads between neighboring intersections; and phase sequence, which is the sequence of each phase within a cycle. Thus, a cycle length which could provide good performance for a two-way arterial might be a misleading definition.

In the process of resonant cycle development some authors [5, 6, 10], relied on signal timing optimization software (Synchro) that besides developing cycle length also provides optimal values for other important signal timing parameters, such as splits, offsets, phase sequencing. Once such plans were developed and evaluated, it was found that resonant cycle might exist in some specific traffic and network geometry conditions. However, this concept of resonant cycle besides particular cycle length is related to other optimized parameters. Thus, it should be rather defined as resonant signal timing plan then resonant cycle length itself.

1.3 Research Motivation and Objectives

1.3.1 Motivation

Signal timing coordination is undoubtedly one of the most important procedures for traffic engineers to dig deeper. Among all parameters, the selection of cycle length is the most significant section to build an appropriate signal timing plan. The proposal of the concept “resonant cycle”, as a cycle length which can be estimated through simulation results, has magnificent potential to achieve a higher performance than other kinds of cycle length.

However, to the author’s knowledge, the definition of resonant cycle is still ambiguous even has some misleading information. Moreover, many researchers failed to evaluate the performance of the progression in a reasonable way and neglected the impact of the optimization for not only cycle length but also other parameters like offsets and split. Therefore, the primary goal of this study is to revise the concept of resonant cycle through the evaluation of an existing network for 7 hours between morning and evening peak hours, where there is the highest chance to observe a resonant cycle as flow fluctuations are not significant and the volume of each bound is quite balanced.

1.3.2 Objectives

This research including two main objectives: 1) proving that previous resonant cycle studies were insufficient and incomplete, especially in performance measure procedure; 2) exploring the definition of resonant cycle, mainly focus on whether the resonant cycle should be just a cycle length or not. By using PTV Vistro 2020 (SP 0-0) [13] to optimize the field signal timing plan in different scenarios and simulating those optimized signal timing plans in PTV Vissim 2020 (SP 02) [14], simulation results of network level performance (average delay, average stops, PI value, and average travel time) and progression level performance (average delay, average stops, PI value, and average travel time) were evaluated separately and then compared to draw conclusions.

1.4 Organization of Thesis

The thesis is organized as follows: review of relevant literature is provided in Chapter II, followed by methodology used to achieve research objectives (Chapter III). Chapter IV provides description of model development process in deterministic traffic simulation software (PTV Vistro). Process of signal timing plans development is documented in chapter V followed by evaluation in Chapter VI. Finally, research findings are provided in Chapter VII with recommendations for future work.

2.0 Literature Review

For traffic engineers, the performance evaluation of the traffic signal systems is always a problem that cannot be perfectly solved. When considering signal timing control among a series of signalized intersections for operating the coordination, performance measures that account for the interaction of adjacent intersections become important. The most used measurement of the network performance in previous resonant cycle studies is performance index (PI), which represents a combination of delay and stops (calculated separately). However, PI is usually used for network evaluation but not the best one for progression study and there are many other measures of effectiveness for signalized intersection performance, such as bandwidth, arrivals on the green, travel time, etc. Among all these measurements, bandwidth, the time interval between the first vehicle that can pass through the entire system without stopping and the last vehicle that can pass through without stopping, is a good indicator for determining progression performance [11]. Because it provides easy comprehensive visualized images for both professional engineers and the public. However, due to the complexity of network and field conditions, it is not always a simple task to provide good bandwidth and thus good progression. On another hand, lately, authors rely on some emerging measures (e.g. Arrivals on Green) that capture performance on the individual intersection and use them to portray progression efficiency [12]. This measurement does not observe performance for a whole coordinated system. It relates some principles of progression (platoon arrivals on intersection) but still does not measure performance for all coordinated movements. In addition to these, vehicle delays, number of stops, and travel times are commonly used performance measures for signal performance assessment.

According to all the previous work related to the resonant cycle, the definition can be generalized as a cycle length which can provide a good progression on two-way arterials within some ranges of traffic volumes. However, when it comes to calculating resonant cycles for a given network, two distinct methods, one is based on the optimization results of computer software and the other depends on several specific equations, generate some conflicts in their results which make the concept of resonant cycle more confused. This literature review will focus on the previous resonant cycle studies including hypothetical models and field studies, as well as bandwidth progression studies. The main purpose is to illustrate the conflicts in previous work.

2.1 Resonant Cycle Studies on Hypothetical Networks

It can be concluded from previous works that the resonant cycle is a cycle length that accommodates good two-way progressions during a range of traffic volumes. The resonant cycles naturally exist on arterials and are influenced by many factors like intersection spacing, vehicle speeds, volume levels, saturation flow rates, phase sequencing, etc. This section will discuss the causes of the resonant cycle and its benefits on signal timing planning.

2.1.1 Ideal Network Study for the Resonant Cycle

In the year 2005, Shelby et al. [5] investigated how the resonant cycle worked performs. They explored the reason why resonant cycles exist and determined the benefits of the resonant cycle through an experimental design for the traffic flow pattern using the software TRANSYT-7F. The experiment of their study was based on a complete hypothetical network with four equally spaced intersections and balanced traffic flow in both directions of the main street. To find out if there was a particular cycle length that can provide a good progression on this network, they used the TRANSYT-7F for selecting the optimized cycle length (together with splits and offsets).

Shelby et al. [5] tested each cycle length on all the traffic volume levels and use the TRANSYT-7F to evaluate the performance and pick the optimal cycle length for each volume level when neglecting the phase sequence and phasing type. The evaluation results showed that based on the PI, two apparent groups of resonant cycles emerged in the volume ranges from 250 to 400 vehicle per hour per lane (vphpl) and 450 to 650 vehicle per hour per lane (vphpl). One thing that should be noted is that the resonant cycle is not a fixed cycle length which provides the same PI value for every volume in that two ranges. The optimal cycle length is still increasing slightly with the increment of the traffic volume within boundaries. The first resonant cycle located in the range of 32s to 40s and the second one was between 76s and 96s. There was a significant leap of the optimal cycle length (from 42s to 76s) when the traffic volume just increasing slightly (from 420 vphpl to 421 vphpl), however, the difference in PI of these two optimal cycle lengths was almost negligible at the switch point. In other words, if the smaller cycle length (42s in the study) is still used when the traffic volume converts at the turning point (420 vphpl in the study), it can keep providing a good progression based on PI, but not as good as the new optimal cycle length which should be the larger one (76s in the study).

The promising results of the hypothetical study encouraged researchers to simulate resonant cycles on realistic networks and then implement them into field studies to see if this kind of cycle length can still play a role when roadway situation becomes more complicated.

2.1.2 Theoretical Equations for the Resonant Cycle

Henry [8] explained that the resonant cycle as “a function of the speed of the traffic on the links between intersections and the link distance between intersections”. To his point, the specific formulas are listed below:

$$\text{Cycle} = 2 * \text{Distance} / \text{Speed} \tag{2.1}$$

$$\text{Cycle} = 4 * \text{Distance} / \text{Speed} \tag{2.2}$$

$$\text{Cycle} = 6 * \text{Distance} / \text{Speed} \tag{2.3}$$

Where:

Cycle - the cycle length in seconds.

Distance - the link length in feet.

Speed - the average link speed in feet per second. (Measured in field)

These equations hold only if the traffic demand is balanced in both directions on the arterials and the distance between the intersections is approximately equal. In general, the resonant cycle length should be equal to integer multiples of twice the travel time on the segments between neighboring intersections. However, he did not explain why this kind of cycle length can provide good progression for two-way arterials and did not write about the performance measure.

2.1.3 Comment on Theoretical Equations of the Ideal Model

It can be inferred that there is a significant difference between Shelby’s study and Henry’s theory. That is whether the resonant cycle has something to do with the traffic volume or not. If it has, then the potential equations of the resonant cycle should relate to the main-street volume. If it hasn’t, then which variables should be used to reveal the resonant cycle can constantly provide a good performance?

To verify Henry’s equations of the resonant cycle, Shelby’s hypothetical network with equal spacing and balance traffic flow in both directions of the arterial is an ideal model. As the intersection spacing is 600 ft and the travel speed is 35 mph, the travel time between each intersection can be calculated as 11.69s which is around 12s. Then by putting this travel time into Henry’s equations, the potential resonant cycles are 24s, 48s, 72s, 96s. However, back to Shelby’s conclusion which the optimal cycle length was selected by PI favor solution’s software, the two ranges of the potential resonant cycle in his hypothetical network were 32s to 40s and 76s to 96s. Apparently, none of the resonant cycle calculated by Henry’s equations is within the range of Shelby’s results of the potential resonant cycle in his model.

2.2 Resonant Cycle Studies on Realistic Networks

Shelby et al. [5] studied the resonant cycle under ideal hypothetical network conditions. However, the realistic corridor is much more complicated than the hypothetical model because the block length is not only possible to be equally spaced but the realistic roads also contain many affected factors such as left-turn type, phase sequence, type of traffic control, etc. Another insufficient aspect of Shelby’s study is that different performance measurements have not been implemented to make sure the resonant cycle can satisfy the different demands of every situation. Because of the weaknesses that still exist in the hypothetical model, two separate categories of previous studies will be presented in the following section, (i) simulation of various situations at networks that can influence the existence of the resonant cycle, and (ii) different performance measurements used for the field evaluation of the resonant cycle sensitivity.

2.2.1 Network Scale Traffic Simulation Studies

Ladrón de Guevara et al. [6, 10] conducted further research about the specific situations where resonant cycles may exist under various intersection spacing, speeds, and traffic signal operation treatments, focusing on a case study of two existing corridors in Tucson, one has 12 signalized intersections (SR 77) and the other has 4 signalized intersections (22nd Street), both of these two networks were unequal spacing and set as balanced traffic flow in two directions of the main street. Then he collected the traffic data of the morning peak hour period which represented the highest volumes during every time of a day on these two corridors. The software he used for simulation and evaluation on SR 77 was Synchro and on 22nd Street were Synchro and SimTraffic.

In the experiment of SR 77, he split the network into four smaller corridors which contain up to four signalized intersections with similar traffic volumes and more consistent block length. According to his results, a single resonant cycle was found on the whole corridor while two separated resonant cycles were found on the smaller partition corridors which showed different trends from the first one. He proposed that illustrated the non-uniform distribution of traffic volumes and spacing of intersections may have a significant effect on the estimation of cycle lengths using the network approach.

In order to figure out factors that relate to the existing of the resonant cycle, he designed 27 cases on 22nd Street which contained pre-timed or actuated timing type, leading or lagging left-turn type, 4-phase or 8-phase phasing type, unequal or equal spacing type, unbalance or balance main street volume split type, low or high cross street volume type. The results illustrated that the majority of the design cases there would be a resonant cycle for low traffic conditions (from 300 vphpl to 500 vphpl) except cases where cross streets volumes were high and balance splits on the main street. Only 8 cases had resonant cycles for moderate traffic conditions (from 500 vphpl to 650 vphpl). Then he did another comparison for the variables that were directly controlled by the choice of signal timing: type of timing (pre-timed or actuated), type of phasing (4-phase or 8-phase) and left turn type (leading or lagging). The conclusion was the left-turn type and timing type have a significant effect on the form of the resonant cycle, a pre-timed plan was more likely to have resonant cycles compared with an actuated plan while lagging left turn type was more likely to generate resonant cycle compared to leading type.

To study the impact of phase sequence on resonant cycle, Day and Emtenan [9] developed flow-based models on signalized arterials and draw the conclusion from ideal networks with both equally and randomly generated block lengths that resonance may have some utility in developing optimal signal timing plans, particularly when phase sequences cannot be changed. Then they simulated a realistic network located at State Road (SR) 37, in Noblesville, Indiana by using that flow-based model. The conclusion is definitely contrasted to Ladrón de Guevara’s results as Day and Emtenan found that resonant cycles can appear under certain conditions but may not exist for every situation especially when the intersections are not equally spaced. In cases that resonant cycle exists, phase sequence plays a considerable role in the performance of different resonant cycle lengths because compared with fixed sequence, the flexible selection of phase sequences can help establish better coordination under a wider variety of conditions. In cases where the phase sequences cannot be changed, it may be possible to seek a phase sequence that works well for a range of cycle lengths.

2.2.2 Evaluations of the Resonant Cycle’s Sensitivity

Another interesting study that related to the resonant cycle was conducted by Li et al. [7] Different from the other resonant cycle studies, they tested the alleged “resonant cycles” on the field with five intersections and then evaluate the performance of each cycle length. Firstly, they created the model of the testing field in Synchro and to run this model with representative volumes on each movement. After that, cycle length optimization was carried out to obtain the PI of each cycle length. According to the figure of the relationship between cycle length and PI, the feasible cycle length range which provides low PI for the resonant cycle evaluation is between 104s to 124s. Offsets were optimized and implemented for each cycle length adjustment to reduce the effect of offsets in the cycle length comparisons.

One thing should be noted is the performance measures they used is not PI but four more intuitional features: (i) Purdue Coordination Diagram (PCD), (ii) Percent of vehicles arriving on green (POG), (iii) Travel time, and (iv) Number of force-off phase terminations for side-street through movements. (i), (ii), and (iii) were used to evaluate mainline progression and (iv) was used to evaluate how well side-street demand was served at all five intersections.

The results of their study illustrated that there was no resonant cycle within that range of cycle length. The performance got worse with the increasing of the cycle length. However, to the author’s knowledge, the methodology in Li’s study is highly different from the one that Shelby [5] and Guevara [6, 10] used. First of all, Li et al. [7] obtained the figure of PI and cycle length relationship through just one volume scenario, however the value of PI is determined by the amount of traffic volume and the value of optimal cycle length may change a lot with the swap of the volume. Additionally, the volume for each bound was unbalanced in this study, as Li et al. [7] mentioned in the article, “the northbound volumes were about 34% higher than southbound volumes due to regional travel patterns”, but all the previous works of the resonant cycle were based on the balance traffic flow for both directions of the main street. The most significant Thus, it’s not surprising that Li et al. did not find the resonant cycle in their study.

2.3 Comparison Table for Previous Studies

For the purpose of making it more clearly for readers to know the differences among previous studies of the resonant cycle, here is a comparison table contains all critical information.

Based on these resonant cycle studies, it can be inferred that a widely accepted agreement about how will the resonant cycle exist has not been conducted yet. Meanwhile, the result of field study illustrated no resonant cycle exists when taking some other features as performance measures rather than the delay and stops. In a word, a more rigorous study should be implemented to investigate whether the resonant cycle is merely an ideal concept or do exist in the real network.

Table 2-1 The Comparison Table for Previous Resonant Cycle Studies

Researchers	Shelby et al.	Ladrón de Guevara et al.	Henry R. David	Li et al.	Day and Emtenan
Study Types	Hypothetical simulation	Realistic simulation	Theoretical	Realistic simulation & Field study	Hypothetical simulation & Field study
Shape of the Corridor	Linear	1. Irregular Linear 2. Linear	NA	Linear	Linear
Number of Intersections	4	12 & 4	NA	5	9 / 8
Block Length (ft)	600	1. Varies (2500-5300) 2. Varies (1000-2500)	Approximately equal (2265-3030)	Varies (2295-3030)	Equal / Random
Posted Speed Limit (mph)	35	50	NA	55	Not mentioned
Volume Range (vphpl)	250 – 750 (in 50 increments)	1. From 50% to 120% of the AM peak hour volume data (in 5% or 10% increments) 2. 250 - 700 (in 30 increments)	NA	The whole day field data that collected by Bluetooth sensors.	Fixed volume for major street as 1000 vphpl during hypothetical simulation study / Field data for field study.
Traffic Flow Type	Balanced	Balanced	Balanced	Unbalanced	Balanced & Unbalanced
Cycle Length Range (s)	30 – 200 (in 2s increments)	1. 40 – 200 (in 1s increments) 2. 30 – 100 (in 2s increments)	NA	104 – 124 (in 1s increments)	70 – 150 (in 1s increments)
Offsets	Optimized	Optimized	NA	Optimized	Optimized
Splits	Optimized	1. Optimized 2. Balance / Unbalance	NA	Optimized	Keep constant

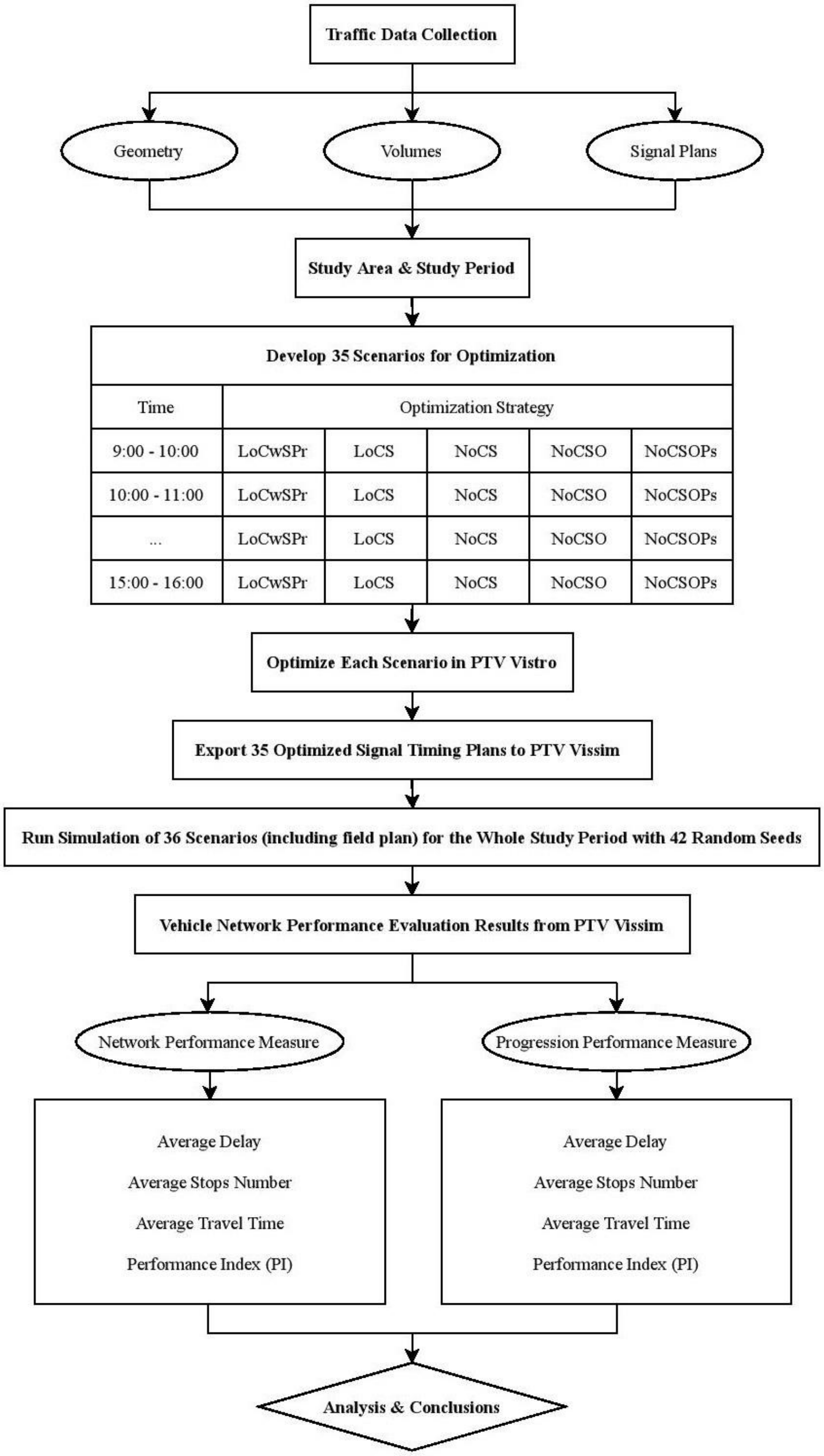
Table 2-1 (Continued)

Phase Sequence	NA	Lead / Lag	NA	NA	Optimized / Default
Signal Type	Pre-timed (Fixed)	Pre-timed / Actuated	NA	Actuated	NA
Software	TRANSYT-7F	Synchro & SimTraffic	NA	Synchro	TRANSYT-7F
Performance Measure	PI (delay plus stops (equal to 8 times of delay) of main streets, delay of side streets, 8s penalty for decelerating and accelerating as lost time.)	PI (delay plus stops (equal to 10 times of delay) of the entire network)	NA	(i) Purdue Coordination Diagram (PCD), (ii) Percent of vehicles arriving on green (POG), (iii) Travel time, and (iv) Number of force-off phase for side-street through movements.	PI (delay plus stops (equal to w times of delay, where the value of w not mentioned) of the entire network)
Results	The resonant cycle has the potential to reduce PI instead of a heuristic cycle times for a hypothetical network.	Resonant cycles might emerge under all the variations except when the minor street has a high volume.	The resonant cycle length should be equal to integer multiples of twice the travel time on the segments between neighboring intersections	A particular cycle length with substantially different performance did not emerge.	Resonant cycles might only exist when the block length is equal and the phase sequence is set in a particular way.

3.0 Research Methodology

To achieve the main objectives of this study, the development of research methodology is based on experimental scenarios. The investigation of each scenario depends on the evaluation of the optimized signal timing plan's quality. The optional combination of main traffic parameters such as cycle length, splits, offsets, and phase sequence may highly affect the optimization of signal timing plans, and influence entire traffic performance as a result. The study methodology consists of five distinctive signal timing optimization scenarios in PTV Vistro [13]. To investigate the existence of resonant cycle length hourly volume data for 7 hours (between AM and PM Peak) are considered. Thirty-six plans (including seven base cases) were then simulated using microscopic traffic simulation model PTV Vissim [14] to make the comparison of performance.

The evaluation of the performance was separated into two groups, network-level (all movements on network) and coordinated movements only (progressed or through movements on arterial). Similar measurements were used to see whether the resonant cycle would be found on the network performance scale or on the progression scale. The author decided to evaluate performance of coordinated movements based on traditional and well understood performance measures (delay, travel time, number of stops). However, it needs to be stated that for same purpose other performance measures can be used, such as, bandwidth, percent of vehicles arriving on green, platoon ratio [18-20]. The flow chart (as shown in Figure 3.1) illustrates the frame of this study and the detailed methodology will be discussed as follows. This study intends on providing some solutions for main problems of the resonant cycle that were described in the introduction part.



Time	Optimization Strategy				
9:00 - 10:00	LoCwSPr	LoCS	NoCS	NoCSO	NoCSOPs
10:00 - 11:00	LoCwSPr	LoCS	NoCS	NoCSO	NoCSOPs
...	LoCwSPr	LoCS	NoCS	NoCSO	NoCSOPs
15:00 - 16:00	LoCwSPr	LoCS	NoCS	NoCSO	NoCSOPs

Figure 3.1 Research Methodology

3.1 Study Network and Traffic Data

The network geometry model was based on an existing corridor in Fort Lauderdale, FL: SR 838, also known as Broward Boulevard, which is an east-west six-lane artery serving central Broward County, Florida. The whole artery is 10.2 miles in length with 52 signalized intersections from SR 869 (west) to SR A1A (east).

3.1.1 Study Area Geometry Data

To conduct this study in comparison with previous work, a segment of Broward Boulevard was selected with an approximately 8,000 ft and five consecutive signalized intersections, from SR 7 to the west to NW 31st Avenue to the east as shown in Figure 3.2. Among these five intersections, only NW 34th Avenue is a 3-leg intersection which has no input from northbound. Spacing between each adjacent intersection is varying from 830 ft to 1770 ft. These intersections operate fully actuated under coordination with leading left turns and the posted speed limit along the study corridor is 40 miles per hour (mph). The expected travel time under desired speed (40 mph) has been calculated for each block as shown in Figure 3.3.

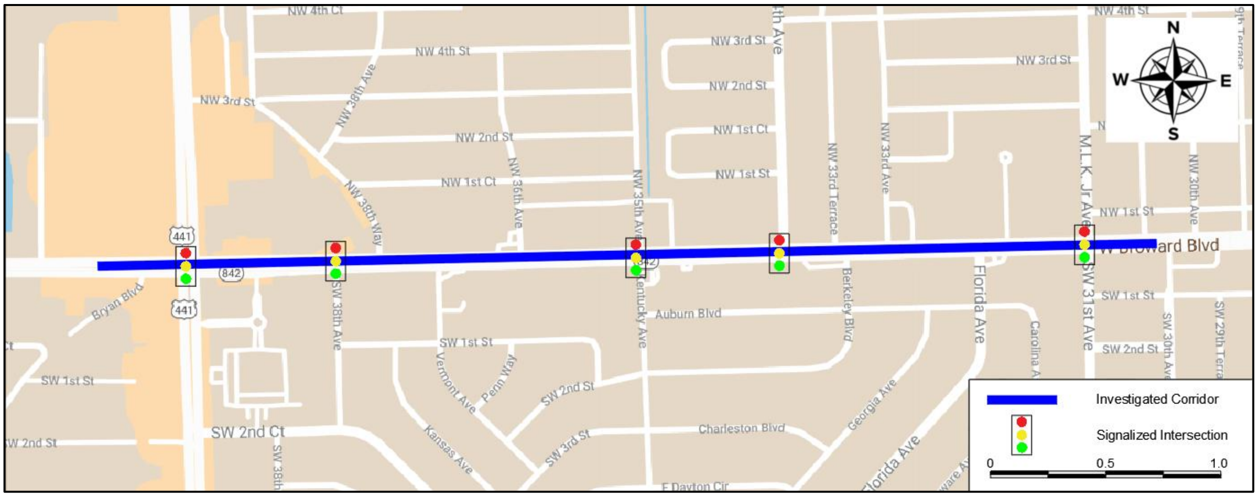


Figure 3.2 The Study Area of Broward Blvd.

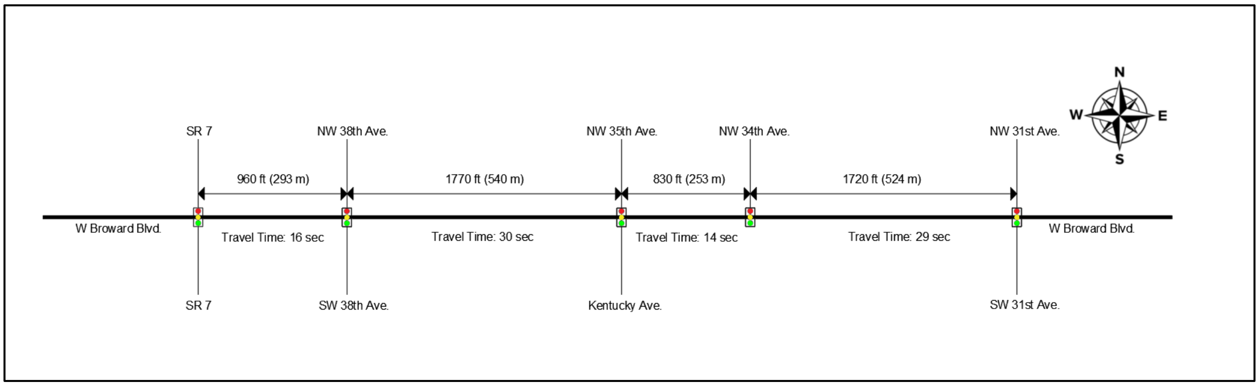


Figure 3.3 Simplified Diagram of the Study Area

3.1.2 Study Area Traffic Data

In this study, volume data from 6:00 AM to 8:00 PM were downloaded from the Regional Integrated Transportation Information System (RITIS), and a balance sheet was developed and used to automatically code the volumes and routing decisions. For each intersection, configurations and signal timing plan sheets provided by the Florida Department of Transportation (FDOT) and speeds were collected from field runs.

According to previous studies, resonant cycles mainly exist on arteries where traffic volume within a low to moderate level and nearly balanced in both directions. To find out the appropriate traffic volume range and save time from unnecessary experiments, three pieces of volume figure related to three different signal timing plans (also known as patterns) have been shown as Figure 3.4, Figure 3.5, and Figure 3.6. Each pattern works for a period of time of day and swiftly changes to the other one. The specific arrangements are listed below:

a) Pattern 1: From 6:00 AM to 9:00 AM, 3 hours. (Morning peak hour period)

b) Pattern 2: From 9:00 AM to 4:00 PM, 7 hours. (Off-peak period)

c) Pattern 3: From 4:00 PM to 8:00 PM, 4 hours. (Evening peak hour period)

One thing that should be noted is the volume data used in these figures. As the Broward Blvd. is an east-west artery, the sum of eastbound and westbound through movement volumes is used to represent the progression volume of each intersection. The direction distribution factor (D factor) and volume-to-capacity (v/c) ratio of westbound are also shown in the figure.

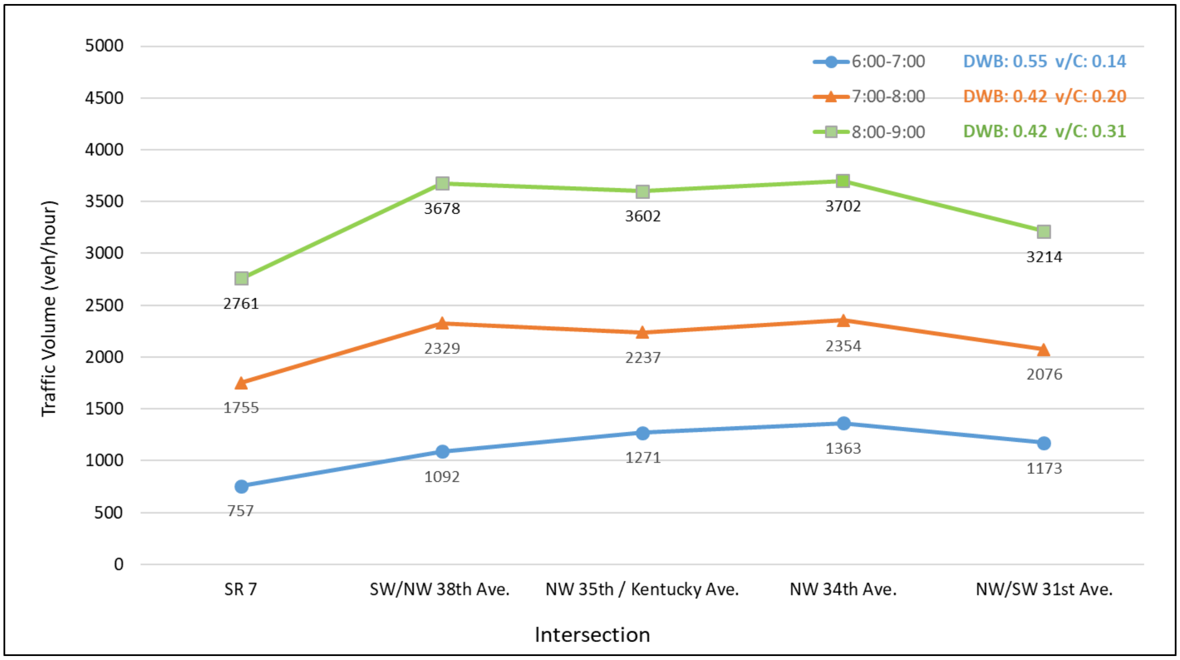


Figure 3.4 Pattern 1 Traffic Volume of the Progression During Morning Peak Period

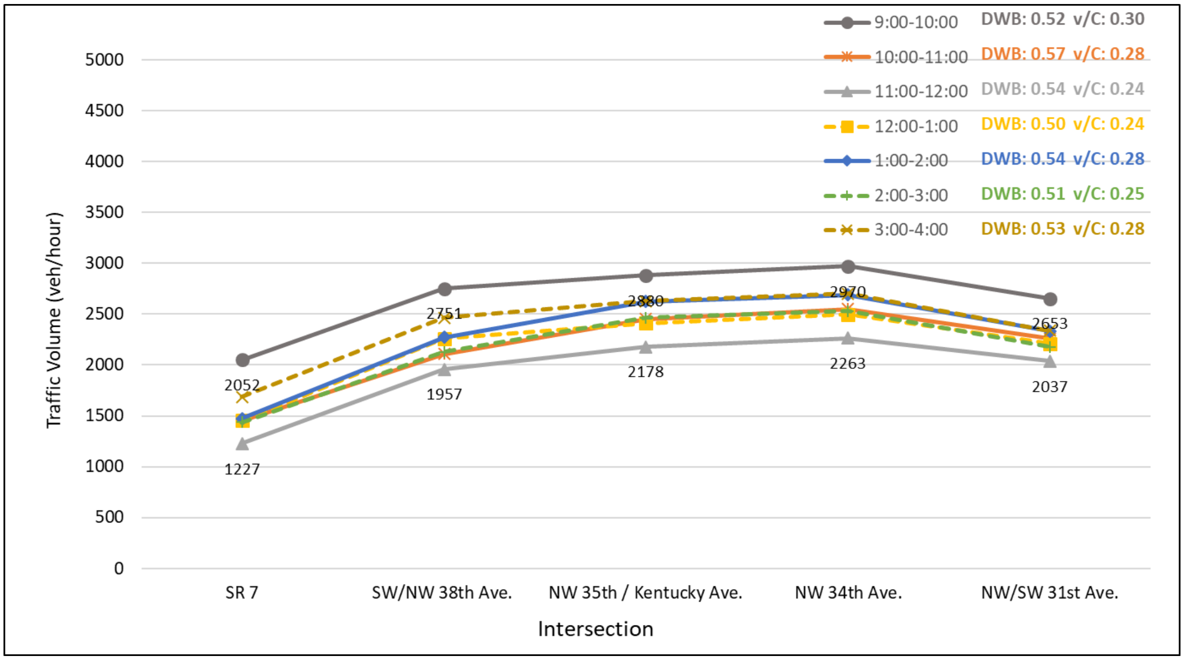


Figure 3.5 Pattern 2 Traffic Volume of the Progression During Off-peak Period

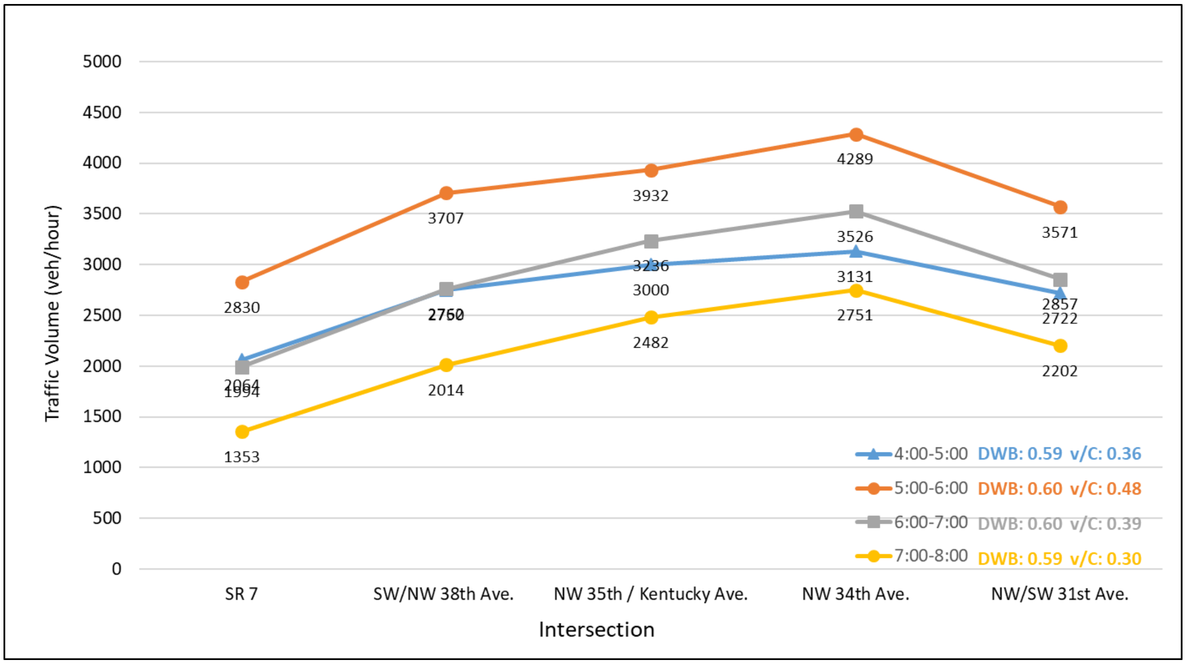


Figure 3.6 Pattern 3 Traffic Volume of the Progression During Evening Peak Period

Through these volume figures, volume data from 9:00 AM to 4:00 PM were selected for the experiment. The main reason for such selection lies in the definition of resonant cycle, or if particular cycle length will be resonant it can be expected to occur for the lowest volume fluctuations through study period (or from 9:00 AM to 4:00 PM). Detailed main directions' traffic volume of each intersection per hour were showed in Appendix A.

In addition to volume fluctuations, v/c ratio was computed for each hour and it is shown in Figure 3.7. Rather than using the v/c ratio of each intersection's eastbound and westbound through movement traffic volume, weighted average v/c ratio was calculated by using the following equation:

$$\text{Weighted Avg. v/c Ratio} = \frac{\sum(\text{ Each Node EB or WB Volume} * \text{Each Node Total EB or WB Volume } \text{v/c Ratio})}{\sum(\text{ Each Node EB or WB Volume})} \tag{3.1}$$

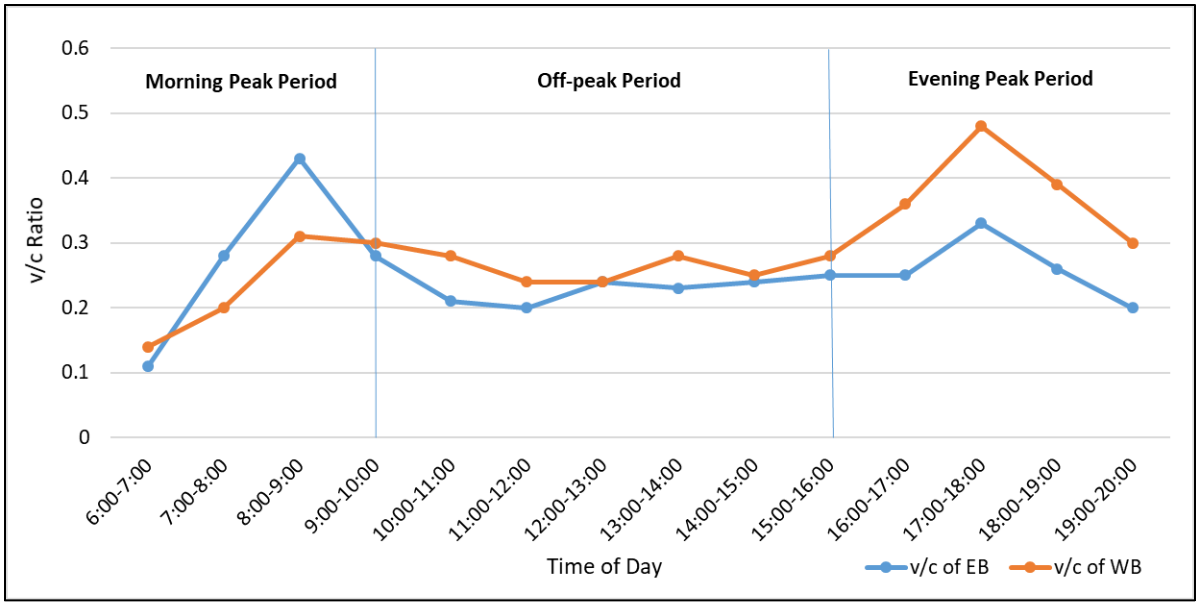


Figure 3.7 Main-street Through Movement Weighted v/c Ratio Change by Time of Day

Results shows in Figure 3.7 illustrated that during the study period from 9:00 AM to 4:00 PM, weighted v/c ratios of eastbound and westbound through movement are more balanced and stable than morning and evening peak hour periods. Compared with the study networks of previous resonant cycle researches, a potential resonant cycle might have a large probability to be found during experiments as this network highly meets the requirements.

3.2 Software Programs Characteristics

Two software programs were used for the entire research, PTV Vistro 2020 (SP 0-0) [13] and PTV Vissim 2020 (SP 02) [14]. As a signal timing optimization program, PTV Vistro was used to seek the optimal signal timing plan for each scenario. The utilization of the traffic simulation program - PTV Vissim, was intended to evaluate the performance of all optimal signal timing plans produced by PTV Vistro.

3.2.1 PTV Vistro

The PTV Vistro [13] is a complete traffic analysis software which allows users to evaluate development impacts, optimize and re-time traffic signals, evaluate intersection levels of service, and generate report-ready tables and figures. In this study, PTV Vistro [13] was mainly used for the optimization of signal timing plans in each scenario.

Based on different optimization modes that PTV Vistro [13] provided, there were two basic options for network signal timing optimization: (i) local optimization, recommended for finding the optimal cycle length and split by minimizing critical movement delay for each intersection according to its traffic volume data; (ii) network optimization, instead of optimizing signal timing plan for individual intersection, this type of optimization evaluate the whole coordination group, which means not only cycle length and splits but also offsets and phase sequence can be optimized based on either the genetic algorithm or the hill-climbing algorithm. Performance Index (PI) was chosen as the objective function, which equaled to delay multiple n times stops (n is an integer) of the whole network.

In order to develop a series of potential resonant cycle values in the study network, PTV Vistro [13] version 2020 (SP 0-0) was selected. Developed signal timing plans, which replaced the previous methodology by increasing cycle length one second by one second for testing, were tested in PTV Vissim [14]. Besides, different optimization strategies will illustrate if the resonant cycle is just a cycle length or a coordinated resonant system.

3.2.2 PTV Vissim

The PTV Vissim [14] is a microscopic multi-modal traffic flow simulation software package developed by Planung Transport Verkehr AG in Karlsruhe, Germany. It has the ability to simulate each entity (car, pedestrian, etc.) and measure the performance individually. In this study, PTV Vissim [14] was mainly used utilized as the Ring Barrier Controller emulator to simulate the actuated signal control under each scenario and measure the performance of the whole network and the main-street through movement.

The simulation of traffic flow is based on various constraints such as vehicle composition, signal control, lane distribution, etc. and the simulation results can get directly from the results list or KNR, MER, RSR, and LDP file. To evaluate the qualities of each signal timing plans, several performance measure indices were chosen in this study. In the comparison of the network performance and the main-street through movement performance, there might be a conclusion of whether the resonant cycle serves for the whole network or the arterial main direction.

3.3 Experimental Design

As mentioned in the problem description, previous studies have not defined the resonant cycle clearly. Shelby [5] and Guevara [6, 10] observed the "resonant cycle" under Performance Index (PI) favor solution software which obtains optimal signal timing plan in terms of cycle lengths, splits, and offsets at the same time. However, they also claimed that the resonant cycle is a cycle length, rather than a coordinated resonant system, which will keep providing good performance for the network.

In order to discover whether the resonant cycle is just a cycle length or a coordinated system, 5 different optimizing scenarios, based on the optimization options offered by PTV Vistro [13], were designed for each hour's volume data and compared together with the Base Case. The comparison of each optimization strategy with the Base Case is shown in Table 3.1 and specific descriptions of each optimization scenario are listed below:

- LoCwSPr: Using locally optimization for each intersection, then select the longest cycle length for the network and increase the rest intersections' split proportionally.
- LoCS: Using locally optimization for each intersection, then select the longest cycle length for the network and optimize the split for the rest intersections.
- NoCS: Using network optimization for the corridor, then only optimize cycle length and split (cause the cycle length optimization is always tied with split during network optimization procedure).
- NoCSO: Using network optimization for the corridor, then optimize the coordinated system (including cycle length, split, and offsets).
- NoCSOPs: Using network optimization for the corridor, then optimize the coordinated system (including cycle length, split, and offsets) and phase sequence.

After getting 5 optimization scenarios for each hour's volume data (There would be 36 different optimization scenarios in total including filed signal timing plan), the optimized and Base Case signal timing plan of each intersection could be imported into the PTV Vissim [14] models. Simulations were performed using 42 seeds for each scenario and the same random seeds were used for all experiments. Then the evaluation of the results was implemented.

Table 3-1 Comparison Table for Field Signal Plan and 5 Optimization Methodologies

Scenario	Optimization Mode	Cycle Length	Split	Offsets	Phase Sequence
Field	NA	NA	NA	NA	NA
LoCwSPr	Locally	Y	N	N	N
LoCS	Locally	Y	Y	N	N
NoCS	Network	Y	Y	N	N
NoCSO	Network	Y	Y	Y	N
NoCSOPs	Network	Y	Y	Y	Y

3.4 Key Performance Measures

The performance evaluation of the resonant cycle is another important topic of this study. For the purpose of making a comparison of network performance measure which used by previous studies to define the resonant cycle and progression performance measure which might be more appropriate for identifying whether the resonant cycle exists or not, the same methodologies of performance measures were chosen as a result. Vehicle Network Performance Evaluation Results from PTV Vissim [14] was directly used to extract the following performance measures as provided by.

3.4.1 Network Level Performance Measures

a) Average Delay: Average delay per vehicle.

$$\text{Avg. Delay} = \frac{\text{Total delay}}{\text{Number of veh in the network} + \text{Number of veh that have arrived}} \qquad (3.2)$$

b) Average Stops Number: Average number of stops per vehicle.

$$\text{Avg. Stops} = \frac{\text{Total Stops}}{\text{Number of veh in the network} + \text{Number of veh that have arrived}} \qquad (3.3)$$

c) Performance Index: Performance Index value of the whole network. (Using the same penalty for stops as Shelby et al. [5] used in their study)

$$\text{Performance Index} = \text{Total Delay} + 8 * \text{Total Stops} \qquad (3.4)$$

d) Average Travel Time: Average travel time per vehicle.

$$\text{Avg. Travel Tm} = \frac{\text{Total Travel Time}}{\text{Number of veh in the network} + \text{Number of veh that have arrived}} \qquad (3.5)$$

3.4.2 Progression Level Performance Measures

a) Average Delay: Average delay of Eastbound/Westbound through movement vehicles.

$$\text{Avg. Delay of One Direction} = \frac{\sum(\text{Each Node Total EB or WB Throughput Delay})}{\text{Average EB or WB Throughput}} \qquad (3.6)$$

b) Average Stops: Average stops of Eastbound/Westbound through movement vehicles.

$$\text{Avg. Stops of One Direction} = \frac{\sum(\text{ Each Node Total EB or WB Throughput Stops})}{\text{Average EB or WB Throughput}} \qquad (3.7)$$

c) Performance Index of One Direction: Performance Index value of Eastbound/ Westbound through movement vehicles.

$$\text{Performance Index} = \text{Total Delay} + 8 * \text{Total Stops (Only for EB or WB Throughput)} \qquad (3.8)$$

d) Average Travel Time: Average travel time of Eastbound/Westbound through movement vehicles (Only collected for vehicles passing through all five intersections).

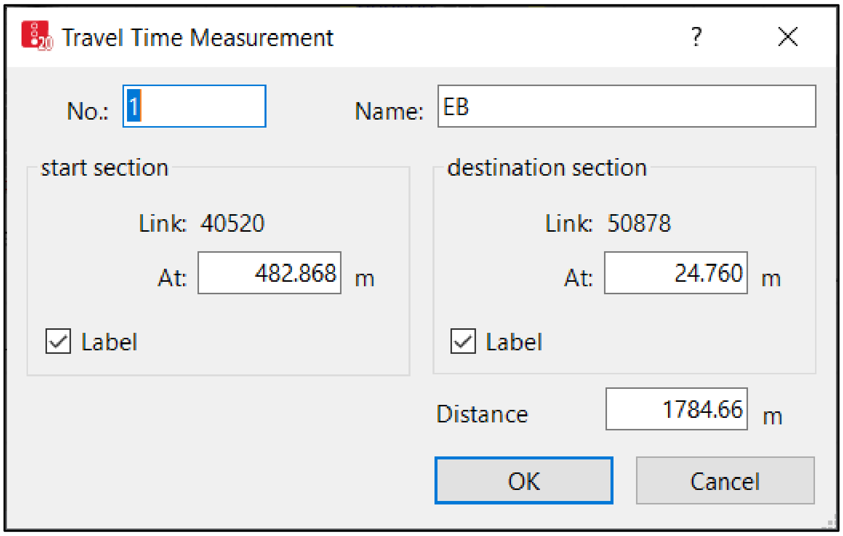
4.0 Building of Models

According to the research methodology, there are several models should be established which respectively based on PTV Vistro and PTV Vissim. An existing PTV Vissim model of the whole W Broward Blvd. corridor was utilized as the base model of this study, which was built, calibrated, validated, and used in previous studies [15]. The network was built in PTV Vistro first and all inputs such as the number of lanes, traffic volume, cycle length, etc. were manually checked. Then part of the previous PTV Vissim model was used as the network in this study, slight modification and calibration implemented afterward.

4.1 PTV Vissim Model

The PTV Vissim model was built based on the previous Vissim model and modified in comparison with the most recent satellite image from Google Maps. Microwave vehicle detection system (MVDS) volumes were downloaded from the Regional Integrated Transportation Information System (RITIS). Florida Department of Transportation (FDOT) provided signal timing sheets of the field which were used to model Ring Barrier Controllers (RBC) in PTV Vissim for the base case.

As mentioned previously, travel time is an important performance index for both network and progression evaluation. The total travel time and total vehicle number of the whole network can be directly exported from the PTV Vissim file, however, the average travel time of the main street through movement vehicles can only be obtained from “Travel Time Measurement” which is one the result lists. The implementation of “Vehicle Travel Time Measurement” was only for evaluating main street through movement, which means eastbound measurement area is from the intersection SR 7 to the intersection SW/NW 31st Ave and westbound measurement area is from the intersection SW/NW 31st Ave to the intersection SR 7. The setting window of “Vehicle Travel Time Measurement” was shown in Figure 4.1.


Travel Time Measurement

No.: 1
Name: EB

start section
Link: 40520
At: 482.868 m
☑ Label

destination section
Link: 50878
At: 24.760 m
☑ Label

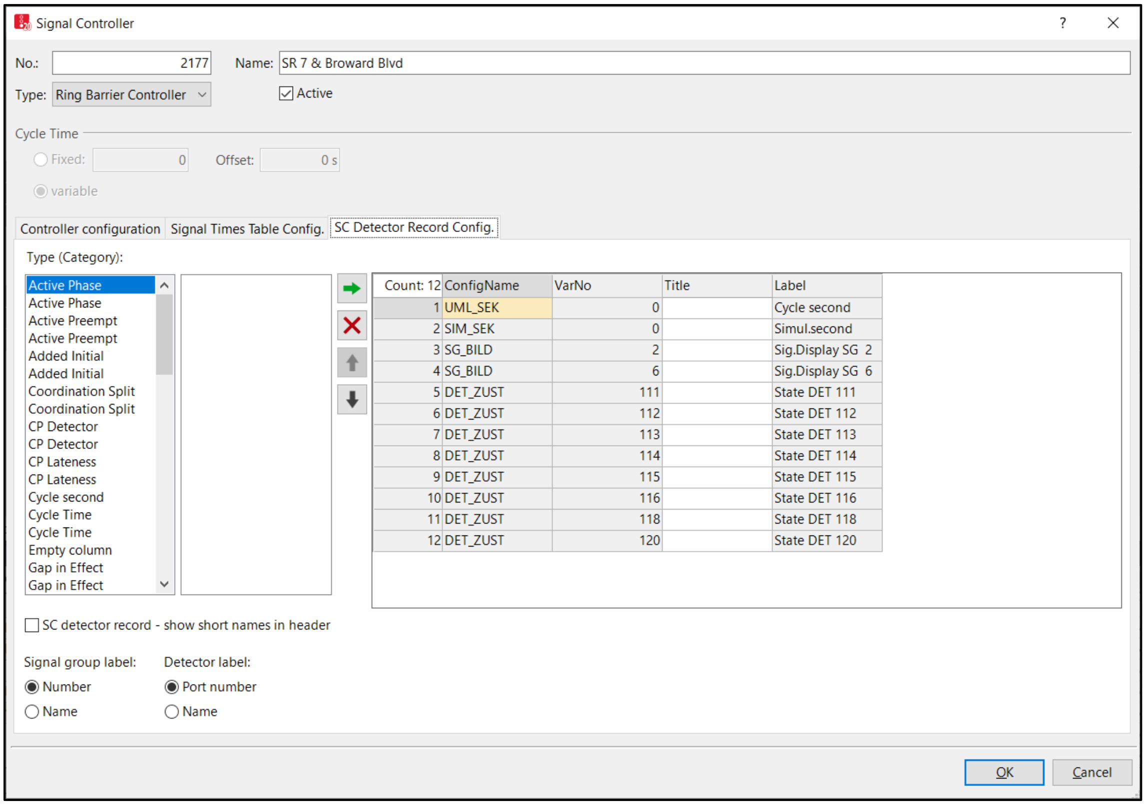
Distance 1784.66 m

Figure 4.1 Vehicle Travel Time Measurement Setting Window

After finishing the insertion of all detectors in the PTV Vissim [14] model, relating them with the specific signal controllers was the next thing that should be done. To collect arriving information, the useful configurations: cycle second, simulation second, signal display of the main street through movements (SG 2 and SG 6), and all detectors of eastbound and westbound, that need to be recorded by detectors were selected for each intersection, as shown in Figure 4.3.

The evaluation configuration includes two sections which needed to be settled, result attributes and direct output. For the result attributes section, to run the simulation efficiently and get the required data, the default running time was set up from 0 to 36000, which represented from

6:00 AM to 4:00 PM. The data collection interval was increased from 900 (15 minutes) to 3600 (1 hour) to directly get the simulation results of each hour, as shown in Figure 4.4. For the direct output section, only data collection, nodes, signal control detector record, and vehicle travel times were selected as the configurations that needed to be output directly, as shown in Figure 4.5.



Signal Controller

No.: 2177 Name: SR 7 & Broward Blvd

Type: Ring Barrier Controller ☑ Active

Cycle Time

○ Fixed: 0 Offset: 0 s

● variable

Controller configuration | Signal Times Table Config. | SC Detector Record Config.

Type (Category):

Active Phase
Active Phase
Active Preempt
Active Preempt
Added Initial
Added Initial
Coordination Split
Coordination Split
CP Detector
CP Detector
CP Lateness
CP Lateness
Cycle second
Cycle Time
Cycle Time
Empty column
Gap in Effect
Gap in Effect

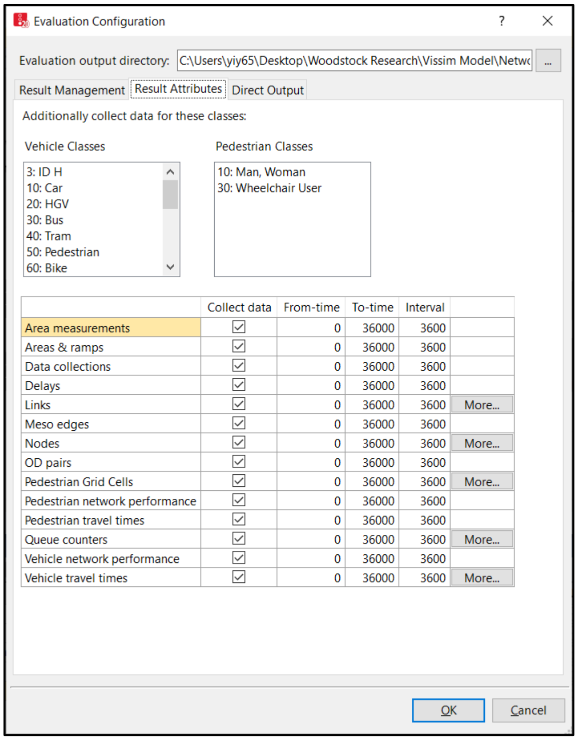
Count: 12	ConfigName	VarNo	Title	Label
1	UML_SEK	0		Cycle second
2	SIM_SEK	0		Simul.second
3	SG_BILD	2		Sig.Display SG 2
4	SG_BILD	6		Sig.Display SG 6
5	DET_ZUST	111		State DET 111
6	DET_ZUST	112		State DET 112
7	DET_ZUST	113		State DET 113
8	DET_ZUST	114		State DET 114
9	DET_ZUST	115		State DET 115
10	DET_ZUST	116		State DET 116
11	DET_ZUST	118		State DET 118
12	DET_ZUST	120		State DET 120

☐ SC detector record - show short names in header

Signal group label: ● Number ○ Name

Detector label: ● Port number ○ Name

Figure 4.2 Detector Record Configuration Window



Evaluation output directory: C:\Users\yiy65\Desktop\Woodstock Research\Vissim Model\Netwo

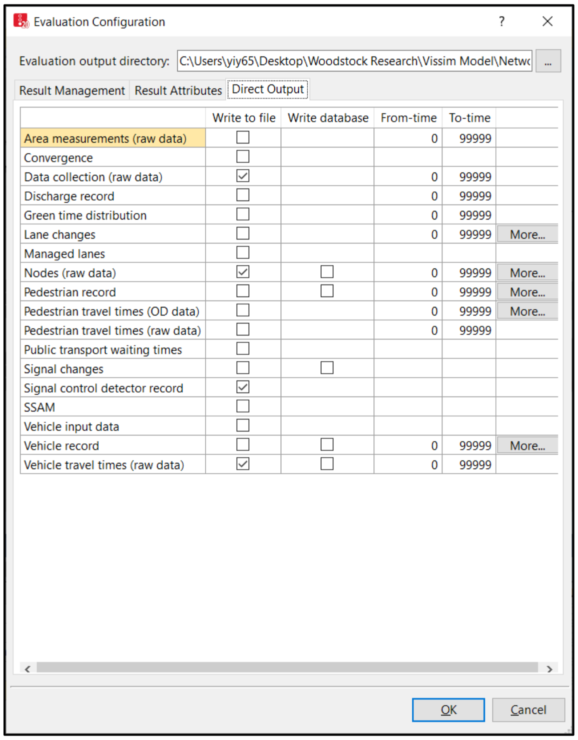
Additionally collect data for these classes:

Vehicle Classes
3: ID H
10: Car
20: HGV
30: Bus
40: Tram
50: Pedestrian
60: Bike

Pedestrian Classes
10: Man, Woman
30: Wheelchair User

	Collect data	From-time	To-time	Interval	
Area measurements	☑	0	36000	3600	
Areas & ramps	☑	0	36000	3600	
Data collections	☑	0	36000	3600	
Delays	☑	0	36000	3600	
Links	☑	0	36000	3600	More...
Meso edges	☑	0	36000	3600	
Nodes	☑	0	36000	3600	More...
OD pairs	☑	0	36000	3600	
Pedestrian Grid Cells	☑	0	36000	3600	More...
Pedestrian network performance	☑	0	36000	3600	
Pedestrian travel times	☑	0	36000	3600	
Queue counters	☑	0	36000	3600	More...
Vehicle network performance	☑	0	36000	3600	
Vehicle travel times	☑	0	36000	3600	More...

Figure 4.3 Result Attributes Editing Window



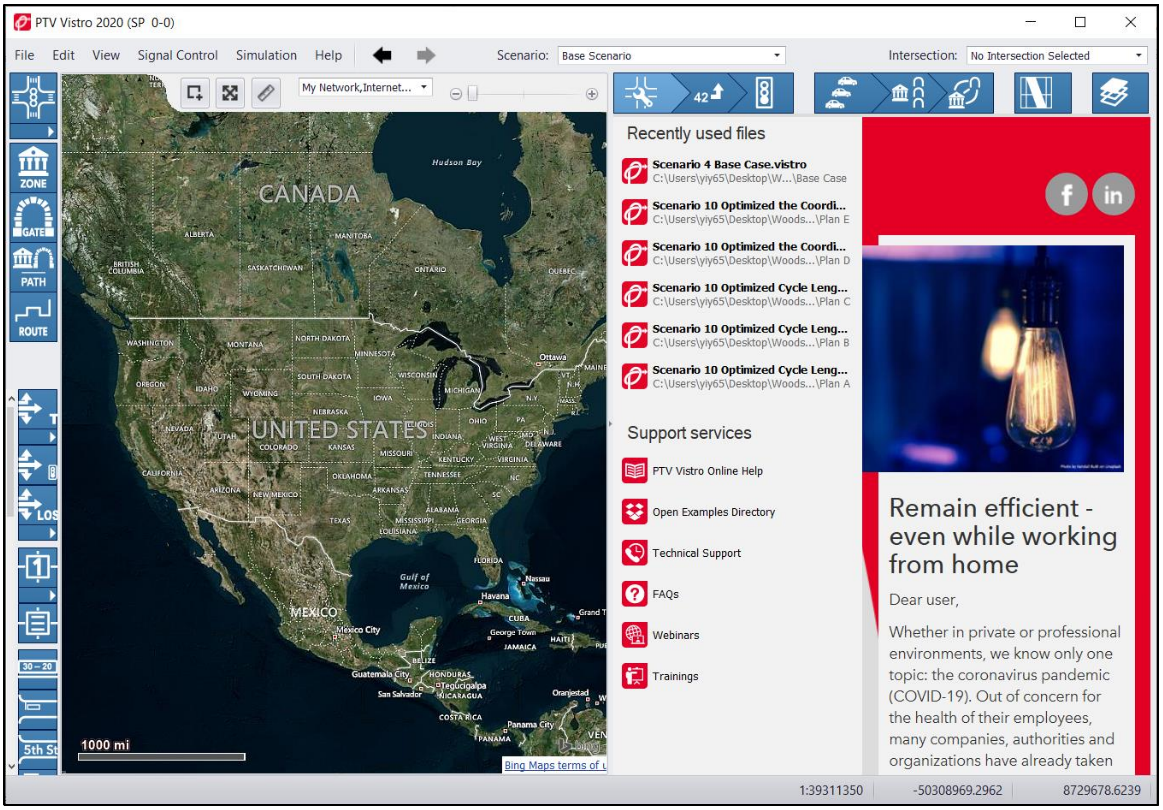
Evaluation output directory: C:\Users\yiy65\Desktop\Woodstock Research\Vissim Model\Netwo

	Write to file	Write database	From-time	To-time	
Area measurements (raw data)	☐		0	99999	
Convergence	☐				
Data collection (raw data)	☑		0	99999	
Discharge record	☐		0	99999	
Green time distribution	☐		0	99999	
Lane changes	☐		0	99999	More...
Managed lanes	☐				
Nodes (raw data)	☑	☐	0	99999	More...
Pedestrian record	☐	☐	0	99999	More...
Pedestrian travel times (OD data)	☐		0	99999	More...
Pedestrian travel times (raw data)	☐		0	99999	
Public transport waiting times	☐				
Signal changes	☐	☐			
Signal control detector record	☑				
SSAM	☐				
Vehicle input data	☐				
Vehicle record	☐	☐	0	99999	More...
Vehicle travel times (raw data)	☑	☐	0	99999	

Figure 4.4 Direct Output Editing Window

4.2 PTV Vistro Model

The PTV Vistro [13] is a traffic analysis software which is used to evaluate development impacts and intersection levels of service, optimize and re-time traffic signals, and generate report-ready tables and figures. PTV Vistro [13] SP 0-0 is a map-based software which allows users to build the network refer to the field situation, as shown in Figure 4.6.



Scenario: Base Scenario

Intersection: No Intersection Selected

Recently used files

- Scenario 4 Base Case.vistro
  C:\Users\yiy65\Desktop\W...\Base Case
- Scenario 10 Optimized the Coordi...
  C:\Users\yiy65\Desktop\Woods...\Plan E
- Scenario 10 Optimized the Coordi...
  C:\Users\yiy65\Desktop\Woods...\Plan D
- Scenario 10 Optimized Cycle Leng...
  C:\Users\yiy65\Desktop\Woods...\Plan C
- Scenario 10 Optimized Cycle Leng...
  C:\Users\yiy65\Desktop\Woods...\Plan B
- Scenario 10 Optimized Cycle Leng...
  C:\Users\yiy65\Desktop\Woods...\Plan A

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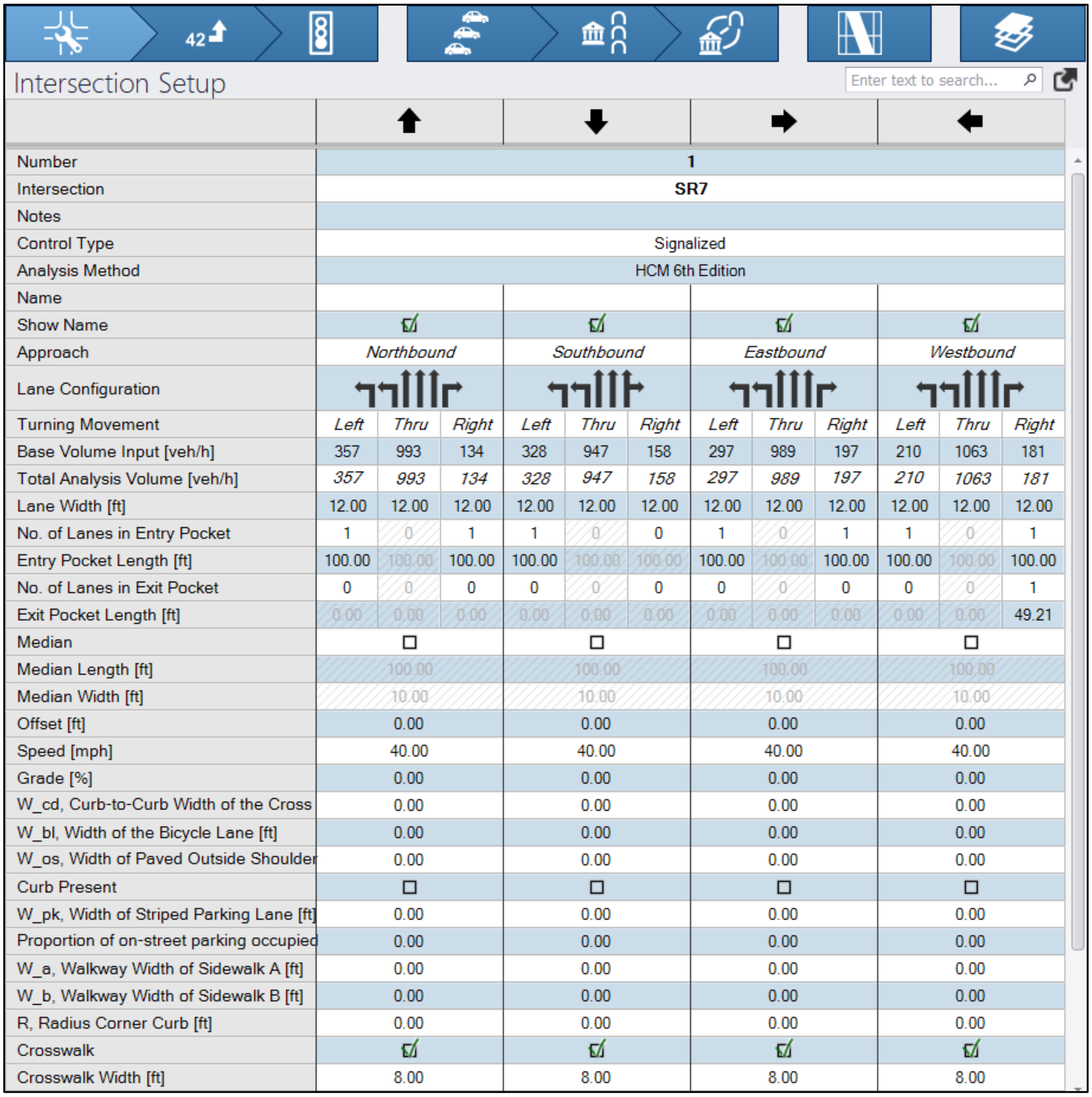
Dear user,

Whether in private or professional environments, we know only one topic: the coronavirus pandemic (COVID-19). Out of concern for the health of their employees, many companies, authorities and organizations have already taken

Figure 4.5 PTV Vistro Start Window

As the map in PTV Vistro [13] is updated with the latest Google map version, it would be easier to build the experimental network based on the aerial image of Broward Boulevard. Once zooming the background map into the appropriate size, five consecutive signalized intersections were created from SR 7 to SW/NW 31st Ave. To make sure the PTV Vistro [13] model is the same as the filed situation, each intersection needs to be modified based on the study network and traffic data.

By clicking the node point on any intersection, the “Intersection Setup” window will open up for the selected one (Figure 4.7). The first step was to name the chosen intersection and determine the control type from “Unknown”, “Signalized”, “Roundabout”, “All-way stop”, and “Two-way stop”. The analysis method used in this study was HCM 6th edition, which was the final version released in October 2016 and incorporated the latest research on highway capacity, quality of service, and travel time reliability. Lane configuration of each movement could be easily edited by clicking the corresponding icon, as shown in Figure 4.8. As the default value of lane width and lanes in entry pocket were entirely fit the study area, the final step was inputting the base volume for each turning movement and set the desired speed. Volume data were directly output from PTV Vissim [14] file while the desired speed data were obtained from the speed limit signs on street images of Google maps.



	↑			↓			→			←		
Number	1											
Intersection	SR7											
Notes												
Control Type	Signalized											
Analysis Method	HCM 6th Edition											
Name												
Show Name	☑			☑			☑			☑		
Approach	*Northbound*			*Southbound*			*Eastbound*			*Westbound*		
Lane Configuration												
Turning Movement	*Left*	*Thru*	*Right*	*Left*	*Thru*	*Right*	*Left*	*Thru*	*Right*	*Left*	*Thru*	*Right*
Base Volume Input [veh/h]	357	993	134	328	947	158	297	989	197	210	1063	181
Total Analysis Volume [veh/h]	*357*	*993*	*134*	*328*	*947*	*158*	*297*	*989*	*197*	*210*	*1063*	*181*
Lane Width [ft]	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00
No. of Lanes in Entry Pocket	1	0	1	1	0	0	1	0	1	1	0	1
Entry Pocket Length [ft]	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
No. of Lanes in Exit Pocket	0	0	0	0	0	0	0	0	0	0	0	1
Exit Pocket Length [ft]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	49.21
Median	☐			☐			☐			☐		
Median Length [ft]	100.00			100.00			100.00			100.00		
Median Width [ft]	10.00			10.00			10.00			10.00		
Offset [ft]	0.00			0.00			0.00			0.00		
Speed [mph]	40.00			40.00			40.00			40.00		
Grade [%]	0.00			0.00			0.00			0.00		
W_cd, Curb-to-Curb Width of the Cross	0.00			0.00			0.00			0.00		
W_bl, Width of the Bicycle Lane [ft]	0.00			0.00			0.00			0.00		
W_os, Width of Paved Outside Shoulder	0.00			0.00			0.00			0.00		
Curb Present	☐			☐			☐			☐		
W_pk, Width of Striped Parking Lane [ft]	0.00			0.00			0.00			0.00		
Proportion of on-street parking occupied	0.00			0.00			0.00			0.00		
W_a, Walkway Width of Sidewalk A [ft]	0.00			0.00			0.00			0.00		
W_b, Walkway Width of Sidewalk B [ft]	0.00			0.00			0.00			0.00		
R, Radius Corner Curb [ft]	0.00			0.00			0.00			0.00		
Crosswalk	☑			☑			☑			☑		
Crosswalk Width [ft]	8.00			8.00			8.00			8.00		

Figure 4.6 Intersection Setup Window

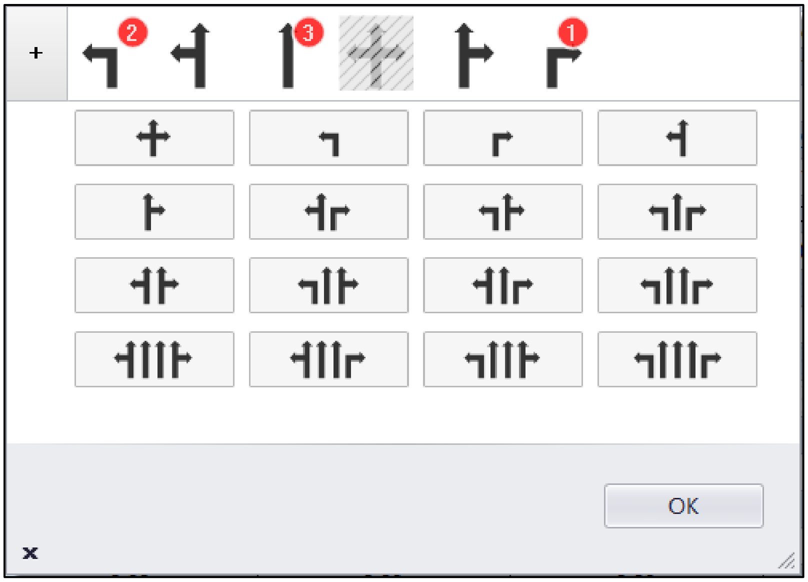


Figure 4.7 Lane Configuration Window

The field signal timing plan was manually imported through the "Traffic Control" window, as shown in Figure 4.9. In the intersection setting part (Figure 4.10), major direction and minor direction were determined through the priority scheme. As the volume data were input hourly, the analysis period should be kept in the same interval. Cycle length, coordination type, actuated type, offsets, offsets reference, and permissive mode were all entered following the original field PTV Vissim [14] model. According to HCM 2010 [1], the lost time of each phase was assumed as 3 seconds and pedestrian walking speed was normally set in 3.5 ft/s. The next step was editing control types, splits, etc. in the phasing and timing part. Users are allowed to choose the control type of each phase by clicking the icon, e.g. protected, permissive, overlap, etc. and all parameters in this part with a unit in second could be set into a certain number. Noticing that east-west bound was the main direction of the study area, thus, southbound and northbound did not possess coordination, maximum recall, and detectors. The rest sections were kept as default. Figure 4.11 shows the phasing and timing section after it was completed.

Traffic Control

☐ Automatic Optimization

Enter text to search...

	↑			↓			→			←		
Number	1											
Intersection	**SR7**											
Notes												
Control Type	Signalized											
Analysis Method	HCM 6th Edition											
Name												
Show Name	☑			☑			☑			☑		
Approach	*Northbound*			*Southbound*			*Eastbound*			*Westbound*		
Lane Configuration												
Turning Movement	*Left*	*Thru*	*Right*	*Left*	*Thru*	*Right*	*Left*	*Thru*	*Right*	*Left*	*Thru*	*Right*
Base Volume Input [veh/h]	357	993	134	328	947	158	297	989	197	210	1063	181
Total Analysis Volume [veh/h]	*357*	*993*	*134*	*328*	*947*	*158*	*297*	*989*	*197*	*210*	*1063*	*181*

Intersection Settings

Phasing & Timing

Exclusive Pedestrian Phase

Lane Group Calculations

Saturation Flow

Capacity Analysis

Lane Group Results

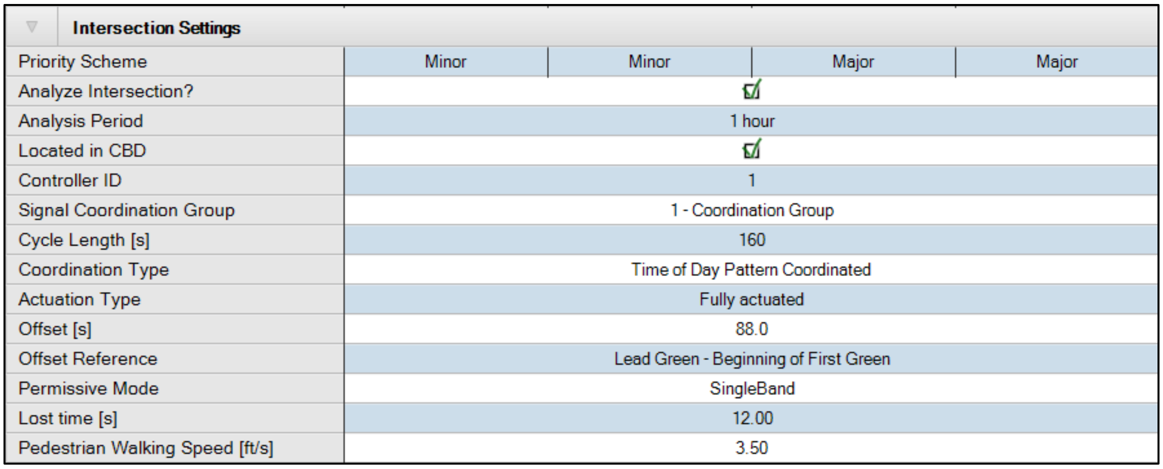
Movement, Approach, & Intersection Results

Other Modes

Sequence

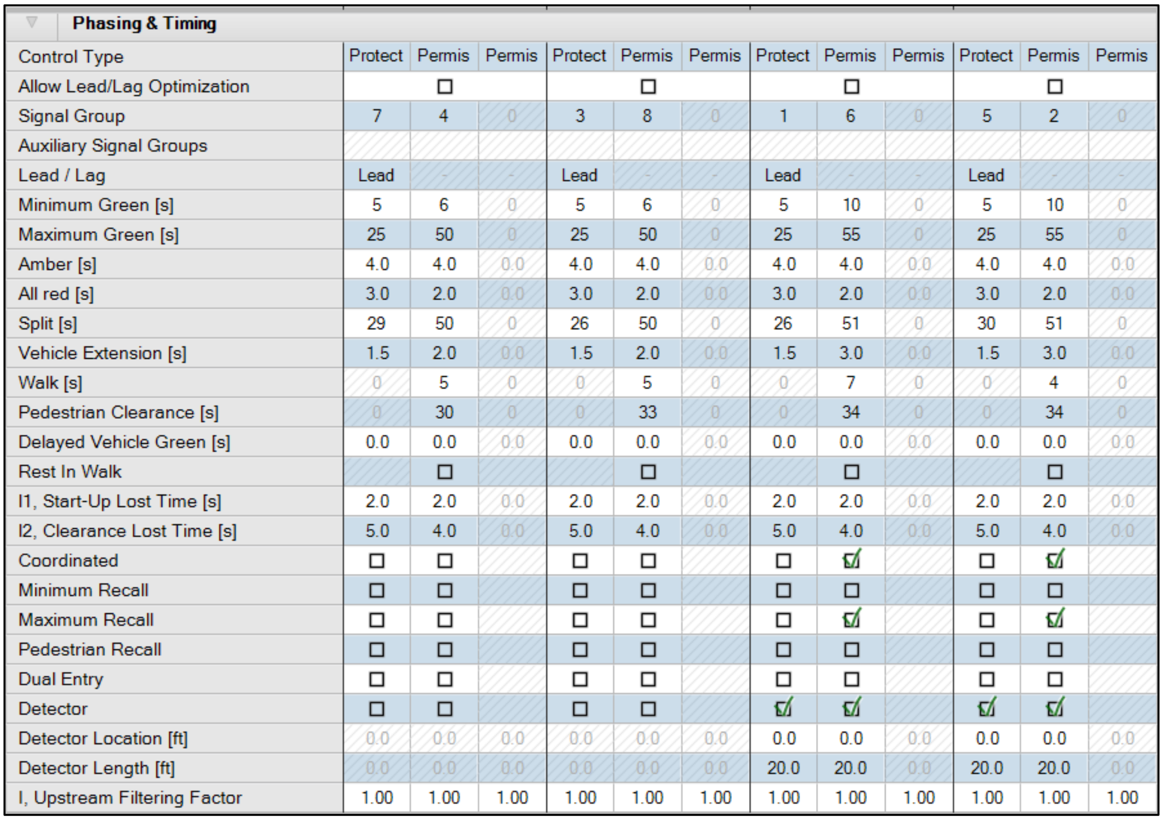
SG: 1 26s
SG: 2 51s
SG: 102 38s
SG: 3 26s
SG: 4 50s
SG: 104 35s
SG: 5 30s
SG: 6 51s
SG: 106 41s
SG: 7 29s
SG: 8 50s
SG: 108 38s

Figure 4.8 Traffic Control Window



Intersection Settings				
Priority Scheme	Minor	Minor	Major	Major
Analyze Intersection?	☑			
Analysis Period	1 hour			
Located in CBD	☑			
Controller ID	1			
Signal Coordination Group	1 - Coordination Group			
Cycle Length [s]	160			
Coordination Type	Time of Day Pattern Coordinated			
Actuation Type	Fully actuated			
Offset [s]	88.0			
Offset Reference	Lead Green - Beginning of First Green			
Permissive Mode	SingleBand			
Lost time [s]	12.00			
Pedestrian Walking Speed [ft/s]	3.50			

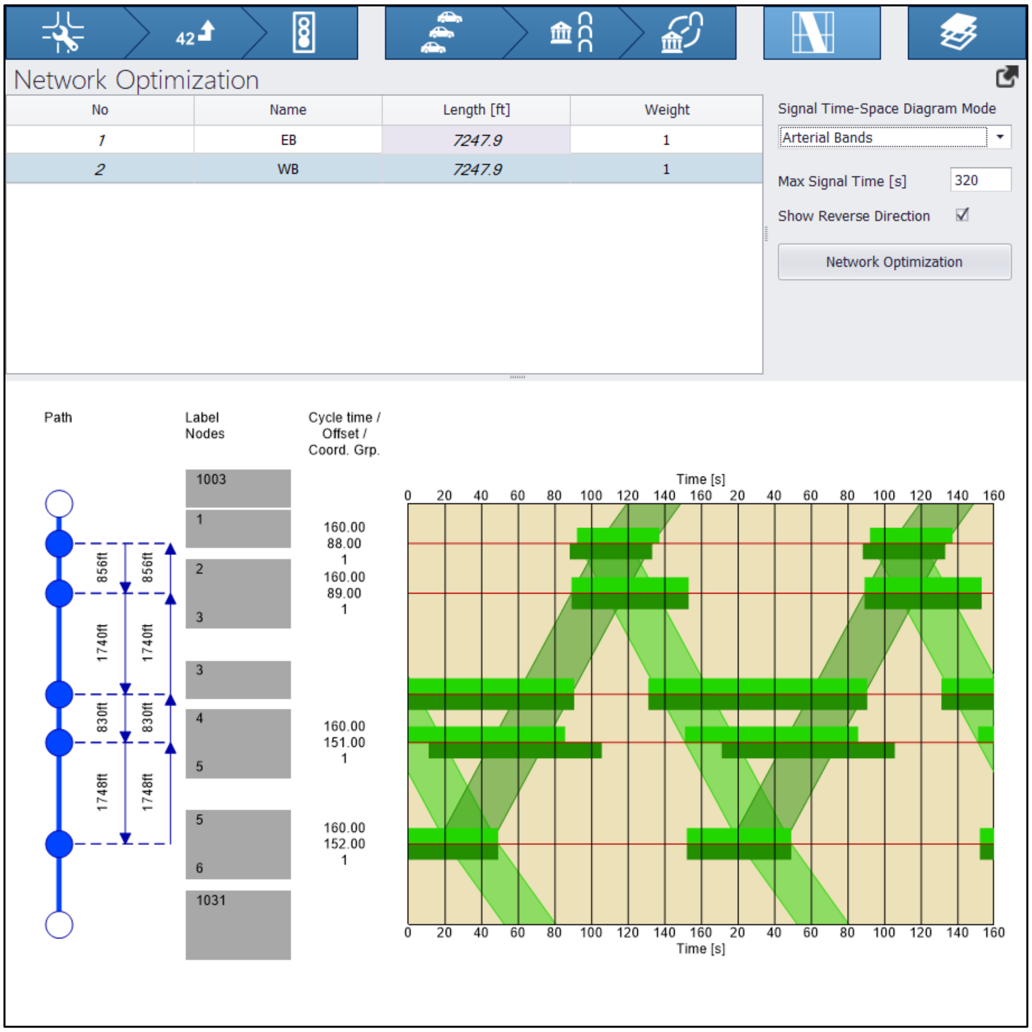
Figure 4.9 Intersection Settings Section



Phasing & Timing												
Control Type	Protect	Permis	Permis	Protect	Permis	Permis	Protect	Permis	Permis	Protect	Permis	Permis
Allow Lead/Lag Optimization	☐			☐			☐			☐		
Signal Group	7	4	0	3	8	0	1	6	0	5	2	0
Auxiliary Signal Groups												
Lead / Lag	Lead	-	-	Lead	-	-	Lead	-	-	Lead	-	-
Minimum Green [s]	5	6	0	5	6	0	5	10	0	5	10	0
Maximum Green [s]	25	50	0	25	50	0	25	55	0	25	55	0
Amber [s]	4.0	4.0	0.0	4.0	4.0	0.0	4.0	4.0	0.0	4.0	4.0	0.0
All red [s]	3.0	2.0	0.0	3.0	2.0	0.0	3.0	2.0	0.0	3.0	2.0	0.0
Split [s]	29	50	0	26	50	0	26	51	0	30	51	0
Vehicle Extension [s]	1.5	2.0	0.0	1.5	2.0	0.0	1.5	3.0	0.0	1.5	3.0	0.0
Walk [s]	0	5	0	0	5	0	0	7	0	0	4	0
Pedestrian Clearance [s]	0	30	0	0	33	0	0	34	0	0	34	0
Delayed Vehicle Green [s]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rest In Walk		☐			☐			☐			☐	
I1, Start-Up Lost Time [s]	2.0	2.0	0.0	2.0	2.0	0.0	2.0	2.0	0.0	2.0	2.0	0.0
I2, Clearance Lost Time [s]	5.0	4.0	0.0	5.0	4.0	0.0	5.0	4.0	0.0	5.0	4.0	0.0
Coordinated	☐	☐		☐	☐		☐	☑		☐	☑	
Minimum Recall	☐	☐		☐	☐		☐	☐		☐	☐	
Maximum Recall	☐	☐		☐	☐		☐	☑		☐	☑	
Pedestrian Recall	☐	☐		☐	☐		☐	☐		☐	☐	
Dual Entry	☐	☐		☐	☐		☐	☐		☐	☐	
Detector	☐	☐		☐	☐		☑	☑		☑	☑	
Detector Location [ft]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Detector Length [ft]	0.0	0.0	0.0	0.0	0.0	0.0	20.0	20.0	0.0	20.0	20.0	0.0
I, Upstream Filtering Factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Figure 4.10 Phasing & Timing Section

The last step of building the PTV Vistro [13] model was establishing coordination for each intersection in "Network Optimization", as shown in Figure 4.12. According to the previous definition of the resonant cycle, an arterial that provided good performance for both directions of the main street was the ideal target. Thus, two network optimization plans that went through the whole network for eastbound and westbound were added here. The weight of each direction was set as the same value, while max signal time was using the default. The signal time-space diagram mode has two options, flowing off and arterial bands, which satisfy users' different needs. Besides, by clicking the "Show Reverse Direction" button, the time-space diagram of both directions would directly emerge.



Network Optimization

No	Name	Length [ft]	Weight
1	EB	7247.9	1
2	WB	7247.9	1

Signal Time-Space Diagram Mode: Arterial Bands

Max Signal Time [s]: 320

Show Reverse Direction ☑

Figure 4.11 Network Optimization Window

5.0 Optimization and Evaluation of Signal Timing Plans

The word optimization means selecting the best or most effective alternative for a given situation under some constrains. Signal timing optimization is one of the crucial and easiest strategies to get a good performance under the certain traffic flow for urban arterial streets. To achieve the goal of generating the best signal timing plan for several signalized intersection, parameters like cycle length, split, offsets, phase sequence, etc. are usually selected by the performance measure algorithm in computer software.

Different from previous resonant cycle studies, in this study, the field scenario and signal timing plan were imported into the PTV Vistro [13] model for signal timing optimization instead of testing a range of cycle length by one-second increment per time. To figure out whether the resonant cycle will work in the study network, several optimization plans contain different parameters were designed and implemented for each scenario.

Simulation is defined as an approximate imitation of the operation of a process or system and this imitation is widely used in the transportation area. As optimization results derived from the PTV Vistro [13] model were insufficient to draw any convincing conclusion, the solution is importing optimized signal timing plans into the PTV Vissim [14] model and simulating to get more comprehensive results for evaluations.

All optimization options were studied in the order as shown in Table 3.1. This chapter talks about how the optimization process performed for each plan and how each optimized signal timing plan simulated for different scenarios.

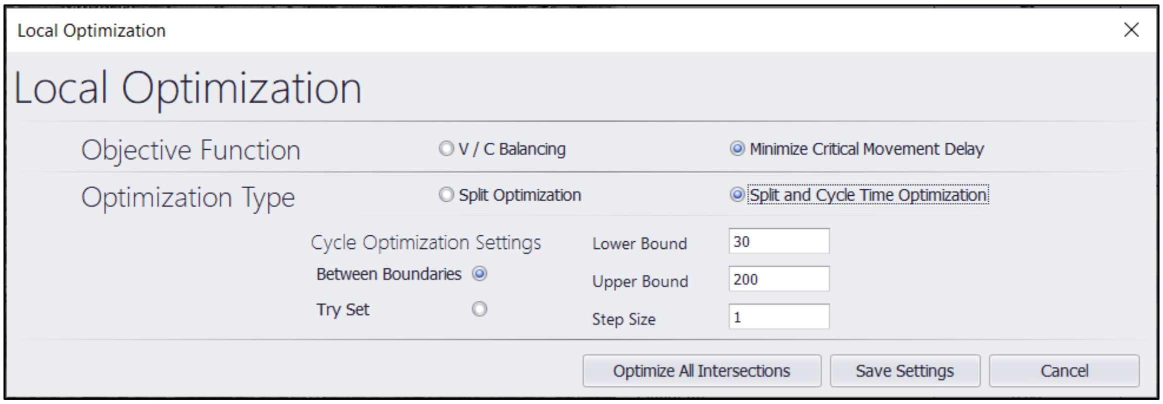
5.1 Optimization of Signal Timing Plans

The optimization in PTV Vistro [13] has two categories: local optimization, which intends to find the optimal cycle length and splits for a single intersection based on traffic volume, and network optimization, which focuses on finding the best cycle length, split, offsets and phase sequence for the selected network based on geometry and other traffic data. Users are allowed to choose the type based on their needs, pick the objective function as they want to use, and select traffic parameters that should be optimized. To study the “resonant cycle”, five optimization plans which include both optimization types and selectively combine the cycle length, split, offsets, and phase sequence together were designed and implemented as described in the research methodology part.

5.1.1 Local Optimization of Cycle Length

This optimization plan aims to find the optimal cycle length for each intersection by using local optimization function in PTV Vistro [13]. As the study network has 5 intersections, there would be at most 5 different cycle length values for each scenario. The largest cycle length of those five was chosen as the cycle length of the whole network and the splits of rest intersections were manually increased proportionally. This is a common strategy for network cycle length selection, the cycle length of the network should satisfy the demanding of the critical intersection then it can meet the needs of the other intersections.

The objective function was chosen as “Minimize Critical Movement Delay” to get better performance. Cycle optimization type was optimizing between boundaries, while the lower bound was 30 seconds and the upper bound was 200 seconds which is the normal range for an intersection. Step size was set as 1. (Figure 5.1)


Local Optimization

Local Optimization

Objective Function ○ V / C Balancing ● Minimize Critical Movement Delay

Optimization Type ○ Split Optimization ● Split and Cycle Time Optimization

Cycle Optimization Settings

Between Boundaries ●

Try Set ○

Lower Bound 30

Upper Bound 200

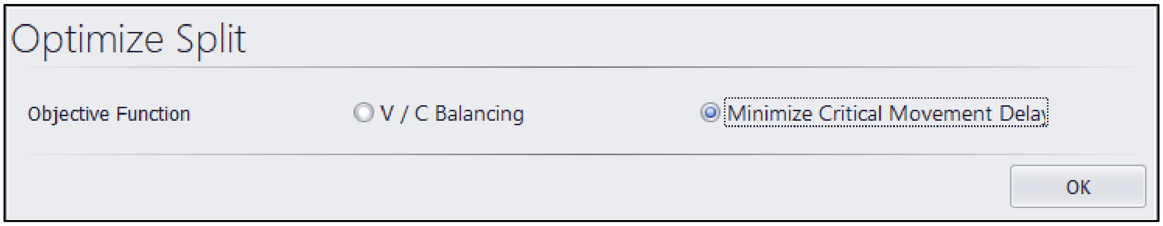
Step Size 1

Figure 5.1 Local Optimization Window

One thing that should be pointed out is the optimization process. PTV Vistro [13] does not have the function that can optimize cycle length and splits separately, so the local optimization here not only optimized cycle length for each intersection but also redistributed the split for each intersection. After the longest cycle length of this network has been calculated, the optimal cycle lengths and split of each phase for every other intersection have been recorded in a spreadsheet, by increasing the cycle length of each intersection to the largest one and using simple arithmetic, the proportional split can be manually modified in Vistro model.

5.1.2 Local Optimization of Cycle Length and Splits

This optimization plan is similar to the previous one, difference happens after the largest cycle length has been selected from local optimization results of those five intersections. Once the largest cycle length has been implemented into each intersection, instead of increasing splits of each phase proportionally, another function called “Optimize Split” has been used to optimize phase split of each intersection, as shown in Figure 5.2. The same objective function which intends to minimize critical movement delay has been selected.


Optimize Split

Objective Function ○ V / C Balancing ● Minimize Critical Movement Dela

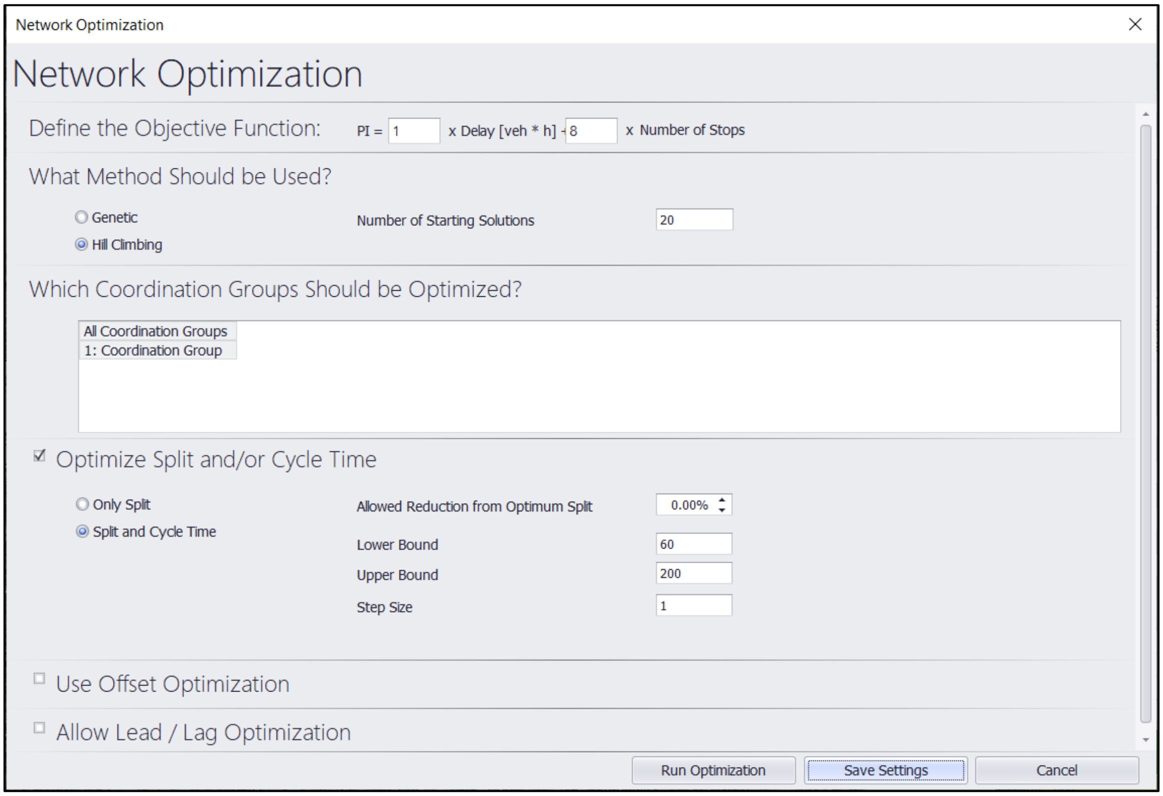
Figure 5.2 Split Optimization Window

In this way, the split of each intersection is the optimal one based on the cycle length which used for the whole network. Noticing that the signal timing plan of the intersection that provides the largest cycle length in local optimization of the cycle length and split is the same as local optimization of the cycle length and increasing split proportionally.

5.1.3 Network Optimization of Cycle Length and Splits

Previous optimization plans are all based on local optimization, which only takes the single intersection into consideration and seeks the cycle length which could satisfy the largest demand of those five intersections. Instead of focusing on one particular intersection, network optimization emphasizes the coordination of each intersection.

As PTV Vistro [13] doesn’t allow users to optimize cycle length only, this optimization plan intends to optimize cycle length and split for the whole network by using network optimization mode. The network optimization setting window as shown in Figure 5.3 illustrates all parameters that can be optimized in PTV Vistro [13].



Network Optimization

Network Optimization

Define the Objective Function: PI = 1 x Delay [veh * h] + 8 x Number of Stops

What Method Should be Used?

○ Genetic

● Hill Climbing

Number of Starting Solutions 20

Which Coordination Groups Should be Optimized?

All Coordination Groups

1: Coordination Group

☑ Optimize Split and/or Cycle Time

○ Only Split

● Split and Cycle Time

Allowed Reduction from Optimum Split 0.00%

Lower Bound 60

Upper Bound 200

Step Size 1

☐ Use Offset Optimization

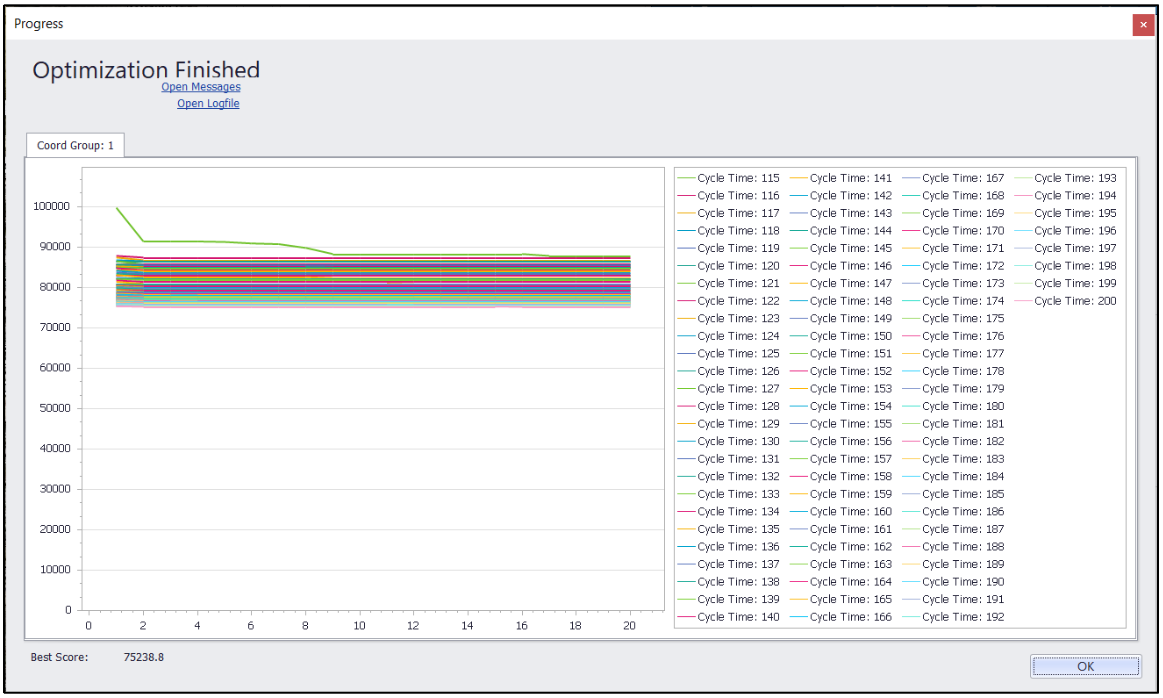
☐ Allow Lead / Lag Optimization

Figure 5.3 Network Optimization Setting Window

Performance Index (PI) was used as the objective function and defined as delay plus 8 times stops, which was the same as Shelby did in his resonant cycle study. Hill climbing was chosen as the optimization algorithm in this study, and the number of starting solutions was set as 20. Reduction from optimum split was not needed for this study and the upper bound of the cycle length was kept the same with local optimization as 200 seconds while the lower bound was increased to 60 seconds as a reasonable minimum cycle length of a network as suggested by various literature review [1, 8]. The optimization step size was set as 1 second per time.

5.1.4 Network Optimization of Cycle Length, Splits, and Offsets

Combining cycle length, split, and offsets together are the generalized coordinated system, which usually considered as the main part of network signal timing control. In this optimization, offsets which precise into 1 second was optimized together with cycle length and split. The optimization progress was shown in Figure 5.4.


Progress

Optimization Finished

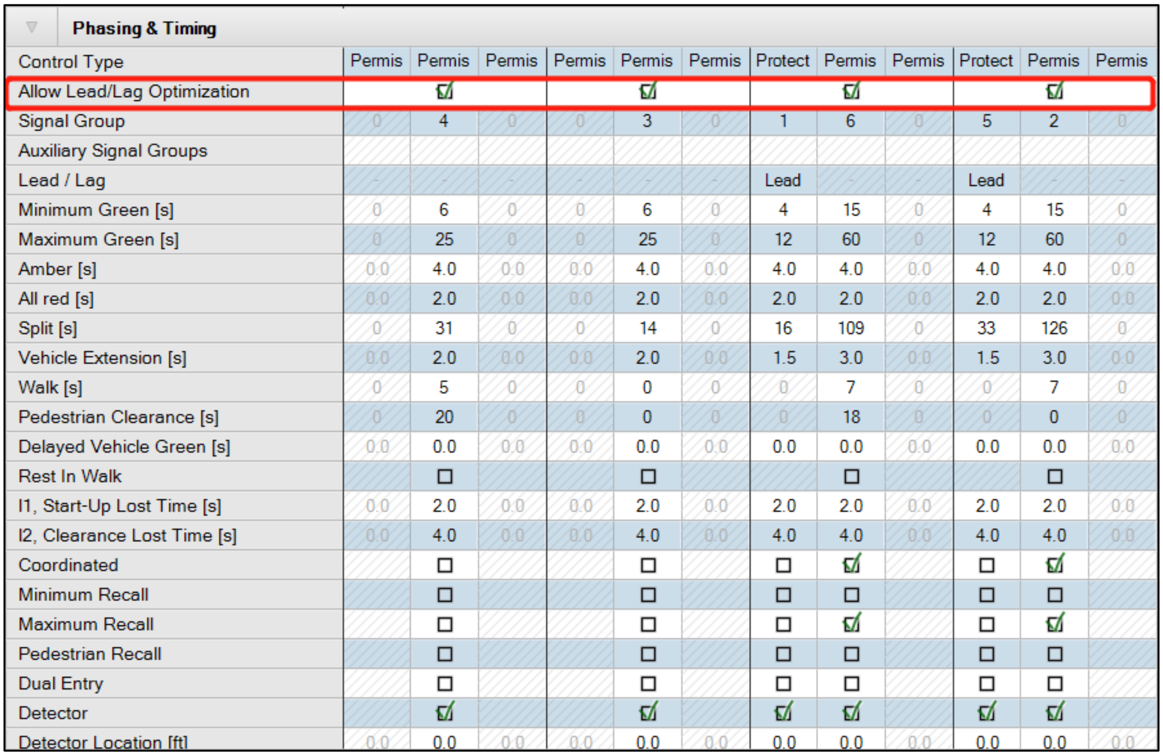
Best Score: 75238.8

Figure 5.4 Optimization Progress Window

Noticing the starting cycle length was 115 seconds which could be caused by the inner algorithm of PTV Vistro. Another phenomenon was only the first line had a big difference with other lines, this might be also caused by Vistro itself.

5.1.5 Network Optimization of All Signal Timing and Phasing Parameters

The last optimization plan includes every optional parameter provided by PTV Vistro [13]. After selecting allow lead/lag optimization in phase & timing window as shown in Figure 5.5, phase sequence was also added into the network optimization plan incorporate with cycle length, split, and offsets. The optimization process was the same as the previous one.



Phasing & Timing												
Control Type	Permis	Permis	Permis	Permis	Permis	Permis	Protect	Permis	Permis	Protect	Permis	Permis
Allow Lead/Lag Optimization		☑			☑			☑			☑	
Signal Group	0	4	0	0	3	0	1	6	0	5	2	0
Auxiliary Signal Groups												
Lead / Lag	-	-	-	-	-	-	Lead	-	-	Lead	-	-
Minimum Green [s]	0	6	0	0	6	0	4	15	0	4	15	0
Maximum Green [s]	0	25	0	0	25	0	12	60	0	12	60	0
Amber [s]	0.0	4.0	0.0	0.0	4.0	0.0	4.0	4.0	0.0	4.0	4.0	0.0
All red [s]	0.0	2.0	0.0	0.0	2.0	0.0	2.0	2.0	0.0	2.0	2.0	0.0
Split [s]	0	31	0	0	14	0	16	109	0	33	126	0
Vehicle Extension [s]	0.0	2.0	0.0	0.0	2.0	0.0	1.5	3.0	0.0	1.5	3.0	0.0
Walk [s]	0	5	0	0	0	0	0	7	0	0	7	0
Pedestrian Clearance [s]	0	20	0	0	0	0	0	18	0	0	0	0
Delayed Vehicle Green [s]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rest In Walk		☐			☐			☐			☐	
I1, Start-Up Lost Time [s]	0.0	2.0	0.0	0.0	2.0	0.0	2.0	2.0	0.0	2.0	2.0	0.0
I2, Clearance Lost Time [s]	0.0	4.0	0.0	0.0	4.0	0.0	4.0	4.0	0.0	4.0	4.0	0.0
Coordinated		☐			☐		☐	☑		☐	☑	
Minimum Recall		☐			☐		☐	☐		☐	☐	
Maximum Recall		☐			☐		☐	☑		☐	☑	
Pedestrian Recall		☐			☐		☐	☐		☐	☐	
Dual Entry		☐			☐		☐	☐		☐	☐	
Detector		☑			☑		☑	☑		☑	☑	
Detector Location [ft]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 5.5 Allow Lead/Lag Optimization Option in Phasing & Timing Window

To examine if a cycle length which has the same function as the previous definition of “resonant cycle”, a chart of all the optimal cycle lengths derived from the optimization plans for each scenario has been made, as shown in Figure 5.6. Different scenarios represent different traffic volumes within the capacity of the network.

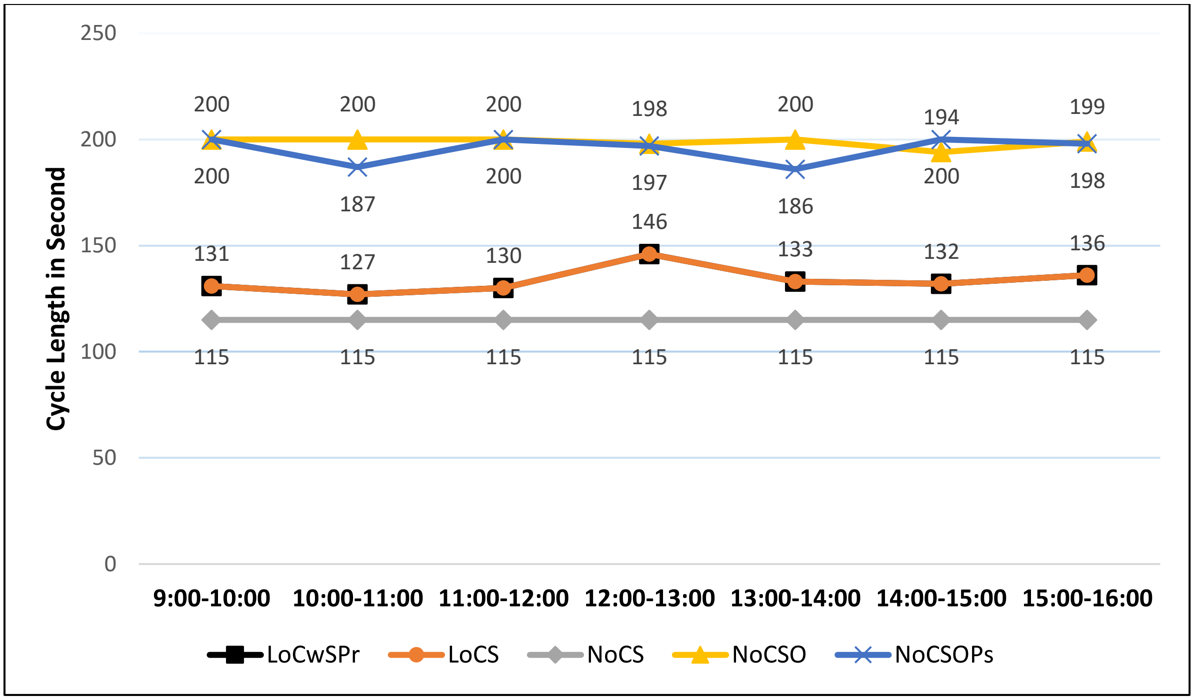


Figure 5.6 Optimized Cycle Lengths of Each Scenario

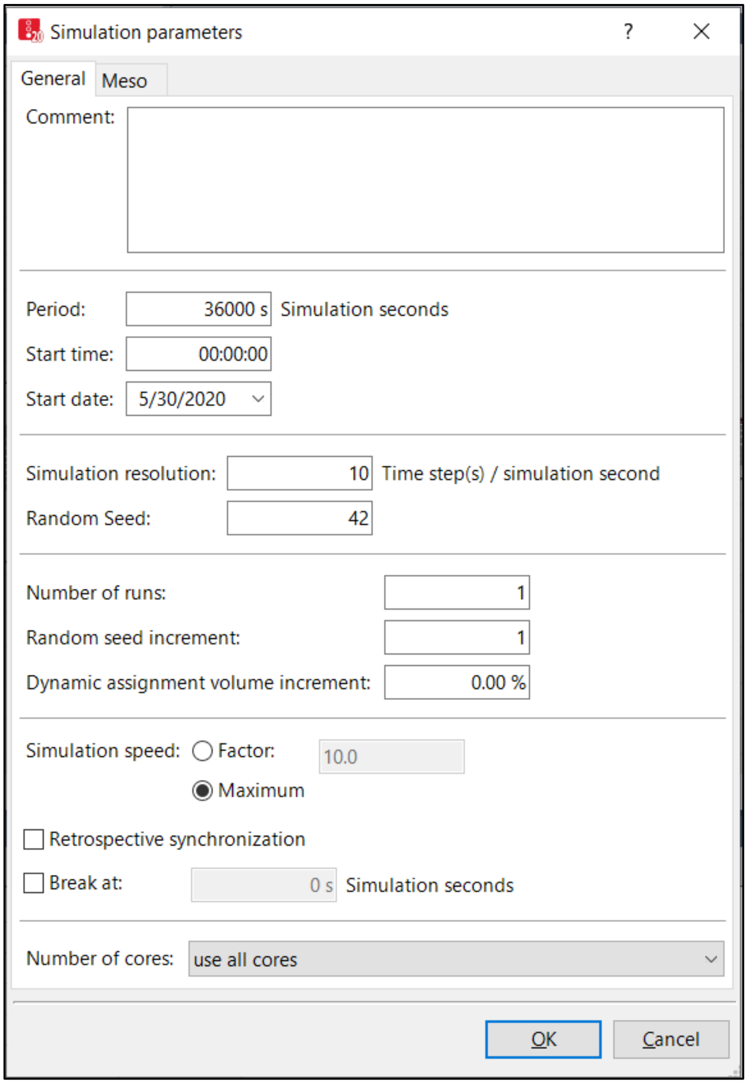
Noticing that the line of local optimization of the cycle length with increasing split proportionally is coinciding with the line of local optimization of the cycle length and split. This is because of both optimization plans using the largest cycle length of the local optimization results of each intersection for the same scenario as the network cycle length. The result of network optimization of cycle length and split is a horizontal line which means no matter how the traffic volume change, the optimal cycle length of the whole network is always the same value. To explain this phenomenon, the only possible reason is the inner algorithm of PTV Vistro [13] is limited, which cannot provide the right calculation.

A further test was established by running simulations of all the optimal signal timing plans generated from each optimization plan in the PTV Vissim [14] model. Through the comparison of key performance measures, a potential resonant cycle may get discovered.

5.2 Evaluation of Signal Timing Plans

As mentioned before, PTV Vissim [14] has the ability to simulate each entity (car, pedestrian, etc.) and measure the performance individually. Due to the lack of function in PTV Vistro [13] to provide enough performance measurements on spatial and temporal level for this study, all optimized signal timing plans derived from PTV Vistro [13] were imported into the same model which has already been built in PTV Vissim [14] and simulated to get precise and adequate performance indices.

The first step of the simulation after opening up the PTV Vissim [14] file was to set the simulation parameters, as shown in Figure 5.7. The simulation period was set for 10 hours, from 6:00 am to 4:00 pm, which equals to 36,000 seconds. The number of random seeds was given as 42, and the simulation resolution was determined as 10-time steps per simulation second. The only one-time simulation should be run for each scenario.



Comment:

Period: 36000 s Simulation seconds

Start time: 00:00:00

Start date: 5/30/2020

Simulation resolution: 10 Time step(s) / simulation second

Random Seed: 42

Number of runs: 1

Random seed increment: 1

Dynamic assignment volume increment: 0.00 %

Simulation speed: ○ Factor: 10.0

● Maximum

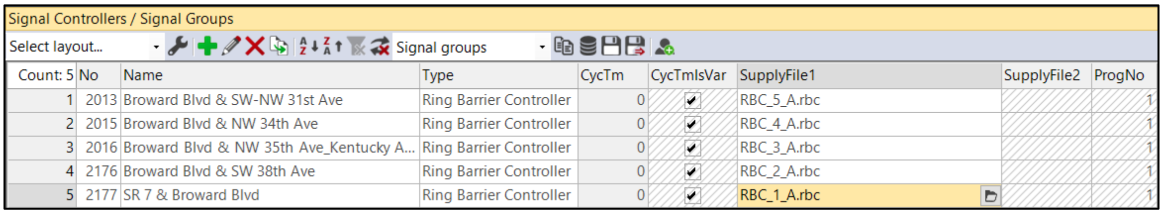
☐ Retrospective synchronization

☐ Break at: 0 s Simulation seconds

Number of cores: use all cores

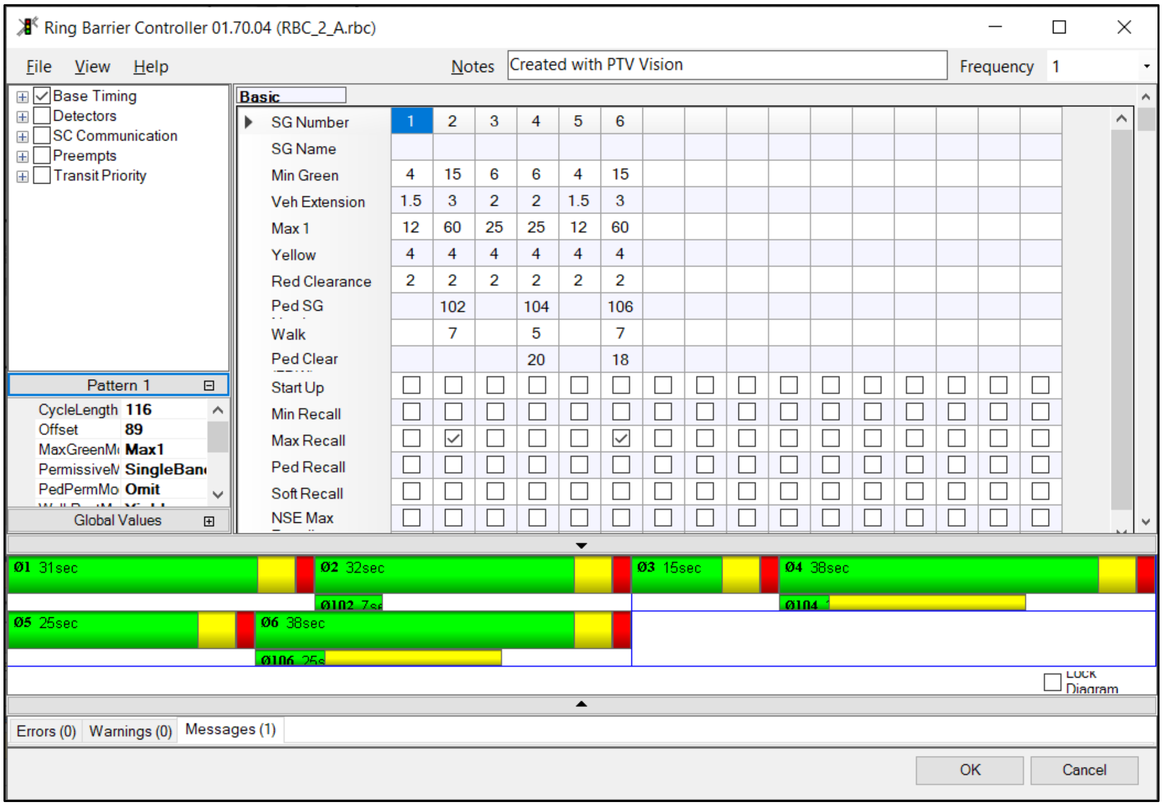
Figure 5.7 Simulation Parameters Window

To import signal timing plans that generated by PTV Vistro [13] in the PTV Vissim [14] model, each scenario should be exported from PTV Vistro [13] first as 5 RBC files which were corresponding to 5 intersections. Then, by clicking the “Signal Control” button and selecting “Signal Controllers”, the signal controller modification window would be opened (See Figure 5.8). All controllers type was set as Ring Barrier Controller (RBC) to match with the RBC files which should be imported. After adding all RBC files into certain signal controllers, the last step was opening signal groups editing window and checking the cycle length, split, offsets, phase sequence, etc. were exactly the same as the settings in PTV Vistro [13] file (See Figure 5.9).



Count: 5	No	Name	Type	CycTm	CycTmIsVar	SupplyFile1	SupplyFile2	ProgNo
1	2013	Broward Blvd & SW-NW 31st Ave	Ring Barrier Controller	0	☑	RBC_5_A.rbc		1
2	2015	Broward Blvd & NW 34th Ave	Ring Barrier Controller	0	☑	RBC_4_A.rbc		1
3	2016	Broward Blvd & NW 35th Ave_Kentucky A...	Ring Barrier Controller	0	☑	RBC_3_A.rbc		1
4	2176	Broward Blvd & SW 38th Ave	Ring Barrier Controller	0	☑	RBC_2_A.rbc		1
5	2177	SR 7 & Broward Blvd	Ring Barrier Controller	0	☑	RBC_1_A.rbc		1

Figure 5.8 Signal Controllers Modification Window



Notes: Created with PTV Vision

Frequency: 1

☑ Base Timing
☐ Detectors
☐ SC Communication
☐ Preempts
☐ Transit Priority

Pattern 1	
CycleLength	116
Offset	89
MaxGreenM	Max1
PermissiveM	SingleBan
PedPermMo	Omit

SG Number	1	2	3	4	5	6										
SG Name																
Min Green	4	15	6	6	4	15										
Veh Extension	1.5	3	2	2	1.5	3										
Max 1	12	60	25	25	12	60										
Yellow	4	4	4	4	4	4										
Red Clearance	2	2	2	2	2	2										
Ped SG		102		104		106										
Walk		7		5		7										
Ped Clear				20		18										
Start Up	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Min Recall	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Max Recall	☐	☑	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Ped Recall	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Soft Recall	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
NSE Max	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Errors (0) Warnings (0) Messages (1)

Figure 5.9 Signal Groups Editing Window

The useful results performance evaluation including 3 categories: 1) Vehicle Travel Time Results, which was collected for average travel time of eastbound and westbound vehicles passing through the whole network; 2) Vehicle Network Performance Evaluation Results, which included delay, stops, total travel time, etc. and used for network performance measure; 3) Node Results, which included delay, stops, queue length, etc. and used for progression performance measure. In addition, the LDP files that directly output from the PTV Vissim [14] model were converted from texts to tables for percent of vehicles arriving on green analysis.

6.0 Results and Analysis

After the optimization of 7 hours field scenarios in PTV Vistro [13], 35 new signal timing plans which represented different optimization plans for different time of the day were developed. By manually implementing all the signal timing plans in the PTV Vissim [14] model and running the simulation, 36 different versions of the Vissim model were generated for the performance measure comparison. As the simulation period was a time consuming, each version was run once for 10 hours (from 6:00 am to 4:00 pm). The results of each simulation from 9:00 am to 4:00 pm were used to compare performance measures.

According to the previous description, the evaluation of performance was based on several indices which could be directly extracted from PTV Vissim Evaluation Results Lists [14] : Average Delay, Average Stops could be accessed from Vehicle Network Performance Evaluation Results and Node Results; PI was calculated by the equation contains total delay and stops, which could also be directly obtained from Vehicle Network Performance Evaluation Results and Node Results; Average Travel Time was collected in Vehicle Travel Time Results for eastbound and westbound. Scenarios were compared together for each performance index and the one with the best performance for each hour would be highlighted. The comparison was divided into two groups, as mentioned in the methodology part, as follows:

1. Network level evaluation, including average delay, average stops, PI value, and average travel time of the vehicles in the whole network.

2. Progression level evaluation, including average delay, average stops, PI value, and average travel time of the main-street through movement vehicles.

6.1 Network Level Evaluation

According to Shelby [5] and Guevara [6, 10], the “resonant cycle” would provide good performance for the whole network, not only the progression. To test if there would be any “resonant cycle” like Shelby and Guevara found in their experiments, exist in this study network, the first type of evaluation was based on the network level.

6.1.1 Evaluation of the Average Delay

The average delay is an index that illustrates the additional travel time for vehicles on the network caused by traffic signal systems. Thus, decrease in average delay caused by developed signal timing plan indicates performance improvement. Figure 6.1 shows the average delay of all the 36 scenarios under the network level evaluation. Highlighted lines and marks represent scenarios which have a minimum average delay for a certain hour. To make readers get a clear view through these bundled lines, those optimal scenarios were respectively picked and drew in Figure 6.2.

Noticing that from 9:00 to 10:00, the optimized signal timing plan “LoCwSPr 14 – 15” (“14 – 15” means the scenario 14:00 – 15:00, using the same abbreviation in the following text) provided the lowest average delay. From 10:00 to 14:00, the optimized signal timing plan “LoCwSPr 13 – 14” provided the minimal average delay. And from 14:00 to 16:00, the optimized signal timing plan “LoCS 14 – 15” was the best plan for that period. According to the results, a particular signal timing plan which could provide the lowest average delay for all 7 hours under the network level evaluation was not discovered. Besides, three optimal signal timing plans which performed well for a certain or several hours were all based on the local optimization scenarios and did not optimize either offsets or phase sequence.

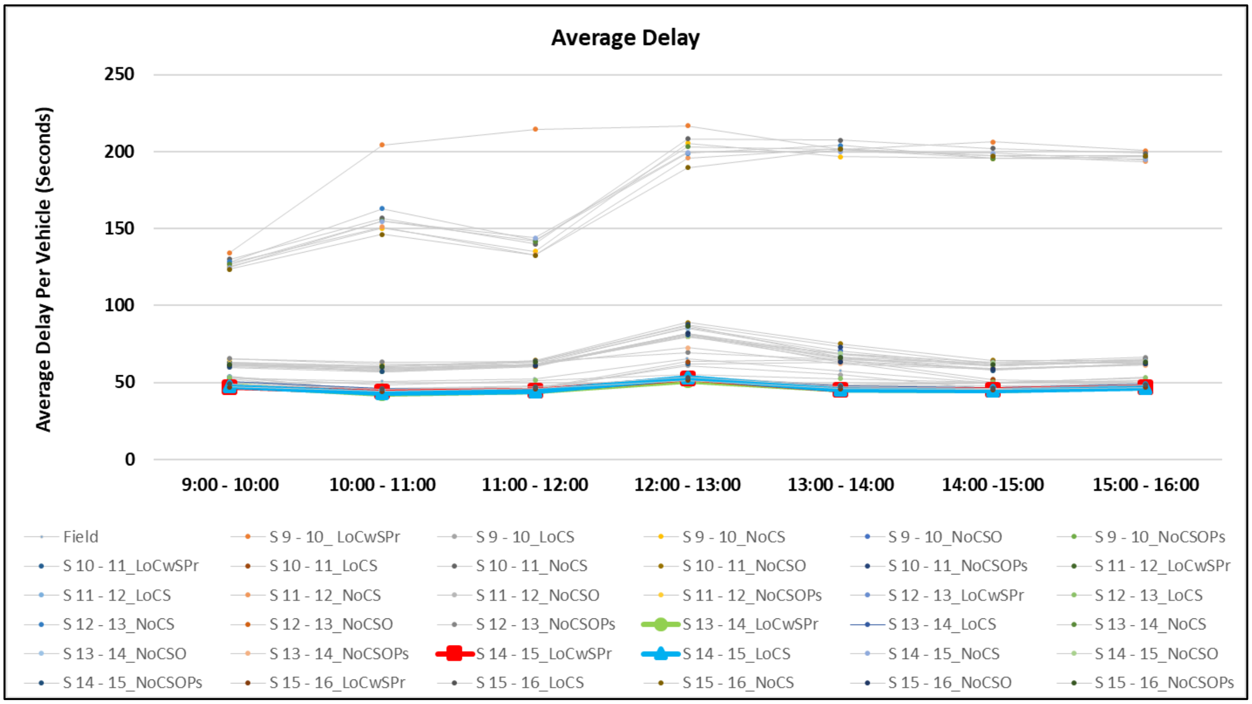


Figure 6.1 Average Delay for Network

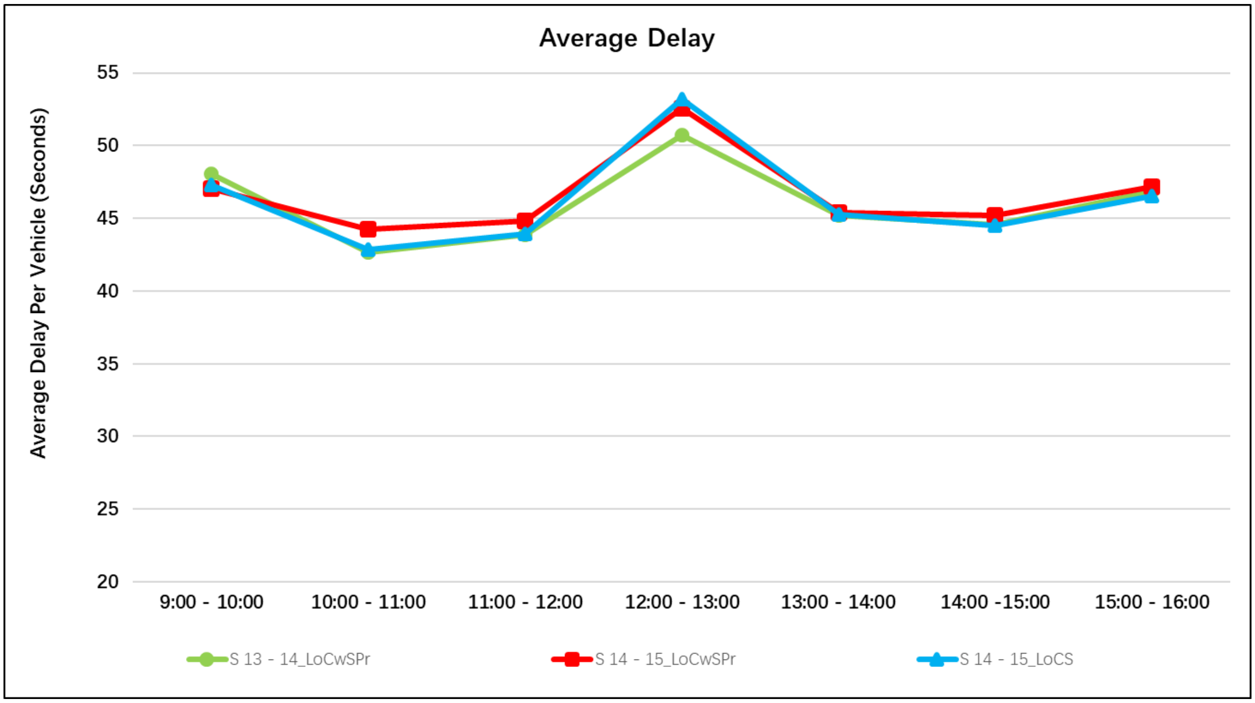


Figure 6.2 Scenarios with the Lowest Average Delay for Each Hour

For a further investigation of which scenario performed better than the others, a rank of all 36 scenarios has been developed based on each hour's average delay value, which can be seen in Appendix B. Table 6-1 shows each hour's average delay value of 20 best scenarios where all the highlighted cells represent a minimal average delay of each hour. It is noticeable that, although no single signal timing plan provides the lowest average delay for all 7 hours, several signal timing plans generate delays which are quite close to the minimal values for each hour. This means that there might be several potential resonant signal timing plans if we introduce a certain threshold for an acceptable average delay. To explore this concept further, various thresholds were used at leveles of 3%, 5%, 10%, 15%, and 20% of the minimal average delay value for each hour. Scenarios which could provide average delay value within a certain threshold for all 7 hours were listed in Table 6-2.

Table 6-1 Best Scenarios of Network Average Delay

Rank	Scenario	9:00 - 10:00	10:00 - 11:00	11:00 - 12:00	12:00 - 13:00	13:00 - 14:00	14:00 -15:00	15:00 - 16:00
1	S 13 - 14_LoCwSPr	48.06	42.66	43.86	50.73	45.22	44.58	46.86
2	S 14 - 15_LoCS	47.32	42.84	43.90	53.18	45.26	44.47	46.51
3	S 14 - 15_LoCwSPr	47.01	44.23	44.79	52.57	45.36	45.18	47.19
4	S 15 - 16_LoCwSPr	47.14	44.28	45.96	51.29	45.79	45.29	46.88
5	S 13 - 14_LoCS	50.32	45.79	45.33	52.74	47.80	46.73	48.74
6	S 15 - 16_LoCS	48.91	45.71	47.04	53.27	47.24	46.11	48.37
7	S 12 - 13_LoCwSPr	50.31	46.04	47.90	51.74	48.00	47.91	49.54
8	S 9 - 10_LoCS	48.57	45.05	45.84	60.89	54.91	45.78	50.16
9	S 10 - 11_LoCwSPr	52.32	43.37	45.22	62.00	63.11	49.85	49.54
10	S 11 - 12_LoCwSPr	53.74	43.63	45.61	53.81	48.42	49.76	51.09
11	S 11 - 12_LoCS	53.60	44.29	45.38	53.60	48.59	49.37	51.19
12	S 10 - 11_LoCS	50.50	44.15	45.99	63.46	64.74	51.94	50.08
13	S 12 - 13_LoCS	53.22	48.17	51.24	54.88	52.55	50.30	52.97
14	Field	52.93	50.55	52.15	65.35	57.34	49.61	53.38
15	S 13 - 14_NoCSOPs	60.12	57.75	61.72	72.49	62.01	58.63	61.26
16	S 12 - 13_NoCSO	61.57	58.07	60.68	79.84	64.37	58.69	61.88
17	S 14 - 15_NoCSOPs	59.76	57.08	60.81	80.91	66.01	57.76	62.33
18	S 15 - 16_NoCSO	60.91	59.76	61.26	81.93	63.07	58.95	62.17
19	S 9 - 10_NoCSOPs	62.53	56.91	60.24	81.78	66.49	58.76	61.89
20	S 14 - 15_NoCSO	61.49	57.48	61.48	79.51	68.74	62.90	62.42

Table 6-2 Optimal Scenarios Under Different Thresholds - Average Delay

Treshold	Scenario				
3%	S 13 - 14_LoCwSPr				
5%	S 13 - 14_LoCwSPr	S 14 - 15_LoCS	S 14 - 15_LoCwSPr	S 15 - 16_LoCwSPr	
10%	S 13 - 14_LoCwSPr	S 14 - 15_LoCS	S 14 - 15_LoCwSPr	S 15 - 16_LoCwSPr	S 13 - 14_LoCS
	S 15 - 16_LoCS	S 12 - 13_LoCwSPr			
15%	S 13 - 14_LoCwSPr	S 14 - 15_LoCS	S 14 - 15_LoCwSPr	S 15 - 16_LoCwSPr	S 13 - 14_LoCS
	S 15 - 16_LoCS	S 12 - 13_LoCwSPr	S 11 - 12_LoCwSPr	S 11 - 12_LoCS	
20%	S 13 - 14_LoCwSPr	S 14 - 15_LoCS	S 14 - 15_LoCwSPr	S 15 - 16_LoCwSPr	S 13 - 14_LoCS
	S 15 - 16_LoCS	S 12 - 13_LoCwSPr	S 11 - 12_LoCwSPr	S 11 - 12_LoCS	S 12 - 13_LoCS

6.1.2 Evaluation of the Average Stops

Similar to the average delay, the average stop is an index that represents the number of stops for each vehicle passing through the network. Less number of stops means better signal performance. Figure 6.3 shows the average stops (stop/vehicle) of all the 36 scenarios under the network level's evaluation. Highlighted lines and marks represent scenarios which have minimal average stops for a certain hour. To make results more readable, highlighted scenarios from Figure 6.3 were represented in Figure 6.4.

All scenarios that provided minimal average stops value were different from those that yielded the lowest average delays. For instance, from 9:00 to 10:00 and 14:00 to 15:00, the optimized signal timing plan “NoCSOPs 14 – 15” provided the minimal average stops value. From 10:00 to 12:00, 13:00 to 14:00, and 15:00 to 16:00, the optimized signal timing plan “NoCSOPs 9 – 10” was the best plan with lowest average stops. Similarly, for the period from 12:00 to 13:00, the optimized signal timing plan “NoCSOPs 12 – 13” provided the best performance among all 36 timing plans. Similar to average network delays, due to mixed performance of developed plans, there was no absolutely best plan (one that would provide best performance throughout the study period). However, three best plans for the average stops all required network optimization of all signal timing and phasing parameters, although they were from different hours (e.g. 9:00-10:00, 12:00-13:00).

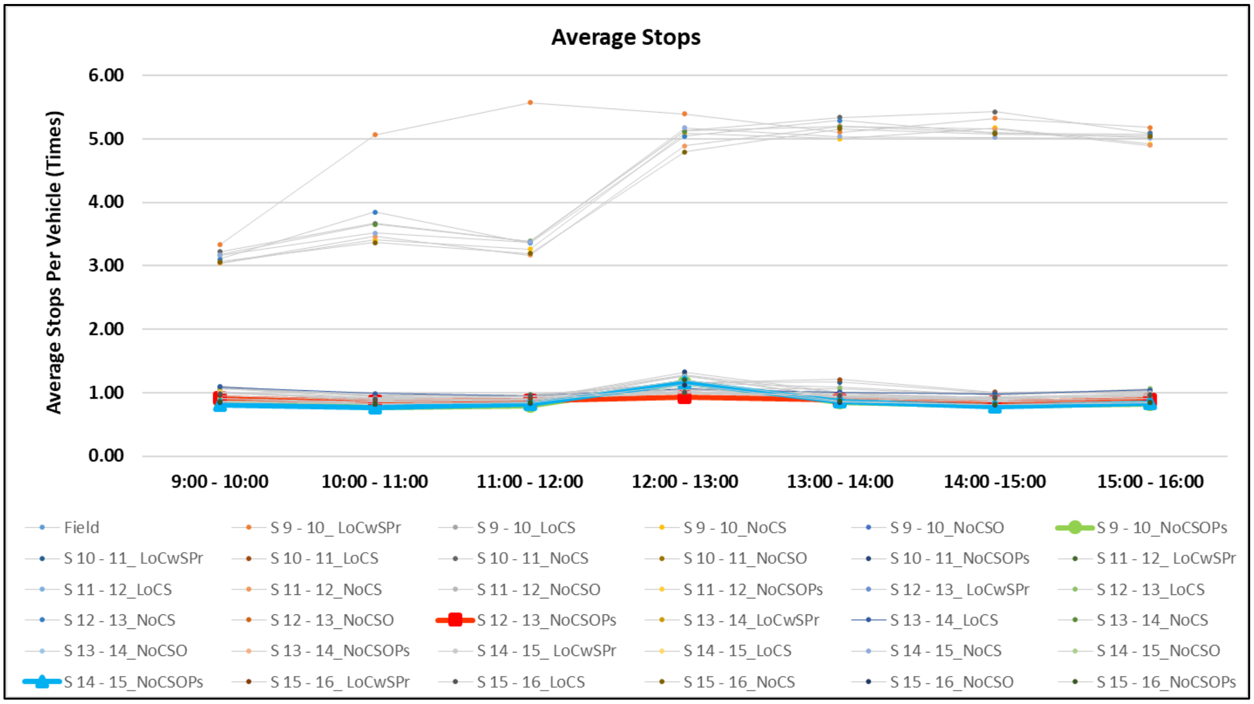


Figure 6.3 Average Stops for Network

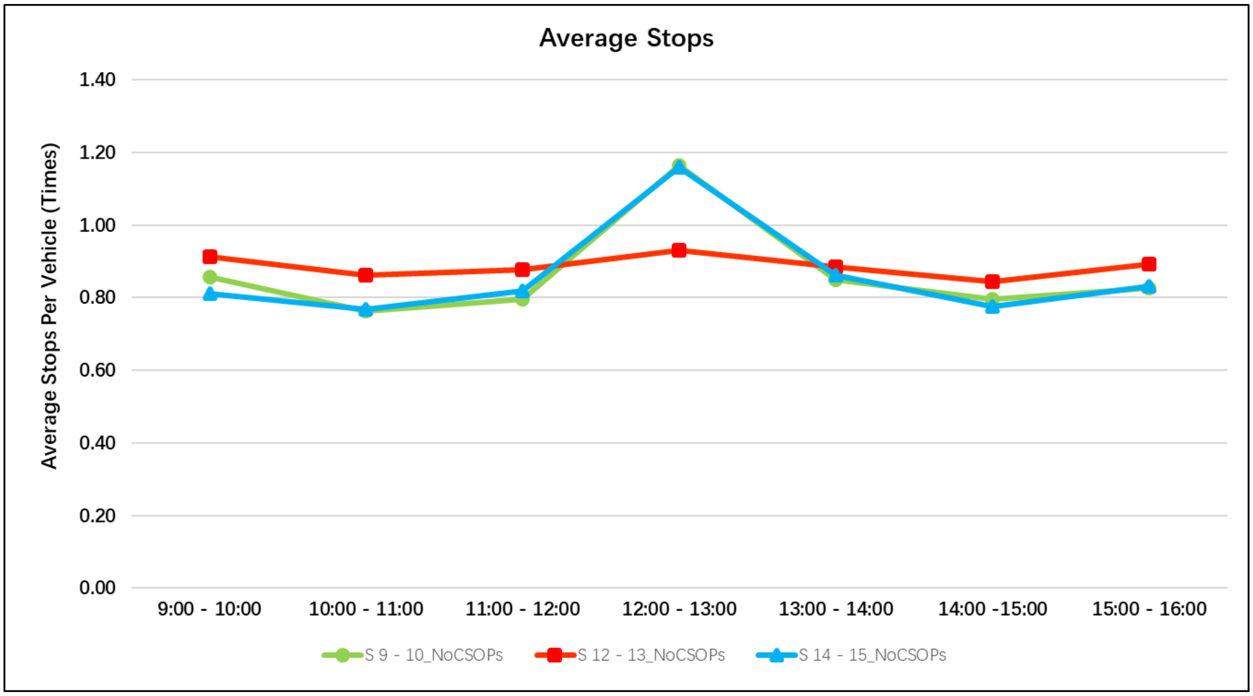


Figure 6.4 Scenarios with Lowest Average Stops for a Each Hour

Like for the average delays, a further investigation of the potential resonant signal timing plan was implemented here. A rank of all the 36 signal timing plans, based on the average stops, was shown in Appendix B. Table 6-3 shows each hour’s average stops for 20 best scenarios where all of the highlighted cells represent minimal average stops for each hour. A series of thresholds were also set at 3%, 5%, 10%, 15%, and 20% of each hour’s lowest average stops. All scenarios whose average stops fall within a certain threshold, for all 7 hours, were listed in Table 6-4.

Table 6-3 Best Scenarios for Network Average Stops

Rank	Scenario	9:00 - 10:00	10:00 - 11:00	11:00 - 12:00	12:00 - 13:00	13:00 - 14:00	14:00 -15:00	15:00 - 16:00
1	S 14 - 15_NoCSOPs	0.81	0.77	0.82	1.16	0.86	0.78	0.83
2	S 9 - 10_NoCSOPs	0.86	0.76	0.80	1.16	0.85	0.80	0.83
3	S 15 - 16_NoCSO	0.85	0.82	0.83	1.13	0.85	0.81	0.85
4	S 11 - 12_NoCSOPs	0.89	0.84	0.83	1.15	0.87	0.83	0.86
5	S 15 - 16_NoCSOPs	0.86	0.82	0.85	1.20	0.87	0.82	0.84
6	S 13 - 14_NoCSOPs	0.87	0.85	0.88	1.02	0.90	0.85	0.87
7	S 12 - 13_NoCSOPs	0.91	0.86	0.88	0.93	0.89	0.84	0.89
8	S 12 - 13_NoCSO	0.91	0.82	0.83	1.18	0.89	0.83	0.88
9	S 11 - 12_NoCSO	0.90	0.84	0.84	1.15	0.91	0.85	0.89
10	S 14 - 15_NoCSO	0.90	0.83	0.84	1.08	0.91	0.88	0.91
11	S 9 - 10_NoCSO	0.90	0.82	0.84	1.27	0.92	0.84	0.90
12	S 13 - 14_NoCSO	0.91	0.86	0.88	1.26	0.94	0.87	0.90
13	S 12 - 13_ LoCwSPr	0.95	0.88	0.91	0.99	0.93	0.90	0.95
14	S 13 - 14_LoCwSPr	1.02	0.87	0.90	1.00	0.93	0.91	0.96
15	S 14 - 15_LoCS	1.01	0.89	0.90	1.02	0.92	0.90	0.96
16	S 15 - 16_ LoCwSPr	0.95	0.88	0.91	1.00	0.95	0.91	0.95
17	Field	0.93	0.90	0.91	1.05	0.95	0.89	0.92
18	S 10 - 11_NoCSOPs	0.91	0.87	0.90	1.32	1.01	0.88	0.91
19	S 15 - 16_LoCS	0.99	0.91	0.95	1.02	0.95	0.93	0.98
20	S 10 - 11_NoCSO	0.94	0.88	0.91	1.28	0.99	0.92	0.94

Table 6-4 Optimal Scenarios Under Different Thresholds - Average Stops

Treshold	**Scenario**				
3%	NA				
5%	NA				
10%	NA				
15%	S 13 - 14_NoCSOPs	S 12 - 13_NoCSOPs			
20%	S 13 - 14_NoCSOPs	S 12 - 13_NoCSOPs	S 14 - 15_NoCSO	S 12 - 13_ LoCwSPr	S 15 - 16_ LoCwSPr
	Field				

6.1.3 Evaluation of the PI Value

As described previously, PI is an index which combines total delay and total stops together to indicate how good the performance is. Since the PI value consists of delays and number of stops, a lower value of PI indicates performance improvement. Figure 6.5 shows the PI value of all the 36 scenarios under the network level evaluation. Highlighted lines and marks represent scenarios which have minimal PI value for a certain hour. Figure 6.6 only contains highlighted lines, in order to give readers a clear view of those scenarios with the best performance.

For the results shown from 9:00 to 10:00, the optimized signal timing plan “LoCwSPr 15 – 16” had the lowest PI value. From 10:00 to 14:00, the best optimized signal timing plan was “LoCwSPr 13 – 14”. Also, for the remaining 2 hours, Scenario “LoCS 14 – 15” became one with minimal PI value. Similarly as previous evaluations, no single signal timing plan reached the lowest PI value for all 7 hours, when PI is considered for network evaluation. Three best signal timing plans for individual hours were close to the ones selected in average delay evaluation and did not relate to network scale optimization which considered offsets and phase parameters.

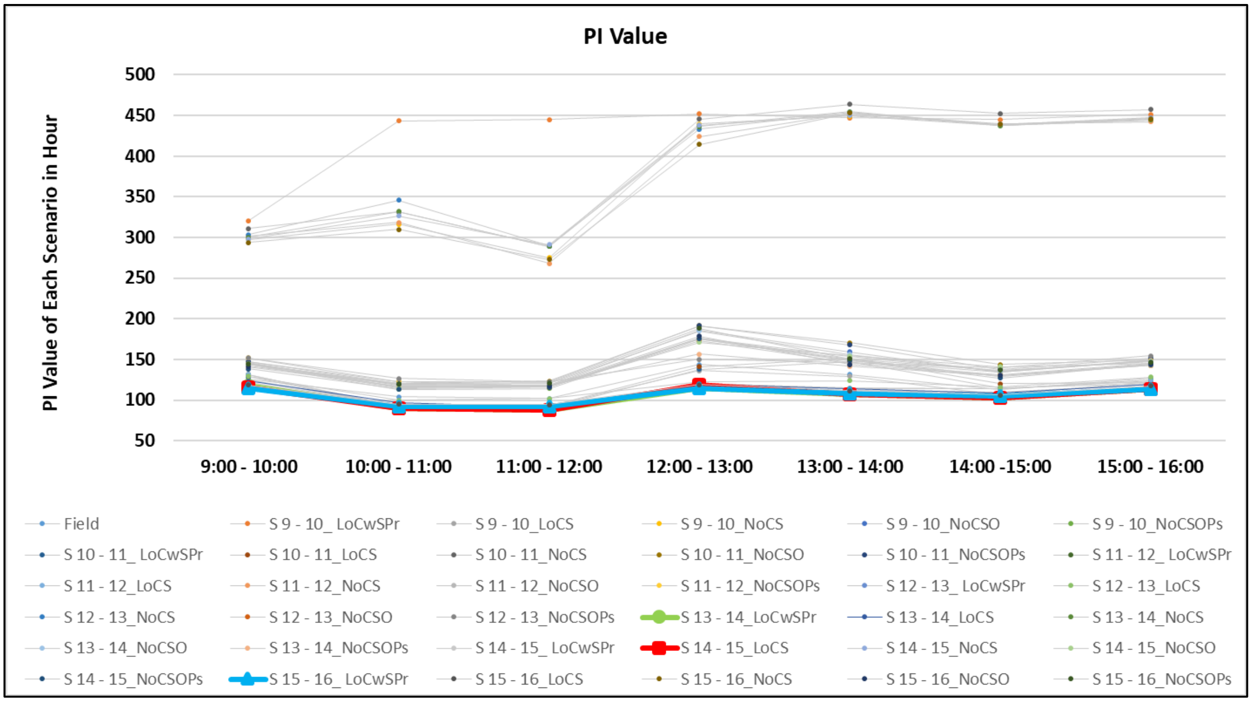


Figure 6.5 PI Values for Network

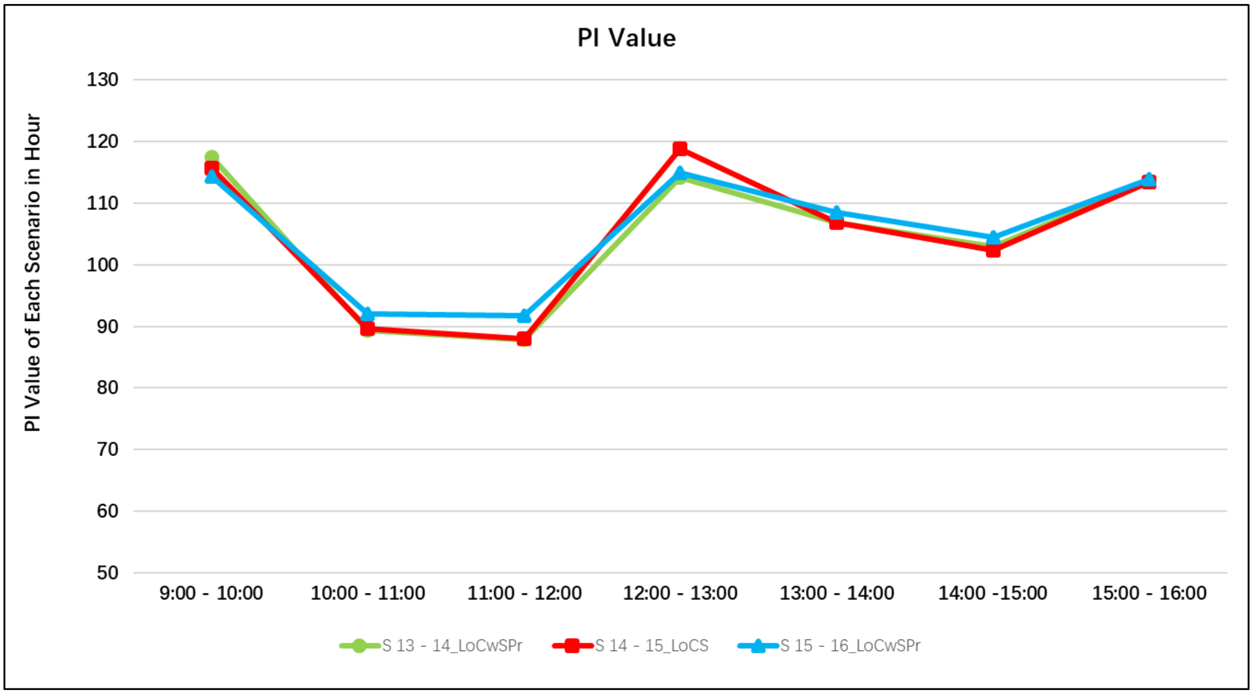


Figure 6.6 Scenarios with the Minimal PI Value for Each Hour

Although none of those 36 signal timing plans performed consistently well for all 7 hours, all scenarios were ranked to provide a clear view of which signal timing plans worked better than others (See Appendix B). Table 6-5 lists each hour's PI value of the 20 best scenarios where the highlighted cells show the lowest PI value of each hour. Similar to previous evaluations, 5 different thresholds were set at 3%, 5%, 10%, 15%, and 20% of the lowest PI value; to investigate existence of potential resonant signal timing plans. Table 6-6 indicates scenarios which consistenly provide a low PI for 7 hours within a certain threshold.

Table 6-5 Best Scenarios of Network PI Value

Rank	Scenario	9:00 - 10:00	10:00 - 11:00	11:00 - 12:00	12:00 - 13:00	13:00 - 14:00	14:00 -15:00	15:00 - 16:00
1	S 13 - 14_LoCwSPr	117.46	89.34	87.90	114.16	106.82	102.90	113.50
2	S 14 - 15_LoCS	115.61	89.69	88.04	118.82	106.86	102.41	113.49
3	S 14 - 15_ LoCwSPr	115.02	92.52	90.07	117.82	107.71	104.45	115.38
4	S 15 - 16_ LoCwSPr	114.33	92.05	91.75	114.90	108.51	104.42	113.91
5	S 15 - 16_LoCS	118.58	95.01	94.20	119.07	111.47	106.43	117.50
6	S 12 - 13_ LoCwSPr	121.85	95.16	95.15	115.58	112.06	109.98	118.91
7	S 13 - 14_LoCS	123.48	96.67	91.25	119.21	113.54	108.48	119.01
8	S 11 - 12_ LoCwSPr	131.37	91.34	91.31	120.85	114.13	114.46	123.82
9	S 9 - 10_LoCS	118.97	94.46	92.08	136.14	129.21	106.58	122.15
10	S 11 - 12_LoCS	131.55	93.00	91.11	120.07	114.57	113.70	124.30
11	S 10 - 11_ LoCwSPr	128.90	91.54	90.78	137.88	147.50	115.35	120.09
12	S 10 - 11_LoCS	124.16	93.45	92.24	140.90	151.69	120.32	121.24
13	S 12 - 13_LoCS	129.33	99.98	101.80	122.76	123.79	116.01	128.12
14	Field	125.78	103.84	102.07	143.54	131.54	112.90	126.40
15	S 14 - 15_NoCSOPs	138.40	113.79	115.62	175.52	149.30	127.35	143.71
16	S 13 - 14_NoCSOPs	140.28	116.92	118.25	156.72	141.46	130.38	142.86
17	S 9 - 10_NoCSOPs	144.43	113.26	114.39	176.58	149.94	129.36	142.60
18	S 12 - 13_NoCSO	144.91	115.99	115.63	173.42	146.28	130.73	145.16
19	S 15 - 16_NoCSO	141.52	119.84	117.76	178.41	143.52	130.40	144.05
20	S 14 - 15_NoCSO	143.99	115.41	117.18	171.22	154.63	141.04	145.23

Table 6-6 Optimal Scenarios for Under Different Thresholds – PI Value

PI					
Treshold	**Scenario**				
3%	S 13 - 14_LoCwSPr				
5%	S 13 - 14_LoCwSPr	S 14 - 15_LoCS	S 14 - 15_ LoCwSPr	S 15 - 16_ LoCwSPr	
10%	S 13 - 14_LoCwSPr	S 14 - 15_LoCS	S 14 - 15_ LoCwSPr	S 15 - 16_ LoCwSPr	S 15 - 16_LoCS
	S 12 - 13_ LoCwSPr	S 13 - 14_LoCS			
15%	S 13 - 14_LoCwSPr	S 14 - 15_LoCS	S 14 - 15_ LoCwSPr	S 15 - 16_ LoCwSPr	S 15 - 16_LoCS
	S 12 - 13_ LoCwSPr	S 13 - 14_LoCS	S 11 - 12_ LoCwSPr		
20%	S 13 - 14_LoCwSPr	S 14 - 15_LoCS	S 14 - 15_ LoCwSPr	S 15 - 16_ LoCwSPr	S 15 - 16_LoCS
	S 12 - 13_ LoCwSPr	S 13 - 14_LoCS	S 11 - 12_ LoCwSPr	S 11 - 12_LoCS	S 12 - 13_LoCS

6.1.4 Evaluation of the Average Travel Time

Average travel time is an intuitive index that directly shows the performance of the study area, the less a vehicle spends on passing through a network, the better performance this network has. To calculate the average travel time of the whole network, total travel time including all streets and all directions was used, which could be accessed from Vehicle Network Performance Evaluation Results in PTV Vissim. By dividing that value with the total amount of vehicles within the network and arrived at destinations, the average travel time of the network could be inferred. (Figure 6.7 and 6.8)

It can be seen that from 9:00 to 10:00, the optimized signal timing plan “LoCwSPr 15 – 16” had the shortest average travel time. From 10:00 to 11:00 and 12:00 to 14:00, the best-optimized signal timing plan was one developed as “LoCwSPr 13 – 14”. From 11:00 to 12:00 and 14:00 to 16:00, scenario “LoCS 14 – 15” was the best one which reached the lowest average travel time. It is noticeable that these three optimal signal timing plans were the same as the best ones found for the network level’s PI value. Only slight difference occurred for the period 11:00 to 12:00, as the average travel time of scenario “LoCwSPr 13 – 14” was negligibly lower (0.13s) than the average travel time of scenario “LoCwSPr 13 – 14”. Although there was still no clear resonance that was found among the signal timing plans, there are several potential resonant signal timing plans which provide the lowest PI value and may also lead to the shortest average travel time.

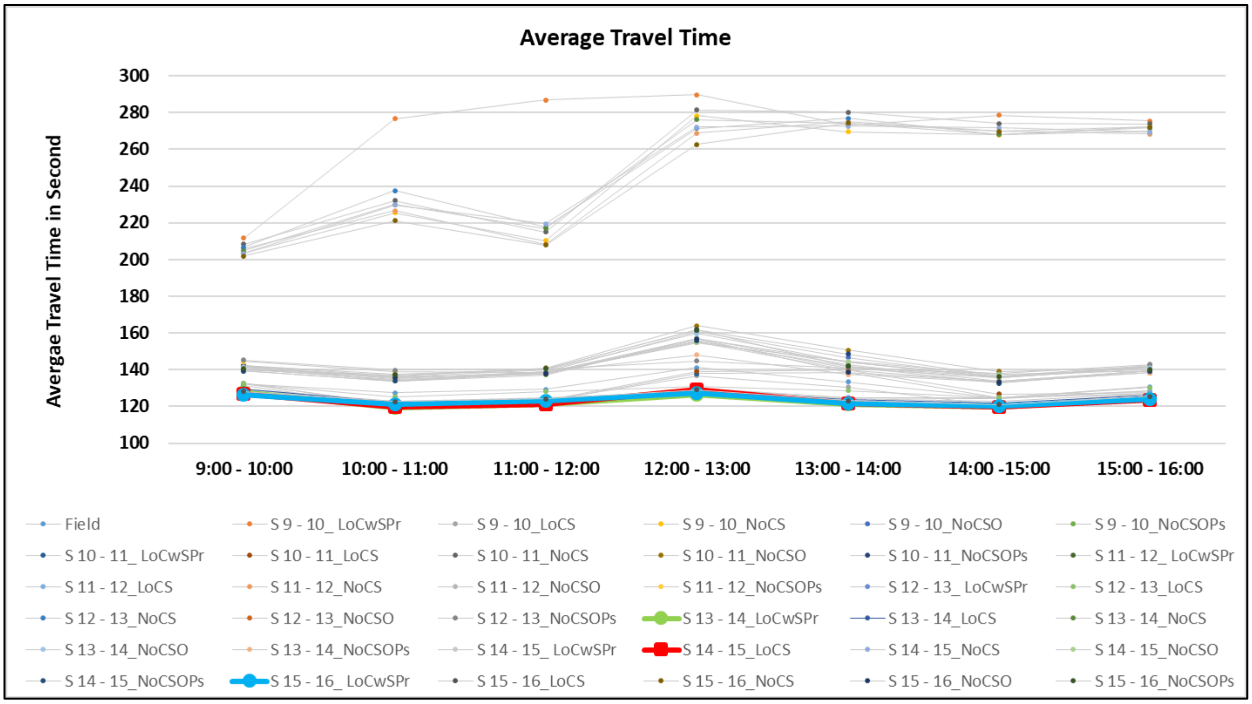


Figure 6.7 Average Travel Time for Network

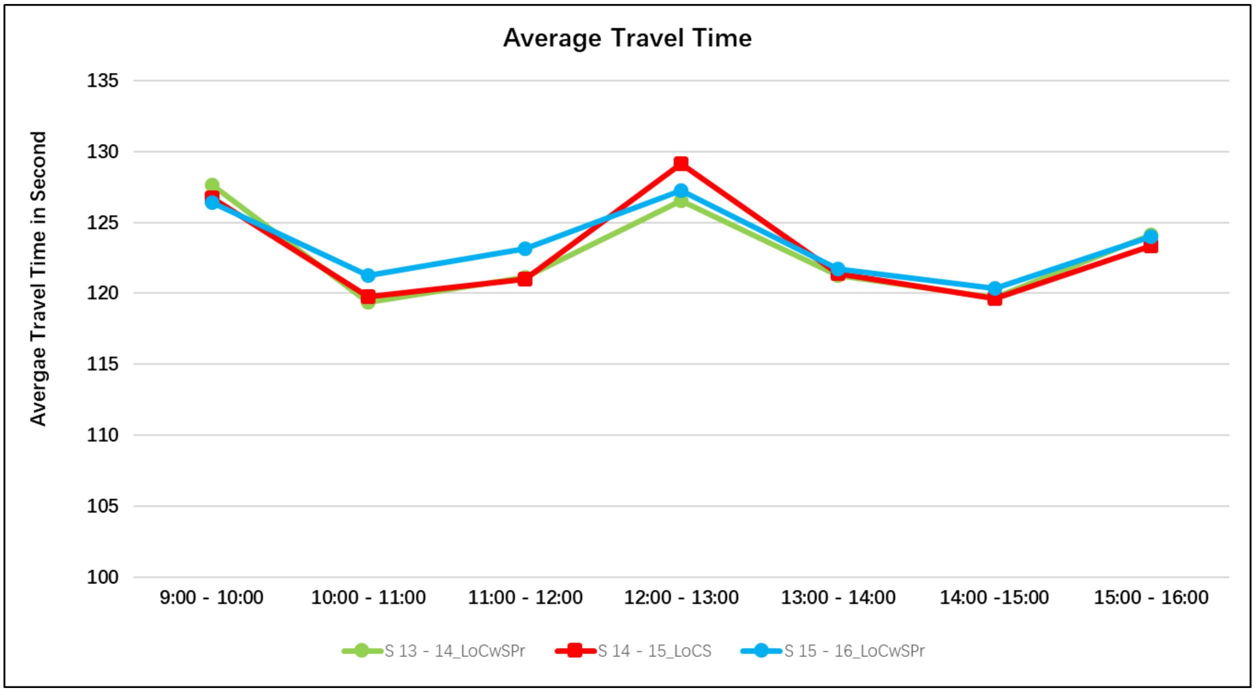


Figure 6.8 Scenarios with the Shortest Average Travel Time for Each Hour

Similar to previous evaluations, a ranking of all 36 scenarios was created to find out the which signal timing plan was relatively better than others; even when no single plan could provide robust performance over all 7 hours (See Appendix B). Table 6-7 contains each hour's average travel time of the best 20 scenarios, where the highlighted cells represent the lowest average travel times of each hour. Different levels of thresholds from 3% to 20% were set for further investigation of possible resonant signal timing plans. All scenairos which could provide the average travel time under a particular threshold were listed in Table 6-8.

Table 6-7 Best Scenarios of Network Average Travel Time

Rank	Scenario	9:00 - 10:00	10:00 - 11:00	11:00 - 12:00	12:00 - 13:00	13:00 - 14:00	14:00 -15:00	15:00 - 16:00
1	S 13 - 14_LoCwSPr	127.61	119.38	121.13	126.51	121.24	119.73	124.15
2	S 14 - 15_LoCS	126.76	119.76	121.00	129.14	121.42	119.63	123.36
3	S 14 - 15_ LoCwSPr	126.52	121.17	122.02	128.60	121.64	120.19	124.21
4	S 15 - 16_ LoCwSPr	126.38	121.29	123.14	127.27	121.71	120.32	124.01
5	S 13 - 14_LoCS	129.63	122.50	122.42	128.52	123.75	121.78	125.94
6	S 15 - 16_LoCS	128.22	122.72	124.13	129.13	123.23	121.03	125.51
7	S 12 - 13_ LoCwSPr	129.49	123.02	124.86	127.84	124.24	122.56	127.04
8	S 9 - 10_LoCS	127.93	122.05	123.08	136.64	130.56	120.64	127.18
9	S 10 - 11_ LoCwSPr	131.40	119.86	122.64	137.84	138.37	124.91	126.94
10	S 11 - 12_ LoCwSPr	132.73	120.60	122.80	129.69	124.63	124.66	128.37
11	S 11 - 12_LoCS	132.52	121.25	122.66	129.58	124.73	124.33	128.38
12	S 10 - 11_LoCS	129.67	120.74	123.34	139.12	139.81	126.81	127.55
13	S 12 - 13_LoCS	132.49	125.17	128.16	130.86	128.51	124.87	130.38
14	Field	132.46	127.35	129.24	141.11	133.29	124.46	130.70
15	S 13 - 14_NoCSOPs	139.29	133.89	138.85	147.95	137.47	133.35	138.29
16	S 12 - 13_NoCSO	140.18	134.85	137.79	155.06	139.83	133.12	138.41
17	S 14 - 15_NoCSOPs	139.24	133.73	138.01	155.77	141.98	132.52	139.62
18	S 15 - 16_NoCSO	139.98	135.97	137.63	156.75	138.47	133.67	139.29
19	S 9 - 10_NoCSOPs	142.15	133.86	137.17	157.04	142.50	133.73	139.27
20	S 14 - 15_NoCSO	140.59	133.99	138.38	154.78	144.50	137.27	139.54

Table 6-8 Optimal Scenarios Under Different Thresholds - Average Travel Time

Treshold	Scenario				
3%	S 13 - 14_LoCwSPr	S 14 - 15_LoCS	S 14 - 15_ LoCwSPr	S 15 - 16_ LoCwSPr	S 13 - 14_LoCS
	S 15 - 16_LoCS				
5%	S 13 - 14_LoCwSPr	S 14 - 15_LoCS	S 14 - 15_ LoCwSPr	S 15 - 16_ LoCwSPr	S 13 - 14_LoCS
	S 15 - 16_LoCS	S 12 - 13_ LoCwSPr	S 11 - 12_LoCS		
10%	S 13 - 14_LoCwSPr	S 14 - 15_LoCS	S 14 - 15_ LoCwSPr	S 15 - 16_ LoCwSPr	S 13 - 14_LoCS
	S 15 - 16_LoCS	S 12 - 13_ LoCwSPr	S 9 - 10_LoCS	S 11 - 12_ LoCwSPr	S 11 - 12_LoCS
	S 12 - 13_LoCS				
15%	S 13 - 14_LoCwSPr	S 14 - 15_LoCS	S 14 - 15_ LoCwSPr	S 15 - 16_ LoCwSPr	S 13 - 14_LoCS
	S 15 - 16_LoCS	S 12 - 13_ LoCwSPr	S 9 - 10_LoCS	S 10 - 11_ LoCwSPr	S 11 - 12_ LoCwSPr
	S 11 - 12_LoCS	S 12 - 13_LoCS	Field		
20%	S 13 - 14_LoCwSPr	S 14 - 15_LoCS	S 14 - 15_ LoCwSPr	S 15 - 16_ LoCwSPr	S 13 - 14_LoCS
	S 15 - 16_LoCS	S 12 - 13_ LoCwSPr	S 9 - 10_LoCS	S 10 - 11_ LoCwSPr	S 11 - 12_ LoCwSPr
	S 11 - 12_LoCS	S 10 - 11_LoCS	S 12 - 13_LoCS	Field	S 13 - 14_NoCSOPs

6.1.5 Summary Analysis

In summary, based on the results of four performance measures of the network level evaluation (average delay, average stops, PI value, and average travel time), it can be concluded that no single signal timing plan performs the best for the entire experimental period in the study network. However, two optimized signal timing plans, for “13:00 – 14:00” and “14:00 – 15:00”, have appeared frequently as the signal timing plans which could provide the best performance for a certain hour in terms of: average delays, PI values, and average travel times. It is noticeable that the cycle lengths of these two signal timing plans are very similar, 132 and 133 seconds. Considering that cycle lengths are often defined in 5-second increments [5, 6, 10], one could claim that these two actually represent the same cycle length that could be defined as a resonant cycle length of the study network. However, a sole value of cycle length means is not sufficient to properly represent coordinated traffic signal operations because the split, offsets, phase sequence, etc. are all important elements which should be also taken into consideration when setting optimal signal timings.

Several optimized signal timing plans have the potential to be identified as resonant signal timing plans if a certain performance threshold is accepted. Table 6-9 shows scenarios which consistently provide good performance for all 7 hours, for all network-level performance measures. For example, within a 3% threshold, scenario “LoCwSPr 13 – 14” can be identified as a resonant signal timing plan as it emerged as one of the best timing plans for 3 of 4 performance measures (except for average stops). For a 5% threshold, number of potential resonant signal timing plans increased to four and still not including average stops. Similarly, seven optimized signal timing plans have been identified as resonant signal timing plans under the 10% threshold; again, if the average stops are neglected. When the threshold was set as 15% of minimal value, one additional resonant signal timing plan is identified. The situation became a bit different when the threshold was increased to 20%. In that case, scenarios “LoCwSPr 12 – 13” and “LoCwSPr 15 – 16” were two signal timing plans which could be identified as resonant for all four performance measures. However, if the average stops are still excluded from consideration, there would be 10 possible resonant signal timing plans for the study network.

Generally speaking, although there was no single optimal signal timing plan that could provide the best performance for the entire 7-hour period (under network level evaluation), several signal timing plans have potential to be identified as resonant plans, when one accepts the threshold-based performance for various performance measure. In spite of the inconsistencies related to the average number of stops, signal timing plan “LoCwSPr 13 – 14” which developed for the interval between 13:00 – 14:00 could be identified as the resonant signal timing plan, as it performed better than other signal timing plans within different thresholds of 3%, 5%, 10%, 15%, and 20%. In addition, no matter how high or low the threshold is set, most of the potential resonant signal timing plans were based on local optimizations, which means that the offsets and phase sequence remained the same as those in the field. Therefore, these findings raise the question if network level evaluation, in Vistro, is suitable method for studying existence of resonant signal timing plans. As a consequence, we may need to review again results of the previous studies, which used the PI value combining the network's delay and stops, to investigate if the analyses were done appropriately.

Table 6-9 Resonant Signal Timing Plans Under Different Thresholds - Network

Average Delay					
Treshold	**Scenario**				
3%	**S 13 - 14_LoCwSPr**				
5%	**S 13 - 14_LoCwSPr**	**S 14 - 15_LoCS**	**S 14 - 15_LoCwSPr**	**S 15 - 16_LoCwSPr**	
10%	**S 13 - 14_LoCwSPr**	**S 14 - 15_LoCS**	**S 14 - 15_LoCwSPr**	**S 15 - 16_LoCwSPr**	**S 13 - 14_LoCS**
	S 15 - 16_LoCS	**S 12 - 13_LoCwSPr**			
15%	**S 13 - 14_LoCwSPr**	**S 14 - 15_LoCS**	**S 14 - 15_LoCwSPr**	**S 15 - 16_LoCwSPr**	**S 13 - 14_LoCS**
	S 15 - 16_LoCS	**S 12 - 13_LoCwSPr**	**S 11 - 12_LoCwSPr**	S 11 - 12_LoCS	
20%	**S 13 - 14_LoCwSPr**	**S 14 - 15_LoCS**	**S 14 - 15_LoCwSPr**	**S 15 - 16_LoCwSPr**	**S 13 - 14_LoCS**
	S 15 - 16_LoCS	**S 12 - 13_LoCwSPr**	**S 11 - 12_LoCwSPr**	**S 11 - 12_LoCS**	**S 12 - 13_LoCS**

Average Stops					
Treshold	**Scenario**				
3%	NA				
5%	NA				
10%	NA				
15%	S 13 - 14_NoCSOPs	S 12 - 13_NoCSOPs			
20%	S 13 - 14_NoCSOPs	S 12 - 13_NoCSOPs	S 14 - 15_NoCSO	**S 12 - 13_ LoCwSPr**	**S 15 - 16_ LoCwSPr**
	Field				

PI					
Treshold	**Scenario**				
3%	**S 13 - 14_LoCwSPr**				
5%	**S 13 - 14_LoCwSPr**	**S 14 - 15_LoCS**	**S 14 - 15_ LoCwSPr**	**S 15 - 16_ LoCwSPr**	
10%	**S 13 - 14_LoCwSPr**	**S 14 - 15_LoCS**	**S 14 - 15_ LoCwSPr**	**S 15 - 16_ LoCwSPr**	**S 15 - 16_LoCS**
	S 12 - 13_ LoCwSPr	**S 13 - 14_LoCS**			
15%	**S 13 - 14_LoCwSPr**	**S 14 - 15_LoCS**	**S 14 - 15_ LoCwSPr**	**S 15 - 16_ LoCwSPr**	**S 15 - 16_LoCS**
	S 12 - 13_ LoCwSPr	**S 13 - 14_LoCS**	**S 11 - 12_ LoCwSPr**		
20%	**S 13 - 14_LoCwSPr**	**S 14 - 15_LoCS**	**S 14 - 15_ LoCwSPr**	**S 15 - 16_ LoCwSPr**	**S 15 - 16_LoCS**
	S 12 - 13_ LoCwSPr	**S 13 - 14_LoCS**	**S 11 - 12_ LoCwSPr**	**S 11 - 12_LoCS**	**S 12 - 13_LoCS**

Average Travel Time					
Treshold	**Scenario**				
3%	**S 13 - 14_LoCwSPr**	S 14 - 15_LoCS	S 14 - 15_ LoCwSPr	S 15 - 16_ LoCwSPr	S 13 - 14_LoCS
	S 15 - 16_LoCS				
5%	**S 13 - 14_LoCwSPr**	**S 14 - 15_LoCS**	**S 14 - 15_ LoCwSPr**	**S 15 - 16_ LoCwSPr**	S 13 - 14_LoCS
	S 15 - 16_LoCS	S 12 - 13_ LoCwSPr	S 11 - 12_LoCS		
10%	**S 13 - 14_LoCwSPr**	**S 14 - 15_LoCS**	**S 14 - 15_ LoCwSPr**	**S 15 - 16_ LoCwSPr**	**S 13 - 14_LoCS**
	S 15 - 16_LoCS	**S 12 - 13_ LoCwSPr**	S 9 - 10_LoCS	S 11 - 12_ LoCwSPr	S 11 - 12_LoCS
	S 12 - 13_LoCS				
15%	**S 13 - 14_LoCwSPr**	**S 14 - 15_LoCS**	**S 14 - 15_ LoCwSPr**	**S 15 - 16_ LoCwSPr**	**S 13 - 14_LoCS**
	S 15 - 16_LoCS	**S 12 - 13_ LoCwSPr**	S 9 - 10_LoCS	S 10 - 11_ LoCwSPr	**S 11 - 12_ LoCwSPr**
	S 11 - 12_LoCS	S 12 - 13_LoCS	Field		
20%	**S 13 - 14_LoCwSPr**	**S 14 - 15_LoCS**	**S 14 - 15_ LoCwSPr**	**S 15 - 16_ LoCwSPr**	**S 13 - 14_LoCS**
	S 15 - 16_LoCS	**S 12 - 13_ LoCwSPr**	S 9 - 10_LoCS	S 10 - 11_ LoCwSPr	**S 11 - 12_ LoCwSPr**
	S 11 - 12_LoCS	S 10 - 11_LoCS	**S 12 - 13_LoCS**	Field	S 13 - 14_NoCSOPs

6.2 Progression Level Evaluation

To find out the right performance evaluation scale, the progression level evaluation was designed in comparison with the network level evaluation as the definition of resonant cycles mentioned that a resonant cycle should provide good performance for the two-way progression. The performance measures used in this evaluation were similar to network level evaluation but only the main-street through movements were taken into account. As the study network was a two-way arterial road, progression level evaluation was respectively analyzed the performance of average delay, average stops, PI value, and average travel time for eastbound and westbound.

6.2.1 Evaluation of the Average Delay

Figure 6.9 shows the average delay (sec/veh) of eastbound progression and Figure 6.10 shows the average delay (sec/veh) of westbound progression. Same as network level evaluations, all highlighted lines and markers represent scenarios which have a minimum average delay for a certain hour. Contrary to network level evaluation, performance between each scenario provides more distinctive results (as seen in Figure 6.9).

For eastbound progression, the optimized signal timing plan “NoCSOPs 13 – 14” was the best one for the period from 9:00 to 10:00. From 10:00 to 11:00, “NoCSOPs 14 – 15” became the best signal timing plan. Then from 11:00 to 12:00, the signal timing plan which provided the lowest average delay for eastbound progression was “NoCSOPs 9 – 10”. Finally, the optimized signal timing plan “NoCSOPs 12 – 13” dominantly acted as the best plan for the rest of hours (from 12:00 to 16:00).

The results are different when it comes to the westbound direction. From 9:00 to 10:00, 11:00 to 12:00, and 13:00 to 14:00, the optimized signal timing plan “NoCSOPs 9 – 10” consistently provided the lowest average delay for those 3 hours. Then from 10:00 to 11:00 and 14:00 to 15:00, the best signal timing plan was one for “NoCSOPs 14 – 15”. For the period 12:00 to 13:00, scenario “NoCSO 11 – 12” was the best one and for the period from 13:00 to 14:00, scenario developed for the same hours “NoCSO 13 – 14” was better than all other signal timing plans.

It can be concluded that none of these 36 signal timing plans consistently perform best for all 7 hours, when average delay for progressed movements for either eastbound or westbound direction. All of the best signal timing plans for eastbound were based on optimization of all signal timings and phasing and scenario “NoCSOPs 12 – 13” which developed for period between 12:00 – 13:00, can be identified as a resonant signal timing plan with the lowest average delay for 4 hours. For westbound, the optimal signal timing plan for period between 9:00 and 10:00 is identified as a resonant signal timing plan, as it performed best for a 3-hour period.

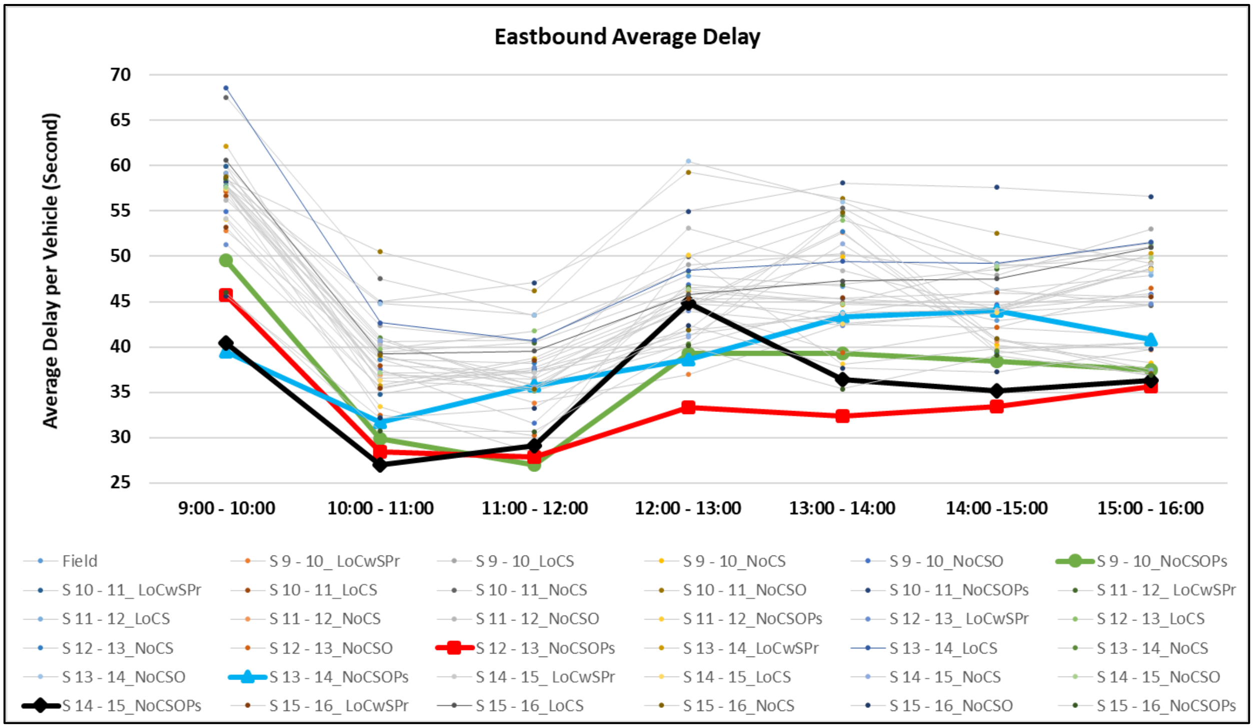


Figure 6.9 Average Delay for EB Progression

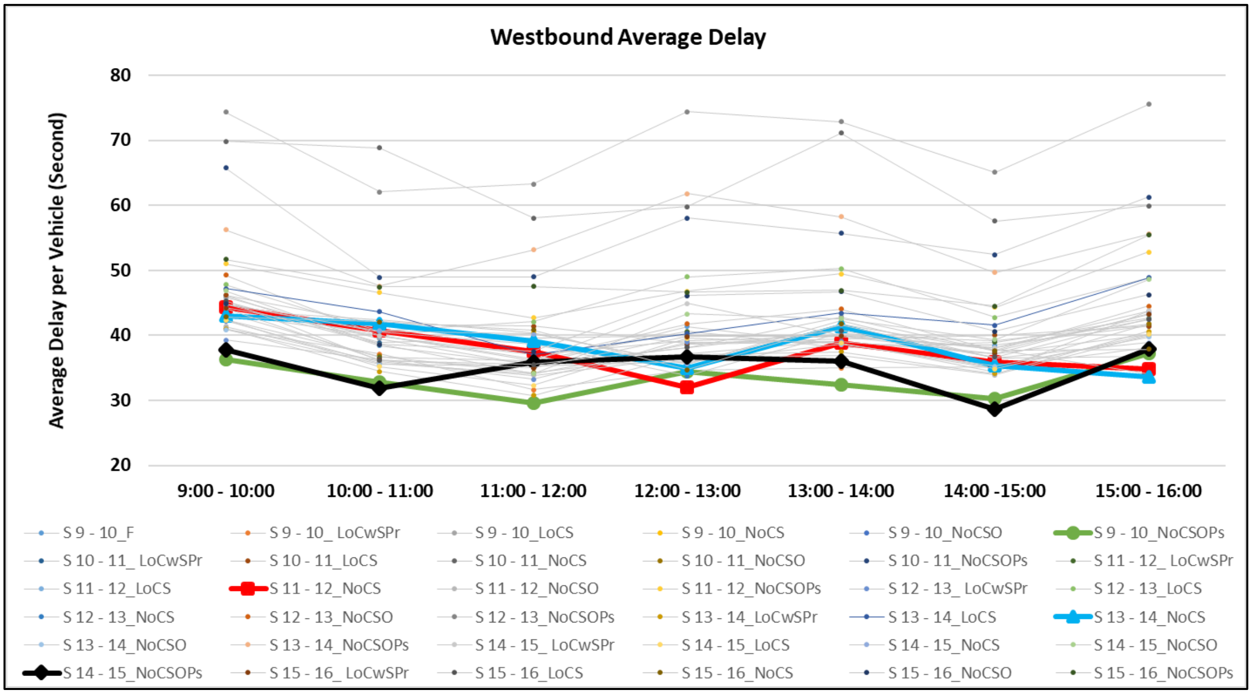


Figure 6.10 Average Delay for WB Progression

A further investigation was done to find out which signal timing plan has better performance than the other plans, and all 36 scenarios were ranked for both eastbound and westbound progressions, based on each hour's average delay (See Appendix B). Table 6-10 and Table 6-11 respectively represent the best 20 signal timing plans which provided low average delay for all 7 hours in two directions. A series of thresholds were set at 3%, 5%, 10%, 15%, and 20%, of each hour's lowest average stops, to explore if there would be a resonant signal timing plan whose performance falls within an acceptable threshold. Scenarios which result in average stops that fall within each threshold, for all 7 hours, were listed in Table 6-10 (Eastbound) and Table 6-11 (Westbound).

Table 6-10 Best Scenarios of EB Progression - Average Delay

Rank	Scenario	9:00 - 10:00	10:00 - 11:00	11:00 - 12:00	12:00 - 13:00	13:00 - 14:00	14:00 -15:00	15:00 - 16:00
1	S 12 - 13_NoCSOPs	45.68	28.45	27.85	33.36	32.34	33.41	35.59
2	S 15 - 16_NoCSOPs	45.99	30.72	30.63	40.11	35.38	39.08	36.89
3	S 9 - 10_NoCSOPs	49.52	29.82	26.95	39.27	39.29	38.43	37.46
4	S 14 - 15_NoCSOPs	40.46	27.02	29.12	44.87	36.39	35.10	36.26
5	S 15 - 16_NoCSO	45.60	32.15	33.26	42.39	37.66	37.25	39.76
6	S 13 - 14_NoCSOPs	39.44	31.67	35.76	38.66	43.35	43.98	40.83
7	S 9 - 10_ LoCwSPr	52.82	38.63	33.85	36.96	42.46	42.15	41.27
8	S 11 - 12_NoCSOPs	54.05	33.42	28.39	50.19	38.12	39.78	40.44
9	S 12 - 13_NoCSO	57.21	32.48	30.25	44.36	39.37	42.14	46.45
10	S 12 - 13_ LoCwSPr	51.34	35.54	37.74	43.96	42.38	43.84	44.73
11	S 11 - 12_NoCS	57.46	36.91	36.42	44.41	52.60	40.63	39.68
12	S 9 - 10_NoCS	57.37	38.94	35.86	44.55	49.95	40.24	38.25
13	S 14 - 15_LoCS	57.43	36.28	35.44	45.61	42.58	43.80	48.63
14	S 13 - 14_NoCS	59.20	41.06	35.10	40.38	54.57	39.61	36.85
15	S 10 - 11_LoCS	56.65	37.95	37.25	40.13	44.86	44.20	48.59
16	S 15 - 16_NoCS	58.76	39.06	35.35	41.85	54.85	40.91	37.10
17	S 14 - 15_ LoCwSPr	54.22	36.52	37.14	44.81	43.71	44.12	49.17
18	S 9 - 10_NoCSO	54.94	37.51	31.55	46.91	45.31	44.64	45.85
19	S 11 - 12_LoCS	57.54	37.08	37.26	41.31	43.68	46.25	47.90
20	S 14 - 15_NoCS	59.22	40.74	35.67	41.11	51.38	40.93	37.46

Table 6-11 Best Scenarios of WB Progression - Average Delay

Rank	Scenario	9:00 - 10:00	10:00 - 11:00	11:00 - 12:00	12:00 - 13:00	13:00 - 14:00	14:00 -15:00	15:00 - 16:00
1	S 9 - 10_NoCSOPs	36.35	32.79	29.58	34.49	32.44	30.26	37.25
2	S 14 - 15_NoCSOPs	37.74	31.90	35.88	36.68	36.03	28.61	37.86
3	S 9 - 10_ LoCwSPr	40.96	37.14	31.62	34.65	35.00	35.19	38.13
4	S 13 - 14_LoCwSPr	41.02	34.45	30.82	37.08	37.48	34.16	40.62
5	S 11 - 12_NoCSO	41.37	35.92	33.88	36.61	36.92	33.95	39.98
6	S 13 - 14_NoCSO	40.90	35.52	35.35	35.92	38.65	35.30	39.76
7	S 14 - 15_LoCS	42.35	35.18	32.34	39.55	38.82	34.88	40.13
8	S 12 - 13_ LoCwSPr	39.29	36.28	33.26	38.93	39.11	37.19	40.14
9	S 9 - 10_NoCSO	42.26	35.76	34.15	38.64	39.05	34.40	43.71
10	S 10 - 11_NoCSO	42.39	36.79	34.24	37.21	39.15	35.04	41.78
11	S 11 - 12_NoCS	44.37	40.75	37.50	32.07	38.90	35.84	34.82
12	S 13 - 14_NoCS	43.08	41.76	39.17	34.99	41.46	35.34	33.67
13	S 12 - 13_NoCS	44.85	40.60	38.71	33.79	40.44	37.86	34.04
14	S 15 - 16_ LoCwSPr	44.17	36.30	35.02	39.82	39.90	37.25	43.33
15	S 15 - 16_LoCS	45.30	36.15	35.56	38.16	40.77	36.66	42.49
16	S 11 - 12_ LoCwSPr	43.55	36.64	36.12	40.60	38.16	38.98	42.67
17	S 9 - 10_NoCS	43.84	42.40	40.43	35.57	42.27	36.50	36.83
18	S 15 - 16_NoCS	42.87	42.10	40.85	34.71	41.79	37.70	37.90
19	S 14 - 15_NoCS	44.82	40.73	40.22	35.71	41.66	36.57	38.87
20	Field	46.14	38.39	35.51	41.40	38.64	38.49	41.42

Table 6-12 Optimal Scenarios for Different Thresholds - EB Average Delay

Treshold	Scenario
3%	NA
5%	NA
10%	NA
15%	NA
20%	S 12 - 13_NoCSOPs

Table 6-13 Optimal Scenarios for Different Thresholds - WB Average Delay

Treshold	Scenario	
3%	NA	
5%	NA	
10%	NA	
15%	S 9 - 10_NoCSOPs	S 11 - 12_NoCSO

6.2.2 Evaluation of the Average Stops

Figure 6.11 and 6.12 respectively show all scenarios simulation results of average stops (veh/stop) for eastbound and westbound direction for under the progression level evaluation.

It is noticeable for the eastbound direction, that the signal timing plan “NoCSOPs 14 – 15” was the best one for period between 9:00 and 10:00. From 10:00 to 11:00 and 15:00 to 16:00, the plan “NoCSOPs 15 – 16” which developed for 15:00 – 16:00 yielded minimum average stops. From 11:00 to 12:00, the best signal timing plan was “NoCSOPs 11 – 12”, which is expected. Finally, for the remaining 3 hours from 12:00 to 15:00, the optimal plan, whose average stops were lowest among all 36 plans, was the one “NoCSOPs 12 – 13”.

The results became more distinctive for westbound direction, as only two plans stood out. From 9:00 to 10:00 and 14:00 to 16:00, the best signal timing plan was one “NoCSOPs 14 – 15” which developed for 14:00 – 15:00, whereas from 10:00 to 14:00, the plan developed “NoCSOPs 9 – 10” performed better than other signal timing plans.

In general, there was still no single timing plan that could provide the minimal average stops for all 7 hours, for both directions. One thing that should be noted is that all of the best signal timing plans for eastbound and westbound directions were obtained when all of the signal timing and phasing parameters were optimized. Similar to the results from average delay analysis, a plan developed for period between 12:00 – 13:00 (“NoCSOPs 12 – 13”) has potential to be identified as a resonant signal timing plan for eastbound progression as it consistently provides the lowest average delay for 3 hours. Similarly, a plan developed for “9:00 – 10:00” scenario (“NoCSOPs 9 – 10”), is the one identified as resonant plan for the westbound progression, where it was dominant for 4 hours.

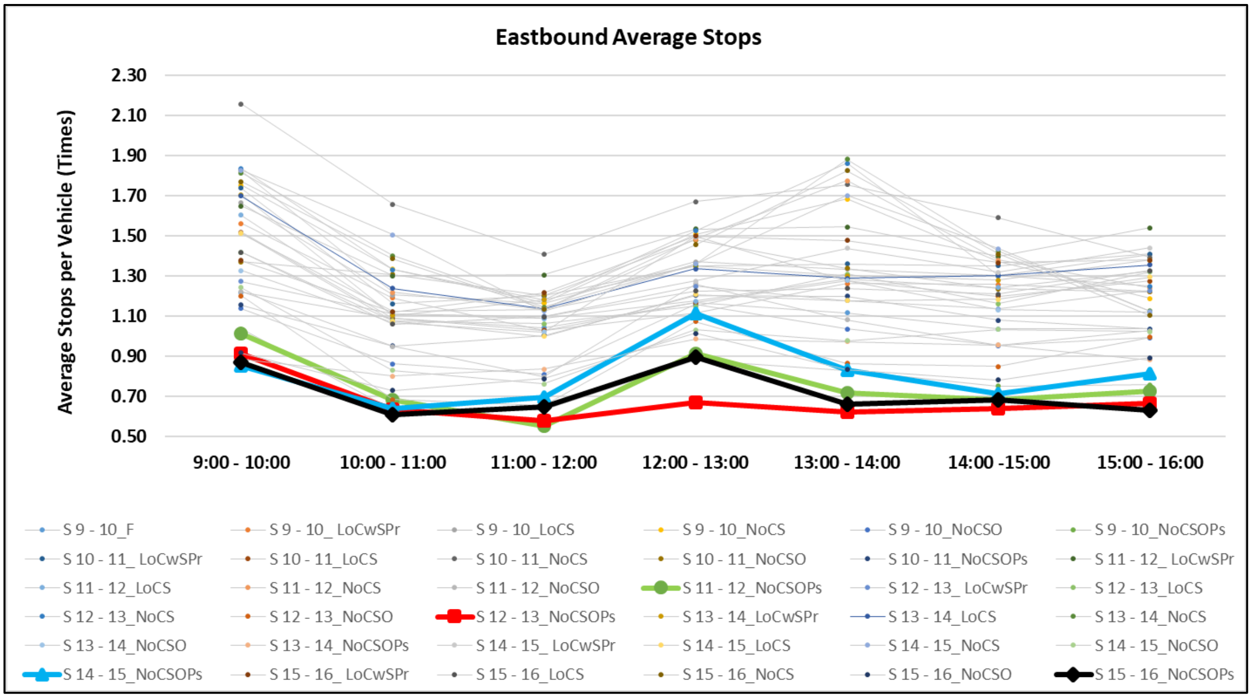


Figure 6.11 Average Stops for EB Progression

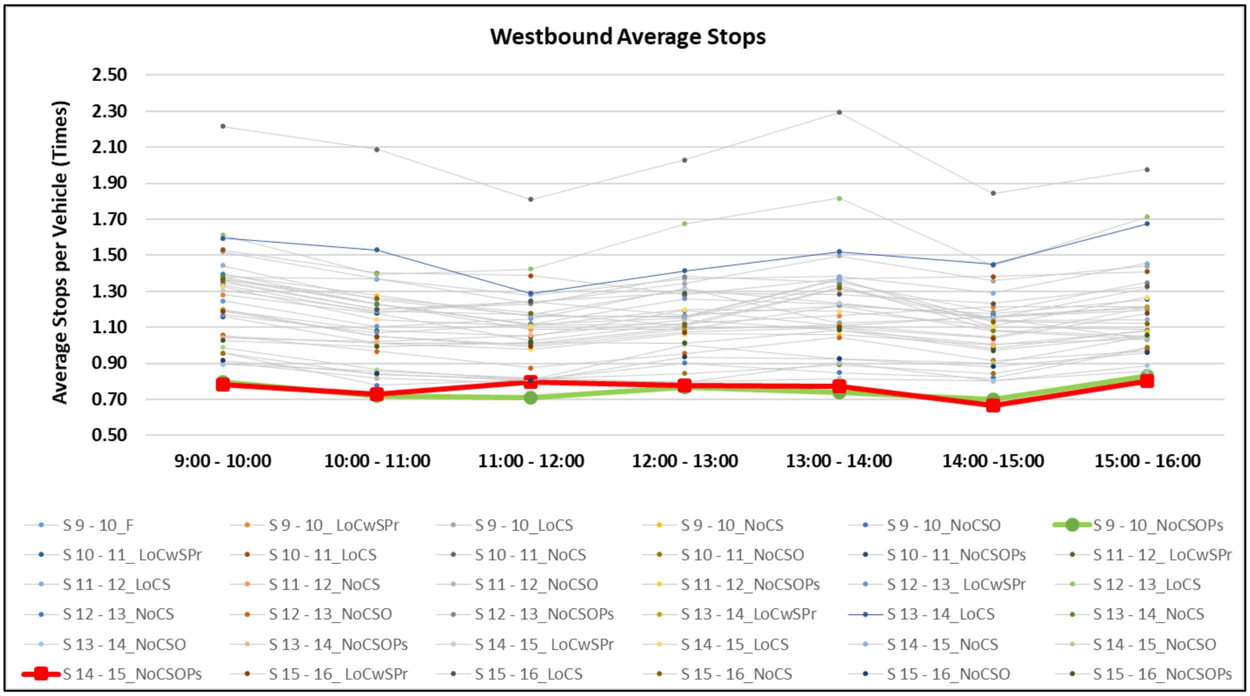


Figure 6.12 Average Stops for WB Progression

To investigate which signal timing plan could provide the best performance among all 36 scenarios for eastbound and westbound directions, such plans were ranked based on the average stops and shown in Appendix B. Table 6-14 and Table 6-15 separately listed each hour's average stops of the best 20 scenarios for two directions, where the highlighted cells represent the lowest average stops for each hour. Similarly to the previous evaluation, 5 different thresholds (3%, 5%, 10%, 15%, and 20%) were applied to the lowest average stops to investigate existence of potential resonant signal timing plan. Table 6-16 and Table 6-17 contain the signal timing plans whose average stops could fit into those thresholds for all of the 7 hours, in eastbound and westbound directions, respectively.

Table 6-14 Best Scenarios of EB Progression - Average Stops

Rank	Scenario	9:00 - 10:00	10:00 - 11:00	11:00 - 12:00	12:00 - 13:00	13:00 - 14:00	14:00 -15:00	15:00 - 16:00
1	S 12 - 13_NoCSOPs	0.92	0.63	0.58	0.67	0.62	0.64	0.67
2	S 15 - 16_NoCSOPs	0.87	0.61	0.65	0.90	0.66	0.68	0.63
3	S 11 - 12_NoCSOPs	1.02	0.68	0.55	0.91	0.72	0.69	0.73
4	S 9 - 10_NoCSOPs	1.04	0.63	0.63	0.88	0.83	0.75	0.76
5	S 14 - 15_NoCSOPs	0.85	0.64	0.70	1.11	0.83	0.71	0.82
6	S 15 - 16_NoCSO	0.92	0.73	0.79	1.01	0.83	0.78	0.89
7	S 13 - 14_NoCSOPs	0.89	0.80	0.84	0.99	0.97	0.96	0.88
8	S 12 - 13_NoCSO	1.20	0.69	0.66	1.07	0.87	0.85	1.00
9	S 14 - 15_NoCSO	1.24	0.83	0.76	1.03	0.98	1.03	1.02
10	S 9 - 10_NoCSO	1.14	0.86	0.81	1.16	1.04	0.95	0.99
11	S 11 - 12_NoCSO	1.22	0.95	0.80	1.26	1.08	0.96	1.03
12	S 10 - 11_NoCSOPs	1.16	0.95	1.00	1.20	1.20	1.08	1.04
13	Field	1.22	1.09	1.04	1.17	1.12	1.04	1.04
14	S 14 - 15_LoCS	1.51	1.08	1.00	1.21	1.18	1.18	1.30
15	S 13 - 14_NoCSO	1.33	1.07	1.02	1.50	1.28	1.13	1.12
16	S 12 - 13_ LoCwSPr	1.27	1.11	1.10	1.25	1.18	1.14	1.23
17	S 10 - 11_LoCS	1.52	1.09	1.03	1.17	1.28	1.20	1.28
18	S 12 - 13_LoCS	1.42	1.08	1.06	1.15	1.31	1.16	1.32
19	S 15 - 16_LoCS	1.42	1.06	1.10	1.23	1.24	1.21	1.33
20	S 9 - 10_ LoCwSPr	1.56	1.19	1.03	1.12	1.26	1.26	1.22

Table 6-15 Best Scenarios of WB Progression - Average Stops

Rank	Scenario	9:00 - 10:00	10:00 - 11:00	11:00 - 12:00	12:00 - 13:00	13:00 - 14:00	14:00 -15:00	15:00 - 16:00
1	S 9 - 10_NoCSOPs	0.80	0.72	0.71	0.77	0.74	0.70	0.83
2	S 14 - 15_NoCSOPs	0.78	0.73	0.80	0.78	0.77	0.67	0.80
3	S 11 - 12_NoCSO	0.91	0.82	0.79	0.80	0.81	0.80	0.86
4	S 13 - 14_NoCSO	0.89	0.86	0.82	0.79	0.91	0.80	0.89
5	S 9 - 10_NoCSO	0.96	0.78	0.81	0.90	0.85	0.82	0.98
6	S 10 - 11_NoCSO	0.96	0.84	0.81	0.85	0.89	0.84	0.99
7	S 15 - 16_NoCSO	0.92	0.85	0.81	0.94	0.93	0.88	0.96
8	S 14 - 15_NoCSO	0.99	0.87	0.81	1.00	0.92	0.90	1.05
9	S 12 - 13_NoCSO	1.06	0.97	0.88	0.96	1.04	0.92	0.97
10	S 15 - 16_NoCSOPs	1.03	0.99	1.02	1.01	1.08	0.97	1.06
11	S 11 - 12_NoCSOPs	1.05	1.01	0.98	1.07	1.06	1.00	1.08
12	S 10 - 11_NoCSOPs	1.16	1.01	1.01	1.10	1.10	0.98	1.08
13	S 13 - 14_NoCSOPs	1.04	1.02	1.06	1.14	1.08	1.01	1.04
14	S 15 - 16_ LoCwSPr	1.19	1.05	0.99	1.07	1.10	1.04	1.18
15	S 13 - 14_LoCwSPr	1.20	1.05	1.00	1.09	1.11	1.05	1.21
16	S 11 - 12_NoCS	1.37	1.23	1.09	1.09	1.22	1.08	1.04
17	S 11 - 12_ LoCwSPr	1.20	1.08	1.05	1.20	1.11	1.16	1.21
18	S 9 - 10_ LoCwSPr	1.28	1.18	1.03	1.12	1.17	1.21	1.21
19	S 12 - 13_ LoCwSPr	1.17	1.07	1.12	1.26	1.23	1.16	1.21
20	S 14 - 15_LoCS	1.33	1.14	1.11	1.20	1.19	1.11	1.27

Table 6-16 Optimal Scenarios Under Different Thresholds - EB Average Stops

Treshold	Scenario
3%	NA
5%	NA
10%	S 12 - 13_NoCSOPs
15%	S 12 - 13_NoCSOPs
20%	S 12 - 13_NoCSOPs

Table 6-17 Optimal Scenarios Under Different Thresholds - WB Average Stops

Treshold	Scenario	
3%	NA	
5%	NA	
10%	S 9 - 10_NoCSOPs	
15%	S 9 - 10_NoCSOPs	S 14 - 15_NoCSOPs
20%	S 9 - 10_NoCSOPs	S 14 - 15_NoCSOPs

6.2.3 Evaluation of the PI Value

The PI value was used as a combination of total delay and stops for the main street through movement vehicles. Figure 6.13 and 6.14 separately showed simulation results of PI value for eastbound progression and westbound progression.

Apparently, for eastbound progression, between 9:00 and 10:00 the signal timing plan “NoCSOPs 13 – 14” performed as the best one. From 10:00 to 11:00, “NoCSOPs 14 – 15” was the signal timing plan which provided the lowest PI value. For the hour from 11:00 to 12:00, the optimal signal timing plan became “Scenario 9:00 – 10:00, network optimization of the cycle length, split, offsets, and phase sequence”. Finally, the scenario “NoCSOPs 12 – 13” kept being the best one for the remaining four hours from 12:00 to 16:00.

For westbound direction, the signal timing plan “NoCSOPs 9 – 10” dominated the hours 9:00 to 10:00, 11:00 to 12:00, and 13:00 to 14:00. During periods between 10:00 and 11:00 as well as 14:00 to 15:00, “NoCSOPs 14 – 15” performed better than any other signal timing plan. The plan developed for “11:00 – 12:00” which used network optimization of the cycle length and split owned the lowest PI value during 11:00 to 12:00. For the last hour from 15:00 to 16:00, the optimal scenario became to “NoCS 13 – 14”.

Compared with the results of average delay evaluation, it can be concluded that these two kinds of evaluations have the same pattern in results. Although there was no signal timing plan constantly offering the lowest PI value for the whole 7 hours in either eastbound or westbound, . All of the best signal timing plans for eastbound were based on optimization of all signal timings and phasing and one developed for period between “12:00 – 13:00” , can be identified as a resonant signal timing plan with the lowest average delay for 4 hours. For westbound, the optimal signal timing plan for period between 9:00 and 10:00 which also optimized all signal timings and phasing parameters is identified as a resonant signal timing plan, as it performed best for a 3-hour period.

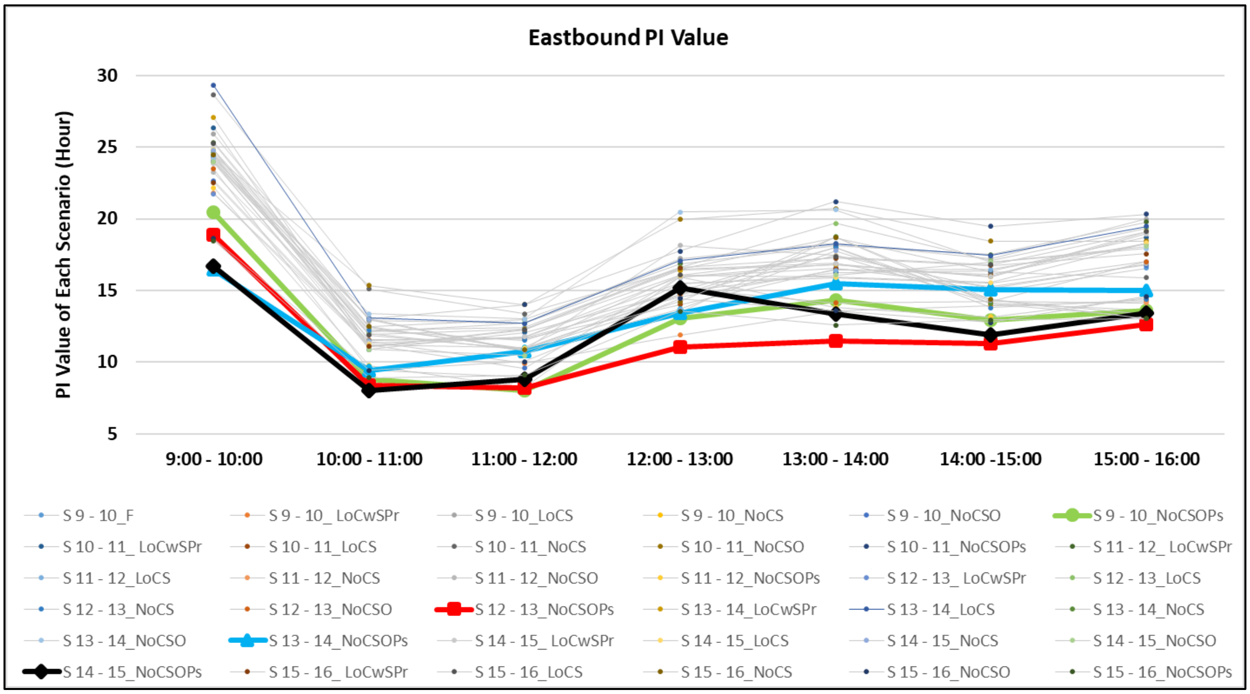


Figure 6.13 PI Value for EB Progression

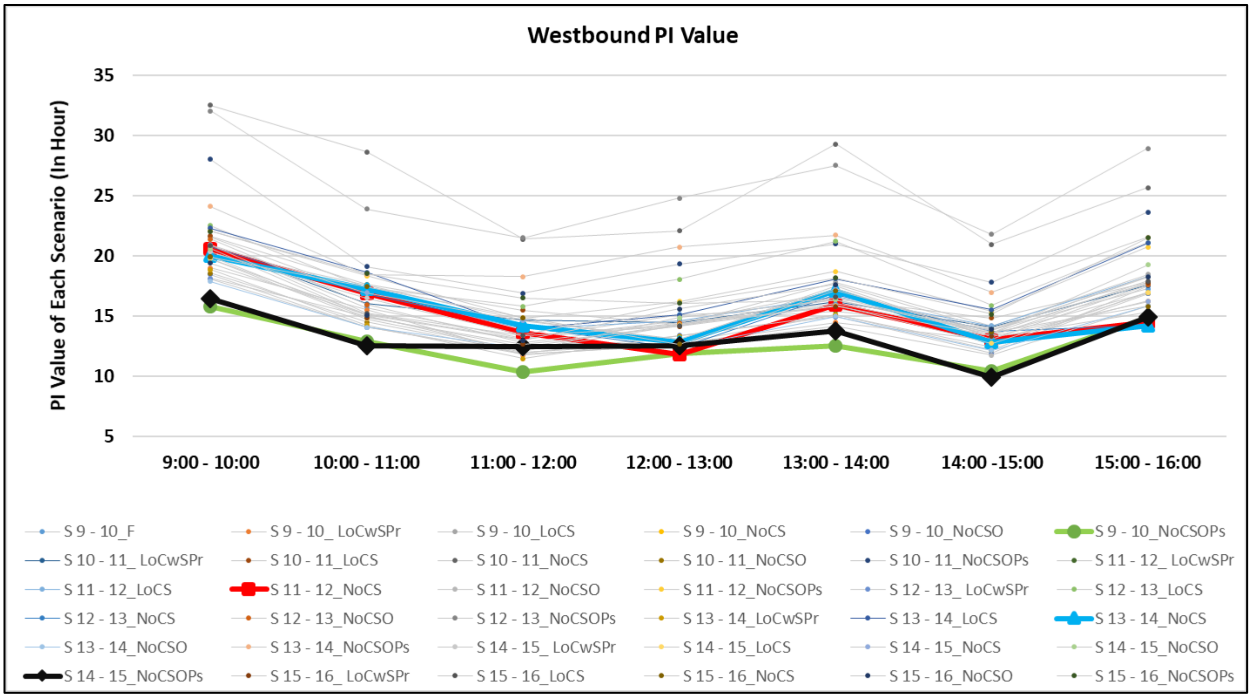


Figure 6.14 PI Value for WB Progression

In spite of the fact that the results of PI value evaluation for both directions have the same pattern as the results of average delay evaluation, ranking all signal timing plans individually for eastbound and westbound is still needed to find out which signal timing plan could provide the best performance among all 36 scenarios (See Appendix B). Table 6-18 represented the best 20 scenarios for eastbound progression which owned low PI value during all 7 hours while Table 6-19 was presented for the westbound. All highlighted cells illustrated the lowest PI value for each hour. Different thresholds were also set for each bound at 3%, 5%, 10%, 15%, and 20% of each hour's lowest PI value to explore the potential resonant signal timing plan. Scenarios which owned the PI value that fall within each threshold for all the study period were listed in Table 6-20 (Eastbound) and Table 6-21 (Westbound).

Table 6-18 Best Scenarios of EB Progression - PI Value

Rank	Scenario	9:00 - 10:00	10:00 - 11:00	11:00 - 12:00	12:00 - 13:00	13:00 - 14:00	14:00 -15:00	15:00 - 16:00
1	S 12 - 13_NoCSOPs	18.87	8.37	8.21	11.04	11.46	11.30	12.64
2	S 15 - 16_NoCSOPs	18.46	8.93	9.09	13.56	12.59	12.96	13.05
3	S 9 - 10_NoCSOPs	20.44	8.81	8.01	13.07	14.31	12.94	13.62
4	S 14 - 15_NoCSOPs	16.71	8.05	8.82	15.17	13.38	11.89	13.40
5	S 15 - 16_NoCSO	18.61	9.44	10.05	14.43	13.58	12.76	14.58
6	S 9 - 10_ LoCwSPr	21.78	11.46	9.91	11.90	13.59	13.96	14.26
7	S 13 - 14_NoCSOPs	16.48	9.41	10.78	13.41	15.49	15.06	15.03
8	S 11 - 12_NoCSOPs	22.18	9.78	8.26	15.97	13.84	13.16	14.49
9	S 12 - 13_NoCSO	23.48	9.47	8.99	15.16	14.14	14.27	17.02
10	S 9 - 10_NoCSO	22.65	11.20	9.58	15.93	16.57	15.26	16.78
11	S 12 - 13_ LoCwSPr	21.76	11.16	11.78	15.53	15.86	15.49	17.03
12	S 9 - 10_NoCS	23.94	12.40	10.95	14.70	17.45	14.10	13.67
13	S 11 - 12_NoCS	24.22	11.88	10.89	14.73	17.99	14.24	14.15
14	S 13 - 14_NoCS	24.62	12.99	10.72	13.43	18.74	14.07	13.16
15	S 14 - 15_NoCS	24.78	13.03	10.80	13.70	17.79	14.36	13.31
16	S 14 - 15_NoCSO	24.00	10.90	10.46	15.46	16.08	16.96	18.07
17	S 12 - 13_NoCS	24.34	12.22	11.53	14.97	18.01	13.80	14.38
18	S 15 - 16_NoCS	24.49	12.51	10.89	14.22	18.71	14.37	13.05
19	S 10 - 11_LoCS	24.42	11.55	11.64	14.00	16.50	16.10	18.31
20	S 11 - 12_NoCSO	23.24	12.03	10.86	18.15	17.43	15.13	16.88

Table 6-19 Best Scenarios of WB Progression - PI Value

Rank	Scenario	9:00 - 10:00	10:00 - 11:00	11:00 - 12:00	12:00 - 13:00	13:00 - 14:00	14:00 -15:00	15:00 - 16:00
1	S 9 - 10_NoCSOPs	15.81	12.91	10.35	11.91	12.51	10.46	14.83
2	S 14 - 15_NoCSOPs	16.47	12.57	12.45	12.51	13.80	9.92	14.96
3	S 11 - 12_NoCSO	18.11	14.12	11.87	12.56	14.16	11.76	15.87
4	S 13 - 14_NoCSO	17.88	14.09	12.38	12.34	14.98	12.17	15.87
5	S 10 - 11_NoCSO	18.58	14.50	12.02	12.82	15.10	12.20	16.85
6	S 9 - 10_NoCSO	18.48	14.07	11.94	13.39	14.96	11.91	17.51
7	S 13 - 14_LoCwSPr	18.88	14.27	11.47	13.34	15.12	12.41	17.00
8	S 9 - 10_ LoCwSPr	18.99	15.54	11.75	12.72	14.48	13.05	16.25
9	S 14 - 15_LoCS	19.76	14.78	12.16	14.26	15.88	12.76	16.94
10	S 12 - 13_ LoCwSPr	18.15	14.98	12.44	14.29	16.02	13.49	16.89
11	S 11 - 12_NoCS	20.55	16.89	13.66	11.82	15.96	13.01	14.53
12	S 15 - 16_ LoCwSPr	19.95	14.87	12.68	14.14	15.82	13.37	17.75
13	S 13 - 14_NoCS	20.03	17.28	14.20	12.84	17.14	12.81	14.20
14	S 12 - 13_NoCS	20.78	16.86	14.08	12.39	16.79	13.71	14.26
15	S 11 - 12_ LoCwSPr	19.73	15.17	13.10	14.61	15.41	14.00	17.76
16	S 14 - 15_NoCSO	20.59	15.04	12.07	14.87	16.36	13.61	19.25
17	S 15 - 16_NoCS	19.93	17.45	14.87	12.65	17.13	13.68	15.82
18	S 9 - 10_NoCS	20.37	17.58	14.71	13.03	17.48	13.21	15.35
19	Field	20.91	15.72	13.18	15.13	15.60	13.89	17.27
20	S 12 - 13_NoCSO	21.39	15.98	12.82	14.44	17.08	13.09	17.60

Table 6-20 Optimal Scenarios Under Different Thresholds - EB PI Value

Treshold	Scenario
3%	NA
5%	NA
10%	NA
15%	S 12 - 13_NoCSOPs
20%	S 12 - 13_NoCSOPs

Table 6-21 Optimal Scenarios Under Different Thresholds - WB PI Value

Treshold	Scenario	
3%	NA	
5%	NA	
10%	S 9 - 10_NoCSOPs	
15%	S 9 - 10_NoCSOPs	
20%	S 9 - 10_NoCSOPs	S 11 - 12_NoCSO

6.2.4 Evaluation of the Average Travel Time

As mentioned before, the average travel time for the progression level evaluation was directly accessed from the PTV Vissim simulation results list. It measured the average time a vehicle spends on traveling from the first intersection to the last one. Figure 6.15 shows the results of eastbound progression average travel time evaluation while Figure 6.16 is for westbound progression.

It is noticeable for the eastbound direction, the optimal signal timing plan during 9:00 to 11:00 was “NoCSOPs 13 – 14”. From 11:00 to 12:00, the best one still developed for “13:00–14:00”, but the optimization methodology changed to network optimization of the cycle length and split. The signal timing plan “NoCS 15 – 16” yielded the shortest average travel time for the period 12:00 to 13:00 and 15:00 to 16:00. And for the remaining two hours from 13:00 to 15:00, scenario “NoCSOPs 14 – 15” performed better than any other.

The situation was much more complex for westbound progression. It is observed that for each hour, there was a particular optimal signal timing plan and none of them was the same. From 9:00 to 10:00, the best one was “LoCwSPr 12 – 13”. Between 10:00 and 11:00, “LoCS 14 – 15” became the optimal one. Then for the hour 11:00 to 12:00, “LoCwSPr 13 – 14” performed better than the others. “NoCS 11– 12” yielded the lowest average travel time for from 12:00 to 13:00. During the period from 13:00 to 14:00, the best signal timing plan was still developed for “11:00 – 12:00”, but the optimization methodology was local optimization for cycle length and split. Throughout the hour between 14:00 and 15:00, scenario developed for “9:00 – 10:00” which used local optimization for cycle length with increasing split proportionally provided the lowest average travel time. And for the last hour from 15:00 to 16:00, the signal timing plan “NoCS 13 – 14” was the best one among all 36 signal timing plans.

In common with previous evaluations, there was no single scenario for both eastbound and westbound to provide the shortest average travel time throughout all 7 hours. All the best signal timing plans for eastbound progression were based on network optimization 2 hours was the longest period a single signal timing plan could perform as the best. For westbound progression, there was no apparent regulation of the optimal signal timing plans as they discretely distributed in different scenarios and optimization types.

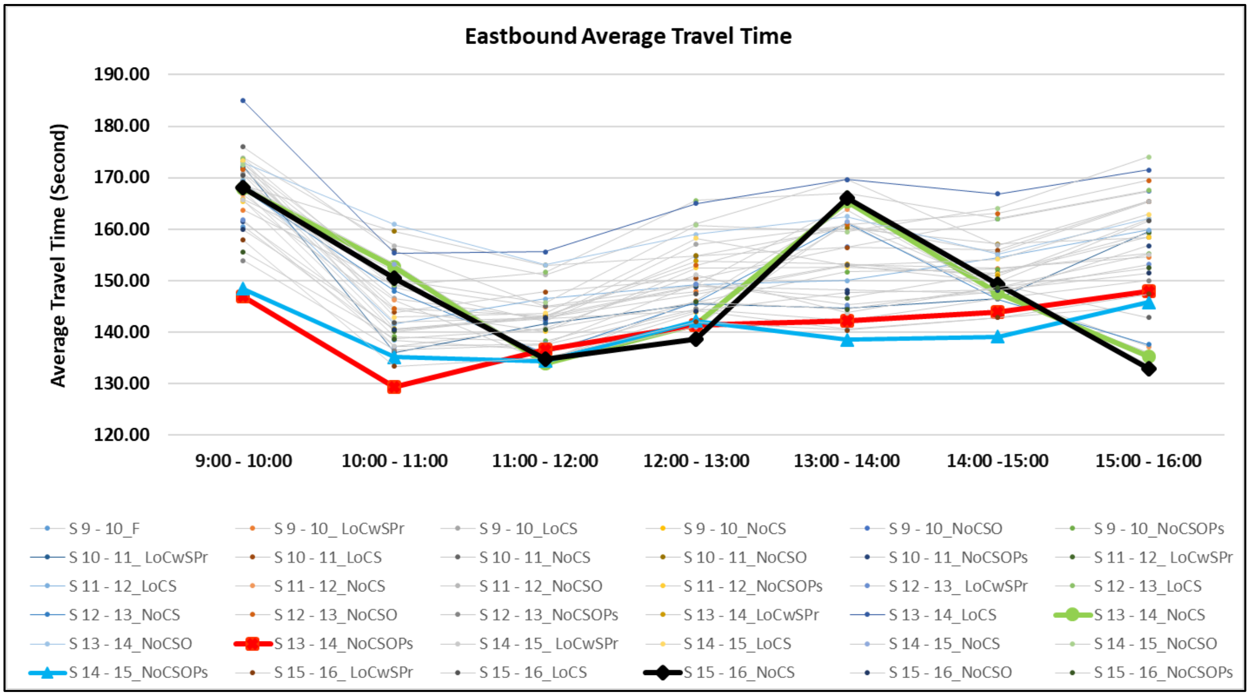


Figure 6.15 Average Travel Time for EB Progression

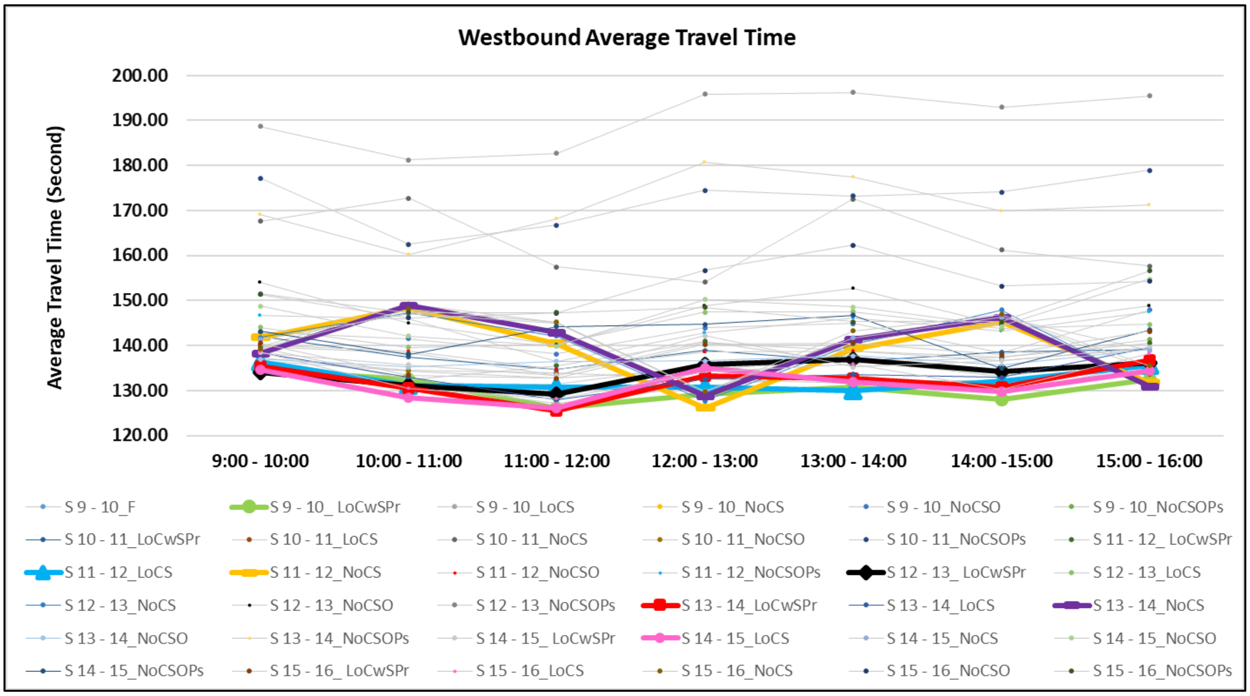


Figure 6.16 Average Travel Time for WB Progression

Although none of those 36 signal timing plans performed consistently well for all 7 hours, all scenarios were ranked to provide a clear view of which signal timing plans worked better than others by providing a shorter average travel time (See Appendix B). Table 6-22 and Table 6-23 independently shows the 20 optimal scenarios for eastbound and westbound based on the average travel time evaluation. All the highlighted cells represented the minimal average travel time for each hour. Similar to previous evaluation, 5 different level of thresholds from 3% to 20% of each hour’s lowest average travel time were designed for the exploration of potential resonant signal timing plans. Scenarios which consistently provide average travel time within a certain threshold were listed in Table 6-24 for eastbound and Table 6-25 for westbound.

Table 6-22 Best Scenarios of EB Progression - Average Travel Time

Rank	Scenario	9:00 - 10:00	10:00 - 11:00	11:00 - 12:00	12:00 - 13:00	13:00 - 14:00	14:00 -15:00	15:00 - 16:00
1	S 14 - 15_NoCSOPs	148.42	135.11	134.42	142.15	138.57	139.14	145.81
2	S 13 - 14_NoCSOPs	146.87	129.44	136.56	141.44	142.28	143.98	147.92
3	S 15 - 16_ LoCwSPr	157.92	133.37	134.97	142.00	140.40	142.89	147.45
4	Field	160.53	138.47	136.61	144.11	140.59	142.84	145.11
5	S 12 - 13_NoCSOPs	153.92	136.52	137.64	144.55	142.32	146.50	150.05
6	S 15 - 16_NoCSOPs	155.57	138.70	140.58	145.93	144.43	148.64	152.48
7	S 15 - 16_NoCSO	159.90	140.59	142.64	144.10	147.63	148.15	151.45
8	S 12 - 13_ LoCwSPr	161.75	137.20	137.78	149.34	145.27	147.80	153.13
9	S 9 - 10_NoCS	165.86	151.92	134.76	143.85	160.94	147.18	136.09
10	S 11 - 12_NoCS	166.66	146.26	134.35	146.12	163.84	147.56	137.21
11	S 12 - 13_NoCS	167.73	148.00	135.85	145.78	161.30	146.36	137.59
12	S 14 - 15_ LoCwSPr	165.70	137.29	140.84	151.15	143.75	148.74	155.07
13	S 10 - 11_ LoCwSPr	172.17	136.05	141.69	145.54	144.72	146.52	159.59
14	S 13 - 14_NoCS	167.84	152.62	133.90	141.61	165.44	147.62	135.32
15	S 10 - 11_NoCSOPs	161.49	140.50	142.83	148.81	148.16	147.62	156.75
16	S 14 - 15_NoCS	168.60	153.25	134.33	141.09	161.44	148.85	133.72
17	S 15 - 16_NoCS	168.05	150.45	134.74	138.67	166.03	149.26	132.97
18	S 9 - 10_NoCSOPs	167.53	139.11	138.26	145.87	151.74	152.19	155.26
19	S 11 - 12_NoCSOPs	165.40	144.52	140.16	152.46	152.63	151.37	158.51
20	S 11 - 12_ LoCwSPr	169.41	140.11	143.09	149.13	146.61	151.51	159.26

Table 6-23 Best Scenarios of WB Progression - Average Travel Time

Rank	Scenario	9:00 - 10:00	10:00 - 11:00	11:00 - 12:00	12:00 - 13:00	13:00 - 14:00	14:00 -15:00	15:00 - 16:00
1	S 9 - 10_ LoCwSPr	134.57	132.42	126.16	129.29	130.68	128.03	132.51
2	S 14 - 15_LoCS	134.71	128.41	126.16	134.99	131.98	129.75	134.34
3	S 11 - 12_LoCS	136.28	131.11	130.70	130.69	130.01	132.15	135.66
4	S 13 - 14_LoCwSPr	135.30	130.61	125.58	133.31	132.72	130.82	136.77
5	S 9 - 10_LoCS	136.35	131.16	127.19	131.05	133.57	129.39	135.93
6	S 10 - 11_LoCS	137.26	134.47	133.86	132.65	131.68	130.35	133.74
7	Field	136.83	131.60	131.36	135.74	132.18	132.16	136.06
8	S 15 - 16_LoCS	138.64	130.38	128.14	134.15	135.95	130.26	138.19
9	S 12 - 13_ LoCwSPr	134.11	131.10	129.16	135.88	136.87	134.24	136.08
10	S 13 - 14_LoCS	138.45	133.05	127.97	132.57	133.56	132.90	139.47
11	S 10 - 11_NoCSO	136.63	134.36	132.75	134.69	136.87	133.24	136.81
12	S 13 - 14_NoCSO	137.03	135.21	136.47	136.57	137.77	135.63	139.19
13	S 14 - 15_ LoCwSPr	138.46	135.75	133.38	142.21	135.29	136.73	139.57
14	S 11 - 12_ LoCwSPr	139.63	132.35	135.53	140.94	136.07	137.37	140.57
15	S 13 - 14_NoCS	138.29	148.89	142.95	128.73	141.43	146.25	131.02
16	S 11 - 12_NoCSO	140.07	138.86	134.75	138.63	138.72	136.69	139.38
17	S 11 - 12_NoCS	141.73	148.37	140.34	126.16	139.26	145.28	131.65
18	S 10 - 11_LoCwSPr	142.12	137.51	134.64	138.91	136.38	138.50	139.17
19	S 15 - 16_ LoCwSPr	140.56	133.41	132.72	140.29	140.54	137.93	143.20
20	S 9 - 10_NoCSOPs	139.77	138.30	133.45	140.64	138.87	137.40	141.37

Table 6-24 Optimal Scenarios Under Different Thresholds - EB Average Travel Time

Threshold	Scenario				
3%	NA				
5%	NA				
10%	S 14 - 15_NoCSOPs	Field			
15%	S 14 - 15_NoCSOPs	S 13 - 14_NoCSOPs	S 15 - 16_ LoCwSPr	Field	S 12 - 13_NoCSOPs
	S 15 - 16_NoCSOPs	S 15 - 16_NoCSO			
20%	S 14 - 15_NoCSOPs	S 13 - 14_NoCSOPs	S 15 - 16_ LoCwSPr	Field	S 12 - 13_NoCSOPs
	S 15 - 16_NoCSOPs	S 15 - 16_NoCSO	S 12 - 13_ LoCwSPr	S 9 - 10_NoCS	S 11 - 12_NoCS
	S 12 - 13_NoCS	S 14 - 15_ LoCwSPr			

Table 6-25 Optimal Scenarios Under Different Thresholds - WB Average Travel Time

Threshold	Scenario				
3%	NA				
5%	S 9 - 10_ LoCwSPr	S 11 - 12_LoCS	S 9 - 10_LoCS		
10%	S 9 - 10_ LoCwSPr	S 14 - 15_LoCS	S 11 - 12_LoCS	S 13 - 14_LoCwSPr	S 9 - 10_LoCS
	S 10 - 11_LoCS	Field	S 15 - 16_LoCS	S 12 - 13_ LoCwSPr	S 13 - 14_LoCS
	S 10 - 11_NoCSO	S 13 - 14_NoCSO	S 11 - 12_NoCSO		
15%	S 9 - 10_ LoCwSPr	S 14 - 15_LoCS	S 11 - 12_LoCS	S 13 - 14_LoCwSPr	S 9 - 10_LoCS
	S 10 - 11_LoCS	Field	S 15 - 16_LoCS	S 12 - 13_ LoCwSPr	S 13 - 14_LoCS
	S 10 - 11_NoCSO	S 13 - 14_NoCSO	S 14 - 15_ LoCwSPr	S 11 - 12_ LoCwSPr	S 11 - 12_NoCSO
	S 10 - 11_LoCwSPr	S 15 - 16_ LoCwSPr	S 9 - 10_NoCSOPs		
20%	S 9 - 10_ LoCwSPr	S 14 - 15_LoCS	S 11 - 12_LoCS	S 13 - 14_LoCwSPr	S 9 - 10_LoCS
	S 10 - 11_LoCS	Field	S 15 - 16_LoCS	S 12 - 13_ LoCwSPr	S 13 - 14_LoCS
	S 10 - 11_NoCSO	S 13 - 14_NoCSO	S 14 - 15_ LoCwSPr	S 11 - 12_ LoCwSPr	S 13 - 14_NoCS
	S 11 - 12_NoCSO	S 11 - 12_NoCS	S 10 - 11_LoCwSPr	S 15 - 16_ LoCwSPr	S 9 - 10_NoCSOPs

6.2.5 Summary Analysis

In summary, although there was no a single signal timing plan (which could be identified as a resonant plan because it performed as the best one for all of the 7 hours) the optimal signal timing plans developed for progressed movements (under all performance measures, except average stops) were significantly distinctive from those that were optimal on the network level. While the potential resonant signal timing plans for network level were all based on local optimizations (does not include optimization of offsets and phase sequence), for the analysis for progression movements show that all of the plans identified as resonant benefit from network optimization.

According to the results of the evaluations of average delays, stops, and PI values, the signal timing plan developed for period between 12:00 – 13:00 (when all signal timing and phasing parameters are optimized) provided consistently best performance for 3 or 4 hours under those performance measures. However, that signal timing plan was not identified as resonant for average travel times as the results show that no signal timing plan performed as the best for more than 2 hours. For westbound progression, the best signal timing plan was one developed for period between 9:00 – 10:00, when again all of the signal timing and phasing parameters were optimized. This plan was the best in terms of average delays, average stops, and PI values and it provided consistent performance for more than 3 hours. Similar to eastbound progression, this resonant signal timing plan (for other performance measures) failed to prove its resonance in terms of the average travel times.

Potential resonant signal timing plans were found under all of the proposed thresholds. Table 6-26 shows scenarios which provided resonantly good performance for all of the 7 hours and for each of the progression level performance measures. It can be concluded that within a 3%

or a 5% threshold, there is no emerging resonant signal timing plan, either for eastbound or westbound direction. When the threshold increases to 10%, two different signal timing plans (one for eastbound, the other for westbound) provide best performance in terms of average stops during all study periods but failed to emerge as resonant in terms of other performance measures. Signal timing plan developed for period between 12:00 – 13:00 ("NoCSOPs 12 – 13"), was found to be resonant for eastbound progression when the thresholds are 15% and 20%. For westbound progression, signal timing plan developed for period between 9:00 – 10:00, when all signal timing and phasing parameters were optimized, is found to be resonant under thresholds of 15% and 20%. Finally signal timing plan developed for period between 11:00 – 12:00 ("NoCSO 11 – 12"), has resonance for a 20% threshold. Although there are many signal timing plans who appeared to be resonant in terms of the average travel times, those were not found to be even near resonant for other types of performance measure, which means that average travel time does not work consistently with other investigated measures.

Table 6-26 Resonant Signal Timing Plans for Different Thresholds – Progression

EB Average Delay	
Treshold	**Scenario**
3%	NA
5%	NA
10%	NA
15%	NA
20%	**S 12 - 13_NoCSOPs**

WB Average Delay		
Treshold	**Scenario**	
3%	NA	
5%	NA	
10%	NA	
15%	**S 9 - 10_NoCSOPs**	
20%	**S 9 - 10_NoCSOPs**	**S 11 - 12_NoCSO**

EB Average Stops	
Treshold	**Scenario**
3%	NA
5%	NA
10%	S 12 - 13_NoCSOPs
15%	**S 12 - 13_NoCSOPs**
20%	**S 12 - 13_NoCSOPs**

WB Average Stops		
Treshold	**Scenario**	
3%	NA	
5%	NA	
10%	**S 9 - 10_NoCSOPs**	
15%	**S 9 - 10_NoCSOPs**	S 14 - 15_NoCSOPs
20%	**S 9 - 10_NoCSOPs**	S 14 - 15_NoCSOPs

EB PI	
Treshold	**Scenario**
3%	NA
5%	NA
10%	NA
15%	**S 12 - 13_NoCSOPs**
20%	**S 12 - 13_NoCSOPs**

WB PI		
Treshold	**Scenario**	
3%	NA	
5%	NA	
10%	**S 9 - 10_NoCSOPs**	
15%	**S 9 - 10_NoCSOPs**	
20%	**S 9 - 10_NoCSOPs**	**S 11 - 12_NoCSO**

EB Average Travel Time					
Threshold	**Scenario**				
3%	NA				
5%	NA				
10%	S 14 - 15_NoCSOPs	Field			
15%	S 14 - 15_NoCSOPs	S 13 - 14_NoCSOPs	S 15 - 16_ LoCwSPr	Field	**S 12 - 13_NoCSOPs**
	S 15 - 16_NoCSOPs	S 15 - 16_NoCSO			
20%	S 14 - 15_NoCSOPs	S 13 - 14_NoCSOPs	S 15 - 16_ LoCwSPr	Field	**S 12 - 13_NoCSOPs**
	S 15 - 16_NoCSOPs	S 15 - 16_NoCSO	S 12 - 13_ LoCwSPr	S 9 - 10_NoCS	S 11 - 12_NoCS
	S 12 - 13_NoCS	S 14 - 15_ LoCwSPr			

WB Average Travel Time					
Threshold	**Scenario**				
3%	NA				
5%	S 9 - 10_ LoCwSPr	S 11 - 12_LoCS	S 9 - 10_LoCS		
10%	S 9 - 10_ LoCwSPr	S 14 - 15_LoCS	S 11 - 12_LoCS	S 13 - 14_LoCwSPr	S 9 - 10_LoCS
	S 10 - 11_LoCS	Field	S 15 - 16_LoCS	S 12 - 13_ LoCwSPr	S 13 - 14_LoCS
	S 10 - 11_NoCSO	S 13 - 14_NoCSO	S 11 - 12_NoCSO		
15%	S 9 - 10_ LoCwSPr	S 14 - 15_LoCS	S 11 - 12_LoCS	S 13 - 14_LoCwSPr	S 9 - 10_LoCS
	S 10 - 11_LoCS	Field	S 15 - 16_LoCS	S 12 - 13_ LoCwSPr	S 13 - 14_LoCS
	S 10 - 11_NoCSO	S 13 - 14_NoCSO	S 14 - 15_ LoCwSPr	S 11 - 12_ LoCwSPr	S 11 - 12_NoCSO
	S 10 - 11_LoCwSPr	S 15 - 16_ LoCwSPr	**S 9 - 10_NoCSOPs**		
20%	S 9 - 10_ LoCwSPr	S 14 - 15_LoCS	S 11 - 12_LoCS	S 13 - 14_LoCwSPr	S 9 - 10_LoCS
	S 10 - 11_LoCS	Field	S 15 - 16_LoCS	S 12 - 13_ LoCwSPr	S 13 - 14_LoCS
	S 10 - 11_NoCSO	S 13 - 14_NoCSO	S 14 - 15_ LoCwSPr	S 11 - 12_ LoCwSPr	S 13 - 14_NoCS
	S 11 - 12_NoCSO	S 11 - 12_NoCS	S 10 - 11_LoCwSPr	S 15 - 16_ LoCwSPr	**S 9 - 10_NoCSOPs**

To conclude, several potential resonant signal timing plans have been found if some reasonable thresholds are applied to qualify their performance in terms of various performance measures. In spite of the fact that there was no single optimal signal timing plan that could best serve traffic demand for the entire 7-hour period (either for eastbound or westbound progression), performance of the plans in threshold analysis is encouraging. For analysis of progressed movements, the minimal threshold to define a resonant signal timing plan (for both directions) was 15%, which was much higher than the one observed when performance was evaluated on network level. This could be results of the fact that it is difficult to provide good progression, with the same signal timing plan, for both directions. Thus, a truly resonant signal timing plan (with a small threshold) for good bi-directional performance may not exist. In addition, unlike the results obtained on network level, all resonant signal timing plans for progressed movements benefited from network optimization, which took offsets and phase sequence in consideration. Thus, the progression-level evaluation which calculated each performance measure based only on the main-street through movements may be more reasonable approach to assess bi-directional nature of resonant signal timing plans, than the network-level evaluation.

7.0 Concluding Remarks

7.1 Conclusions

As mentioned before, the main objective of this research contains two aspects: 1) the verifications of previous resonant cycle studies were not rigorous especially in the way that performance measures were not selected accordingly to proclaimed goals; 2) the exploration of whether the concept of the resonant cycle should be related just to cycle length or an entire signal timing plan. The experiments have been done by building the model of the study area in different software programs. PTV Vistro was used for the optimization of the field signal timing plan while PTV Vissim was in charge of the simulation procedure to evaluate all signal timing plans. The following conclusions were drawn based on the results of this study:

- Based on the definition of progression, Guevara's [6, 10] resonant cycle study which took the PI value of the whole network as the performance measure, was not rigorous while in Shelby's [5] study, side-street delay was also taken into consideration when calculating the PI.
- The so-called "resonant cycle" should be replaced by the new concept called "resonant signal timing plan", because merely determining the value of cycle length is insufficient for the coordination of signal controllers. Parameters such as split, offsets and phase sequence must be considered at the same time.
- The optimization algorithms of PTV Vistro has some limitations, as the cycle length results of the optimizations were always the same (115 seconds) and only changed to around 200 seconds (the upper bound of the optimization) when all of the signal timing and phasing parameters were optimized.

- The results of the network-level evaluation were entirely different from the progression-level evaluation as the charts of the like performance measures never showed similar patterns. Most of the optimal signal timing plans under the network-level evaluation did not benefit from network optimization (except for the evaluation of average stops). For the progression-level evaluation, the majority of optimal signal timing plans were based on "network optimization of the cycle length, split, offsets, and phase sequence".
- None of 36 investigated signal timing plans could provide the best performance for the entire 7-hour period. However, several signal timing plans have been identified as resonant ones when their performance fits within 3% thresholds of each performance measure. Among all of the potentially resonant signal timing plans, one developed for period between "13:00 – 14:00", seems to be the best one.
- Similar to network-level evaluation, no signal timing plan could perform as the best/resonant for the entire 7-hour period under the progression-level evaluation, neither in eastbound nor in westbound direction. However, two optimized signal timing plans, separately performed better than others for either inbound or outbound directions. Within the thresholds of 15% and 20%, a signal timing plan developed for period between 12:00 – 13:00, was found to be a resonant signal timing plan for eastbound progression. Similarly, a plan developed for period between 9:00 – 10:00, was found to be resonant one for westbound direction.
- Network-level evaluation does not seem to be suitable for determination of resonant signal timing plans. The reason is that the delay and stops happening on the side-streets are not as important as what happens on the main street. Also, when such plans are developed in PTV Vistro, it does not seem that network-level optimization has an impact on network-level evaluation. In comparison, progression-level evaluation, which only takes the performance of

main-street through movements into account, is more appropriate for the investigation of resonant signal timing plans.

- Simulating different scenarios before determining the signal timing plan of a network during off-peak period can be used as a strategy for selecting resonant signal timing plans. One thing that should be noted is that the resonance may show distinctive patterns for different directions. This, the question is - how to balance the needs of both directions of the main street?

7.2 Future Studies

This research was conducted based on the field data of a realistic network. Many other important performance measures have not been tested for the resonant cycle study. Future work will mainly focus on the following aspects:

1) As recommended by Shelby et al. [5], future work can focus on building a hypothetical network with changeable parameters such as block length, travel speed, signal controller type, etc. to test whether the resonant signal timing plans exist in general conditions. If they do, the question is how such changeable parameters affect the resonant signal timing plans.

2) According to Li et al. [7], the percent of vehicles arriving on green (POG) is a good measurement for progression which better visualizes signal performance than delays and stops. Due to the lack of related software licenses, experiments related to POG have not been conducted in this study but need to be done as a future research extension.

3) In this study, the partition of different scenarios was based on the time of day (TOD) split of periods, which is not the ideal approach to describe how traffic volumes may increase. This may be one of the reasons for not finding a single resonant signal timing plan. The improvement

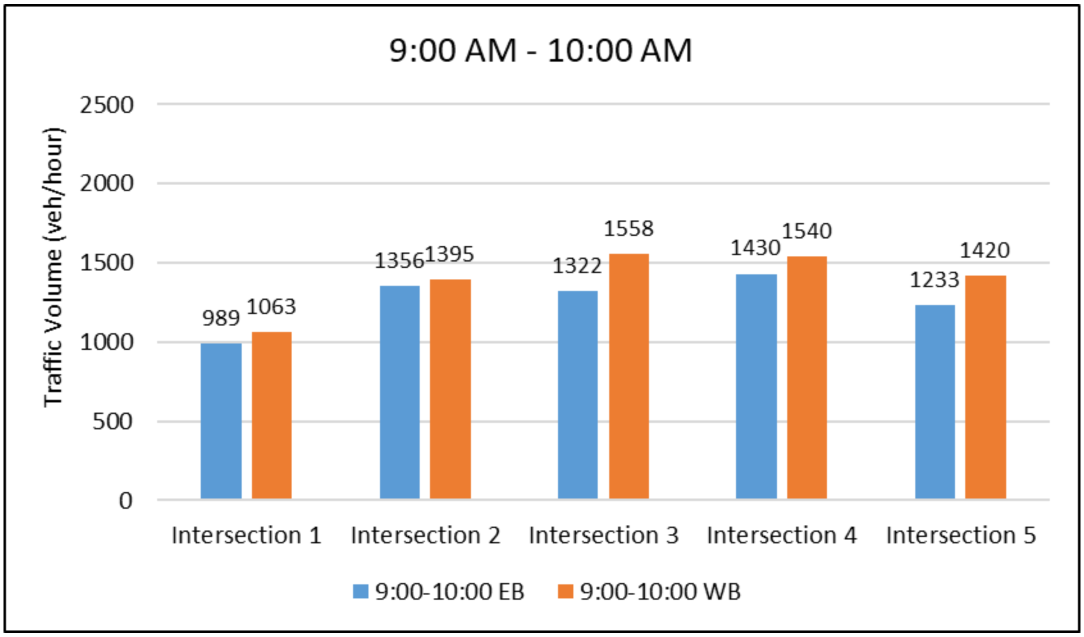
may focus on designing a gradient test set for the main-street through movements by using different percentages of the peak hour volume.

4) This research provided a potential strategy to develop guidelines for cycle lengths selection during off-peak period. As the basic methodology is to simulate various traffic conditions, more field studies should be implemented to test and verify results obtained in this study.

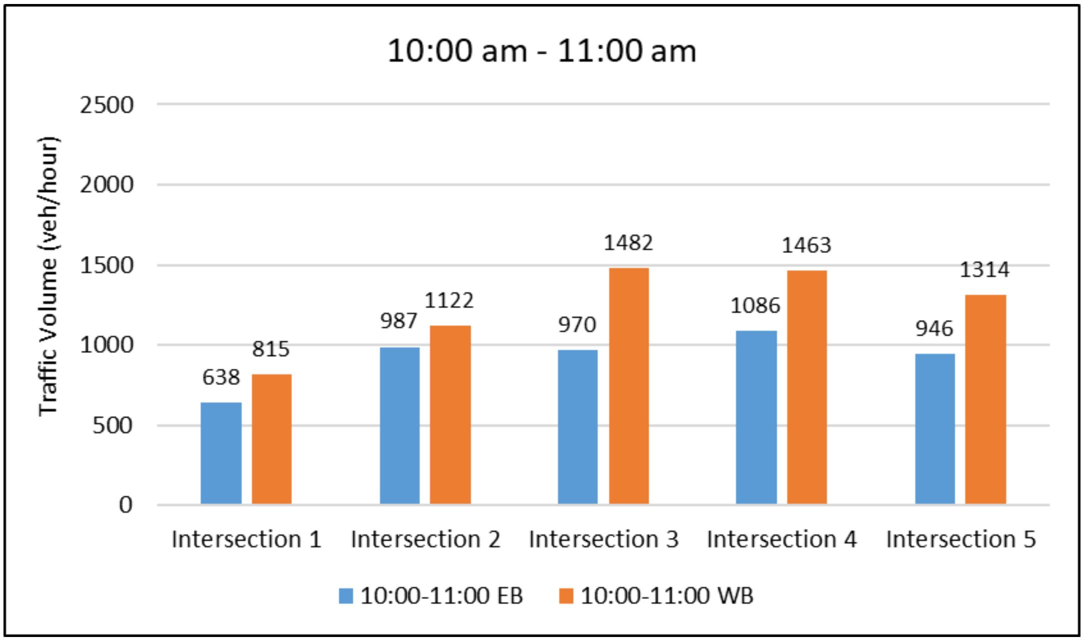
5) The PTV Vistro was used as the only signal timing optimization tool for this study regardless of some limitations in algorithms. Thereby, future work should try other optimization tools like Synchro or SimTraffic or maybe some software related to bandwidth optimization to get several optimized signal timing plans and evaluate them in PTV Vissim, as a comparison of the optimization results from PTV Vistro.

6) Due to time constraint, simulation runs were performed for limited number of random seeds. In order to obtain results that take into account randomness of vehicle arrivals, several simulations run for different random seeds should be performed. Also, calibration and validation for models should be implemented for prevent some factors from adding systematic errors in analysis.

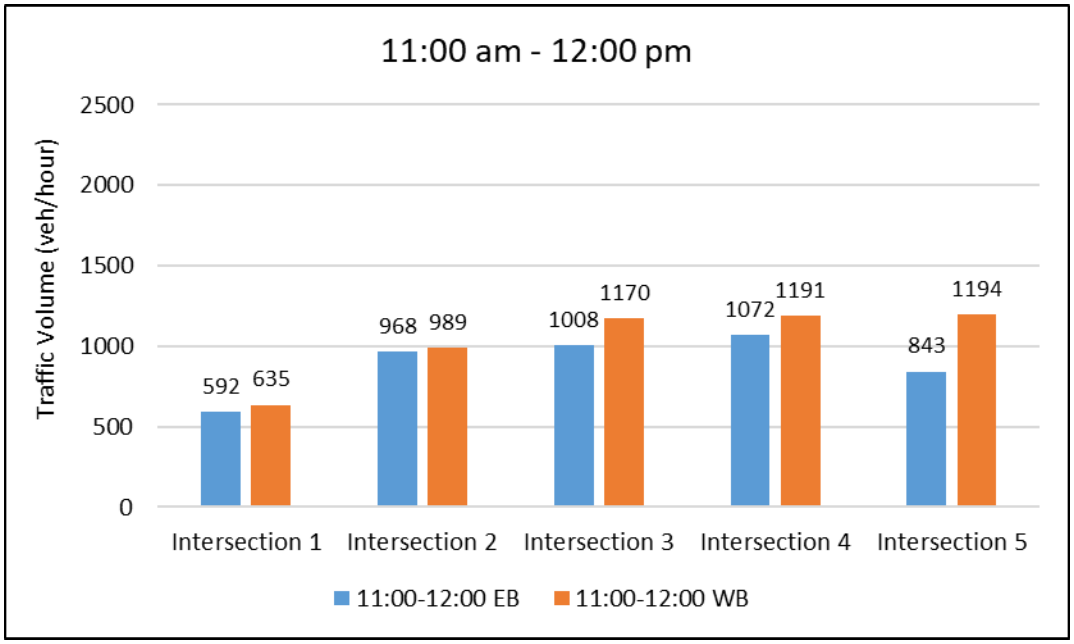
Appendix A Through Movement Volume of Main Street



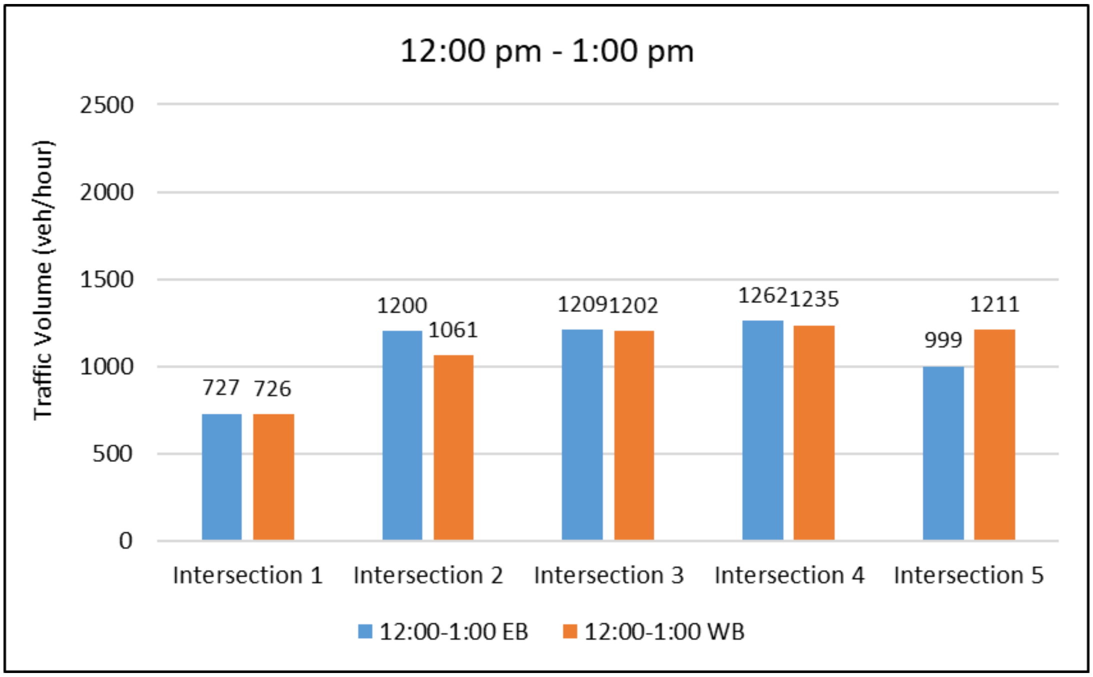
Appendix Figure 1 9:00 AM - 10:00 AM Through Movement Volume of EB & WB



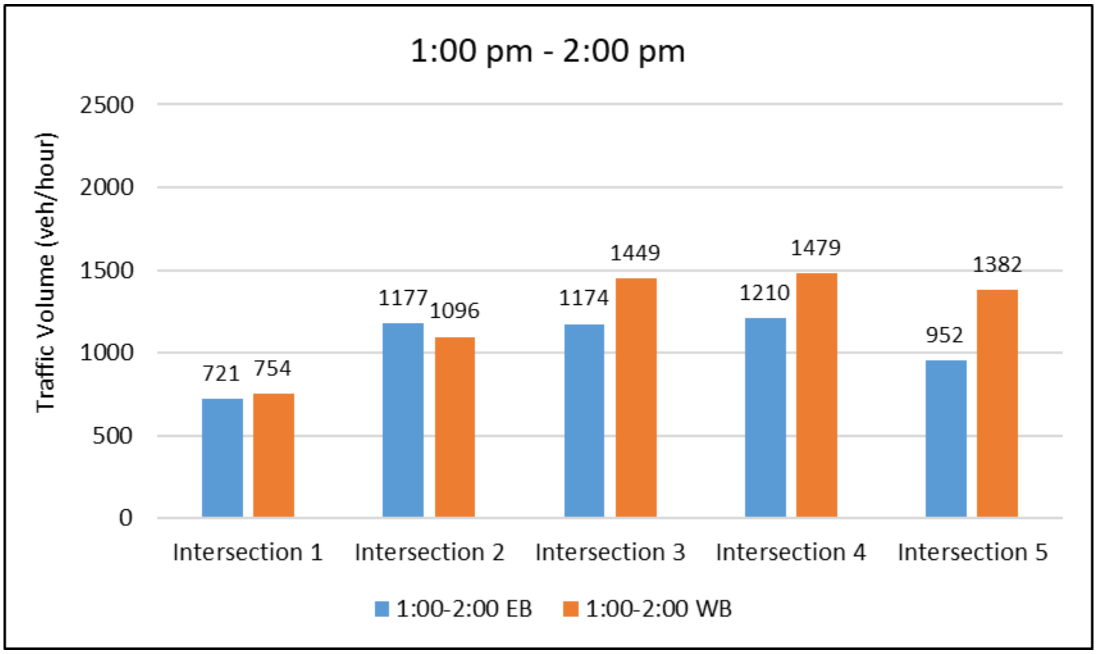
Appendix Figure 2 10:00 AM - 11:00 AM Through Movement Volume of EB & WB



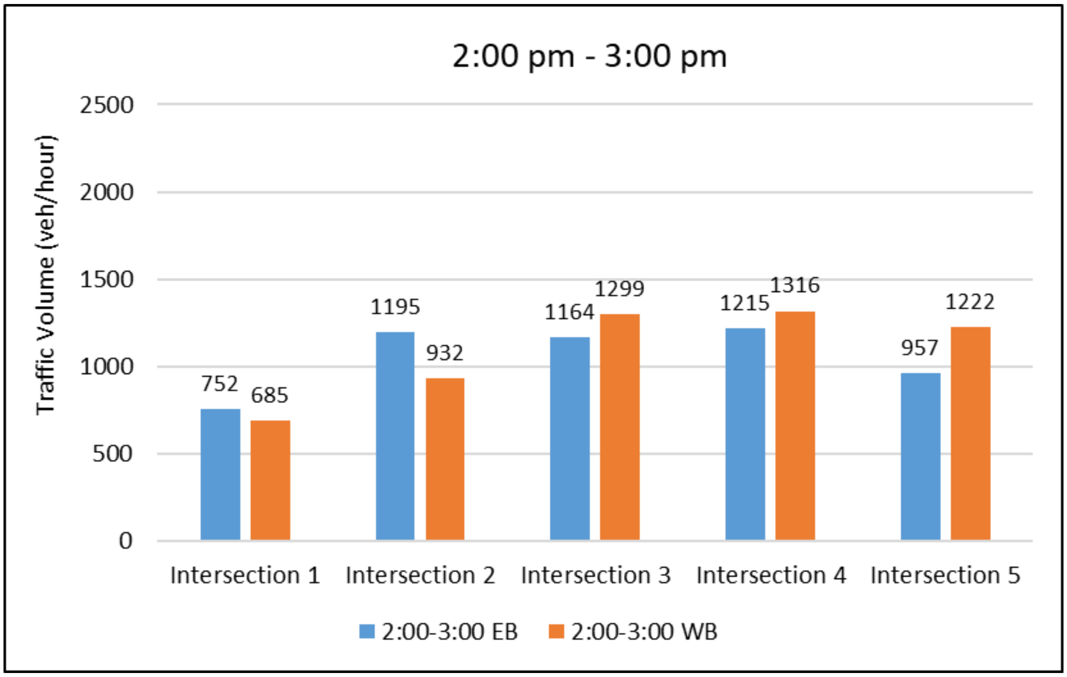
Appendix Figure 3 11:00 AM - 12:00 PM Through Movement Volume of EB & WB



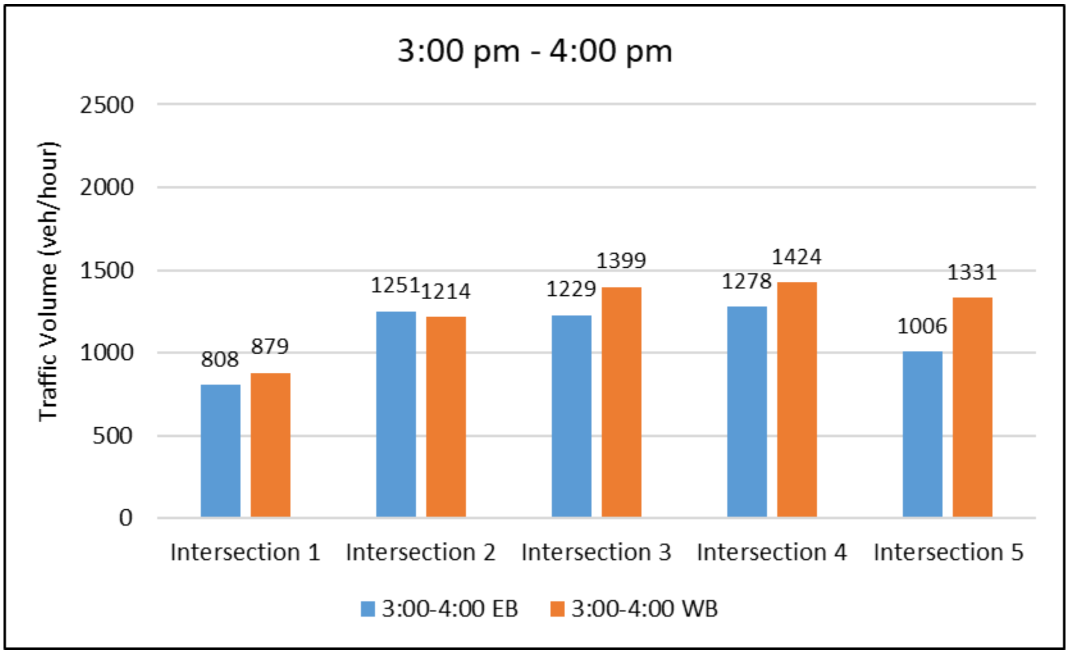
Appendix Figure 4 12:00 PM - 1:00 PM Through Movement Volume of EB & WB



Appendix Figure 5 1:00 PM - 2:00 PM Through Movement Volume of EB & WB



Appendix Figure 6 2:00 PM - 3:00 PM Through Movement Volume of EB & WB



Appendix Figure 7 3:00 PM - 4:00 PM Through Movement Volume of EB & WB

Appendix B Ranks Under Diverse Performance Measures

Appendix Table 1 Rank of Scenarios - Network Average Delay

Scenario	9:00 - 10:00		10:00 - 11:00		11:00 - 12:00		12:00 - 13:00		13:00 - 14:00		14:00 -15:00		15:00 - 16:00		Total	Rank
	Delay	Rank	Delay	Rank	Delay	Rank	Delay	Rank	Delay	Rank	Delay	Rank	Delay	Rank		
S 13 - 14_LoCwSPr	48.06	4	42.66	1	43.86	1	50.73	1	45.22	1	44.58	2	46.86	2	12	1
S 14 - 15_LoCS	47.32	3	42.84	2	43.90	2	53.18	6	45.26	2	44.47	1	46.51	1	17	2
S 14 - 15_LoCwSPr	47.01	1	44.23	6	44.79	3	52.57	4	45.36	3	45.18	3	47.19	4	24	3
S 15 - 16_LoCwSPr	47.14	2	44.28	7	45.96	9	51.29	2	45.79	4	45.29	4	46.88	3	31	4
S 13 - 14_LoCS	50.32	8	45.79	11	45.33	5	52.74	5	47.80	6	46.73	7	48.74	6	48	5
S 15 - 16_LoCS	48.91	6	45.71	10	47.04	11	53.27	7	47.24	5	46.11	6	48.37	5	50	6
S 12 - 13_LoCwSPr	50.31	7	46.04	12	47.90	12	51.74	3	48.00	7	47.91	8	49.54	8	57	7
S 9 - 10_LoCS	48.57	5	45.05	9	45.84	8	60.89	11	54.91	11	45.78	5	50.16	10	59	8
S 10 - 11_LoCwSPr	52.32	10	43.37	3	45.22	4	62.00	12	63.11	15	49.85	12	49.54	7	63	9
S 11 - 12_LoCwSPr	53.74	14	43.63	4	45.61	7	53.81	9	48.42	8	49.76	11	51.09	11	64	10
S 11 - 12_LoCS	53.60	13	44.29	8	45.38	6	53.60	8	48.59	9	49.37	9	51.19	12	65	11
S 10 - 11_LoCS	50.50	9	44.15	5	45.99	10	63.46	13	64.74	17	51.94	14	50.08	9	77	12
S 12 - 13_LoCS	53.22	12	48.17	13	51.24	13	54.88	10	52.55	10	50.30	13	52.97	13	84	13
Field	52.93	11	50.55	14	52.15	14	65.35	14	57.34	12	49.61	10	53.38	14	89	14
S 13 - 14_NoCSOPs	60.12	16	57.75	18	61.72	22	72.49	16	62.01	13	58.63	16	61.26	15	116	15
S 12 - 13_NoCSO	61.57	19	58.07	19	60.68	16	79.84	18	64.37	16	58.69	17	61.88	16	121	16
S 14 - 15_NoCSOPs	59.76	15	57.08	16	60.81	17	80.91	19	66.01	20	57.76	15	62.33	19	121	17
S 15 - 16_NoCSO	60.91	17	59.76	23	61.26	18	81.93	23	63.07	14	58.95	19	62.17	18	132	18
S 9 - 10_NoCSOPs	62.53	23	56.91	15	60.24	15	81.78	22	66.49	22	58.76	18	61.89	17	132	19
S 14 - 15_NoCSO	61.49	18	57.48	17	61.48	19	79.51	17	68.74	25	62.90	26	62.42	20	142	20
S 11 - 12_NoCSO	62.30	22	58.96	21	61.54	20	81.53	21	68.35	23	61.03	23	63.93	23	153	21
S 13 - 14_NoCSO	61.90	21	59.32	22	62.82	24	84.95	24	68.51	24	60.97	21	63.82	22	158	22
S 11 - 12_NoCSOPs	65.19	27	61.74	27	61.64	21	81.12	20	65.19	19	60.62	20	64.37	25	159	23
S 15 - 16_NoCSOPs	61.86	20	60.33	25	63.45	25	86.67	26	66.33	21	61.71	24	63.30	21	162	24
S 9 - 10_NoCSO	62.54	24	58.28	20	61.97	23	85.79	25	70.54	26	61.00	22	64.66	26	166	25
S 12 - 13_NoCSOPs	65.50	28	63.32	28	63.58	26	69.56	15	64.78	18	63.29	27	66.19	28	170	26
S 10 - 11_NoCSO	62.97	25	59.97	24	64.21	28	88.86	28	75.08	28	64.37	28	64.13	24	185	27
S 10 - 11_NoCSOPs	62.99	26	61.02	26	63.64	27	87.64	27	73.03	27	61.92	25	65.20	27	185	28
S 15 - 16_NoCS	123.48	29	146.13	29	132.65	29	189.64	29	201.41	32	197.25	32	197.13	34	214	29
S 9 - 10_NoCS	125.34	31	150.11	30	135.08	31	205.50	34	196.64	29	195.65	30	194.98	31	216	30
S 11 - 12_NoCS	127.59	33	151.02	31	132.86	30	195.80	30	202.00	34	197.48	33	193.56	29	220	31
S 14 - 15_NoCS	124.77	30	154.79	32	144.08	35	199.45	32	199.83	30	199.05	34	194.66	30	223	32
S 13 - 14_NoCS	126.54	32	155.09	33	141.78	33	203.10	33	201.41	33	195.65	29	196.89	33	226	33
S 12 - 13_NoCS	128.33	34	162.96	35	142.33	34	198.86	31	203.89	35	195.76	31	196.56	32	232	34
S 10 - 11_NoCS	129.98	35	156.82	34	140.03	32	208.41	35	207.32	36	201.95	35	199.07	35	242	35
S 9 - 10_ LoCwSPr	134.33	36	204.25	36	214.64	36	216.67	36	201.07	31	206.24	36	200.54	36	247	36

Appendix Table 2 Rank of Scenarios - Network Average Stops

Scenario	9:00 - 10:00		10:00 - 11:00		11:00 - 12:00		12:00 - 13:00		13:00 - 14:00		14:00 -15:00		15:00 - 16:00		Total	Rank
	Stops	Rank	Stops	Rank	Stops	Rank	Stops	Rank	Stops	Rank	Stops	Rank	Stops	Rank		
S 14 - 15_NoCSOPs	0.81	1	0.77	2	0.82	2	1.16	20	0.86	3	0.78	1	0.83	2	31	1
S 9 - 10_NoCSOPs	0.86	3	0.76	1	0.80	1	1.16	22	0.85	1	0.80	2	0.83	1	31	2
S 15 - 16_NoCSO	0.85	2	0.82	4	0.83	5	1.13	15	0.85	2	0.81	3	0.85	4	35	3
S 11 - 12_NoCSOPs	0.89	6	0.84	9	0.83	4	1.15	17	0.87	4	0.83	5	0.86	5	50	4
S 15 - 16_NoCSOPs	0.86	4	0.82	5	0.85	9	1.20	24	0.87	5	0.82	4	0.84	3	54	5
S 13 - 14_NoCSOPs	0.87	5	0.85	10	0.88	12	1.02	5	0.90	8	0.85	9	0.87	6	55	6
S 12 - 13_NoCSOPs	0.91	13	0.86	12	0.88	10	0.93	1	0.89	6	0.84	8	0.89	9	59	7
S 12 - 13_NoCSO	0.91	10	0.82	6	0.83	3	1.18	23	0.89	7	0.83	6	0.88	7	62	8
S 11 - 12_NoCSO	0.90	8	0.84	8	0.84	7	1.15	19	0.91	9	0.85	10	0.89	8	69	9
S 14 - 15_NoCSO	0.90	9	0.83	7	0.84	6	1.08	14	0.91	10	0.88	12	0.91	12	70	10
S 9 - 10_NoCSO	0.90	7	0.82	3	0.84	8	1.27	26	0.92	11	0.84	7	0.90	10	72	11
S 13 - 14_NoCSO	0.91	11	0.86	11	0.88	11	1.26	25	0.94	15	0.87	11	0.90	11	95	12
S 12 - 13_ LoCwSPr	0.95	17	0.88	17	0.91	17	0.99	2	0.93	13	0.90	16	0.95	16	98	13
S 13 - 14_LoCwSPr	1.02	21	0.87	14	0.90	14	1.00	3	0.93	14	0.91	18	0.96	18	102	14
S 14 - 15_LoCS	1.01	20	0.89	18	0.90	13	1.02	6	0.92	12	0.90	15	0.96	19	103	15
S 15 - 16_ LoCwSPr	0.95	16	0.88	15	0.91	19	1.00	4	0.95	16	0.91	17	0.95	17	104	16
Field	0.93	14	0.90	19	0.91	16	1.05	11	0.95	18	0.89	14	0.92	14	106	17
S 10 - 11_NoCSOPs	0.91	12	0.87	13	0.90	15	1.32	28	1.01	23	0.88	13	0.91	13	117	18
S 15 - 16_LoCS	0.99	18	0.91	20	0.95	22	1.02	7	0.95	17	0.93	21	0.98	20	125	19
S 10 - 11_NoCSO	0.94	15	0.88	16	0.91	18	1.28	27	0.99	20	0.92	19	0.94	15	130	20
S 14 - 15_ LoCwSPr	1.00	19	0.92	22	0.94	20	1.04	9	0.98	19	0.93	20	0.99	21	130	21
S 11 - 12_ LoCwSPr	1.08	24	0.91	21	0.94	21	1.05	10	0.99	21	0.99	26	1.02	23	146	22
S 11 - 12_LoCS	1.09	27	0.95	24	0.95	24	1.04	8	1.00	22	0.98	25	1.04	27	157	23
S 12 - 13_LoCS	1.07	23	0.96	25	0.97	28	1.06	12	1.06	25	0.97	23	1.06	28	164	24
S 13 - 14_LoCS	1.09	26	0.99	28	0.95	23	1.06	13	1.01	24	0.98	24	1.04	26	164	25
S 9 - 10_LoCS	1.07	22	0.96	26	0.96	25	1.16	21	1.08	26	0.96	22	1.03	25	167	26
S 10 - 11_ LoCwSPr	1.10	28	0.93	23	0.96	26	1.15	16	1.17	27	0.99	27	1.01	22	169	27
S 10 - 11_LoCS	1.08	25	0.96	27	0.96	27	1.15	18	1.21	28	1.01	28	1.03	24	177	28
S 15 - 16_NoCS	3.06	31	3.37	29	3.19	30	4.79	29	5.16	32	5.07	30	5.04	33	214	29
S 9 - 10_NoCS	3.04	29	3.41	30	3.26	31	5.08	32	5.00	29	5.17	34	4.92	30	215	30
S 11 - 12_NoCS	3.04	30	3.46	31	3.16	29	4.89	30	5.20	34	5.15	33	4.90	29	216	31
S 14 - 15_NoCS	3.16	33	3.52	32	3.37	33	5.18	35	5.03	30	5.02	29	5.01	31	223	32
S 12 - 13_NoCS	3.10	32	3.85	35	3.36	32	5.04	31	5.29	35	5.09	31	5.07	34	230	33
S 13 - 14_NoCS	3.17	34	3.65	33	3.39	35	5.12	33	5.19	33	5.10	32	5.02	32	232	34
S 10 - 11_NoCS	3.22	35	3.67	34	3.38	34	5.13	34	5.34	36	5.42	36	5.09	35	244	35
S 9 - 10_ LoCwSPr	3.33	36	5.06	36	5.57	36	5.39	36	5.10	31	5.33	35	5.18	36	246	36

Appendix Table 3 Rank of Scenarios - Network PI Value

Scenario	9:00 - 10:00		10:00 - 11:00		11:00 - 12:00		12:00 - 13:00		13:00 - 14:00		14:00 -15:00		15:00 - 16:00		Total	Rank
	PI	Rank	PI	Rank	PI	Rank	PI	Rank	PI	Rank	PI	Rank	PI	Rank		
S 13 - 14_LoCwSPr	117.46	4	89.34	1	87.90	1	114.16	1	106.82	1	102.90	2	113.50	2	12	1
S 14 - 15_LoCS	115.61	3	89.69	2	88.04	2	118.82	5	106.86	2	102.41	1	113.49	1	16	2
S 14 - 15_ LoCwSPr	115.02	2	92.52	6	90.07	3	117.82	4	107.71	3	104.45	4	115.38	4	26	3
S 15 - 16_ LoCwSPr	114.33	1	92.05	5	91.75	8	114.90	2	108.51	4	104.42	3	113.91	3	26	4
S 15 - 16_LoCS	118.58	5	95.01	10	94.20	11	119.07	6	111.47	5	106.43	5	117.50	5	47	5
S 12 - 13_ LoCwSPr	121.85	7	95.16	11	95.15	12	115.58	3	112.06	6	109.98	8	118.91	6	53	6
S 13 - 14_LoCS	123.48	8	96.67	12	91.25	6	119.21	7	113.54	7	108.48	7	119.01	7	54	7
S 11 - 12_ LoCwSPr	131.37	13	91.34	3	91.31	7	120.85	9	114.13	8	114.46	11	123.82	11	62	8
S 9 - 10_LoCS	118.97	6	94.46	9	92.08	9	136.14	11	129.21	11	106.58	6	122.15	10	62	9
S 11 - 12_LoCS	131.55	14	93.00	7	91.11	5	120.07	8	114.57	9	113.70	10	124.30	12	65	10
S 10 - 11_ LoCwSPr	128.90	11	91.54	4	90.78	4	137.88	12	147.50	17	115.35	12	120.09	8	68	11
S 10 - 11_LoCS	124.16	9	93.45	8	92.24	10	140.90	13	151.69	22	120.32	14	121.24	9	85	12
S 12 - 13_LoCS	129.33	12	99.98	13	101.80	13	122.76	10	123.79	10	116.01	13	128.12	14	85	13
Field	125.78	10	103.84	14	102.07	14	143.54	14	131.54	12	112.90	9	126.40	13	86	14
S 14 - 15_NoCSOPs	138.40	15	113.79	16	115.62	16	175.52	20	149.30	19	127.35	15	143.71	17	118	15
S 13 - 14_NoCSOPs	140.28	16	116.92	20	118.25	23	156.72	16	141.46	13	130.38	17	142.86	16	121	16
S 9 - 10_NoCSOPs	144.43	20	113.26	15	114.39	15	176.58	22	149.94	20	129.36	16	142.60	15	123	17
S 12 - 13_NoCSO	144.91	22	115.99	18	115.63	17	173.42	18	146.28	16	130.73	19	145.16	19	129	18
S 15 - 16_NoCSO	141.52	17	119.84	23	117.76	21	178.41	23	143.52	14	130.40	18	144.05	18	134	19
S 14 - 15_NoCSO	143.99	18	115.41	17	117.18	18	171.22	17	154.63	24	141.04	27	145.23	20	141	20
S 11 - 12_NoCSO	145.05	23	118.05	21	117.29	19	176.09	21	154.10	23	134.93	22	147.92	22	151	21
S 11 - 12_NoCSOPs	151.60	27	122.99	27	117.52	20	175.38	19	147.85	18	133.87	20	148.47	24	155	22
S 15 - 16_NoCSOPs	144.26	19	120.17	24	121.02	25	188.05	26	150.82	21	136.54	24	146.71	21	160	23
S 13 - 14_NoCSO	144.57	21	119.33	22	120.05	24	184.89	24	155.99	25	135.22	23	148.22	23	162	24
S 9 - 10_NoCSO	145.67	24	116.48	19	118.20	22	185.94	25	159.27	26	134.81	21	149.62	26	163	25
S 12 - 13_NoCSOPs	151.84	28	126.53	28	122.38	27	150.28	15	145.77	15	139.87	26	154.24	28	167	26
S 10 - 11_NoCSOPs	147.49	26	122.28	26	122.32	26	191.58	28	167.65	27	137.80	25	151.67	27	185	27
S 10 - 11_NoCSO	147.18	25	120.72	25	123.18	28	191.54	27	170.43	28	143.54	28	149.40	25	186	28
S 15 - 16_NoCS	293.76	29	310.03	29	272.88	30	414.55	29	452.83	33	439.35	33	446.02	32	215	29
S 9 - 10_NoCS	297.77	30	316.29	30	275.08	31	439.88	34	449.26	30	438.14	31	444.28	30	216	30
S 11 - 12_NoCS	301.63	33	318.45	31	268.16	29	423.99	30	452.58	32	439.50	34	442.51	29	218	31
S 13 - 14_NoCS	300.42	32	331.88	34	288.87	33	436.60	32	454.63	35	437.69	29	445.15	31	226	32
S 14 - 15_NoCS	298.11	31	326.44	32	291.14	35	438.04	33	450.61	31	439.17	32	447.33	34	228	33
S 12 - 13_NoCS	303.39	34	345.72	35	289.78	34	433.45	31	454.34	34	437.97	30	446.70	33	231	34
S 10 - 11_NoCS	311.16	35	331.63	33	288.77	32	445.58	35	464.06	36	452.66	36	457.20	36	243	35
S 9 - 10_ LoCwSPr	320.46	36	443.23	36	445.22	36	451.83	36	447.37	29	444.83	35	451.31	35	243	36

Appendix Table 4 Rank of Scenarios - Network Average Travel Time

Scenario	9:00 - 10:00		10:00 - 11:00		11:00 - 12:00		12:00 - 13:00		13:00 - 14:00		14:00 -15:00		15:00 - 16:00		Total	Rank
	Travel Time	Rank	Travel Time	Rank	Travel Time	Rank	Travel Time	Rank	Travel Time	Rank	Travel Time	Rank	Travel Time	Rank		
S 13 - 14_LoCwSPr	127.61	4	119.38	1	121.13	2	126.51	1	121.24	1	119.73	2	124.15	3	14	1
S 14 - 15_LoCS	126.76	3	119.76	2	121.00	1	129.14	7	121.42	2	119.63	1	123.36	1	17	2
S 14 - 15_ LoCwSPr	126.52	2	121.17	6	122.02	3	128.60	5	121.64	3	120.19	3	124.21	4	26	3
S 15 - 16_ LoCwSPr	126.38	1	121.29	8	123.14	9	127.27	2	121.71	4	120.32	4	124.01	2	30	4
S 13 - 14_LoCS	129.63	8	122.50	10	122.42	4	128.52	4	123.75	6	121.78	7	125.94	6	45	5
S 15 - 16_LoCS	128.22	6	122.72	11	124.13	11	129.13	6	123.23	5	121.03	6	125.51	5	50	6
S 12 - 13_ LoCwSPr	129.49	7	123.02	12	124.86	12	127.84	3	124.24	7	122.56	8	127.04	8	57	7
S 9 - 10_LoCS	127.93	5	122.05	9	123.08	8	136.64	11	130.56	11	120.64	5	127.18	9	58	8
S 10 - 11_ LoCwSPr	131.40	10	119.86	3	122.64	5	137.84	12	138.37	14	124.91	13	126.94	7	64	9
S 11 - 12_ LoCwSPr	132.73	14	120.60	4	122.80	7	129.69	9	124.63	8	124.66	11	128.37	11	64	10
S 11 - 12_LoCS	132.52	13	121.25	7	122.66	6	129.58	8	124.73	9	124.33	9	128.38	12	64	11
S 10 - 11_LoCS	129.67	9	120.74	5	123.34	10	139.12	13	139.81	16	126.81	14	127.55	10	77	12
S 12 - 13_LoCS	132.49	12	125.17	13	128.16	13	130.86	10	128.51	10	124.87	12	130.38	13	83	13
Field	132.46	11	127.35	14	129.24	14	141.11	14	133.29	12	124.46	10	130.70	14	89	14
S 13 - 14_NoCSOPs	139.29	16	133.89	17	138.85	22	147.95	16	137.47	13	133.35	17	138.29	15	116	15
S 12 - 13_NoCSO	140.18	18	134.85	19	137.79	17	155.06	18	139.83	17	133.12	16	138.41	16	121	16
S 14 - 15_NoCSOPs	139.24	15	133.73	15	138.01	18	155.77	19	141.98	21	132.52	15	139.62	20	123	17
S 15 - 16_NoCSO	139.98	17	135.97	23	137.63	16	156.75	21	138.47	15	133.67	18	139.29	18	128	18
S 9 - 10_NoCSOPs	142.15	25	133.86	16	137.17	15	157.04	23	142.50	22	133.73	19	139.27	17	137	19
S 14 - 15_NoCSO	140.59	20	133.99	18	138.38	19	154.78	17	144.50	25	137.27	26	139.54	19	144	20
S 11 - 12_NoCSO	141.64	22	135.72	21	138.67	21	156.97	22	144.14	23	135.88	22	141.31	23	154	21
S 11 - 12_NoCSOPs	144.52	27	138.69	27	138.48	20	156.13	20	140.98	19	135.48	20	141.63	25	158	22
S 13 - 14_NoCSO	141.26	21	135.97	22	139.92	24	159.80	24	144.34	24	135.72	21	141.08	22	158	23
S 15 - 16_NoCSOPs	140.56	19	137.17	25	140.41	27	161.50	26	141.78	20	136.09	24	140.21	21	162	24
S 9 - 10_NoCSO	141.79	23	135.12	20	138.87	23	160.98	25	146.54	26	135.88	23	142.00	26	166	25
S 12 - 13_NoCSOPs	145.16	28	139.70	28	140.41	26	144.73	15	140.90	18	137.85	27	142.76	28	170	26
S 10 - 11_NoCSOPs	142.09	24	137.63	26	140.39	25	161.81	27	148.59	27	136.59	25	142.11	27	181	27
S 10 - 11_NoCSO	142.27	26	136.62	24	141.05	28	163.84	28	150.76	28	139.15	28	141.36	24	186	28
S 15 - 16_NoCS	202.02	29	221.22	29	207.85	29	262.66	29	274.37	33	269.68	32	272.06	33	214	29
S 9 - 10_NoCS	203.69	31	225.34	30	210.31	31	278.39	34	269.50	29	267.98	29	269.89	31	215	30
S 11 - 12_NoCS	206.02	33	226.54	31	208.22	30	268.83	30	275.04	34	269.89	33	268.33	29	220	31
S 14 - 15_NoCS	203.27	30	229.73	32	219.41	35	272.19	32	272.73	30	271.61	34	269.24	30	223	32
S 13 - 14_NoCS	204.76	32	229.90	33	216.78	33	276.29	33	274.15	32	268.09	30	272.17	34	227	33
S 12 - 13_NoCS	206.68	34	237.60	35	217.50	34	271.49	31	276.85	35	268.20	31	271.65	32	232	34
S 10 - 11_NoCS	208.33	35	231.97	34	215.09	32	281.45	35	280.16	36	274.14	35	273.87	35	242	35
S 9 - 10_ LoCwSPr	211.75	36	276.60	36	286.81	36	289.77	36	273.33	31	278.55	36	275.43	36	247	36

Appendix Table 5 Rank of Scenarios - Progression Average Delay (EB)

Scenario	9:00 - 10:00		10:00 - 11:00		11:00 - 12:00		12:00 - 13:00		13:00 - 14:00		14:00 -15:00		15:00 - 16:00		Total	Rank
	Delay	Rank	Delay	Rank	Delay	Rank	Delay	Rank	Delay	Rank	Delay	Rank	Delay	Rank		
S 12 - 13_NoCSOPs	45.68	4	28.45	2	27.85	2	33.36	1	32.34	1	33.41	1	35.59	1	12	1
S 15 - 16_NoCSOPs	45.99	5	30.72	4	30.63	6	40.11	5	35.38	2	39.08	5	36.89	4	31	2
S 9 - 10_NoCSOPs	49.52	6	29.82	3	26.95	1	39.27	4	39.29	6	38.43	4	37.46	7	31	3
S 14 - 15_NoCSOPs	40.46	2	27.02	1	29.12	4	44.87	19	36.39	3	35.10	2	36.26	2	33	4
S 15 - 16_NoCSO	45.60	3	32.15	6	33.26	8	42.39	12	37.66	4	37.25	3	39.76	10	46	5
S 13 - 14_NoCSOPs	39.44	1	31.67	5	35.76	15	38.66	3	43.35	11	43.98	18	40.83	13	66	6
S 9 - 10_ LoCwSPr	52.82	8	38.63	20	33.85	9	36.96	2	42.46	9	42.15	14	41.27	14	76	7
S 11 - 12_NoCSOPs	54.05	10	33.42	8	28.39	3	50.19	32	38.12	5	39.78	8	40.44	11	77	8
S 12 - 13_NoCSO	57.21	15	32.48	7	30.25	5	44.36	14	39.37	7	42.14	13	46.45	21	82	9
S 12 - 13_ LoCwSPr	51.34	7	35.54	11	37.74	23	43.96	13	42.38	8	43.84	17	44.73	17	96	10
S 11 - 12_NoCS	57.46	18	36.91	15	36.42	17	44.41	15	52.60	28	40.63	10	39.68	9	112	11
S 9 - 10_NoCS	57.37	16	38.94	22	35.86	16	44.55	16	49.95	25	40.24	9	38.25	8	112	12
S 14 - 15_LoCS	57.43	17	36.28	13	35.44	13	45.61	21	42.58	10	43.80	16	48.63	25	115	13
S 13 - 14_NoCS	59.20	29	41.06	30	35.10	10	40.38	7	54.57	31	39.61	7	36.85	3	117	14
S 10 - 11_LoCS	56.65	14	37.95	19	37.25	20	40.13	6	44.86	17	44.20	22	48.59	24	122	15
S 15 - 16_NoCS	58.76	28	39.06	23	35.35	12	41.85	11	54.85	32	40.91	11	37.10	5	122	16
S 14 - 15_ LoCwSPr	54.22	11	36.52	14	37.14	19	44.81	18	43.71	14	44.12	20	49.17	27	123	17
S 9 - 10_NoCSO	54.94	12	37.51	18	31.55	7	46.91	26	45.31	18	44.64	24	45.85	20	125	18
S 11 - 12_LoCS	57.54	19	37.08	16	37.26	21	41.31	9	43.68	13	46.25	26	47.90	22	126	19
S 14 - 15_NoCS	59.22	30	40.74	29	35.67	14	41.11	8	51.38	27	40.93	12	37.46	6	126	20
S 15 - 16_ LoCwSPr	53.19	9	35.42	10	38.50	25	45.33	20	45.40	19	45.98	25	45.50	18	126	21
S 10 - 11_ LoCwSPr	59.93	31	34.78	9	37.53	22	41.84	10	43.49	12	44.04	19	48.68	26	129	22
S 12 - 13_NoCS	57.78	23	38.65	21	38.19	24	44.74	17	52.79	29	39.35	6	40.44	12	132	23
S 14 - 15_NoCSO	57.68	21	37.20	17	35.22	11	46.40	24	44.78	16	48.91	31	49.84	29	149	24
S 11 - 12_NoCSO	56.23	13	40.27	27	36.59	18	53.12	33	48.41	23	44.13	21	45.64	19	154	25
Field	57.77	22	40.54	28	40.76	31	47.87	27	46.69	20	42.92	15	44.63	16	159	26
S 13 - 14_LoCwSPr	62.17	34	35.77	12	38.75	26	46.18	23	44.67	15	44.35	23	50.33	30	163	27
S 15 - 16_LoCS	60.59	33	39.28	24	39.57	27	45.82	22	47.30	22	47.51	28	51.00	31	187	28
S 11 - 12_ LoCwSPr	58.64	27	39.41	25	40.48	28	46.58	25	46.92	21	48.59	30	51.03	32	188	29
S 12 - 13_LoCS	57.86	24	39.76	26	41.74	32	48.32	28	54.00	30	49.16	33	51.44	33	206	30
S 10 - 11_NoCS	67.55	35	47.54	35	43.47	33	49.99	31	55.37	33	46.34	27	44.62	15	209	31
S 13 - 14_NoCSO	57.66	20	44.78	33	43.53	34	60.49	36	56.01	34	49.10	32	48.30	23	212	32
S 9 - 10_LoCS	59.97	32	42.34	31	40.59	29	49.06	30	50.29	26	47.92	29	53.01	35	212	33
S 13 - 14_LoCS	68.56	36	42.66	32	40.71	30	48.42	29	49.46	24	49.22	34	51.56	34	219	34
S 10 - 11_NoCSO	58.47	26	50.52	36	46.19	35	59.28	35	56.36	35	52.57	35	49.28	28	230	35
S 10 - 11_NoCSOPs	58.25	25	44.98	34	47.09	36	54.96	34	58.08	36	57.64	36	56.59	36	237	36

Appendix Table 6 Rank of Scenarios - Progression Average Delay (WB)

Scenario	9:00 - 10:00		10:00 - 11:00		11:00 - 12:00		12:00 - 13:00		13:00 - 14:00		14:00 -15:00		15:00 - 16:00		Total	Rank
	Delay	Rank	Delay	Rank	Delay	Rank	Delay	Rank	Delay	Rank	Delay	Rank	Delay	Rank		
S 9 - 10_NoCSOPs	36.35	1	32.79	2	29.58	1	34.49	3	32.44	1	30.26	2	37.25	5	15	1
S 14 - 15_NoCSOPs	37.74	2	31.90	1	35.88	15	36.68	11	36.03	3	28.61	1	37.86	6	39	2
S 9 - 10_ LoCwSPr	40.96	5	37.14	13	31.62	3	34.65	4	35.00	2	35.19	8	38.13	8	43	3
S 13 - 14_LoCwSPr	41.02	6	34.45	3	30.82	2	37.08	12	37.48	5	34.16	4	40.62	14	46	4
S 11 - 12_NoCSO	41.37	7	35.92	7	33.88	6	36.61	10	36.92	4	33.95	3	39.98	11	48	5
S 13 - 14_NoCSO	40.90	4	35.52	5	35.35	11	35.92	9	38.65	8	35.30	9	39.76	10	56	6
S 14 - 15_LoCS	42.35	9	35.18	4	32.34	4	39.55	20	38.82	9	34.88	6	40.13	12	64	7
S 12 - 13_ LoCwSPr	39.29	3	36.28	9	33.26	5	38.93	18	39.11	12	37.19	15	40.14	13	75	8
S 9 - 10_NoCSO	42.26	8	35.76	6	34.15	8	38.64	16	39.05	11	34.40	5	43.71	24	78	9
S 10 - 11_NoCSO	42.39	10	36.79	12	34.24	9	37.21	13	39.15	13	35.04	7	41.78	18	82	10
S 11 - 12_NoCS	44.37	18	40.75	25	37.50	21	32.07	1	38.90	10	35.84	11	34.82	3	89	11
S 13 - 14_NoCS	43.08	12	41.76	27	39.17	24	34.99	6	41.46	21	35.34	10	33.67	1	101	12
S 12 - 13_NoCS	44.85	20	40.60	22	38.71	23	33.79	2	40.44	19	37.86	20	34.04	2	108	13
S 15 - 16_ LoCwSPr	44.17	16	36.30	10	35.02	10	39.82	21	39.90	16	37.25	16	43.33	23	112	14
S 15 - 16_LoCS	45.30	23	36.15	8	35.56	14	38.16	15	40.77	20	36.66	14	42.49	20	114	15
S 11 - 12_ LoCwSPr	43.55	14	36.64	11	36.12	16	40.60	24	38.16	6	38.98	24	42.67	21	116	16
S 9 - 10_NoCS	43.84	15	42.40	29	40.43	27	35.57	7	42.27	24	36.50	12	36.83	4	118	17
S 15 - 16_NoCS	42.87	11	42.10	28	40.85	28	34.71	5	41.79	23	37.70	18	37.90	7	120	18
S 14 - 15_NoCS	44.82	19	40.73	24	40.22	26	35.71	8	41.66	22	36.57	13	38.87	9	121	19
Field	46.14	25	38.39	14	35.51	13	41.40	25	38.64	7	38.49	23	41.42	15	122	20
S 11 - 12_LoCS	43.35	13	39.83	19	37.01	20	39.18	19	39.89	15	38.16	22	42.47	19	127	21
S 9 - 10_LoCS	45.84	24	39.52	18	35.44	12	38.14	14	42.84	26	37.54	17	43.20	22	133	22
S 10 - 11_ LoCwSPr	45.23	22	38.87	17	39.65	25	39.94	22	39.97	17	39.18	25	41.69	17	145	23
S 14 - 15_ LoCwSPr	44.24	17	39.97	20	36.12	17	44.92	28	39.97	18	38.10	21	43.75	25	146	24
S 10 - 11_LoCS	46.17	26	41.68	26	41.44	29	38.76	17	39.42	14	40.02	27	41.47	16	155	25
S 14 - 15_NoCSO	46.87	27	38.60	15	34.13	7	43.33	27	42.57	25	39.39	26	48.58	28	155	26
S 12 - 13_NoCSO	49.31	30	39.99	21	36.36	18	41.79	26	44.02	28	37.75	19	44.51	26	168	27
S 15 - 16_NoCSO	44.85	21	38.60	16	37.57	22	46.13	29	46.76	29	40.60	28	46.24	27	172	28
S 13 - 14_LoCS	47.23	28	43.65	30	36.99	19	40.28	23	43.46	27	41.56	29	48.90	30	186	29
S 12 - 13_LoCS	47.82	29	40.64	23	42.12	30	48.99	32	50.27	32	42.80	30	48.81	29	205	30
S 11 - 12_NoCSOPs	51.00	31	46.63	31	42.71	31	46.82	31	49.47	31	44.31	31	52.81	31	217	31
S 15 - 16_NoCSOPs	51.71	32	47.50	32	47.57	32	46.67	30	46.96	30	44.52	32	55.44	32	220	32
S 13 - 14_NoCSOPs	56.27	33	47.59	33	53.18	34	61.83	35	58.29	34	49.66	33	55.58	33	235	33
S 10 - 11_NoCSOPs	65.76	34	48.97	34	48.98	33	58.03	33	55.72	33	52.43	34	61.25	35	236	34
S 10 - 11_NoCS	69.82	35	68.86	36	58.02	35	59.82	34	71.13	35	57.58	35	59.96	34	244	35
S 12 - 13_NoCSOPs	74.36	36	62.04	35	63.28	36	74.40	36	72.89	36	65.07	36	75.52	36	251	36

Appendix Table 7 Rank of Scenarios - Progression Average Stops (EB)

Scenario	9:00 - 10:00		10:00 - 11:00		11:00 - 12:00		12:00 - 13:00		13:00 - 14:00		14:00 -15:00		15:00 - 16:00		Total	Rank
	Stops	Rank	Stops	Rank	Stops	Rank	Stops	Rank	Stops	Rank	Stops	Rank	Stops	Rank		
S 12 - 13_NoCSOPs	0.92	4	0.63	3	0.58	2	0.67	1	0.62	1	0.64	1	0.67	2	14	1
S 15 - 16_NoCSOPs	0.87	2	0.61	1	0.65	4	0.90	3	0.66	2	0.68	2	0.63	1	15	2
S 11 - 12_NoCSOPs	1.02	6	0.68	5	0.55	1	0.91	4	0.72	3	0.69	3	0.73	3	25	3
S 9 - 10_NoCSOPs	1.04	7	0.63	2	0.63	3	0.88	2	0.83	4	0.75	5	0.76	4	27	4
S 14 - 15_NoCSOPs	0.85	1	0.64	4	0.70	6	1.11	9	0.83	5	0.71	4	0.82	5	34	5
S 15 - 16_NoCSO	0.92	5	0.73	7	0.79	8	1.01	6	0.83	6	0.78	6	0.89	7	45	6
S 13 - 14_NoCSOPs	0.89	3	0.80	8	0.84	11	0.99	5	0.97	8	0.96	10	0.88	6	51	7
S 12 - 13_NoCSO	1.20	10	0.69	6	0.66	5	1.07	8	0.87	7	0.85	7	1.00	9	52	8
S 14 - 15_NoCSO	1.24	13	0.83	9	0.76	7	1.03	7	0.98	9	1.03	11	1.02	10	66	9
S 9 - 10_NoCSO	1.14	8	0.86	10	0.81	10	1.16	12	1.04	10	0.95	8	0.99	8	66	10
S 11 - 12_NoCSO	1.22	12	0.95	11	0.80	9	1.26	20	1.08	11	0.96	9	1.03	11	83	11
S 10 - 11_NoCSOPs	1.16	9	0.95	12	1.00	13	1.20	16	1.20	15	1.08	13	1.04	12	90	12
Field	1.22	11	1.09	18	1.04	17	1.17	14	1.12	12	1.04	12	1.04	13	97	13
S 14 - 15_LoCS	1.51	21	1.08	15	1.00	12	1.21	17	1.18	14	1.18	17	1.30	25	121	14
S 13 - 14_NoCSO	1.33	15	1.07	14	1.02	14	1.50	31	1.28	19	1.13	14	1.12	15	122	15
S 12 - 13_ LoCwSPr	1.27	14	1.11	21	1.10	21	1.25	19	1.18	13	1.14	15	1.23	21	124	16
S 10 - 11_LoCS	1.52	22	1.09	17	1.03	16	1.17	13	1.28	18	1.20	18	1.28	24	128	17
S 12 - 13_LoCS	1.42	19	1.08	16	1.06	18	1.15	11	1.31	23	1.16	16	1.32	26	129	18
S 15 - 16_LoCS	1.42	18	1.06	13	1.10	20	1.23	18	1.24	16	1.21	19	1.33	28	132	19
S 9 - 10_ LoCwSPr	1.56	23	1.19	25	1.03	15	1.12	10	1.26	17	1.26	22	1.22	20	132	20
S 11 - 12_LoCS	1.60	24	1.11	20	1.09	19	1.18	15	1.28	20	1.24	21	1.32	27	146	21
S 10 - 11_NoCSO	1.37	16	1.31	30	1.20	33	1.48	29	1.34	25	1.24	20	1.22	19	172	22
S 13 - 14_LoCwSPr	1.71	28	1.10	19	1.18	30	1.35	23	1.30	22	1.28	23	1.38	30	175	23
S 14 - 15_ LoCwSPr	1.51	20	1.12	23	1.14	24	1.28	21	1.44	27	1.32	27	1.44	35	177	24
S 13 - 14_LoCS	1.70	27	1.24	28	1.14	26	1.34	22	1.29	21	1.30	26	1.36	29	179	25
S 9 - 10_LoCS	1.67	26	1.21	26	1.16	28	1.37	27	1.34	24	1.30	25	1.41	33	189	26
S 15 - 16_ LoCwSPr	1.38	17	1.12	22	1.22	34	1.50	32	1.48	28	1.37	29	1.38	31	193	27
S 10 - 11_ LoCwSPr	1.74	29	1.16	24	1.20	32	1.35	24	1.36	26	1.35	28	1.41	34	197	28
S 15 - 16_NoCS	1.77	31	1.39	33	1.14	25	1.46	28	1.82	34	1.41	33	1.10	14	198	29
S 11 - 12_NoCS	1.83	33	1.22	27	1.13	23	1.48	30	1.78	33	1.38	31	1.24	22	199	30
S 14 - 15_NoCS	1.83	34	1.51	35	1.13	22	1.36	26	1.70	31	1.44	35	1.12	16	199	31
S 9 - 10_NoCS	1.75	30	1.33	32	1.17	29	1.51	33	1.68	30	1.37	30	1.19	18	202	32
S 13 - 14_NoCS	1.82	32	1.40	34	1.15	27	1.36	25	1.88	36	1.42	34	1.13	17	205	33
S 12 - 13_NoCS	1.84	35	1.33	31	1.18	31	1.53	34	1.86	35	1.30	24	1.25	23	213	34
S 11 - 12_ LoCwSPr	1.65	25	1.30	29	1.31	35	1.53	35	1.55	29	1.40	32	1.54	36	221	35
S 10 - 11_NoCS	2.16	36	1.66	36	1.41	36	1.67	36	1.76	32	1.59	36	1.39	32	244	36

Appendix Table 8 Rank of Scenarios - Progression Average Stops (WB)

Scenario	9:00 - 10:00		10:00 - 11:00		11:00 - 12:00		12:00 - 13:00		13:00 - 14:00		14:00 -15:00		15:00 - 16:00		Total	Rank
	Stops	Rank	Stops	Rank	Stops	Rank	Stops	Rank	Stops	Rank	Stops	Rank	Stops	Rank		
S 9 - 10_NoCSOPs	0.80	2	0.72	1	0.71	1	0.77	1	0.74	1	0.70	2	0.83	2	10	1
S 14 - 15_NoCSOPs	0.78	1	0.73	2	0.80	3	0.78	2	0.77	2	0.67	1	0.80	1	12	2
S 11 - 12_NoCSO	0.91	4	0.82	4	0.79	2	0.80	4	0.81	3	0.80	4	0.86	3	24	3
S 13 - 14_NoCSO	0.89	3	0.86	7	0.82	8	0.79	3	0.91	6	0.80	3	0.89	4	34	4
S 9 - 10_NoCSO	0.96	7	0.78	3	0.81	5	0.90	6	0.85	4	0.82	5	0.98	7	37	5
S 10 - 11_NoCSO	0.96	6	0.84	5	0.81	7	0.85	5	0.89	5	0.84	6	0.99	8	42	6
S 15 - 16_NoCSO	0.92	5	0.85	6	0.81	4	0.94	7	0.93	8	0.88	7	0.96	5	42	7
S 14 - 15_NoCSO	0.99	8	0.87	8	0.81	6	1.00	9	0.92	7	0.90	8	1.05	13	59	8
S 12 - 13_NoCSO	1.06	12	0.97	9	0.88	9	0.96	8	1.04	9	0.92	9	0.97	6	62	9
S 15 - 16_NoCSOPs	1.03	9	0.99	10	1.02	14	1.01	10	1.08	11	0.97	10	1.06	14	78	10
S 11 - 12_NoCSOPs	1.05	11	1.01	11	0.98	10	1.07	11	1.06	10	1.00	12	1.08	15	80	11
S 10 - 11_NoCSOPs	1.16	13	1.01	12	1.01	13	1.10	15	1.10	13	0.98	11	1.08	16	93	12
S 13 - 14_NoCSOPs	1.04	10	1.02	13	1.06	17	1.14	19	1.08	12	1.01	13	1.04	11	95	13
S 15 - 16_ LoCwSPr	1.19	15	1.05	14	0.99	11	1.07	12	1.10	14	1.04	14	1.18	20	100	14
S 13 - 14_LoCwSPr	1.20	17	1.05	15	1.00	12	1.09	13	1.11	16	1.05	15	1.21	22	110	15
S 11 - 12_NoCS	1.37	26	1.23	27	1.09	18	1.09	14	1.22	20	1.08	16	1.04	10	131	16
S 11 - 12_ LoCwSPr	1.20	16	1.08	17	1.05	16	1.20	24	1.11	15	1.16	26	1.21	24	138	17
S 9 - 10_ LoCwSPr	1.28	19	1.18	20	1.03	15	1.12	18	1.17	18	1.21	29	1.21	25	144	18
S 12 - 13_ LoCwSPr	1.17	14	1.07	16	1.12	22	1.26	26	1.23	22	1.16	25	1.21	23	148	19
S 14 - 15_LoCS	1.33	21	1.14	19	1.11	19	1.20	25	1.19	19	1.11	19	1.27	27	149	20
S 12 - 13_NoCS	1.40	30	1.23	25	1.11	20	1.12	17	1.32	26	1.15	23	1.04	9	150	21
Field	1.25	18	1.10	18	1.15	23	1.31	30	1.12	17	1.16	24	1.20	21	151	22
S 13 - 14_NoCS	1.38	28	1.23	26	1.12	21	1.15	20	1.33	27	1.08	17	1.05	12	151	23
S 15 - 16_NoCS	1.37	25	1.26	29	1.18	27	1.11	16	1.32	25	1.13	20	1.12	18	160	24
S 14 - 15_ LoCwSPr	1.30	20	1.19	22	1.17	26	1.31	29	1.23	23	1.15	22	1.32	28	170	25
S 10 - 11_ LoCwSPr	1.34	22	1.18	21	1.24	31	1.17	23	1.22	21	1.17	27	1.25	26	171	26
S 9 - 10_NoCS	1.39	29	1.28	30	1.16	24	1.16	22	1.37	31	1.10	18	1.09	17	171	27
S 14 - 15_NoCS	1.44	31	1.25	28	1.17	25	1.16	21	1.36	29	1.14	21	1.14	19	174	28
S 15 - 16_LoCS	1.36	24	1.20	23	1.24	30	1.29	28	1.28	24	1.23	30	1.33	29	188	29
S 12 - 13_NoCSOPs	1.35	23	1.20	24	1.23	28	1.38	33	1.35	28	1.18	28	1.35	30	194	30
S 11 - 12_LoCS	1.38	27	1.37	32	1.28	32	1.37	32	1.38	32	1.29	31	1.45	33	219	31
S 9 - 10_LoCS	1.52	32	1.37	31	1.24	29	1.34	31	1.50	33	1.36	32	1.44	32	220	32
S 10 - 11_LoCS	1.53	33	1.40	34	1.39	34	1.28	27	1.37	30	1.38	33	1.41	31	222	33
S 13 - 14_LoCS	1.60	34	1.53	35	1.29	33	1.41	34	1.52	34	1.45	35	1.68	34	239	34
S 12 - 13_LoCS	1.61	35	1.40	33	1.42	35	1.67	35	1.82	35	1.44	34	1.71	35	242	35
S 10 - 11_NoCS	2.22	36	2.09	36	1.81	36	2.03	36	2.29	36	1.84	36	1.98	36	252	36

Appendix Table 9 Rank of Scenarios - Progression PI Value (EB)

Scenario	9:00 - 10:00		10:00 - 11:00		11:00 - 12:00		12:00 - 13:00		13:00 - 14:00		14:00 -15:00		15:00 - 16:00		Total	Rank
	PI	Rank	PI	Rank	PI	Rank	PI	Rank	PI	Rank	PI	Rank	PI	Rank		
S 12 - 13_NoCSOPs	18.87	5	8.37	2	8.21	2	11.04	1	11.46	1	11.30	1	12.64	1	13	1
S 15 - 16_NoCSOPs	18.46	3	8.93	4	9.09	6	13.56	6	12.59	2	12.96	5	13.05	2	28	2
S 9 - 10_NoCSOPs	20.44	6	8.81	3	8.01	1	13.07	3	14.31	8	12.94	4	13.62	7	32	3
S 14 - 15_NoCSOPs	16.71	2	8.05	1	8.82	4	15.17	17	13.38	3	11.89	2	13.40	6	35	4
S 15 - 16_NoCSO	18.61	4	9.44	6	10.05	9	14.43	10	13.58	4	12.76	3	14.58	13	49	5
S 9 - 10_ LoCwSPr	21.78	8	11.46	17	9.91	8	11.90	2	13.59	5	13.96	8	14.26	10	58	6
S 13 - 14_NoCSOPs	16.48	1	9.41	5	10.78	12	13.41	4	15.49	9	15.06	16	15.03	14	61	7
S 11 - 12_NoCSOPs	22.18	9	9.78	8	8.26	3	15.97	22	13.84	6	13.16	6	14.49	12	66	8
S 12 - 13_NoCSO	23.48	13	9.47	7	8.99	5	15.16	16	14.14	7	14.27	12	17.02	19	79	9
S 9 - 10_NoCSO	22.65	11	11.20	14	9.58	7	15.93	21	16.57	16	15.26	18	16.78	17	104	10
S 12 - 13_ LoCwSPr	21.76	7	11.16	13	11.78	22	15.53	19	15.86	10	15.49	19	17.03	20	110	11
S 9 - 10_NoCS	23.94	15	12.40	26	10.95	17	14.70	12	17.45	23	14.10	10	13.67	8	111	12
S 11 - 12_NoCS	24.22	20	11.88	20	10.89	15	14.73	13	17.99	25	14.24	11	14.15	9	113	13
S 13 - 14_NoCS	24.62	26	12.99	30	10.72	11	13.43	5	18.74	32	14.07	9	13.16	4	117	14
S 14 - 15_NoCS	24.78	27	13.03	31	10.80	13	13.70	7	17.79	24	14.36	13	13.31	5	120	15
S 14 - 15_NoCSO	24.00	17	10.90	10	10.46	10	15.46	18	16.08	12	16.96	30	18.07	23	120	16
S 12 - 13_NoCS	24.34	21	12.22	24	11.53	19	14.97	15	18.01	26	13.80	7	14.38	11	123	17
S 15 - 16_NoCS	24.49	25	12.51	28	10.89	16	14.22	9	18.71	31	14.37	14	13.05	3	126	18
S 10 - 11_LoCS	24.42	23	11.55	19	11.64	20	14.00	8	16.50	15	16.10	23	18.31	25	133	19
S 11 - 12_NoCSO	23.24	12	12.03	22	10.86	14	18.15	34	17.43	22	15.13	17	16.88	18	139	20
S 14 - 15_ LoCwSPr	23.88	14	11.36	16	11.79	23	15.91	20	16.88	18	15.95	21	18.95	29	141	21
S 14 - 15_LoCS	24.81	28	11.23	15	11.01	18	16.05	23	15.92	11	15.56	20	18.32	26	141	22
S 15 - 16_ LoCwSPr	22.55	10	11.10	11	12.27	25	16.60	28	17.26	20	16.74	27	17.57	21	142	23
S 11 - 12_LoCS	24.82	29	11.50	18	11.72	21	14.57	11	16.42	14	16.48	26	18.26	24	143	24
S 10 - 11_ LoCwSPr	26.36	33	10.90	9	12.09	24	14.92	14	16.26	13	16.34	25	18.72	28	146	25
Field	24.06	18	12.25	25	12.41	28	16.48	27	16.90	19	14.94	15	16.57	16	148	26
S 13 - 14_LoCwSPr	27.07	34	11.12	12	12.31	27	16.41	25	16.82	17	15.97	22	19.13	31	168	27
S 15 - 16_LoCS	25.26	30	11.93	21	12.28	26	16.07	24	17.35	21	16.80	28	19.11	30	180	28
S 10 - 11_NoCS	28.64	35	15.12	35	13.37	34	16.47	26	18.68	30	16.28	24	15.88	15	199	29
S 12 - 13_LoCS	24.38	22	12.12	23	12.76	31	16.63	29	19.68	33	17.09	31	19.36	32	201	30
S 13 - 14_NoCSO	24.21	19	13.39	34	13.01	33	20.48	36	20.64	34	16.95	29	17.93	22	207	31
S 11 - 12_ LoCwSPr	25.33	31	12.46	27	12.99	32	16.86	30	18.10	27	17.51	34	19.77	34	215	32
S 9 - 10_LoCS	25.92	32	12.90	29	12.72	30	17.25	32	18.29	29	17.22	32	19.99	35	219	33
S 13 - 14_LoCS	29.29	36	13.08	33	12.70	29	17.09	31	18.27	28	17.44	33	19.47	33	223	34
S 10 - 11_NoCSOPs	23.98	16	13.03	32	14.01	35	17.73	33	21.19	36	19.49	36	20.33	36	224	35
S 10 - 11_NoCSO	24.44	24	15.34	36	14.02	36	19.95	35	20.71	35	18.46	35	18.45	27	228	36

Appendix Table 10 Rank of Scenarios - Progression PI Value (WB)

Scenario	9:00 - 10:00		10:00 - 11:00		11:00 - 12:00		12:00 - 13:00		13:00 - 14:00		14:00 -15:00		15:00 - 16:00		Total	Rank
	PI	Rank	PI	Rank	PI	Rank	PI	Rank	PI	Rank	PI	Rank	PI	Rank		
S 9 - 10_NoCSOPs	15.81	1	12.91	2	10.35	1	11.91	2	12.51	1	10.46	2	14.83	4	13	1
S 14 - 15_NoCSOPs	16.47	2	12.57	1	12.45	11	12.51	5	13.80	2	9.92	1	14.96	5	27	2
S 11 - 12_NoCSO	18.11	4	14.12	5	11.87	4	12.56	6	14.16	3	11.76	3	15.87	8	33	3
S 13 - 14_NoCSO	17.88	3	14.09	4	12.38	9	12.34	3	14.98	6	12.17	5	15.87	9	39	4
S 10 - 11_NoCSO	18.58	7	14.50	7	12.02	6	12.82	9	15.10	7	12.20	6	16.85	12	54	5
S 9 - 10_NoCSO	18.48	6	14.07	3	11.94	5	13.39	14	14.96	5	11.91	4	17.51	17	54	6
S 13 - 14_LoCwSPr	18.88	8	14.27	6	11.47	2	13.34	13	15.12	8	12.41	7	17.00	15	59	7
S 9 - 10_ LoCwSPr	18.99	9	15.54	15	11.75	3	12.72	8	14.48	4	13.05	11	16.25	11	61	8
S 14 - 15_LoCS	19.76	12	14.78	8	12.16	8	14.26	17	15.88	12	12.76	8	16.94	14	79	9
S 12 - 13_ LoCwSPr	18.15	5	14.98	10	12.44	10	14.29	18	16.02	14	13.49	16	16.89	13	86	10
S 11 - 12_NoCS	20.55	19	16.89	22	13.66	20	11.82	1	15.96	13	13.01	10	14.53	3	88	11
S 15 - 16_ LoCwSPr	19.95	14	14.87	9	12.68	12	14.14	15	15.82	11	13.37	15	17.75	20	96	12
S 13 - 14_NoCS	20.03	15	17.28	25	14.20	24	12.84	10	17.14	24	12.81	9	14.20	1	108	13
S 12 - 13_NoCS	20.78	22	16.86	21	14.08	23	12.39	4	16.79	21	13.71	20	14.26	2	113	14
S 11 - 12_ LoCwSPr	19.73	11	15.17	13	13.10	15	14.61	24	15.41	9	14.00	24	17.76	21	117	15
S 14 - 15_NoCSO	20.59	20	15.04	11	12.07	7	14.87	25	16.36	16	13.61	17	19.25	28	124	16
S 15 - 16_NoCS	19.93	13	17.45	27	14.87	29	12.65	7	17.13	23	13.68	19	15.82	7	125	17
S 9 - 10_NoCS	20.37	18	17.58	28	14.71	27	13.03	11	17.48	26	13.21	13	15.35	6	129	18
Field	20.91	24	15.72	16	13.18	16	15.13	27	15.60	10	13.89	22	17.27	16	131	19
S 12 - 13_NoCSO	21.39	26	15.98	17	12.82	13	14.44	22	17.08	22	13.09	12	17.60	19	131	20
S 15 - 16_LoCS	20.89	23	15.24	14	13.41	18	14.20	16	16.56	19	13.62	18	17.93	23	131	21
S 14 - 15_NoCS	20.93	25	16.95	24	14.63	25	13.06	12	17.27	25	13.30	14	16.21	10	135	22
S 15 - 16_NoCSO	19.42	10	15.08	12	12.99	14	15.59	28	17.62	27	13.90	23	18.26	24	138	23
S 10 - 11_ LoCwSPr	20.76	21	16.03	18	14.65	26	14.43	21	16.24	15	14.12	25	17.54	18	144	24
S 14 - 15_ LoCwSPr	20.33	17	16.52	19	13.43	19	16.08	30	16.37	17	13.79	21	18.27	25	148	25
S 11 - 12_LoCS	20.20	16	16.95	23	13.96	22	14.60	23	16.66	20	14.18	26	18.29	26	156	26
S 9 - 10_LoCS	21.58	27	16.82	20	13.38	17	14.30	19	17.82	28	14.18	27	18.48	27	165	27
S 10 - 11_LoCS	21.67	28	17.65	29	15.48	30	14.35	20	16.45	18	14.85	28	17.82	22	175	28
S 13 - 14_LoCS	22.30	31	18.66	33	13.92	21	15.08	26	18.10	29	15.54	31	21.07	30	201	29
S 11 - 12_NoCSOPs	22.09	30	18.35	30	14.85	28	16.23	31	18.72	31	15.38	30	20.73	29	209	30
S 15 - 16_NoCSOPs	22.07	29	18.54	32	16.52	32	16.07	29	18.17	30	15.16	29	21.50	32	213	31
S 12 - 13_LoCS	22.51	32	17.33	26	15.82	31	18.08	32	21.21	33	15.91	32	21.10	31	217	32
S 13 - 14_NoCSOPs	24.10	33	18.45	31	18.28	34	20.75	34	21.72	34	16.99	33	21.55	33	232	33
S 10 - 11_NoCSOPs	28.02	34	19.11	34	16.89	33	19.32	33	21.02	32	17.81	34	23.64	34	234	34
S 10 - 11_NoCS	32.52	36	28.64	36	21.39	35	22.11	35	29.29	36	20.96	35	25.66	35	248	35
S 12 - 13_NoCSOPs	32.06	35	23.89	35	21.50	36	24.80	36	27.52	35	21.78	36	28.94	36	249	36

Appendix Table 11 Rank of Scenarios - Progression Average Travel Time (EB)

Scenario	9:00 - 10:00		10:00 - 11:00		11:00 - 12:00		12:00 - 13:00		13:00 - 14:00		14:00 -15:00		15:00 - 16:00		Total	Rank
	Travel Time	Rank	Travel Time	Rank	Travel Time	Rank	Travel Time	Rank	Travel Time	Rank	Travel Time	Rank	Travel Time	Rank		
S 14 - 15_NoCSOPs	148.42	2	135.11	3	134.42	4	142.15	6	138.57	1	139.14	1	145.81	9	26	1
S 13 - 14_NoCSOPs	146.87	1	129.44	1	136.56	9	141.44	3	142.28	4	143.98	4	147.92	11	33	2
S 15 - 16_ LoCwSPr	157.92	5	133.37	2	134.97	7	142.00	5	140.40	2	142.89	3	147.45	10	34	3
Field	160.53	7	138.47	8	136.61	10	144.11	9	140.59	3	142.84	2	145.11	8	47	4
S 12 - 13_NoCSOPs	153.92	3	136.52	5	137.64	11	144.55	10	142.32	5	146.50	6	150.05	12	52	5
S 15 - 16_NoCSOPs	155.57	4	138.70	9	140.58	15	145.93	14	144.43	7	148.64	14	152.48	14	77	6
S 15 - 16_NoCSO	159.90	6	140.59	13	142.64	20	144.10	8	147.63	11	148.15	13	151.45	13	84	7
S 12 - 13_ LoCwSPr	161.75	9	137.20	6	137.78	12	149.34	22	145.27	9	147.80	12	153.13	15	85	8
S 9 - 10_NoCS	165.86	13	151.92	29	134.76	6	143.85	7	160.94	26	147.18	8	136.09	4	93	9
S 11 - 12_NoCS	166.66	14	146.26	21	134.35	3	146.12	15	163.84	30	147.56	9	137.21	5	97	10
S 12 - 13_NoCS	167.73	16	148.00	23	135.85	8	145.78	12	161.30	27	146.36	5	137.59	6	97	11
S 14 - 15_ LoCwSPr	165.70	12	137.29	7	140.84	16	151.15	24	143.75	6	148.74	15	155.07	17	97	12
S 10 - 11_ LoCwSPr	172.17	28	136.05	4	141.69	17	145.54	11	144.72	8	146.52	7	159.59	23	98	13
S 13 - 14_NoCS	167.84	17	152.62	30	133.90	1	141.61	4	165.44	32	147.62	11	135.32	3	98	14
S 10 - 11_NoCSOPs	161.49	8	140.50	12	142.83	21	148.81	18	148.16	12	147.62	10	156.75	19	100	15
S 14 - 15_NoCS	168.60	20	153.25	31	134.33	2	141.09	2	161.44	28	148.85	16	133.72	2	101	16
S 15 - 16_NoCS	168.05	18	150.45	28	134.74	5	138.67	1	166.03	33	149.26	17	132.97	1	103	17
S 9 - 10_NoCSOPs	167.53	15	139.11	10	138.26	13	145.87	13	151.74	14	152.19	23	155.26	18	106	18
S 11 - 12_NoCSOPs	165.40	11	144.52	19	140.16	14	152.46	25	152.63	15	151.37	21	158.51	21	126	19
S 11 - 12_ LoCwSPr	169.41	22	140.11	11	143.09	23	149.13	19	146.61	10	151.51	22	159.26	22	129	20
S 9 - 10_ LoCwSPr	163.74	10	149.01	25	144.85	27	147.96	17	153.20	18	152.43	24	154.59	16	137	21
S 15 - 16_LoCS	170.50	23	141.92	16	142.86	22	147.39	16	152.99	17	149.77	19	161.59	25	138	22
S 11 - 12_LoCS	169.41	21	141.57	15	146.51	30	149.24	20	150.00	13	154.40	26	159.85	24	149	23
S 13 - 14_LoCwSPr	173.15	31	140.67	14	143.20	25	153.81	27	153.22	19	150.94	20	161.93	26	162	24
S 10 - 11_NoCS	176.00	35	155.86	33	145.08	28	149.31	21	164.81	31	149.31	18	142.83	7	173	25
S 14 - 15_LoCS	173.37	32	142.91	17	143.68	26	158.26	31	152.94	16	154.19	25	162.90	28	175	26
S 10 - 11_LoCS	171.64	25	143.83	18	147.83	31	150.42	23	156.43	20	155.97	29	165.42	30	176	27
S 9 - 10_LoCS	170.84	24	146.56	22	142.62	19	157.03	30	160.79	24	155.45	28	165.37	29	176	28
S 9 - 10_NoCSO	172.05	27	148.68	24	142.21	18	154.76	28	156.54	21	161.93	32	167.32	32	182	29
S 12 - 13_NoCSO	171.65	26	144.58	20	143.19	24	153.02	26	160.90	25	163.03	34	169.50	34	189	30
S 10 - 11_NoCSO	168.57	19	159.63	35	152.96	34	154.89	29	160.26	23	157.10	31	158.36	20	191	31
S 14 - 15_NoCSO	172.48	29	150.32	27	145.70	29	160.75	33	159.49	22	164.07	35	174.05	36	211	32
S 13 - 14_NoCSO	172.88	30	160.90	36	153.04	35	158.99	32	162.42	29	155.10	27	162.03	27	216	33
S 12 - 13_LoCS	173.67	33	149.08	26	151.62	33	165.61	36	166.99	34	162.07	33	167.54	33	228	34
S 11 - 12_NoCSO	173.90	34	156.82	34	151.12	32	161.05	34	169.64	35	156.89	30	165.45	31	230	35
S 13 - 14_LoCS	184.91	36	155.39	32	155.58	36	165.01	35	169.64	36	166.89	36	171.53	35	246	36

Appendix Table 12 Rank of Scenarios - Progression Average Travel Time (WB)

Scenario	9:00 - 10:00		10:00 - 11:00		11:00 - 12:00		12:00 - 13:00		13:00 - 14:00		14:00 -15:00		15:00 - 16:00		Total	Rank
	Travel Time	Rank	Travel Time	Rank	Travel Time	Rank	Travel Time	Rank	Travel Time	Rank	Travel Time	Rank	Travel Time	Rank		
S 9 - 10_ LoCwSPr	134.57	2	132.42	9	126.16	3	129.29	4	130.68	2	128.03	1	132.51	4	25	1
S 14 - 15_LoCS	134.71	3	128.41	1	126.16	2	134.99	15	131.98	4	129.75	3	134.34	6	34	2
S 11 - 12_LoCS	136.28	5	131.11	5	130.70	8	130.69	8	130.01	1	132.15	7	135.66	9	43	3
S 13 - 14_LoCwSPr	135.30	4	130.61	3	125.58	1	133.31	12	132.72	6	130.82	6	136.77	13	45	4
S 9 - 10_LoCS	136.35	6	131.16	6	127.19	4	131.05	9	133.57	8	129.39	2	135.93	10	45	5
S 10 - 11_LoCS	137.26	10	134.47	13	133.86	14	132.65	11	131.68	3	130.35	5	133.74	5	61	6
Field	136.83	8	131.60	7	131.36	9	135.74	16	132.18	5	132.16	8	136.06	11	64	7
S 15 - 16_LoCS	138.64	14	130.38	2	128.14	6	134.15	13	135.95	10	130.26	4	138.19	15	64	8
S 12 - 13_ LoCwSPr	134.11	1	131.10	4	129.16	7	135.88	17	136.87	13	134.24	11	136.08	12	65	9
S 13 - 14_LoCS	138.45	12	133.05	10	127.97	5	132.57	10	133.56	7	132.90	9	139.47	20	73	10
S 10 - 11_NoCSO	136.63	7	134.36	12	132.75	11	134.69	14	136.87	14	133.24	10	136.81	14	82	11
S 13 - 14_NoCSO	137.03	9	135.21	14	136.47	18	136.57	18	137.77	15	135.63	13	139.19	18	105	12
S 14 - 15_ LoCwSPr	138.46	13	135.75	15	133.38	12	142.21	24	135.29	9	136.73	15	139.57	21	109	13
S 11 - 12_ LoCwSPr	139.63	16	132.35	8	135.53	17	140.94	23	136.07	11	137.37	16	140.57	22	113	14
S 13 - 14_NoCS	138.29	11	148.89	31	142.95	26	128.73	3	141.43	22	146.25	27	131.02	1	121	15
S 11 - 12_NoCSO	140.07	19	138.86	19	134.75	16	138.63	19	138.72	16	136.69	14	139.38	19	122	16
S 11 - 12_NoCS	141.73	22	148.37	30	140.34	24	126.16	1	139.26	18	145.28	25	131.65	3	123	17
S 10 - 11_LoCwSPr	142.12	24	137.51	16	134.64	15	138.91	20	136.38	12	138.50	20	139.17	17	124	18
S 15 - 16_ LoCwSPr	140.56	20	133.41	11	132.72	10	140.29	21	140.54	21	137.93	18	143.20	24	125	19
S 9 - 10_NoCSOPs	139.77	17	138.30	18	133.45	13	140.64	22	138.87	17	137.40	17	141.37	23	127	20
S 12 - 13_NoCS	141.84	23	147.22	27	142.09	25	127.74	2	140.40	20	147.87	31	131.15	2	130	21
S 9 - 10_NoCS	139.80	18	149.22	32	145.16	29	129.84	6	140.28	19	146.46	29	134.74	7	140	22
S 15 - 16_NoCS	139.27	15	148.11	29	145.23	30	129.79	5	143.29	24	146.94	30	135.51	8	141	23
S 14 - 15_NoCS	141.38	21	147.02	26	144.97	28	129.91	7	141.77	23	146.30	28	138.94	16	149	24
S 14 - 15_NoCSOPs	143.13	26	138.07	17	144.22	27	144.73	27	146.76	28	134.97	12	143.51	25	162	25
S 9 - 10_NoCSO	143.00	25	141.54	21	138.12	20	143.92	26	144.90	25	138.46	19	147.91	28	164	26
S 11 - 12_NoCSOPs	146.69	28	145.98	24	136.55	19	142.84	25	146.08	27	143.17	21	147.50	27	171	27
S 12 - 13_LoCS	144.05	27	139.62	20	140.32	23	147.41	28	147.57	29	143.79	22	144.70	26	175	28
S 14 - 15_NoCSO	148.82	29	142.11	22	139.93	21	150.23	31	148.60	30	144.29	23	154.78	31	187	29
S 12 - 13_NoCSO	154.13	32	144.90	23	140.12	22	148.77	30	152.67	31	144.64	24	148.73	29	191	30
S 15 - 16_NoCSOPs	151.44	31	147.37	28	147.32	32	148.53	29	145.35	26	145.31	26	156.63	32	204	31
S 15 - 16_NoCSO	151.44	30	146.20	25	147.25	31	156.68	33	162.30	32	153.26	32	154.32	30	213	32
S 10 - 11_NoCS	167.66	33	172.71	35	157.48	33	154.12	32	172.52	33	161.20	33	157.66	33	232	33
S 13 - 14_NoCSOPs	169.20	34	160.33	33	168.23	35	180.80	35	177.44	35	169.93	34	171.29	34	240	34
S 10 - 11_NoCSOPs	177.21	35	162.49	34	166.71	34	174.47	34	173.19	34	174.10	35	178.96	35	241	35
S 12 - 13_NoCSOPs	188.65	36	181.22	36	182.73	36	195.84	36	196.19	36	192.98	36	195.43	36	252	36

Bibliography

[1] Webster, F. V., and B. M. Cobbe. Traffic Signals. Her Majesty's Stationery Office, 1966.

[2] Stevanovic, Aleksandar. “Adaptive Traffic Control Systems: Domestic and Foreign State of Practice.” 2010, doi:10.17226/14364.

[3] *HCM 2010: Highway Capacity Manual*. Transportation Research Board, 2010.

[4] Lu, Ting, et al. “Comparison of the Effectiveness of Common Cycle Computing Models.” *Procedia - Social and Behavioral Sciences*, vol. 138, 2014, pp. 358–367., doi:10.1016/j.sbspro.2014.07.214.

[5] Shelby, Steven G., et al. “Resonant Cycles in Traffic Signal Control.” *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1925, no. 1, 2005, pp. 215–226., doi:10.1177/0361198105192500122.

[6] Guevara, Felipe Ladrón De, et al. “Resonant Cycles under Various Intersection Spacing, Speeds, and Traffic Signal Operational Treatments.” *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2488, no. 1, 2015, pp. 87–96., doi:10.3141/2488-09.

[7] Li, Howell, et al. “Field Cycle Length Sweep to Evaluate Resonant Cycle Sensitivity.” 2014, doi:10.5703/1288284315509.

[8] Henry, R. David. *Signal Timing on a Shoestring*. U.S. Dept. of Transportation, Federal Highway Administration, 2005.

[9] Day, Christopher M., and A. M. Tahsin Emtenan. “Impact of Phase Sequence on Cycle Length Resonance.” *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2673, no. 11, 2019, pp. 398–408., doi:10.1177/0361198119852069.

[10] Guevara, Felipe Ladrón De. “Resonant Cycles and Traffic Signal Performance.” 2013.

[11] Roess, Roger P., et al. *Traffic Engineering*. Pearson, 2004.

[12] Bullock, Darcy M, et al. Project 3-79a, NCHPR, 2010, *Vehicle Detector Signal Processing for Travel Time Estimation*.

[13] PTV-Vision, *PTV Vistro 2020 User Manual*, 2019.

[14] PTV-Vision, *PTV Vissim 2020 User Manual*, 2019.

[15] So, Jaehyun., Ostojic Marija., Jolovic, Dusan., Stevanovic, Aleksandar. “Building, Calibrating, and Validating A Large-Scale High-Fidelity Microscopic Traffic Simulation

Model – A Manual Approach". *95th Transportation Research Board Annual Meeting Proceedings*, 2015.

[16] Koshi, Masaki. "Cycle Time Optimization in Traffic Signal Coordination." *Transportation Research Part A: General*, vol. 23, no. 1, 1989, pp. 29–34., doi:10.1016/0191-2607(89)90137-4.

[17] Day, Christopher M., et al. "Cycle-Length Performance Measures." *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2128, no. 1, 2009, pp. 48–57., doi:10.3141/2128-05.

[18] Tian, Zong, and Thomas Urbanik. "System Partition Technique to Improve Signal Coordination and Traffic Progression." *Journal of Transportation Engineering*, vol. 133, no. 2, 2007, pp. 119–128., doi:10.1061/(asce)0733-947x(2007)133:2(119).

[19] Day, Christopher M., et al. "Outcome-Oriented Performance Measures for Management of Signalized Arterial Capacity." *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2192, no. 1, 2010, pp. 24–36., doi:10.3141/2192-03.

[20] Day, Christopher, et al. "Integrating Traffic Signal Performance Measures into Agency Business Processes." 2015, doi:10.5703/1288284316063.