Effective Traffic Signal Timing for Intersections in Bangkok

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A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering in Industrial Engineering
Department of Industrial Engineering
FACULTY OF ENGINEERING
Chulalongkorn University
Academic Year 2021

การให้สัญญาณไฟจราจรอย่างมีประสิทธิภาพสำหรับทางแยกในกรุงเทพมหานคร

นายกษิดิ์เดช ตันติพานิชพันธ์

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต

สาขาวิชาวิศวกรรมอุตสาหการ ภาควิชาวิศวกรรมอุตสาหการ

คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย

ปีการศึกษา 2564

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กษิดิ์เดช ตันติพานิชพันธ์ : การให้สัญญาณไฟจราจรอย่างมีประสิทธิภาพสำหรับทางแยกในกรุงเทพมหานคร. (Effective Traffic Signal Timing for Intersections in Bangkok) อ.ที่ปรึกษาหลัก : ผศ. ดร.พิศิษฐ์ จารุมณีโรจน์

จำนวนยานพาหนะบนท้องถนนที่เพิ่มสูงขึ้นในกรุงเทพฯ ส่งผลทำให้เกิดปัญหาการจราจรมากมายทั้งต่อผู้ขับขี่ และผู้ใช้ถนนโดยทั่วไป เพื่อบรรเทาปัญหาดังกล่าว การจัดการสัญญาณไฟจราจรที่มีประสิทธิภาพจึงเป็นสิ่งจำเป็น และถือเป็นหนึ่งในแนวทางปฏิบัติที่สามารถนำมาประยุกต์ใช้ได้จริง ด้วยเหตุดังกล่าว ผู้วิจัยจึงได้ทำการพัฒนาแนวทางการจัดการสัญญาณไฟจราจรของทางแยกในกรุงเทพฯ ผ่านแบบจำลองทางคณิตศาสตร์ โดยมีจุดมุ่งหมายหลักเพื่อปรับปรุงอัตราการไหลของยานพานหะในแยกดังกล่าว ผู้วิจัยได้เลือกทดสอบแนวทางที่พัฒนาขึ้น โดยอ้างอิงจากข้อมูลของทางแยกในกรุงเทพฯ จำนวน 6 ทางแยก ซึ่งผลของการทดสอบบ่งชี้ว่า แนวทางที่พัฒนาขึ้นให้ผลลัพธ์ที่มีประสิทธิภาพสูงกว่าแนวทางปฏิบัติในปัจจุบัน โดยเราสามารถเพิ่มจำนวนรถที่ออกจากทางแยกโดยรวมได้ดีขึ้นกว่า 23.04% นอกจากนี้ ผู้วิจัยยังพบว่า วิธีการดังกล่าวยังสามารถลดเวลาการเดินทางโดยรวมบนแยกที่ต่อเนื่องกันได้อย่างมีประสิทธิภาพอีกด้วย

สาขาวิชา	วิศวกรรมอุตสาหการ	ลายมือชื่อนิสิต
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ปี	2564	ลายมือชื่อ อ.ที่ปรึกษาหลัก
การศึกษา		....

6370016021 : MAJOR INDUSTRIAL ENGINEERING

KEYWORD: Traffic Signal Optimization, Effective Green Time, Optimization Programming Language

Kasidech Tantipanichaphan : Effective Traffic Signal Timing for Intersections in Bangkok. Advisor: Asst. Prof. PISIT JARUMANEEROJ, Ph.D.

The increasing number of on-road vehicles in Bangkok, as well as the traffic flow conditions, are causing many problems for the citizens. To alleviate the problem, effective traffic signal management by optimizing traffic signal timing can be used. As a result, the goal of this research is to improve Bangkok's traffic signal system and management by establishing an effective green light time at intersections in order to increase the vehicle flow rate. The mathematical model is designed to maximize the number of vehicles leaving intersections. Six Bangkok intersections are selected for the experiments. According to the experimental results, the optimization model outperforms current practice by increasing the number of vehicles leaving the intersection. The overall vehicle flow rate improves by 23.04%. Furthermore, combining the intersections together will allow the synchronization of vehicle flow from one intersection to another.

Field of Study:	Industrial Engineering	Student's Signature ....
Academic Year:	2021	Advisor's Signature ....

ACKNOWLEDGEMENTS

The author would like to thank thesis advisor for helping with thesis suggestions, and Genius Company for helping with data collections and gain greater understanding in traffic concept.

Kasidech Tantipanichaphan

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Chapter 1

Introduction

1.1 Problem Statement

In Bangkok, the increasing number of on-road vehicles and the traffic flow conditions nowadays are getting more and more saturated. New roads with more lanes are built to increase the capacity of the current traffic networks. Due to the following and also the fast development in most of Thailand’s major cities, traffic congestion is still problematic. Traffic signaling is a cumbersome business, causing problems in terms of ineffective traffic flow. According to the Traffic Index 2020, which covers 416 cities across 57 countries, the congestion level in Bangkok is 44% in 2020 which ranked the 10th for the world traffic index (Index, 2020). These problems also caused PM 2.5 and other air pollution due to the congestion level. According to monitoring results of PM 2.5 in Bangkok areas, where there’s a heavy traffic congestion during rush hours, a high PM 2.5 mass concentrations is detected. The key contributor largely came from the diesel-fueled fleets (Narita et al., 2019). In Figure 1-1, shows the map of locations of PM 2.5 monitoring stations in Bangkok Metropolitan Region.

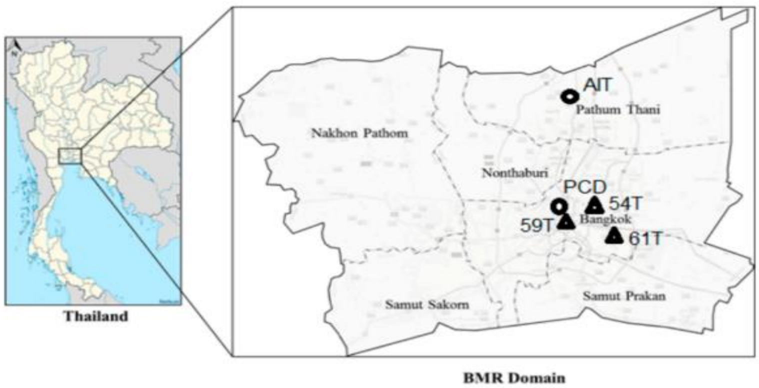

Figure 1-1 Map of the locations of PM 2.5 monitoring stations in Bangkok Metropolitan Region.

Monitoring stations located at the Pollution Control Department (PCD) at 54T, 59T and 61T and Asian Institute of Technology (AIT). The stations that were located at PCD building is situated approximately 60 meters high above the ground and 0.75 km away from the main road, which has heavy traffic congestion during rush hours. Similarly, AIT site is located approximately 0.5 km away from the main road and is about 40 km from the Bangkok center. In Figure 1-2, it is shown that the levels of PM 2.5 concentration at AIT and PCD have a higher total PM 2.5 mass concentrations measured at these stations compares to the air quality standard for PM 2.5 in outdoor air, which should be approximately 12 μg/m^3. Although the level of PM 2.5 at AIT and PCD had similar seasonal variation patterns, 59T-GPRU which is surrounded by the most congested traffic area shows a really high PM 2.5 mass concentration.

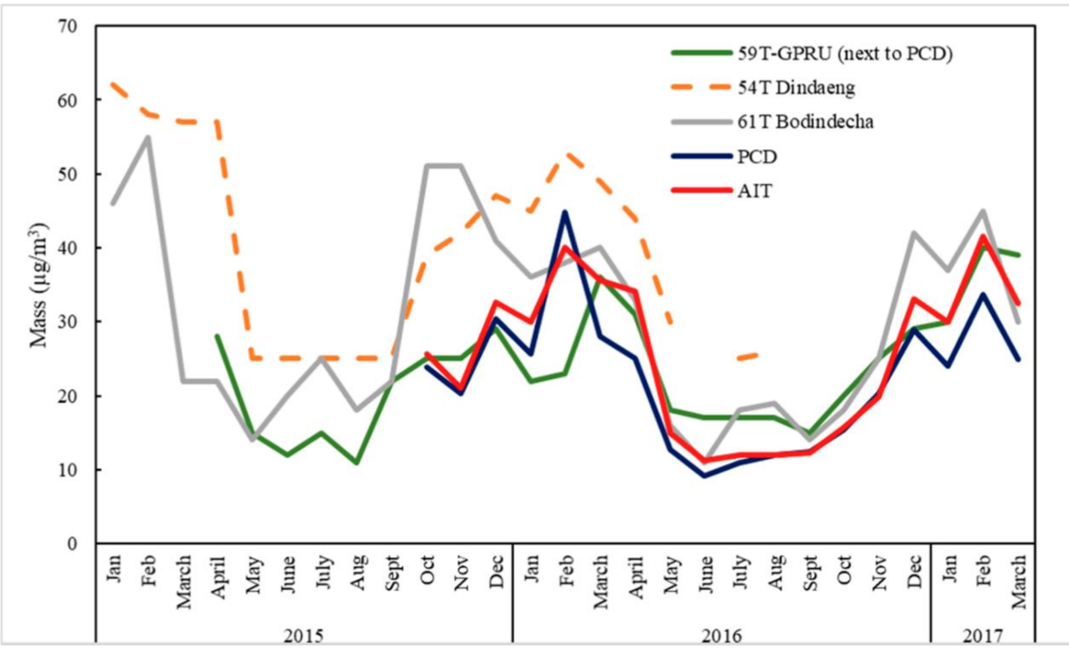

Figure 1-2 Monthly variations of PM 2.5 concentration.

According to Figure 1-2, the chart reveals the source emission shares in the BMR domain based on their collected emission inventory data. It is clear the main source of PM 2.5 pollution in BMR came from on-road mobile source, with 59% accounted for total PM 2.5 emission. Hence, this represented a highest share for PM 2.5 emission. In the previous 3 years, people in Bangkok have experienced PM 2.5 concentration. This will certainly have an adverse effect towards community health condition. According to Muller (2021), during the recent months people in Thailand has experienced PM 2.5 which equivalent to smoking a cigarette for 163.38 roll, which would be 5.51 roll per day. Hence, PM 2.5 is still considered as a big problem in terms of health even today. One of the major causes is from the traffic congestion.

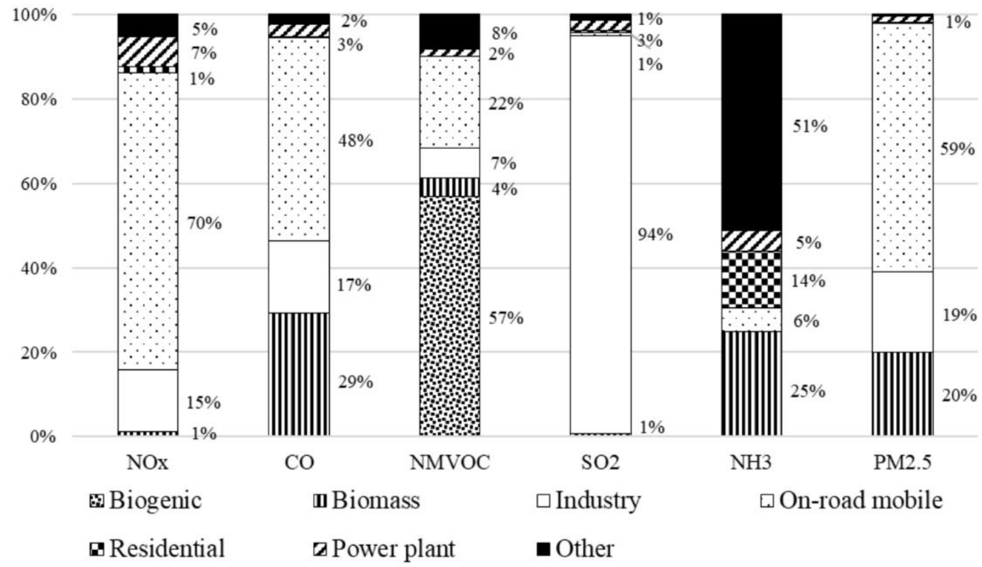

Figure 1-3 Source emission shares in the BMR domain (Bangkok city and surrounding provinces) based on our emission inventory data.

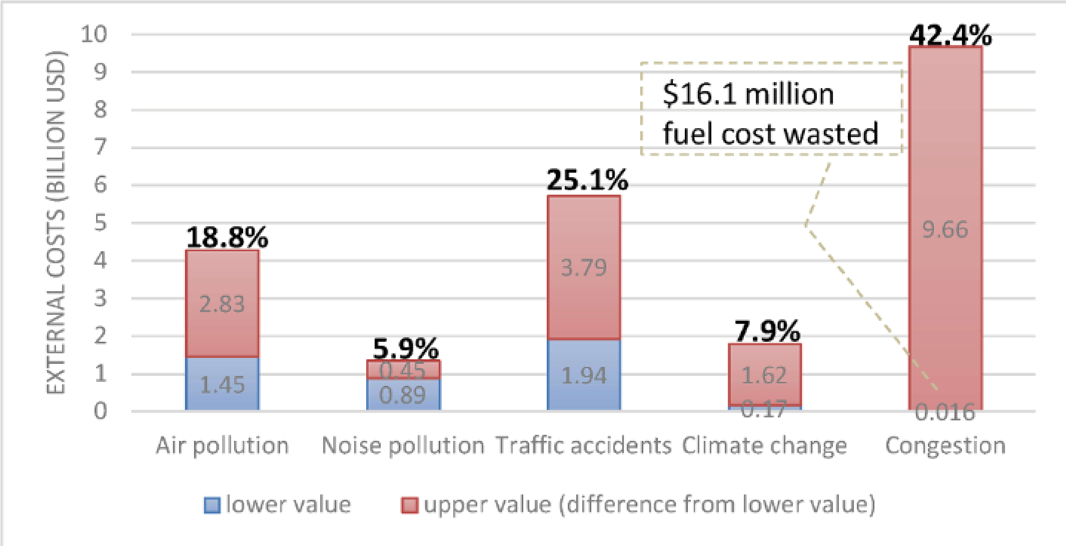

Figure 1-4 The External Cost of Mobility in the BMR.

In terms of the external cost of mobility in the Bangkok Metropolitan Region computed by prince of Songkla University, they focus in the following area: air pollution, noise, climate change, traffic accidents, and congestion. The congestion cost is the major externality and followed by accidents, air pollution, climate change, and noise pollution. According to Figure 1-4, the congestion cost is composed of 16.1-million-dollar fuel cost wasted. For air pollution, there is a possibility that 40% to 75% of deaths are caused by the transport sector. The death could potentially involve air pollution, and respiratory disease. For climate change, carbon dioxide, nitrous oxide, and methane were the major contribution. Other problem related to the noise pollution, in which it exceeds the 70 dB noise level which imply the health issues and annoyance for the Thai community. For transport sector, the main problems have been congestion, accidents, and pollutions. Certainly, it raises the travel time costs and threaten health and life of the Thais. As evident in many sources, accident and congestion are expectedly high.

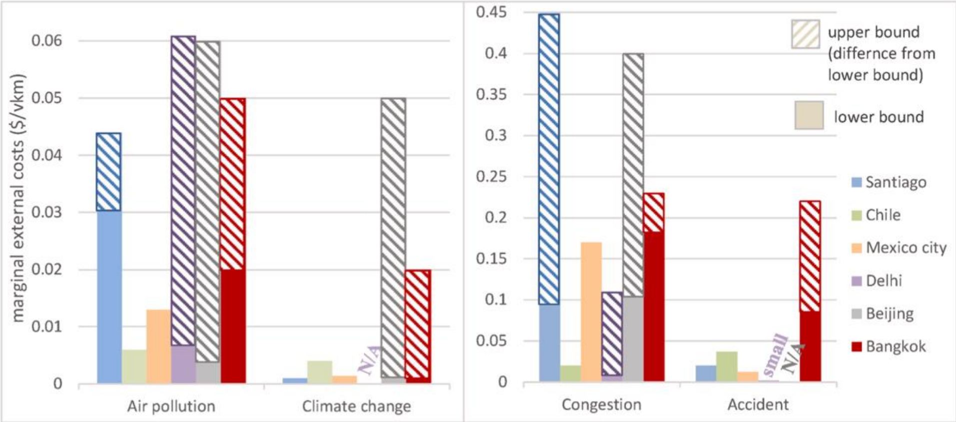

Figure 1-5 External cost comparison across cities/countries

If we examined external cost across the cities and countries such as Santiago, Chile, Mexico City, Delhi, and Beijing, we can see that Bangkok marginal air pollution cost is relatively high. For the marginal cost of accident, Bangkok is higher than those cities. On the other hand, the congestion cost is close to Mexico City and is between Santiago and Beijing. Nevertheless, this shows that Bangkok is comparable to these cities, in which they are all well-known for their congestion and pollution.

In addition, the increased traffic congestion could increase the frequency of crashes, especially rear-end collisions (Champahom et al., 2021). According to World Health Organization, Thailand is ranked the 9^{th} in the world in terms of crash fatality rates in Global Status Report on Road Safety (WHO, 2020). At the same time, an ambulance and the emergency vehicle are unable to respond in an appropriate amount of time because of traffic congestion (Surgeons, 2014). In Bangkok, these problems can be seen almost all the time during the rush hour. Therefore, a bad traffic signal effect disorderly traffic movement, provide for the discontinuous flow of a platoon of traffic, elevate PM 2.5 concentration, increase the frequency of certain types of crashes, and allow fewer essential vehicles to cross a heavy traffic stream (Schroeder et al., 2010).

The rudimentary cause comes from the fact that the traffic signaling control and management system in Bangkok is quite poor, which thereby causes the delay in terms of traffic flow (Marks, 2020). It is a major cause for the excessive delay. For instance, it would take approximately 10 minutes from Pradiphat intersection to Tuk Chai. However, with congestion, the traveling time often changes to 18 minutes due to the traffic delays. This is because the ineffective flow out of the vehicle from the intersection increase the delay of the traffic, since it is correlated with the traveling time from each of the approaches at an intersection. Notice that the delay causes people to travel to the desired destination unpredictably slower than usual. One of the reasons that causes the delay in terms of traffic flow is we have to wait until the cycle length is complete, and not many people have come across an effective way to optimize these traffic signals. Therefore, an engineering study of optimization for traffic signal timing shall be performed.

1.2 Objectives

The objective is to increase the effectiveness of traffic signal timing for road intersections in Bangkok, by using mathematical model to improve the traffic flow problems that are currently occurring. Thus, the condition of the traffic flow in different intersections will be the measurement.

1.3 Scope of the Research

Traffic delay problems are manifesting in many different areas in Bangkok. However, intersections are the critical areas that cause subsequent congestion for the rest. Therefore, they are a perfect place to measure the condition of traffic flow.

1.3.1 Study Area

For study area, intersections are certainly a perfect place to measure the condition of traffic flow, since it is one of the critical areas that causes a subsequent congestion for the rest. The study areas include Pradiphat, Rama VI Soi Siri 37, Rama VI Soi Set Siri 2, Rama VI Soi Set Siri, Rama VI Thanon Nakhon Chaisi, and Tuk Chai intersections as shown in Figure 1-6 and Figure 1-7. These intersections are regarded as busy during the peak period, and yet could potentially have a poor level of service and also a traffic management system. The intersections are controlled by traffic control and traffic wardens. Commercial buildings are found very close to the intersections.

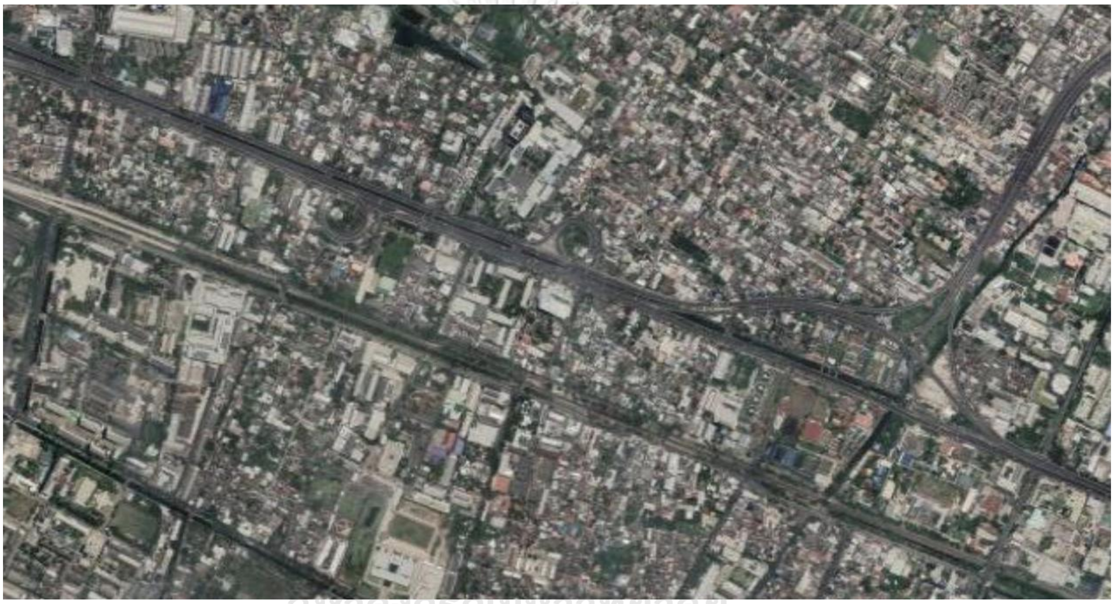

Figure 1-6 Satellite view for intersections of study.

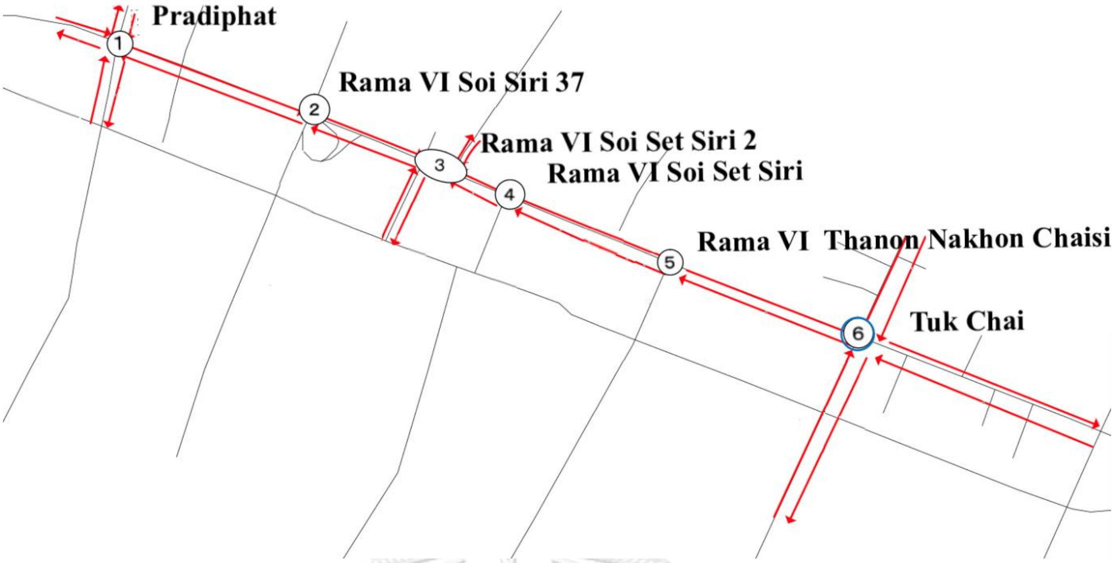

Figure 1-7 Traffic view for intersections of study.

1.3.2 Optimization Programming Language (OPL)

Optimizing the effective green time and the effective flow rate of the vehicle leaving from the intersection will be implemented in Optimization Programming Language (OPL). An algebraic modeling language for mathematical optimization models. The optimization models will be constructed before executing in OPL programming. The models include traffic system parameters, decision variables, objective functions, and essential traffic constraints. Subsequently, the simulation program will be implemented after the satisfaction result have been received from OPL.

1.4 Expected Outcome

After the implementation of the model and traffic coordination, the method improves the traffic flow of all the intersections of study which have a poor traffic management. The time of the green light for different approaches clear most of the queue in different approaches at an intersection. The flow rate of the vehicle increases and improve the number of vehicles leaving from intersection during rush hour. For main result, the overall vehicle flow rate has improved by 23.04%. The reasonable time for the green light is given to different approaches and clear the queue for that approach at an intersection. Approximately 431.85 more vehicles are leaving the intersection.

1.5 Expected Benefits

There are many benefits from this project. One of the main benefits is that it attempts to solve the delay problem. Notice that the traffic congestion causes an unpredicted journey and travel, and inability to estimate travel times. This problem cause people to get to work late, or travel to the desired destination unpredictably slower than usual. Which thereby cause a reduction in terms of traveling time. This research will be beneficial towards the traffic management industry in Bangkok, since it is able to reduce traffic volume and improve traffic flow at each leg of an intersection.

In the context of this project, we perceive that effective flow out of the vehicle from the intersection would reduce the delay of the traffic since it is correlated with the traveling time from each of the approaches. Hence, the improvement in terms of traffic flow is the central focus in this study. Additionally, this project also attempts to fix other external problems such as air pollution, PM 2.5, gasoline consumption, reduce frequency of crashes such as rear-end collision, and other factors which share correlation with excessive delay and traffic congestion.

Chapter 2
Literature Review

2.1 Traffic System Overview

To optimize the traffic signal timing or maximize the flow out of the vehicles from the intersection, it is essential to understand what is the factor that controls the traffic flow efficiency before introduces its underlying problem. In general, traffic signals work as a fixed-time signal that follow a predetermined sequence of signal operation, and usually always providing the same amount of time to each traffic movement (Teo et al., 2010). The actuated signals change the lights according to the amount of traffic in each direction. The objective is to adjust the length of the green light to allow as many vehicles as possible through the intersection before responding to the presence of vehicles on another approaches. To ensure an orderly flow of traffic, which provide an opportunity for vehicles to cross an intersection and reduce the number of conflicts between vehicles entering intersections from different directions.

2.1.1 Traffic Lights

To control the traffic flow, three signals are given by the traffic light. They are green, red, and amber (Teo et al., 2010). Traffic flow of each phase gains permission to pass the vehicle based on green signal. Therefore, green signal is the most important signal in terms of vehicle flow. Conversely, red signal prohibited vehicles to pass through the intersection. While amber, or yellow signal, is given between red and green signal to indicate warning to the traffic flow to slow down their vehicle. The performance of the traffic flow is determined by these three traffic signals (Popescu et al., 2010).

There are few studies that tries to improve the control of the traffic light. Not many algorithms have yet created to improve the system of the traffic control. Specifically, the demand of the green light depends on the traffic control. It is essential that the study of the traffic lights systems will improve the traffic flow of the vehicle in the road networks, and also the incoming flow (Chitour & Piccoli, 2005).

2.1.2 Traffic Junction and Flow

At every junction (or intersection), they have same or different number of approaches. In every approach, traffic flows existed which consist of several important parameter, which are queue length, cycle time, lost time, and incoming traffic flow (Teo et al., 2010). The total number of vehicles that line up in front of the intersection is represented by the queue length. Since there is a wait time to be given before passing the intersection. This is considered as one of the performance indicators for the traffic system. For instance, a long queue length indicates a weak traffic flow control, since it was able to serve a small number of demands and not many vehicles were able to passes through the intersection. On the other hand, a short queue length indicates that the traffic flow was able to let most of the vehicle pass through the intersection. Subsequently, the cycle time is basically the time for traffic light signals to be circulated once after all of the phase having their turn in the green time. On the other hand, lost time is time in which no vehicle was able to pass through the intersection, despite the green signal traffic display. It is the time which lost between the interchange of signals. Lastly, the incoming flow is the one which increasing the queue length and the demand of the green light in the traffic flow control. Essentially, the traffic flow is very important which this will affect all the components of the traffic system. This will be examined in the next section.

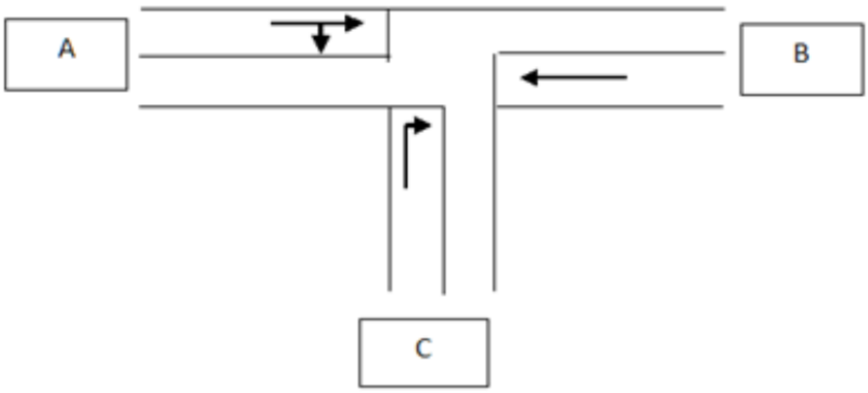

Figure 2-8 Example of T-junction intersection.

2.2 Research Problems in Traffic System.

The disruption of traffic flow or system was mostly due to the ineffective green time that was given in one of the approaches of an intersection, which thereby cause the delay in other approaches of an intersection (Branston & Van Zuylen, 1978). Hence, effective green time is a very important inputs to method of estimating delay-minimizing or capacity maximizing signal settings. In the case of rush hour, traffic management becomes even more challenging, and the overflow queue could be easily observed because they receive an ineffective green time. The overflow queue, or the ineffective queue, is defined as the part of the queue that is not processed during the green interval and that must be served by subsequent cycles as shown in Figure 2-2. Therefore, it is the best indicator for the traffic condition whether it is at a saturated level (Urbanik et al., 2015).

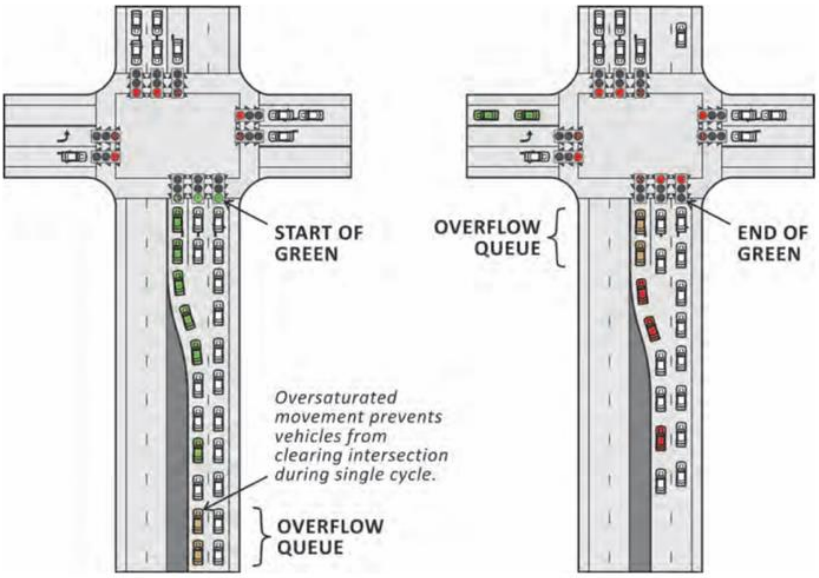

Figure 2-9 Overflowing queue.

In undersaturated condition, demand is equivalent to the measured traffic volume. In Figure 6, more vehicles arrive for a movement than can be served, the movement then considered to be oversaturated. Additional delays will also occur in the network (Urbanik et al., 2015). The true demand at an over capacity intersection is usually unknown, and this can be a problem for developing a signal timing plan. The time may be added to a given movement, only to have it used up by the previously unserved demand and possibly transfer the over-capacity problem to another location (Kulovic, 2015).

2.2.1 Traffic Management in Bangkok

The overflowing queue occurs at the intersection area. Subsequently, intersections are the critical areas that cause subsequent congestion for the rest (Muneera & Krishnamurthy, 2020). In Bangkok, traffic delay problems are manifesting in many different areas (Marks, 2020). Hence, this problem occurs at a very large scale. There are several intersections that are regarded as busy during the peak period, and yet they have a poor level of service and also a traffic management system. Most of the intersections are controlled by traffic control and traffic wardens. Commercial buildings are found very close to the intersections. Traffic management in Bangkok usually released the vehicle based on the total queue at each approach of an intersection. Sometime, it is based on the personal preferences by an officer (Pianuan et al., 1994). This is inadequate for solving the problem in terms of Bangkok Traffic due to its current magnitude and complexity (Poboon et al., 1995).

According to Koganti (2012), preliminary tests found that the optimization method used is very effective in finding the appropriate cycle time for yielding minimal intersection delay. When employing these results into the simulation, in both normal traffic and congested flow conditions, the vehicle throughput was found to increase while the delay was reduced (Koganti, 2012). By giving a reasonable amount of effective green time, this will improve the condition of the flow because more vehicle will leave from the intersection from all of the approaches. Hence, a non-linear programming model for optimization can be considered to alleviate the problems of the improper traffic signals timing. Similarly, Bangkok traffic management can be improved if it incorporates the use of optimization technique.

2.3 Related Theories and Research.

There are some studies for the improvement in the traffic control, which have been conducted in the past. Specifically, theory formulation on optimization of traffic signal timing requires research regarding the flow rate at signalize movement, constraints for traffic systems, and traffic coordination strategy.

2.3.1 Flow Rate at Signalize Movement

National Cooperative Highway Research Program (2016) expand the knowledge regarding traffic flow and a guide for a mobility analysis. The objective is to help practitioners apply methods to improve the transportation system and also give basics regarding the concept. The concept of this research traces the standardized technique for measuring the flow rates at a signalized movement. The flow rate is the hourly rate at which vehicles pass appoint on a lane. This can be computed as the number of vehicles passing the point and divided by the time interval in which they pass. This is expressed as vehicles per hour.

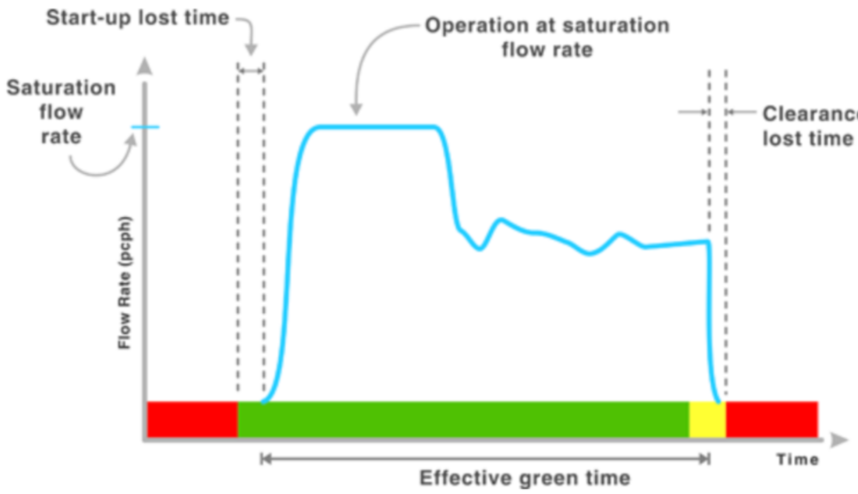

Figure 2-10 Example of flow rates at signalized movement.

According to Urbanik et al. (2015), they conducted research on traffic system and created a signal timing manual. In Figure 2-3 from signal timing manual shows the vehicle flow rate versus the signal time. It is a basic operation of vehicular movement through a signalized intersection. The vertical axis is represented as flow rate, while the horizontal axis is represented as time. The red, green, and yellow extension are represented as red, green, and yellow signal time respectively. There is a start-up lost time, or start-up delay, which has to occur during the process. Lost time is the time at which no vehicle is able to pass through an intersection despite the traffic signal displaying green. Indeed, it would take time to gear down and back up again, and some vehicle take some time to accelerate. After the start-up lost time, we can see that the arrow extension is represented as the effective green time, where there is a presence in terms of flow rate. Effective green time is the time during which a given traffic movement or set of movements may proceed at saturation flow rate (Sasaki & Nagatani, 2003).

Subsequently, the flow rate starts to increase until it operated at saturation. The flow rate stabilizes at the maximum flow rate. When it reaches a certain time, the flow rate decreases until it is completely at zero value. Green time period that receives.

In terms of the vehicle flow rate, National Cooperative Highway Research Program traces the standardized technique for measuring the flow rate at a signalized movement. The flow rate is an hourly rate at which vehicles pass a point on a lane and can be computed as the number of vehicles passing the point divided by the time interval (vehicles per hour).

2.3.2 Boundary Constraints for Traffic System

An understanding of traffic constraints requires a knowledge of an activity during the day time, so that signal time can effectively be implemented. Federal Highway Administration (2016) has collected the data on traffic volumes at critical locations. In their case shows how traffic volumes can change over 24-hour period (Guide & DOT, 2016). There are two cycle lengths that was selected. This specified when the traffic peaks (between 7:00 am to 10 am and 3:00 pm to 8:00 pm) and when the traffic is normal (10:00 am to 3:00 pm). The longer cycle length should be given to the peak period, while the short cycle length is given between the normal period. However, this case contains no boundary constraints.

The traffic volume appears to be higher and more critical in certain hour between 7:00 am to 10 am and 3 pm to 8 pm, and this occurs during rush hour. For example, in their case, a cycle time of 110 seconds has been selected at their study location during peak period. While cycle time of 85 seconds has been selected at this location during regular period. A certain cycle time is required in order to give the intersection time to recover from any negative impacts of transition.

According to TomTom Traffic Index 2022, the peak period for congestion in Bangkok is between 5:00 to 6:00 pm (TomTom Index 2022). At 6:00 pm in Bangkok, the congestion level has average around 64% in 2022. This means that the traveling time were 64% longer than the baseline non-congested condition. Commonly, the average congestion level in Bangkok is around 31%. In other words, driving in a 30-minute trip in free flow condition will take approximately 9 minutes longer for the traveling time. Therefore, it is worth studying between these periods due to the congestion level that occur.

Ajarn Anousack Thammavong and Boualinh Soysouvanh (2016) conducted one of their studies on “Optimization of Traffic Signal Time and Coordination for Road Network with Oversaturated”. In order to determine the optimum cycle length for the intersection, they use webster theory and applied the calculation (Thammavong & Soysouvanh, 2016). The Webster method has shown that for a wide range of practical minimum intersection delay is obtained by the equation below.

$$C_o = \frac{1.5L + 5}{1 - \sum_{i=1} Y_i} \qquad (1)$$

Where : C_0 is the optimum cycle length (sec), L is the total lost time per cycle (sec), Y_i is the maximum value of the ratio of approach flow to saturation flow for all lane groups using phase i (i.e. $q_{ij}s_j$), ϕ is the number of phases, q_{ij} is the flow on lane groups having the right of during phase i, s_j is the saturation flow on lane group i.

$$L = \sum_{i=1}^{n} t_{l_i} \qquad (2)$$

Where : t_{l_i} is the lost time for phase i (sec) and L is the total lost time of entire cycle (sec/cycle)

By using the Webster method, this will determine the suitable signal timing for the intersection using four-phase system. Using a yellow interval of three seconds and saturation flow given (Thammavong & Soysouvanh, 2016). A practical range of cycle length is considered in the optimization. This range is used to set upper and lower bounds. Additionally, one cycle length is also represented by phase duration, or the collection of time in all phase.

Mannering, Washburn, and Kilareski (2009) explains that phase duration is defined as the following,

$$Phase\ Duration = G + Y + AR \quad (3)$$

A phase duration is defined as green, change (yellow), and then clearance (all-red) time intervals in a cycle. A cycle represents the total amount of time to complete one sequence of indicated signalization (Mannering & Washburn, 2020).

In their research, Webster plot the graph using the computer simulation to observe and to develop a cycle-optimization equation, or Equation 1. His intention was to minimize delays when arrivals are random.

According to research at University of Akron (2012), preliminary tests found that the optimization method used is one of the ways in yielding minimal intersection delay. When employing these results shown in the visualization, in the congested flow conditions, the vehicle throughput was found to increase while the delay was reduced (Koganti, 2012).

When a reasonable amount of effective green time was given, this will certainly improve the condition of the flow because more vehicle will leave from the intersection from all of the approaches. In the same research stated that, a non-linear programming model for optimization can be considered to alleviate the problems of the improper traffic signals timing.

Figure 2-4 is an example that Oak Ridge National Laboratory has conducted the visualization of the traffic flow at an intersection after the process optimization (Gregg, 2014).

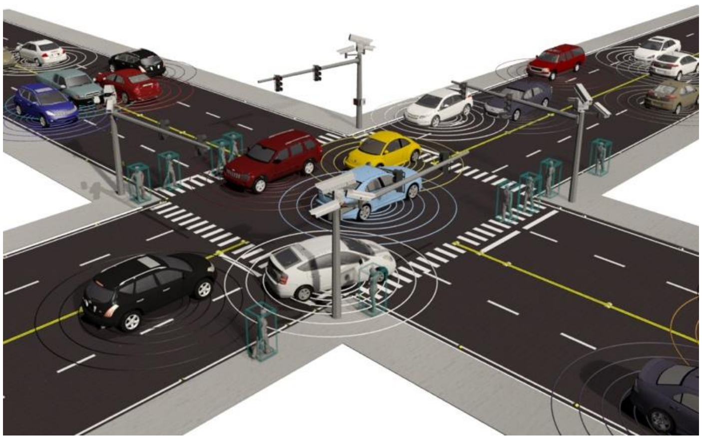

Figure 2-11 Visualization of the traffic flow at an intersection generated by Oak Ridge National Laboratory.

2.3.3 Traffic Coordination Strategy

In the case where the isolated intersections are combined together, one of the solution approaches is to form a traffic coordination. Traffic coordination is a strategic approach to synchronize the signals together to meet specific objectives. This can be examined by the time-space diagram chart in Figure 2-5, which plots ideal vehicle platoon trajectories through a series of signalize intersections. According to Urbanik et al. (2015), the locations of intersections are shown on the distance y-axis. On the other hand, the x-axis represents the time axis, or the signal timing sequence and splits for each signalized intersection. The result of signal coordination is illustrated on the time-space diagram below. The start and end of green time show the potential trajectories for vehicle on the street.

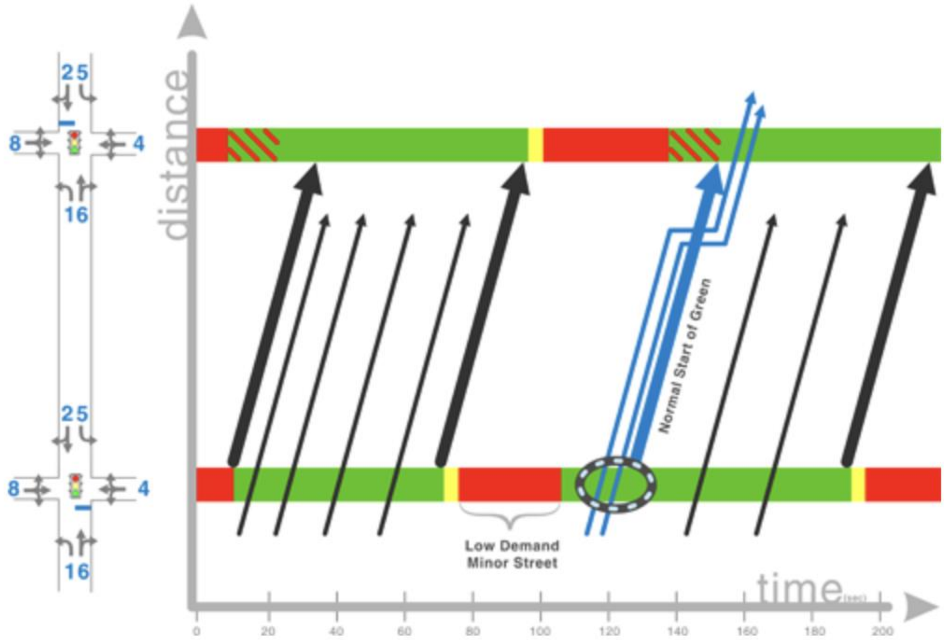

Figure 2-12 Time-space diagram of a coordinated timing plan.

In Figure 2-5, we can see the two intersections at the left diagram, along with the corresponding time for each approach. Assuming that we have the connected intersection between intersection 1 and 2, the signalized movements will look like the following above right diagram. One cycle length is equivalent to one complete cycle of green, red, and yellow band, which represents the color of the traffic signal (Koonce & Rodegerdts, 2008). By observation, we can see the trajectories between intersections' signal. As we move through the time axis, the corresponding distance also increases according to the arrows. Ideally, we should find the greatest range of possible trajectories between two thick arrows, which is the green time-space between the first and second signalized movement. The process will have more signalize movements, if there are more intersections combined.

2.4 Literature Review Summary.

The theories and related research were formulated to develop the specific mathematical model and algorithms. In our research, we want to maximize the number of vehicles that leave or flow out of the intersection, which are calculated using the signal time of the green light from different approaches multiply by the flow rate. The concept is similar to the related work; however, we multiply with the actual flow rate instead of the saturation flow rate because we want the number of vehicles that leaves the intersection. The result is expressed as number of vehicle(s). In order to improve the traveling time and the flow rate of the vehicle, system constraints should be placed to ensure that the result optimize result is obtained. These constraints include upper and lower bound, and may share correlation from one to another. For the lower bound, the lost time is considered. Webster's optimal cycle length model uses lost time, which is another parameter for the traffic signal system and related to optimal cycle length model (Thammavong & Soysouvanh, 2016; Zhou & Zhuang, 2013). As mentioned, lost time is the time at which no vehicle is able to pass through an intersection despite the traffic signal displaying green (Jianhu & Kamitani). According to Ajarn Anousack Thammavong and Boualinh Soysouvanh, by making a platoon of vehicle that can travel along the entire arterial without stopping would be desirable. In our research, in order to maximize the number of vehicles flowing out of the intersection, this requires an effective green time in specific approaches in order to discharge the queue in different approaches (Lin & Thomas, 2005). In our case, the effective green time is the time of the between start-up lost time until when the flow rate reaches the saturated level. For the case of congested flow condition congested, the higher volume causes the additional delay when compares with the case of normal flow condition. Because of this, optimum cycle length is required in order to serve the appropriate green time. By reasonably assign the time according to demand proportionality of each approach. Specifically, if the queue is more than the time limit of the cycle length, then this will potentially cause the worst scenario for every other approach. This is because other approaches will receive the red light. Additionally, the intersections can be combined using the strategic traffic coordination. Meaning that plotting a time-space diagram of a coordinated timing plan is required in order to examine the correlation (Gazis, 1965).

Table 2-1 Main Related Researches Regarding the Traffic System.

Authors	Year	Literature or Related Projects	Classification for Objective					
			Traffic Flow	Effective Green	Optimum Cycle Length	Saturation	Strategic Traffic Coordination	Offset
Urbanik, T. et al.	2015	Signal Timing Manual	X	X			X	X
Thammavong, A. & Soysouvanh, B.	2016	Optimization of Traffic Signal Time and Coordination for Road Network with Oversaturated			X	X		
Teo, K. T. K., Kow, W. Y., & Chin, Y. K.	2013	Optimization of Traffic Flow Within an Urban Traffic Light Intersection with Genetic Algorithm	X					

Table 2-2 Main Related Researches Regarding the Traffic System (Continued)

Authors	Year	Literature or Related Projects	Classification for Objective					
			Traffic Flow	Effective Green	Optimum Cycle Length	Saturation	Strategic Traffic Coordination	Offset
Federal Highway Administration	2016	Traffic Monitoring Guide			X			
Koganti, S. G.	2012	Maximizing Intersection Capacity and Minimizing Delay Through Unconventional Geometric Design of Intersections		X		X		
Mannering, F.L., Washburn, S.S., & Kilareski, W.P.	2009	Principles of Highway Engineering and Traffic Analysis	X					
Branston, D., & Van Zuylen, H.	1978	The Estimation of Saturation Flow, Effective Green Time and Passenger Car Equivalents at Traffic Signals		X		X		

Table 2-3 Main Related Researches Regarding the Traffic System (Continued)

Authors	Year	Literature or Related Projects	Classification for Objective					
			Traffic Flow	Effective Green	Optimum Cycle Length	Saturation	Strategic Traffic Coordination	Offset
Guide, T. M., & Dot, U.	2016	Federal Highway Administration	X	X				
Marks, D.	2020	An Urban Political Ecology of Bangkok's Awful Traffic Congestion	X			X		
Pianuan, K., Kaosa-ard, M.S. & Pienchob, P.	2009	Solution to Bangkok Traffic Congestion				X		
Muneera, C., & Krishnamurthy, K.	2020	Evaluation of Traffic Congestion at an Intersection				X		

Chapter 3
Methodology and Preliminary Result

3.1 Preliminary Concept.

To optimize the traffic signal timing or maximize the flow out of the vehicle from the intersection, it is essential to understand what is the factor that controls the traffic flow. The traffic signal, also known as traffic light, signal lights, stop lights, traffic control signals are signaling devices located at road intersections. The traffic signals are designed to ensure an orderly flow of traffic, which provide an opportunity for vehicles to cross an intersection and can help reduce the number of conflicts between vehicles entering intersections from different directions. Conversely, there are such cases of traffic overflow due to the improper time setting. Our solution is to optimize the effective green time, or making the vehicle leave from the intersection as much as possible from all of the approaches to improve the condition of the flow. This will incorporate the use of optimization programming language (OPL) as well as simulation program in order to generate the result.

The preliminarily design of this research came from the water tank. If we examine Figure 3-1, there are 4 tanks of water and water flowing into the tank. If one can open only one tank of water at a time, then we want to control the flow of the water by opening the tank of water that has the highest chance of overflowing. Therefore, we have to open tank 2 first for a longer period of time. Followed by tank 3, tank 1, and then tank 4. This can be judged by the flow rate of each. If we observe carefully, the pipe size which leads the water to flow into the tank varies. The largest pipe size has the highest flow rate.

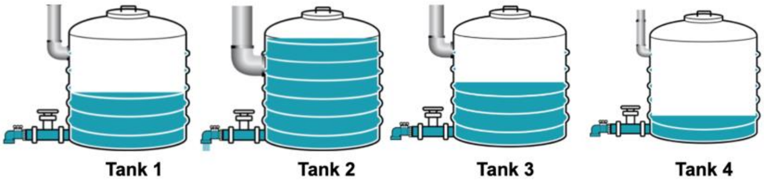

Figure 3-13 The case of the water tanks

The case of water tanks can be applied with the traffic intersection, which can be examined in Figure 3-2. If there are more vehicles or a longer queue in one approach, then we might want to have more time for green light in that approach to prevent the further congestion. Rather than just giving the same usual cycle time to each of the approaches. Therefore, tank 2 is equivalent to approach 2. When we turn on the green light for excessive time in one of the approaches, this would reduce the traveling time of the other approach. Therefore, this would cause the overall bad traffic circumstances. Hence, this is the concept of how to control the flow out of the traffic. Therefore, there will be an optimum cycle length that one might have to consider. This is one of the constraints that we have to take into account for each of the approaches.

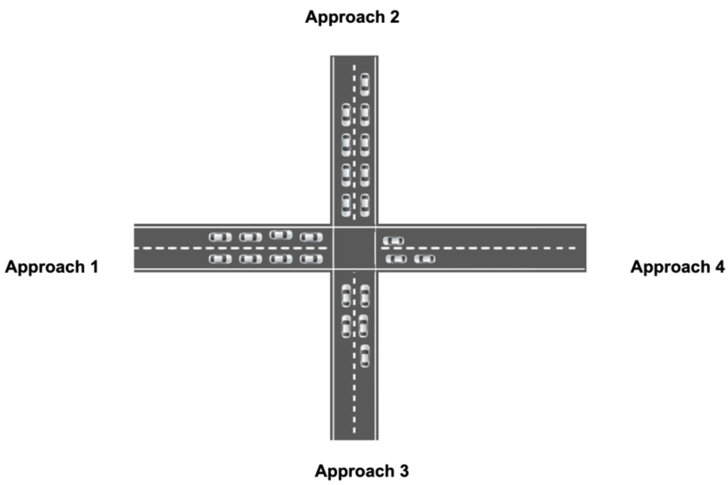

Figure 3-14 The case of traffic intersection.

Since one of the approaches have receive an ineffective green light, therefore the flow out of the vehicle in one approach of intersection could cause the delay in other approaches of intersections. In order to improve the delay of all approaches, we need to have certain boundary constraints. This will be described in the mathematical model section.

3.2 Traffic Coordination Concept

In addition, many intersections could combine together, and a traffic coordination is a strategic approach to synchronize signals together to meet specific objectives. In terms of traffic coordination, we use offset technique in order to provide the smooth flow and reduces the traveling time and the delay. In Figure 3-3, represents the amount of time of time to release total queue. If we want the flow consistency, then we need to release the vehicle that accumulate the previous queues from previous intersection, and also the existing queue for the current intersection.

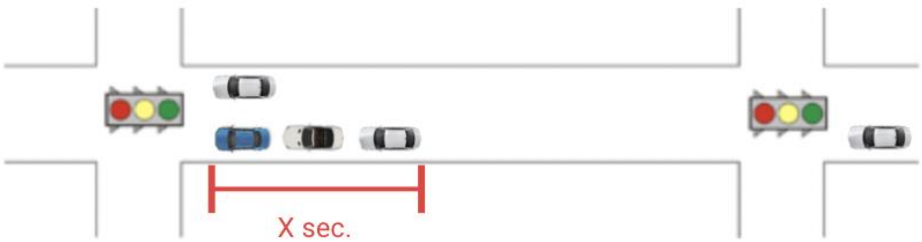

Figure 3-15 The amount of time to release total queue.

If we examined the Figure 3-4 below, we can see an example where two intersections connected and the corresponding time-space diagram.

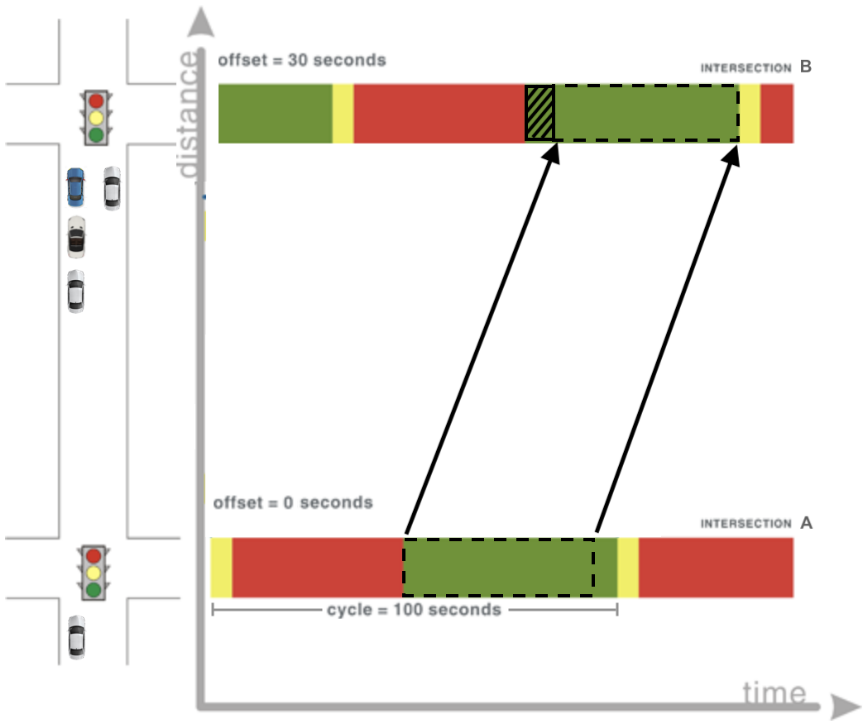

Figure 3-16 Time-space diagram for intersection A and B.

For simplicity, we can see the above left Figure 3-4 shows that intersection A and B are connected. This will form the time-space diagram of combined on the above right. In this case, we can see the corresponding two signalized movement. Note that one cycle length in this case is 100 seconds. In this case, we will use the offset time of 30 seconds for intersection B. Note that using offset technique allow us to adjust the time for certain intersections so that we can get the efficient result and effectively serve the overall demand. By doing so, this will also allow the synchronization for both intersections, because this will clear the old queue occurred at intersection B and vehicles from intersection A, effectively. The stripe area represents the time span of clearing the old queue at intersection B, while the stripe frame represents the time span at which vehicles at intersection A is clear. Then, the vehicles that is clear at intersection A will also be clear at intersection B as well, after it arrives at intersection B.

In Figure 13, we can observe the trajectories between time versus distances. The trajectories also exist between intersections' signal, forming a bandwidth. Our objective is to adjust the offset so that range of the bandwidth is the largest, which will reveal the best traveling time for both intersections in this case. Bandwidth means that this will give green light signal between both intersections correspondingly. However, if there are more intersections combined, the process and objective is the same but with more signalized movements.

3.3 Mathematical Model.

The objective of the optimization model is to maximize the vehicles leaving from these intersections, which can be mathematically described in Equation 1. The number of vehicles that leave from the intersection can be calculated from the flow out of the vehicles (per sec) multiply by the time of the green light of different approaches (sec). The more the vehicles are able to leave the intersection, the more delay will potentially drop. This causes the overall traffic condition to flow out of the intersection better. In order to identify the feasible solution, some particular constraints are required. The constraint equations can be defined in Equation 2 - 8. In order to improve the delay of all approaches, we need to have the constraints. Arrange the time of the green light for different approaches to be equal to the time that we want to discharge the car queue in all approaches in order to improve the delay of all approaches as described in Equation 5. However, there are cases such as larger traffic volume. During rush hour, clearing the queue is required to have more constraint. For instance, by opening the green light for a long time for clearing the queue is not possible, since the time is exceeding the limit of proper cycle length. Therefore, green light needs to be open until it reaches the limit of proper cycle length, which can be calculated from accumulating signal time of green light, yellow light, and all-red light of all approaches as described mathematically in

Equation 8. The total queue from different approaches is calculated by the flow in of the vehicles (per sec) of the vehicle multiply by the time of the red-light signal (sec).

Mathematical equations are modeled with approach i at the intersection. In the case of four-way intersection, the traffic signal at each approach i is denoted by i = {1,2,3,4}. In the case of three-way intersection, approach i is denoted by i = {1,2,3}. j is equivalent to the piecewise step of the flow rate, which is denoted by 1 and 2, or j = {1,2}. Piecewise step is shown in Figure 3-4. The following are the parameters associated with the model.

3.3.1 Parameters

LT_i = A lost time, or an additional amount of time for the first vehicle to begin moving and pass through the intersection approach i;

YT_i = The time of the yellow light signal for each approach of the intersection, where i is the approach for that intersection;

AR_i = The time of the all-red light signal for each approach of the intersection, where i is the approach for that intersection;

SF_i = Saturation flow, or the rate at which vehicles can traverse an intersection approach i under prevailing conditions in vehicles per hour of green or vehicles per hour of green per lane, assuming the green signal is available at all times;

FI_i = The value of which the vehicle flows into the approach i (vehicle per hour).

FO_{ij} = The value of which the vehicle flows out of the approach i (vehicle per hour), where j is the piecewise step of the flow rate;

STQ_i = The length of the vehicle queue at approach i before they will get green light;

BEQ_i = The breakpoint between the changed slope of effective and ineffective flow out;

3.3.2 Decision Variables

Besides the above parameters, following are the list of decision variables required for the proposed optimization model.

GT_{ij} = The time of the green light traffic for each approach of the intersections, where i is the approach for that intersection. Where j is the piecewise step of the flow rate;

CL = The amount of time required to display all phases for each direction of an intersection before returning to the starting point, or the first phase of the cycle;

TQ_{ij} = The total vehicle queue for each of the approaches, where i is the approach for those intersections and j is the piecewise step of the flow rate;

3.3.3 Objective and Constraints

The objective equation for different intersections with approach i and flow step j are defined below along with the constraints, where V number of vehicle (s) that leave from the intersections:

$$Max\ V = \sum_{i \in I, j \in J} \left(FO_{ij} \times GT_{ij} \right) \quad (1)$$

s.t.

$$TQ_{i1} \leq BEQ_i \quad ; \forall i \in I \quad (2)$$

$$TQ_{i2} \leq TQ_{i1} \quad ; \forall i \in I \quad (3)$$

$$TQ_{i1} + TQ_{i2} \leq STQ_i \quad ; \forall i \in I \quad (4)$$

$$GT_{ij} = \frac{TQ_{ij}}{FO_{ij}} \quad ; \forall i \in I, \forall j \in J \tag{5}$$

$$\sum_{j \in J} GT_{ij} \geq LT_i \quad ; \forall i \in I \tag{6}$$

$$CL \leq \frac{1.5 \times \left(\sum_{i \in I} LT_i \right) + 5}{1 - \sum_{i \in I} \frac{FI_i}{SF_i}} \tag{7}$$

$$CL = \sum_{i \in I} \left(\sum_{j \in J} GT_{ij} + YT_i + AR_i \right) \tag{8}$$

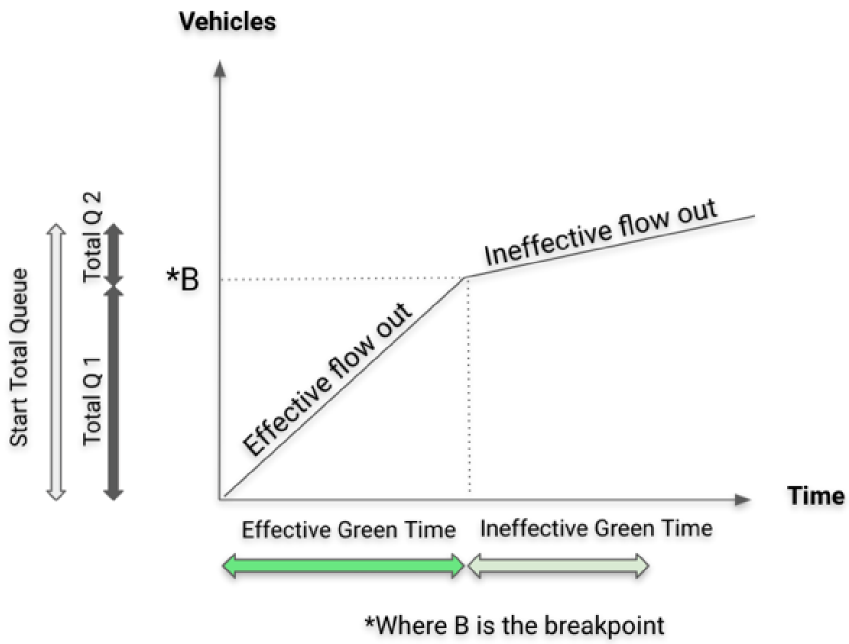

Figure 3-17 The piecewise constraints.

(More detail can be examined in the visualization video)

The piecewise constraints can be examined in the visualization video section. Constraint 2 and 3 are the piecewise constraints. The *total queue 1* is the effective queue and *total queue 2* is the ineffective queue, at approach i. *Total queue 1* has to be less than or equal to the breakpoint. And, the *total queue 2* has to be less than or equal to the *total queue 1*. Constraint 4 is to clear the total queue 1 and 2 from a different approach, by making it less than or equal to *start total queue*. Constraint 5 is to ensure that the time of the green light of a different approach has to be equal to the total queue of that approach. 6 is the lower bound constraint, or the green time for different approaches has to be greater than or equal to the lost time. 7 is the upper bound constraint, or the maximum time limit for the cycle length. In which, if it is more than that optimum cycle length, then it will worsen the delay for overall traffic conditions. Constraint 8 is the combination of time for green, yellow, and all-red light signals in all approaches is limited within the cycle length. Every constraint shares correlation to one and another.

3.4 Implementation.

Study on traffic system at an intersection requires a practical implementation. After an optimization model that maximize the vehicle leave from the intersection is constructed. The following is the operating guideline:

- Record the number of vehicles entering and exiting the intersection in certain hour, from each approach and intersections.
  - Data collection occurred during peak period of, which will be explained in data collection section.
- The objective equation can be calculated by the time of the effective green light (in seconds) multiply by the flow out of the vehicles from each of the approaches (vehicles per second).
- Cycle length can be calculated from accumulating signal time of green, yellow, all red of all approaches.

- The total queue is calculated by the flow in (vehicles per seconds) of the vehicle times the time of the red-light signal (in seconds).
- OPL Programming
    - Use OPL to generate the result of the optimization model.
    - The result will be separated into isolated intersection, before combine using traffic coordination strategy.

The procedure diagram can examine in Figure 3-6.

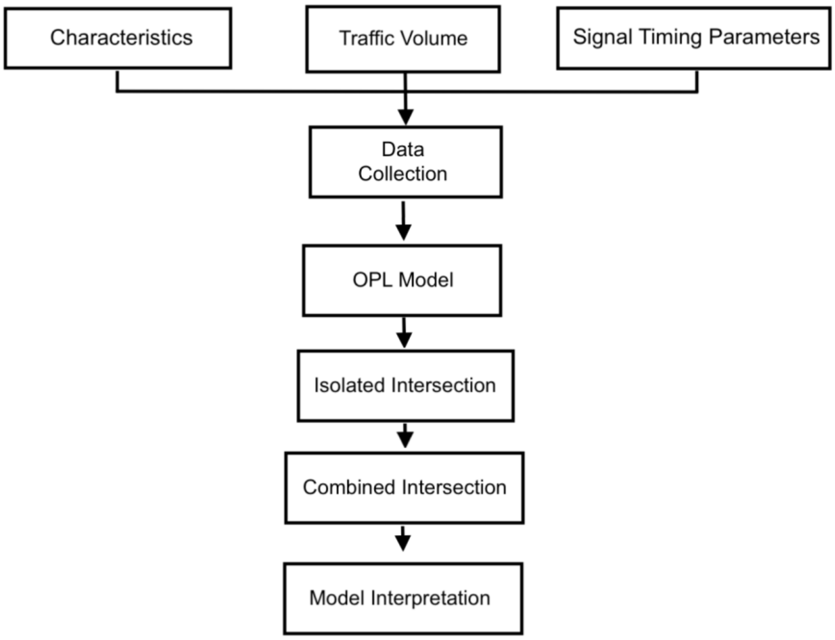

Figure 3-18 Method of Procedure.

3.5 Data Collection.

The data is collected by Japanese Infrastructure Development in Thailand which was able to provide several information regarding the volume of traffics for the intersections. Although, some limitation has occurred during process due to the license information(s).

The data is collected during the peak period of rush hour from each approach. The time collected is between 5:00 pm to 6:00 pm. This is collected every weekday and the month collected is March of 2022. Each intersection includes the several essential input data collections such as flow in, effective flow out, ineffective flow out, effective total queue, ineffective total queue, start total queue, breakpoint queue, effective green, and ineffective green. Flow in is defined as the flow input value from each approach of intersection. Subsequently, the effective and ineffective flow out are defined as the flow output value from each approach of the intersection. The flow in and flow out values are represented on average from the collected data. When the number of cars reaches the average value of breakpoint queue amount, the flow out rate becomes ineffective. Hence, green time is the same as total queue, which contains effective and ineffective queue at each approach. For traffic coordination, the data collection is made at 6pm. The values are recorded in real-time, because this method requires a real-time data to accomplish the process.

3.6 Visualization

The optimization model is implemented in OPL programming with the collected input data. To test if the output to meet towards expectation, Figure 3-6 below illustrates the example of generated traffic visualization result at Pradiphat intersection, one of the intersections of study, by using the result from OPL with the collected data. The vehicles are expected to leave from the intersection for most of the time.

3.7 Hypothesis.

Regarding the research, some hypotheses were made beforehand. The hypothesis was made that this algorithm would certainly improve the traffic flow. As mentioned before, when the green light signal in one of the approaches for a long period, it will make the overall condition worse off because it increases the traveling time for other approaches. Therefore, the prediction was made that if the green light was open within the limit of the optimum cycle length, then the traffic flow will improve.

Chapter 4
Results

4.1 Beginning of the Result Section

In this result section, we focus on the following intersections: Pradiphat, Rama VI SS 37, Rama VI SSS 2, Rama VI SSS, Rama VI TNC, and Tuk Chai intersections. At first, we will optimize the isolated intersection before combining the intersection together. Note that these intersections are regarded as busy during the peak period. These intersections are one of the busiest intersections during the rush hour and yet has a poor level of service and also a traffic management system.

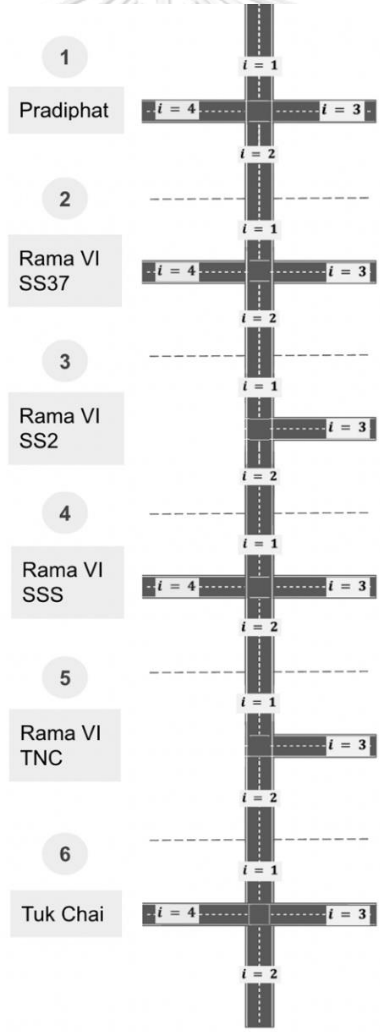

Figure 4-19 Visualization of Six Connected Intersections.

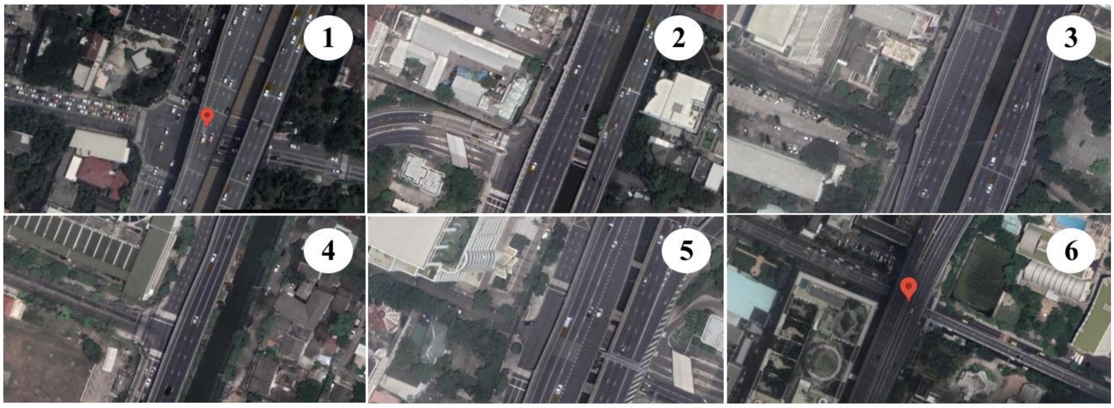

Figure 4-20 Pradiphat, Rama VI SS 37, Rama VI SSS 2, Rama VI SSS, Rama VI TNC, and Tuk Chai (From top left to bottom right).

In the beginning process, the data is gathered from coordinating the intersection. As shown in Figure 4-2, each approach is represented by i = 1,2,3, and 4. However, some intersections may contain three-way intersections. The vehicles leave from different approaches will form the start total queue for different specified intersections. Start total queue can be define as the current queue plus the vehicles that are added to the queue length from the previous intersection. Note that the collected data from this procedure is use to perform the optimization for different intersections that are stated.

For optimizing, the optimization is performed at Pradiphat, Rama VI SS 37, Rama VI SSS 2, Rama VI SSS, Rama VI TNC, and Tuk Chai intersections. To test if the algorithm and theory works as expected, the average values are used to do the testing before doing the offset with real-time approach. For coordinated intersections, real-time data is used because the offset method required real-time calculation. Specifically, each different cycle will always have different offset time in the real-world, therefore we cannot use value in terms of average. At the same time, the issue of dynamic is taken into account in this case, therefore real-time data is supposedly use. Due to the characteristic of the intersection, the arial coordination is establish. In this approach, i = 1 and 2 will be use as the real-time. Since, we will focus on Pradiphat to Tuk Chai intersection. However, for i = 3 and 4, we can use the statistical average value since it is not the major focus in this case.

As mention, the offset technique is used in order to shift the time so that the green light will serve the demand for all of the queue, including the previous queue. Hence, the bottleneck should not occur. The real-time data at 6pm is use. Real-time is use since offset technique requires real-time data. The direction is from Pradiphat to Tuk Chai intersection. Note that intersection 3 and 5 contains three-way intersection.

4.2 Performing Optimization

4.2.1 Pradiphat Intersection Result

The first intersection is Pradiphat intersection. Intersections are controlled by traffic control and traffic wardens. Commercial buildings are found very close to the intersections. The map of the study area is shown in the figure below. 2 main cases from Pradiphat intersection, or one of the intersections of study, is summarized below.

Figure 4-21 Satellite view of Pradiphat intersection.

In terms of the computational results, OPL programming tool was used to generate the outputs from the optimization model. The results can be summarized as follow:

Table 4-4 OPL result from Pradiphat Intersection during the Rush Hour (Case 1).

Pradiphat Intersection				
Case 1 Results	Approaches			
	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Parameters				
Flow in	1,720	1,910	720	780
Effective Flow out	2,680	2,750	2,120	2,060
Ineffective Flow out	1,540	1,620	1,210	1,150
Start Total Queue	73	78	37	45
Decision Variables				
Effective Total Queue	52	55	37	45
Ineffective Queue	21	23	0	0
Effective Green	69.8	72	62.5	73.4
Ineffective Green	49.09	51.11	0	9.39
Objectives				
Number of Vehicle(s) Leave			233.00	
Cycle Length (seconds)			407.67	
Vehicle Flow Rates (vehicles/hour)			2059.20	

Table 4-1 shows an example of case 1 from Pradiphat intersection during the peak period of rush hour in the evening. Flow in is defined as the flow input value from each approach of intersection. Subsequently, the effective and ineffective flow out are defined as the flow output value from each approach of the intersection. The flow in and flow out values are represented on average from the collected data. When the number of cars reaches the average value of breakpoint queue amount, the flow out rate becomes ineffective. Hence, green time is the same as total queue, which contains effective and ineffective queue at each approach. By inspection, we can see that the values are higher for flow out effective than the flow out ineffective. If we examine the Figure 14, the flow out effective rate line shows a steeper slope because there are more vehicle leaving. However, when it reaches the breakpoint, the slope become less steep which represents the ineffective flow out.

During rush hour, we can see that the values are high for flow in approach, meaning that there is a high traffic density during this hour. In this case, constraint 7 is eliminated. This is the case of current traffic management. By inspection, the cycle length is 407.67 sec and the vehicle leaving from the intersection is 233 vehicles. The flow rate in this case is 233 vehicles per 407.67 sec, which is approximately 2059.20 vehicles per hour.

Table 4-5 OPL Result from Pradiphat Intersection during the Rush Hour (Case 2).

Pradiphat Intersection				
Case 2 Results	Approaches			
	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Parameters				
Flow in	1,720	1,910	720	780
Effective Flow out	2,680	2,750	2,120	2,060
Ineffective Flow out	1,540	1,620	1,210	1,150
Start Total Queue	73	78	37	45
Decision Variables				
Effective Total Queue	52	55	37	45
Ineffective Queue	0	0	0	0
Effective Green	69.8	72	62.5	15.9
Ineffective Green	0	0	0	0
Objectives				
Number of Vehicle(s) Leave			153.09	
Cycle Length (seconds)			240.57	
Vehicle Flow Rates (vehicles/hour)			2289.60	

For case 2, is the case after optimization process with the same data of flow in approach. The cycle length is 240.57 seconds, and we can see that the vehicle leaves from the intersection of 153.09 vehicles. Conversely, this is just for one cycle length. This means that if we accumulate all the cycle length in total, there are more vehicles leaving the intersection compared to Table 3-1. In this case, the flow rate is 153.09 vehicles in 240.57 sec, which is 2289.60 vehicles per hour. This means that the flow rate has improved when there is the optimum cycle length. When subtracting with previous case result, it is equivalent to 2289.60 vehicles per hour. Meaning that there are approximately 230.4 more vehicles leaving the intersection each hour. In other words, when there are more vehicles that flow into the approaches, the additional constraint has an effect on the number of vehicles that leave from the intersection.

4.2.2 Rama VI SS 37 Result

For the second intersection, which is the Rama VI SS 37 intersection. Rama VI intersections and road was built during 1900s in the era of King Vajiravudh. Until today, these connected Rama VI intersections are one of the busiest. Therefore, it is worth studying these areas.

The vehicle arrives at this intersection after Pradiphat intersection. The nature of this intersection is that it contains four-way intersection, where $\boldsymbol{i}$ = 4. Below is the satellite view of Rama VI SS 37 intersection.

Figure 4-22 Satellite view of Rama VI SS 37 intersection.

Table 4-3 shows the result from Rama VI SS 37 intersection during the rush hours. Again, we can see that the values are high for flow in approach during the rush hour because there is a high traffic density during this hour. Constraint 7 is eliminated for the first case. By inspection, the cycle length is 262.22 sec and the vehicle leaving from the intersection is 149 vehicles. The flow rate in this case is 149 vehicles per 262.22 sec, which is approximately 2045.61 vehicles per hour.

Table 4-6 OPL Result from Rama VI SS 37 Intersection during the Rush Hour (Case 1).

Rama VI SS 37 Intersection				
Case 1 Results	Approaches			
	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Parameters				
Flow in	1,500	2,000	610	750
Effective Flow out	2,600	2,580	1,820	1,750
Ineffective Flow out	1,420	1,480	1,080	1,020
Start Total Queue	60	70	24	31
Decision Variables				
Effective Total Queue	49	52	24	26
Ineffective Queue	11	18	0	5
Effective Green	67.9	72.6	55.4	53.5
Ineffective Green	65.9	80.3	46.7	77.6
Objectives				
Number of Vehicle(s) Leave			149.00	
Cycle Length (seconds)			262.22	
Vehicle Flow Rates (vehicles/hour)			2045.61	

In Table 4-4, after optimization process with the same data of flow in approach, the cycle length is 195.65 seconds. We can see that the vehicle leaves from the intersection of 123.03 vehicles for case 2. If we accumulate all the cycle length in total, there are more vehicles leaving the intersection compared to Table 4-2. In this case, the flow rate is 149 vehicles in 262.22 sec, which is 2263.78 vehicles per hour. This means that the flow rate has improved when there is the optimum cycle length. When subtracting with previous case result, it is equivalent to 218.17 vehicles per hour. Meaning that there are approximately 218 more vehicles leaving the intersection each hour.

Table 4-7 OPL Result from Rama VI SS 37 Intersection during the Rush Hour (Case 2).

Rama VI SS 37 Intersection				
Case 2 Results	Approaches			
	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Parameters				
Flow in	1,500	2,000	610	750
Effective Flow out	2,600	2,580	1,820	1,750
Ineffective Flow out	1,420	1,480	1,080	1,020
Start Total Queue	60	70	24	31
Decision Variables				
Effective Total Queue	49	52	24	26
Ineffective Queue	0	0	0	0
Effective Green	65.21	66.18	28.10	16.17
Ineffective Green	0	0	0	0
Objectives				
Number of Vehicle(s) Leave			123.03	
Cycle Length (seconds)			195.65	
Vehicle Flow Rates (vehicles/hour)			2263.78	

4.2.3 Rama **VI** SSS 2 Result

For the third intersection, which is the Rama VI SSS 2 intersection. The vehicle arrives at this intersection after Rama VI SS 37 intersection. The nature of this intersection is that it contains three-way intersection, where $i = 3$.

Figure 4-23 Satellite view of Rama VI SSS 2 intersection.

Table 4-4 shows the result from Rama VI SSS 2 intersection during the rush hours. Again, constraint 7 is eliminated for the first case. By inspection, the cycle length is 336.98 sec and the vehicle leaving from the intersection is 183 vehicles. The flow rate in this case is 183 vehicles per 336.98 sec, which is approximately 1955.01 vehicles per hour.

Table 4-8 OPL Result from Rama VI SSS 2 Intersection during the Rush Hour (Case 1).

Rama VI SSS 2 Intersection			
Case 1 Results	Approaches		
	$i = 1$	$i = 2$	$i = 3$
Parameters			
Flow in	1,520	2,010	1,880
Effective Flow out	2,540	2,560	2,040
Ineffective Flow out	1,510	1,540	1,250
Start Total Queue	60	72	51
Decision Variables			
Effective Total Queue	47	52	38
Ineffective Queue	13	20	13
Effective Green	66.61	73.13	67
Ineffective Green	30.99	46.75	37.44
Objectives			
Number of Vehicle(s) Leave	183.00		
Cycle Length (seconds)	336.98		
Vehicle Flow Rates (vehicles/hour)	1955.01		

In Table 4-5, after undergoing the optimization process, the cycle length is 168.81 seconds, and we can see that the vehicle leaves from the intersection of 106.97 vehicles. Again, if we accumulate all the cycle length in total, there are more vehicles leaving the intersection compared to Table 4-4. In this case, the flow rate is 106.97

vehicles in 168.81 sec, which is 2281.22 vehicles per hour. This means that the flow rate has improved when there is the optimum cycle length. When subtracting with previous case result, it is equivalent to 326.21 vehicles per hour. Meaning that there are approximately 326 more vehicles leaving the intersection each hour.

Table 4-9 OPL Result from Rama VI SSS 2 Intersection during the Rush Hour (Case 2).

Rama VI SSS 2 Intersection			
Case 2 Results	Approaches		
	$i = 1$	$i = 2$	$i = 3$
Parameters			
Flow in	1,520	2,010	1,880
Effective Flow out	2,540	2,560	2,040
Ineffective Flow out	1,510	1,540	1,250
Start Total Queue	60	72	51
Decision Variables			
Effective Total Queue	47	52	38
Ineffective Queue	0	0	0
Effective Green	66.6	73.13	14
Ineffective Green	0	0	0
Objectives			
Number of Vehicle(s) Leave	106.97		
Cycle Length (seconds)	168.81		
Vehicle Flow Rates (vehicles/hour)	2281.22		

4.2.4 Rama VI SSS Result

For the fourth intersection, which is the Rama VI SSS intersection. The vehicle arrives at this intersection after Rama VI SS 2 intersection.

Figure 4-24 Satellite view of Rama VI SSS intersection.

Table 4-6 shows the result from Rama VI SSS intersection during the rush hours. Again, we can see that the values are high for flow in approach during the rush hour. In other words, there is a high traffic density during this hour. Constraint 7 is eliminated for the first case. By inspection, the cycle length is 244.19 sec and the vehicle leaving from the intersection is 142 vehicles. The flow rate in this case is 142 vehicles per 244.19 sec, which is approximately 2093.45 vehicles per hour.

Table 4-10 OPL Result from Rama VI SSS Intersection during the Rush Hour (Case 1)

Rama VI SSS Intersection				
Case 1 Results	Approaches			
	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Parameters				
Flow in	1,510	2,020	510	450
Effective Flow out	2,650	2,720	2,050	2,010
Ineffective Flow out	1,560	1,590	1,240	1,210
Start Total Queue	60	50	14	18
Decision Variables				
Effective Total Queue	48	50	14	11
Ineffective Queue	12	0	0	7
Effective Green	65.2	66.2	24.6	19.7
Ineffective Green	27.7	0	0	20.8
Objectives				
Number of Vehicle(s) Leave			142.00	
Cycle Length (seconds)			244.19	
Vehicle Flow Rates (vehicles/hour)			2093.45	

In Table 4-7, after optimization process with the same data of flow in approach, the cycle length is 195.65 seconds, and we can see that the vehicle leaves from the intersection of 122.99 vehicles. If we accumulate all the cycle length in total, there are more vehicles leaving the intersection compared to Table 4-6. In this case, the flow rate

is 122.99 vehicles in 195.65 sec, which is 2263.04 vehicles per hour. This means that the flow rate has improved when there is the optimum cycle length. When subtracting with previous case result, it is equivalent to 169.59 vehicles per hour. Meaning that there are approximately 170 more vehicles leaving the intersection each hour.

Table 4-11 OPL Result from Rama VI SSS Intersection during the Rush Hour (Case 2).

Rama VI SSS Intersection				
Case 2 Results	Approaches			
	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Parameters				
Flow in	1,510	2,020	510	450
Effective Flow out	2,650	2,720	2,050	2,010
Ineffective Flow out	1,560	1,590	1,240	1,210
Start Total Queue	60	50	14	18
Decision Variables				
Effective Total Queue	48	50	14	11
Ineffective Queue	0	0	0	0
Effective Green	65.2	66.2	24.6	19.7
Ineffective Green	0	0	0	0
Objectives				
Number of Vehicle(s) Leave			122.99	
Cycle Length (seconds)			195.65	
Vehicle Flow Rates (vehicles/hour)			2263.04	

4.2.5 Rama VI TNC Result

For the fifth intersection, which is the Rama VI TNC intersection. The vehicle arrives at this intersection after Rama VI SSS intersection. The nature of this intersection is that it contains three-way intersection.

Figure 4-25 Satellite view of Rama VI TNC intersection

Table 4-8 shows the result from Rama VI TNC intersection during the rush hours. Again, we can see that the values are high for flow in approach during the rush hour. In other words, there is a high traffic density during this hour. Constraint 7 is eliminated for the first case. By inspection, the cycle length is 298.21 sec and the vehicle leaving from the intersection is 165 vehicles. The flow rate in this case is 165 vehicles per 298.21 sec, which is approximately 1991.88 vehicles per hour.

Table 4-12 OPL Result from Rama VI TNC Intersection during the Rush Hour (Case 1).

Rama VI TNC Intersection			
Case 1 Results	Approaches		
	$i = 1$	$i = 2$	$i = 3$
Parameters			
Flow in	1,520	2,010	1880
Effective Flow out	2,500	2,550	2,010
Ineffective Flow out	1,500	1,540	1,120
Start Total Queue	60	70	35
Decision Variables			
Effective Total Queue	48	52	30
Ineffective Queue	12	18	5
Effective Green	69.1	73.4	53.7
Ineffective Green	28.8	42.1	16.1
Objectives			
Number of Vehicle(s) Leave			165.00
Cycle Length (seconds)			298.21
Vehicle Flow Rates (vehicles/hour)			1991.88

In Table 4-9, after optimization process with the same data of flow in approach, the cycle length is 173.34 seconds, and we can see that the vehicle leaves from the intersection of 108.83 vehicles. If we accumulate all the cycle length in total, there are more vehicles leaving the intersection compared to Table 4-8. In this case, the flow rate

is 108.83 vehicles in 173.34 sec, which is 2260.23 vehicles per hour. This means that the flow rate has improved when there is the optimum cycle length. When subtracting with previous case result, it is equivalent to 268.35 vehicles per hour. Meaning that there are approximately 268 more vehicles leaving the intersection each hour.

Table 4-13 OPL Result from Rama VI TNC Intersection during the Rush Hour (Case 2).

Rama VI TNC Intersection			
Case 2 Results	Approaches		
	$i = 1$	$i = 2$	$i = 3$
Parameters			
Flow in	1,520	2,010	1880
Effective Flow out	2,500	2,550	2,010
Ineffective Flow out	1,500	1,540	1,120
Start Total Queue	60	70	35
Decision Variables			
Effective Total Queue	48	52	30
Ineffective Queue	0	0	0
Effective Green	69.1	73.4	15.8
Ineffective Green	0	0	0
Objectives			
Number of Vehicle(s) Leave			108.83
Cycle Length (seconds)			173.34
Vehicle Flow Rates (vehicles/hour)			2260.23

4.2.6 Tuk Chai Intersection Result

The last intersection is the Tuk Chai intersection, or one of the well-known intersections in Bangkok. The nature of this intersection is that it contains four-way intersection. The traffic volume is at the considerate amount during rush hour. This is one of the intersections that is regarded as very busy during the evening.

Figure 4-26 Satellite view of Tuk Chai intersection.

Table 4-10 shows the result from Tuk Chai intersection during the rush hours. Again, we can see that the values are high for flow in approach during the rush hour. In other words, there is a high traffic density during this hour. Constraint 7 is eliminated for the first case. By inspection, the cycle length is 392.43 sec and the vehicle leaving from the intersection is 207 vehicles. The flow rate in this case is 207 vehicles per 392.43 sec, which is approximately 1898.94 vehicles per hour.

Table 4-14 OPL Result from Tuk Chai Intersection during the Rush Hour (Case 1)

Tuk Chai Intersection				
Case 1 Results	Approaches			
	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Parameters				
Flow in	1,520	2,010	520	580
Effective Flow out	2,650	2,700	2,050	2,080
Ineffective Flow out	1,550	1,590	1,200	1,250
Start Total Queue	65	76	31	35
Decision Variables				
Effective Total Queue	48	50	23	20
Ineffective Queue	17	26	8	15
Effective Green	65.2	66.7	40.4	34.6
Ineffective Green	39.5	58.9	24	43.2
Objectives				
Number of Vehicle(s) Leave			207.00	
Cycle Length (seconds)			392.43	
Vehicle Flow Rates (vehicles/hour)			1898.94	

In Table 4-11, after optimization process with the same data of flow in approach, the cycle length is 193.31 seconds, and we can see that the vehicle leaves from the intersection of 122.22 vehicles. If we accumulate all the cycle length in total, there are more vehicles leaving the intersection compared to Table 4-10. In this case, the flow rate

is122.22 vehicles in 193.91 sec, which is 2276.10 vehicles per hour. This means that the flow rate has improved when there is the optimum cycle length. When subtracting with previous case result, it is equivalent to 377.16 vehicles per hour. Meaning that there are approximately 377 more vehicles leaving the intersection each hour.

Table 4-15 OPL Result from Tuk Chai Intersection during the Rush Hour (Case 2).

Tuk Chai Intersection				
Case 2 Results	Approaches			
	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Parameters				
Flow in	1,520	2,010	520	580
Effective Flow out	2,650	2,700	2,050	2,080
Ineffective Flow out	1,550	1,590	1,200	1,250
Start Total Queue	65	76	31	35
Decision Variables				
Effective Total Queue	48	50	23	20
Ineffective Queue	0	0	0	0
Effective Green	65.2	66.7	7.4	34.6
Ineffective Green	0	0	0	0
Objectives				
Number of Vehicle(s) Leave			122.22	
Cycle Length (seconds)			193.91	
Vehicle Flow Rates (vehicles/hour)			2276.10	

4.3 Optimization Result Summary

In terms of analytical summary, the overall traffic management for these intersections has improve in decent amount. It is to note that these results correspond after the peak of the covid situation. Meaning that there is more vehicle queue. In Figure 4-9 show charts comparing the current and optimized result for each isolated intersections. We can observe that when comparing with the optimized results, the rate of vehicles per hour in current traffic management for each intersection have improved greater than 10% expectation. Pradiphat shows an improvement of 11.18%. For Rama VI intersection shows an improvement of 10.74% for SS37, 16.76% for SS2, 18.90% for SSS, and 13.56% for TNC. The final destination, or Tuk Chai, shows an improvement of 19.54%.

Isolated Intersections

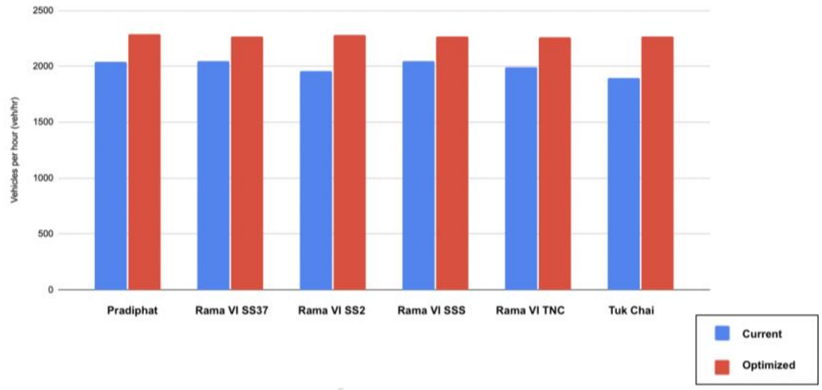

Figure 4-27 Charts comparing current and optimized result for the isolated intersections.

Intersections Improvement on Average

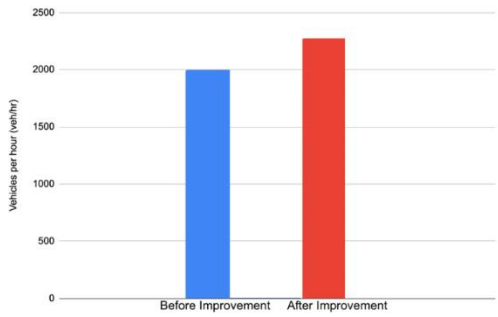

Figure 4-28 Charts comparing current and optimized intersections (On average)

In Figure 4-10 shows the average improvement for all of the intersections, before and after optimization implementation. Overall intersections show an average percentage improvement of 15.11% after the process of optimization.

In Table 4-11 and Table 4-12 summarizes the average number of vehicles leaving from each intersection, the cycle length (in seconds), and the corresponding vehicle flow rates. There are approximately 264.32 number of vehicles leave on average during the peak of rush hour.

Table 4-16 Flow Rate Results from Other Intersections during the Rush Hour.

Intersection(s)	Number of vehicles leave	Cycle Length (sec.)	Vehicle Flow Rates (veh/hr)
Pradiphat	233.00	407.67	2057.55
Rama VI SS37	149.00	262.22	2045.61
Rama VI SS2	183.00	256.08	1955.01
Rama VI SSS	142.00	244.19	2093.45
Rama VI TNC	165.00	298.21	1991.88
TC	207.00	392.43	1898.94

Table 4-17 Flow Rate Results from Other Intersections During the Rush Hour – Case 2.

Intersection(s)	Number of vehicles leave	Cycle Length (sec.)	Vehicle Flow Rates (veh/hr)
Pradiphat	153.09	240.57	2289.60
Rama VI SS37	123.03	195.65	2264.40
Rama VI SS2	106.57	168.81	2281.23
Rama VI SSS	122.99	195.65	2263.04
Rama VI TNC	108.83	173.34	2260.80
TC	122.22	193.91	2269.05

In Table 4-13 summarizes the percentage improvement from each intersection. Overall intersections show a mean improvement of 15.11%. With the highest percentage improvement came from Rama VI SS37 intersection with the percentage improvement of 28.30% during the rush hour. On the other hand, the minimum improvement came from Rama VI TNC intersection with the percentage improvement of 19.66%. Hence, it can be seen that the traffic management for these intersections has sufficiently improve.

Table 4-18 Percentage improvement for each intersection of study.

Intersection(s)	Improvement (%)	Intersection(s)	Improvement (%)
Pradiphat	11.18	Rama VI SSS	18.90
Rama VI SS37	10.74	Rama VI TNC	13.56
Rama VI SS2	16.76	Tuk Chai	19.54
Mean	15.11	Max.	19.54
Med.	12.87	Min.	10.74

Below are the results of percentage improvement of different approaches' flow. Which can be found by calculating using variables from previous OPL results parameter of i = 1,2,3, and 4. Note that Rama VI SS2 and Rama VI TNC is three-way intersection.

Table 4-19 Percentage improvement of different approach.

Intersection(s)	i = 1	i = 2	i =3	i = 4
Pradiphat	21.29	20.56	15.66	15.27
Rama VI SS37	28.80	28.85	25.24	32.80
Rama VI SS2	14.77	18.39	14.02	-
Rama VI SSS	13.97	14.12	15.90	25.71
Rama VI TNC	13.33	16.86	11.35	-
TC	18.56	23.88	18.27	28.45

4.3 Coordinating Intersections

4.3.1 Pradiphat intersections

First, we will examine the experiment and calculation conducted at Pradiphat intersection. In this case, the real-time data is now used to perform offset. Since offset technique *requires* a real-time data.

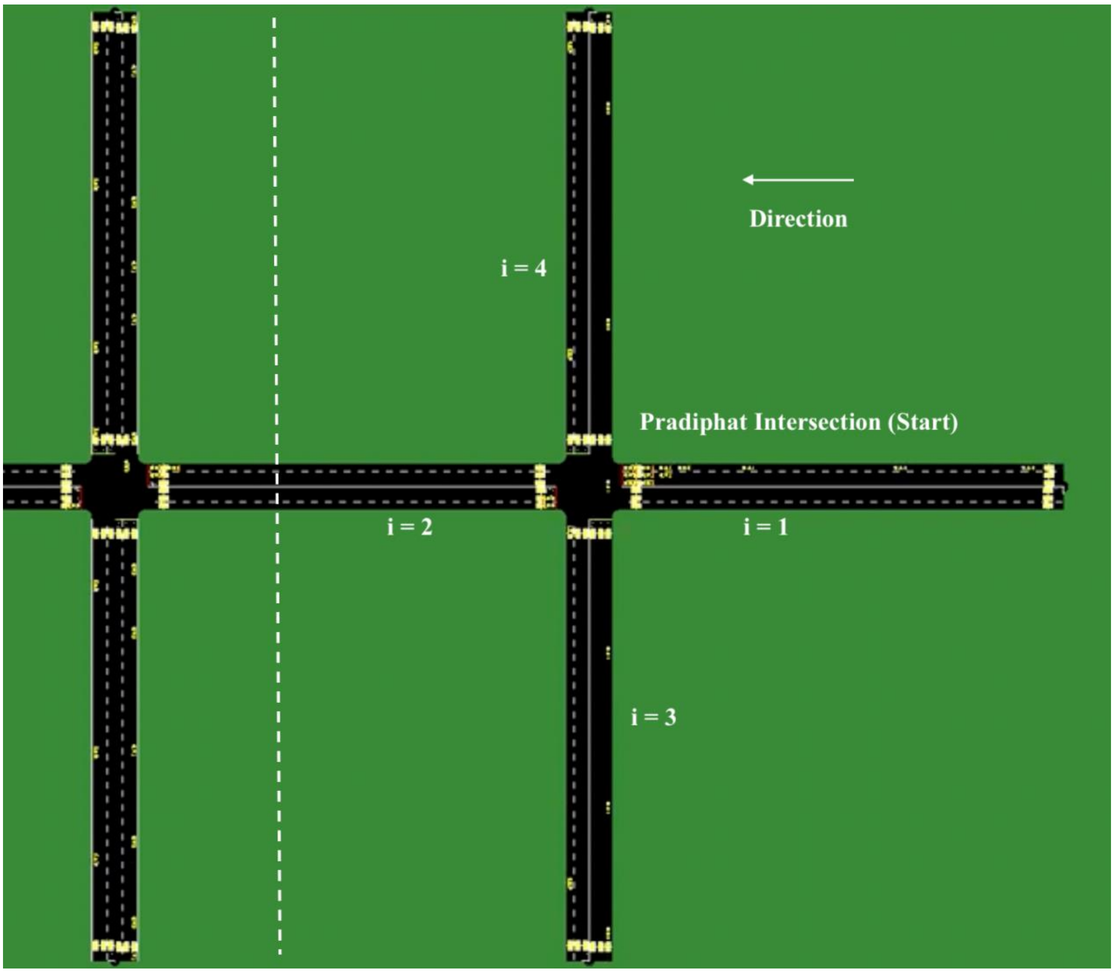

Figure 4-29 Visualization for Starter Intersection – Pradiphat Intersection.

Figure 4-11 represents the visualization for Pradiphat intersection. We can see the visualization along with different approaches of the intersections, where i is represented by the approach of that intersection. Note that i = 2 approach is not taken into account in terms of calculation. This is because the flow is from Pradiphat to Tuk Chai. In this case, Pradiphat intersection is the starter intersection. Therefore, no offset is required.

Table 4-15 is the OPL result of the optimized Pradiphat intersection. These values will be examine later in the subsequent intersection. Here, the number of vehicles leave is 153.12 and the cycle length is 240.57. The vehicle flow rates is 2291.36 vehicles per hour.

Table 4-20 OPL Result of Optimized Pradiphat Intersection.

Pradiphat intersection	Approaches			
	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Parameters				
Flow in	1,720	1,910	720	780
Effective Flow out	2,680	2,750	2,120	2,060
Ineffective Flow out	1,540	1,620	1,210	1,150
Start Total Queue	82	93	53	58
Decision Variables				
Effective Total Queue	52	55	38	8.1
Ineffective Queue	0	0	0	0
Effective Green	69.9	72	64.5	14.2
Ineffective Green	0	0	0	0
Objectives				
Number of Vehicle(s) Leave			153.12	
Cycle Length (seconds)			240.57	
Vehicle Flow Rates (vehicles/hour)			2291.36	

4.3.2 Rama VI SS37 intersection

In Figure 4-12, the coordination is performed between Rama VI SS37 intersection and Pradiphat intersection. At $\boldsymbol{i} = \mathbf{2}$, 55 vehicles from previous intersections are added to the queue. The value of vehicles from previous intersection are accumulated by vehicle leave at each approach from Pradiphat intersection (including $\boldsymbol{i} = \mathbf{1, 3, 4}$). Note that the percentage of vehicles added to the queue length from previous intersection approaches varies. According to Table 4-21, 92% of vehicle leave at approach 1, 16% of vehicle leave at approach 3, and 10% of vehicle leave at approach 4 from Pradiphat intersection. These values are collected from average values based on time and date conferring to the data collection section. The result for vehicle leaves at each approach can also be examine in Table 4-21. The old queue and the new queue form the start total queue parameter, in which we use these values to optimize the intersections. In this case, the value at $\boldsymbol{i} = \mathbf{2}$ for Pradiphat intersection is ignored, because the flow from Pradiphat to Rama VI SS37. The effective flow out rate is recorded as 2600 vehicles per hour, which could be examined in OPL Table 4-17. In this case, the offset would have to shift by 30 seconds. This is because in order to clear the previous queue, the queue length at start calculation has to divide by the flow rate to get the time of clearing those vehicles. Therefore, 20 (or the queue length at start calculation) is divided by 2600 (or the flow rate), which then equivalent to 28.06 (in seconds). Subsequently, the traveling time from Pradiphat intersection to Rama VI SS37 intersection is 58 seconds. If we subtract 58 seconds with 28 seconds, or the time it takes to clear the old queue, then this would equivalent to 30 seconds. Therefore, at Rama VI SS37 intersection, the green time for $\boldsymbol{i} = \mathbf{1}$ would have to be open at 30 seconds in advance, in order to clear the previous queue and then the new queue that arrives from other previous intersection approaches. This would allow the flow consistency from one intersection to another. As demonstration from Figure 4-12, the green time at $\boldsymbol{i} = \mathbf{1}$ for Rama VI SS37 should shift by 30 seconds at 6pm.

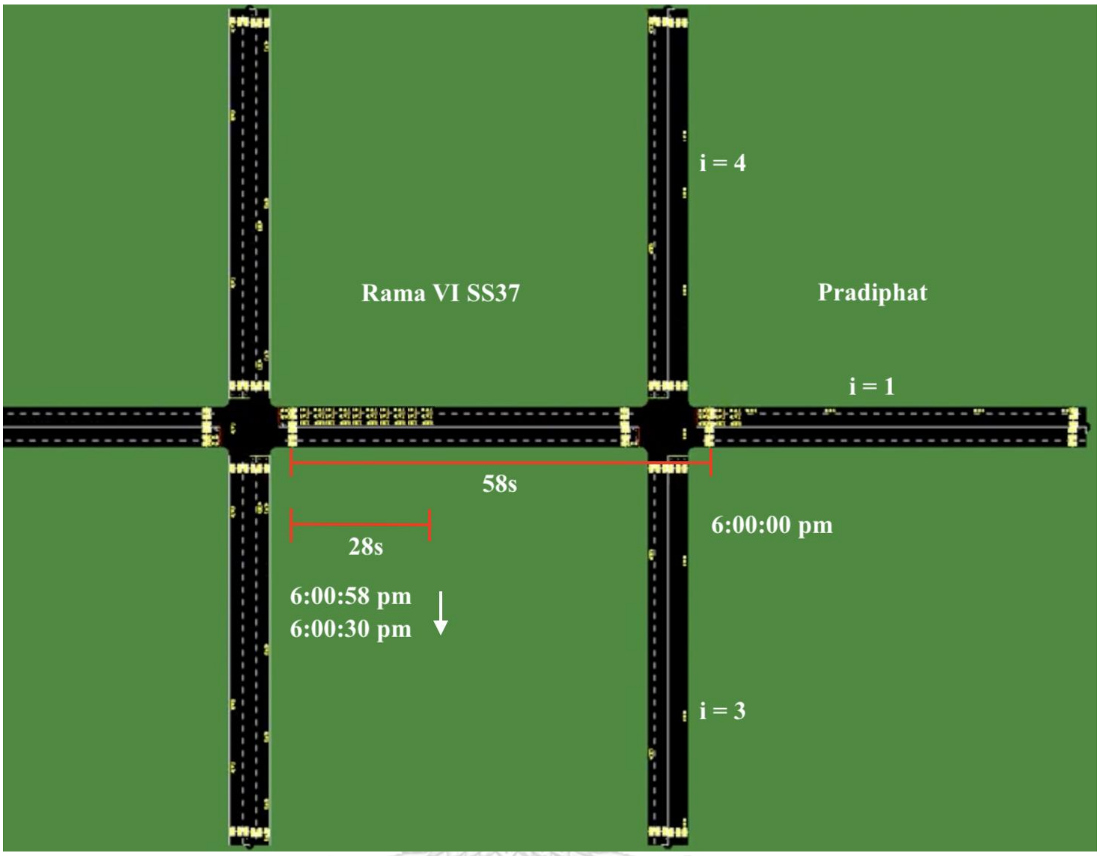

Figure 4-30 Time-Offset Demonstration between Rama VI SS 37 and Pradiphat.

Table 4-16 represents the OPL result of the optimized SS37 intersection. The number of vehicles leave is 153.12, and the cycle length is 240.57. The vehicle flow rates is 2291.36 vehicles per hour. As mentioned, start total queue at $\boldsymbol{i} = \mathbf{1}$ is 75, formed by the calculated queue length from previous intersection's approaches and the existing old queue. In this case, the effective flow out rate at $\boldsymbol{i} = \mathbf{1}$ is found to be 2600. The vehicle leave at each approach is found by flow out rate divided by the effective green time in Table 4-16. Note that the rest of the intersections has the same methodology.

Table 4-21 OPL Result of Optimized Rama VI SS 37 Intersection.

Rama VI SS 37	Approaches			
	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Parameters				
Flow in	1,520	2,010	620	780
Effective Flow out	2,600	2,580	1,000	1,200
Ineffective Flow out	1,420	1,480	1,080	1,020
Start Total Queue	75	85	42	48
Decision Variables				
Effective Total Queue	49	52	28	3.4
Ineffective Queue	0	0	0	0
Effective Green	67.85	72.56	55.4	7.06
Ineffective Green	0	0	0	0
Objectives				
Number of Vehicle(s) Leave			132.43	
Cycle Length (seconds)			222.85	
Vehicle Flow Rates (vehicles/hour)			2139.32	

4.3.3 Rama VI SSS2 intersection

For subsequent combining intersections, the coordination is performed between Rama VI SSS2 intersection and Rama VI SS37 intersection. 47 vehicles from the previous intersection are added to the queue. In this case, there is 88% for approach 1, 14% from approach 3, 12% for approach 4 leaving from Rama 6 SS37 (including $i = 1,3,4$) which can be examine in Table 4-21. Again, the values at $i = 2$ is ignored because the flow is from Rama VI SSS2 to Rama VI to SS37. The effective flow out rate is recorded as 2540 vehicles per hour, which is examined in OPL Table 4-17. In this case, the offset would have to shift by 7 seconds. To calculate the time to clear the previous queue, 24 seconds (or the queue length at start calculation) is divided by 2540 (or the flow rate) which is equivalent to 33.38 or 33 (in seconds). The traveling time from Rama VI SS37 intersection to Rama VI SSS2 intersection is 40 seconds. Therefore, by subtracting 40 seconds with 33 seconds, or the time it takes to clear the old queue, would equivalent to 6.62 seconds. Therefore, at Rama VI SSS2 intersection, the green time for $\boldsymbol{i} = \mathbf{1}$ would have to be open at 6.62 or 7 seconds in advance, in order to clear the previous and the new queue. Therefore, at 6pm 30 seconds, the green time should shift or offset by 7 seconds in advance.

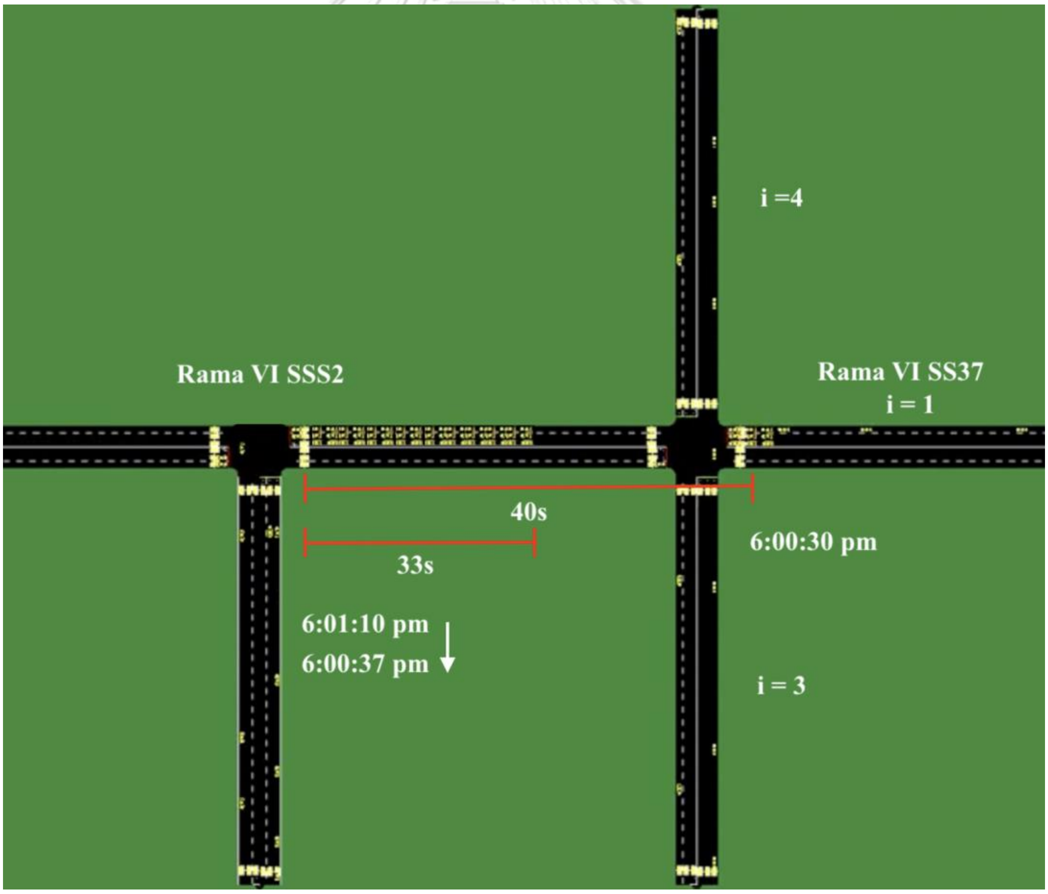

Figure 4-31 Time-Offset Demonstration between Rama VI SS 37 and SSS 2.

Table 4-22 OPL Result from Rama VI SSS 2 Intersection.

Rama VI SSS 2	Approaches		
	$i = 1$	$i = 2$	$i = 3$
Parameters			
Flow in	1,520	2,010	1,880
Effective Flow out	2,540	2,560	2,040
Ineffective Flow out	1,510	1,540	1,250
Start Total Queue	71	84	54
Decision Variables			
Effective Total Queue	47	52	8
Ineffective Queue	0	0	0
Effective Green	66.6	73	14
Ineffective Green	0	0	0
Objectives			
Number of Vehicle(s) Leave	106.97		
Cycle Length (seconds)	168.81		
Vehicle Flow Rates (vehicles/hour)	2,281.22		

4.3.4 Rama VI SSS intersection

The succeeding coordination is performed between Rama VI SSS2 intersection and Rama VI SSS intersection. 43 vehicles from the previous intersection are added to the queue. In this case, since Rama VI SSS 2 is a three-way intersection, there is 89% for approach 1 and 13% from approach 3 (including $i = 1,3$) which can be examine in

Table 4-21. The effective flow out rate is recorded to be 2650 vehicles per hour as examined in OPL Table 4-18. To clear the previous queue, 27 seconds (or the queue length at start calculation) divided by 2650 (or the flow rate) is equivalent to 36.22 or 36 (in seconds) in order to achieve the time. The traveling time from Rama 6 SSS intersection to Rama VI SSS2 intersection is 38 seconds. In this case, the offset would have to shift by 1.78 seconds. This is because if we subtract 38 seconds with 36.2 seconds, or the time it takes to clear the old queue, then it is equivalent to 15 seconds. Therefore, at Rama VI SSS2 intersection, the green time for $\boldsymbol{i} = \mathbf{1}$ would have to be open at 2 seconds in advance, in order to clear the previous and the new queue. Therefore, at 6pm 37 seconds the green time should offset by 2 seconds.

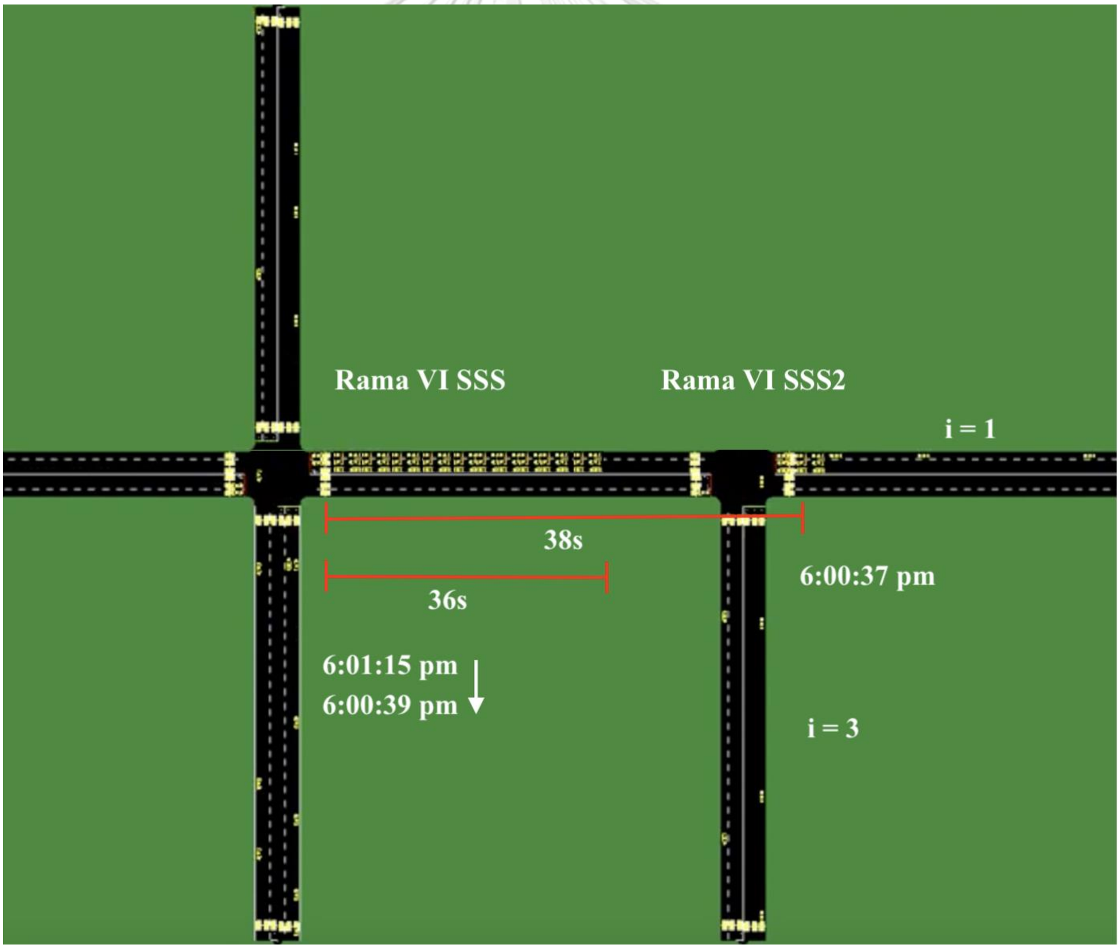

Figure 4-32 Time-Offset Demonstration between Rama VI SSS 2 and SSS.

Table 4-23 OPL Result from Rama VI SSS Intersection

Rama VI SSS	Approaches			
	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Parameters				
Flow in	1,510	2,020	510	450
Effective Flow out	2,650	2,720	2,050	2,010
Ineffective Flow out	1,560	1,590	1,240	1,210
Start Total Queue	70	78	33	27
Decision Variables				
Effective Total Queue	48	54	16	6.1
Ineffective Queue	0	0	0	0
Effective Green	65.2	71.5	28.1	10.9
Ineffective Green	0	0	0	0
Objectives				
Number of Vehicle(s) Leave			124.07	
Cycle Length (seconds)			195.65	
Vehicle Flow Rates (vehicles/hour)			2,282.91	

4.3.5 Rama VI TNC intersection

The consecutive intersection is performed between Rama VI TNC and SSS intersection. 46 vehicles from the previous intersection are added to the queue. According to Table 4-19, 89% of vehicle leave at approach 1 and 15% of vehicle leave at approach 3 from Rama 6 SSS intersection (or $i = 1, 3, 4$). The effective flow out rate is recorded to be 2500 vehicles per hour according to OPL Table 4-19. In this case, 24 (or the queue length at start calculation) divided by 2500 (or the flow rate) is equivalent to 34.95 or 35 (in seconds) in order to clear the previous queue. The traveling time from Rama 6 TNC intersection to Rama VI SSS intersection is 56 seconds.

In this case, the offset would have to shift by 21 seconds. This is because if we subtract 56 seconds with 35 seconds, or the time it takes to clear the old queue, then this is equivalent to 21 seconds. Therefore, at Rama VI TNC intersection, the green time would have to be open at 21 seconds in advance to clear the previous and then the new queue. Hence, at 6pm 39 seconds the green time should offset by 21 seconds.

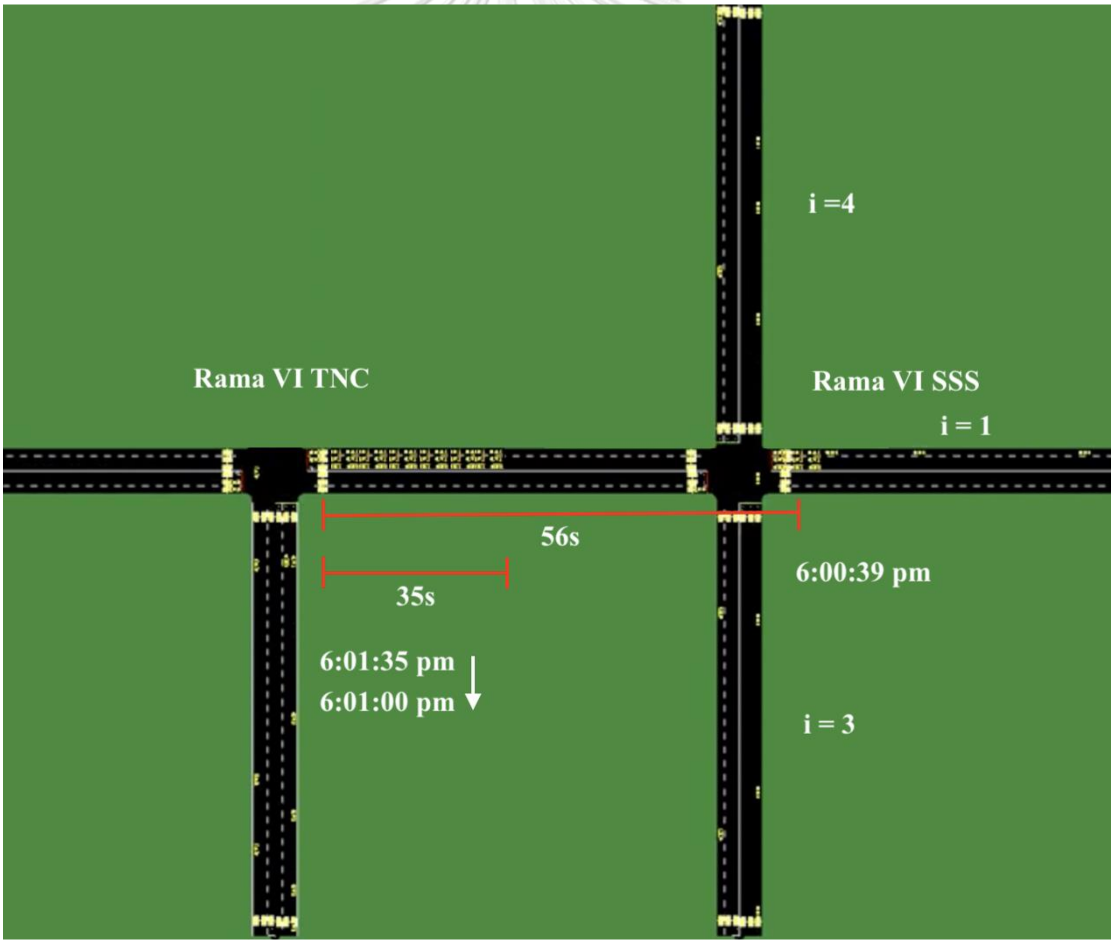

Figure 4-33 Time-Offset Demonstration between Rama VI SSS and TNC

Table 4-24 OPL Result from Rama VI TNC Intersection.

Rama VI TNC	Approaches		
	$i = 1$	$i = 2$	$i = 3$
Parameters			
Flow in	1,520	2,010	1880
Effective Flow out	2,500	2,550	2,010
Ineffective Flow out	1,500	1,540	1,120
Start Total Queue	70	78	41
Decision Variables			
Effective Total Queue	48	52	8.83
Ineffective Queue	0	0	0
Effective Green	69.1	73.4	15.8
Ineffective Green	0	0	0
Objectives			
Number of Vehicle(s) Leave			108.83
Cycle Length (seconds)			173.34
Vehicle Flow Rates (vehicles/hour)			2,260.23

4.3.6 Tuk Chai intersection

Finally, the last intersection is performed between Rama VI TNC intersection and Tuk Chai intersection. 45 vehicles from the previous intersection are added to the queue. According to Table 4-21, 91% of vehicle leave from approach 1 and 14% leave from approach 3 accumulated by vehicle leave at each approach (in percentage) from Rama VI TNC three-way intersection (including $i = 1,3$). The queue length at the start of green light is 72. By examining OPL Table 4-20, the effective flow out rate is recorded to be 2650 vehicles per hour. 27 seconds (or the queue length at start calculation) divided by 2650 (or the flow rate) is equivalent to 36.9 or 37 (in seconds) in order to clear the previous queue. The traveling time from Rama VI TNC intersection to Rama VI SSS intersection is 60 seconds. In this case, the offset would have to shift by 23 seconds. This is because 60 seconds subtracted with 36.9 seconds, or the time it takes to clear the old queue, is equivalent to 23 seconds. Therefore, at Rama VI SSS 2 intersection, the green time for $\boldsymbol{i} = \mathbf{1}$ would have to be open at 23 seconds in advance, in order to clear the previous and the new queue. Hence, at 6pm 1 minute the green time should offset by 23 seconds.

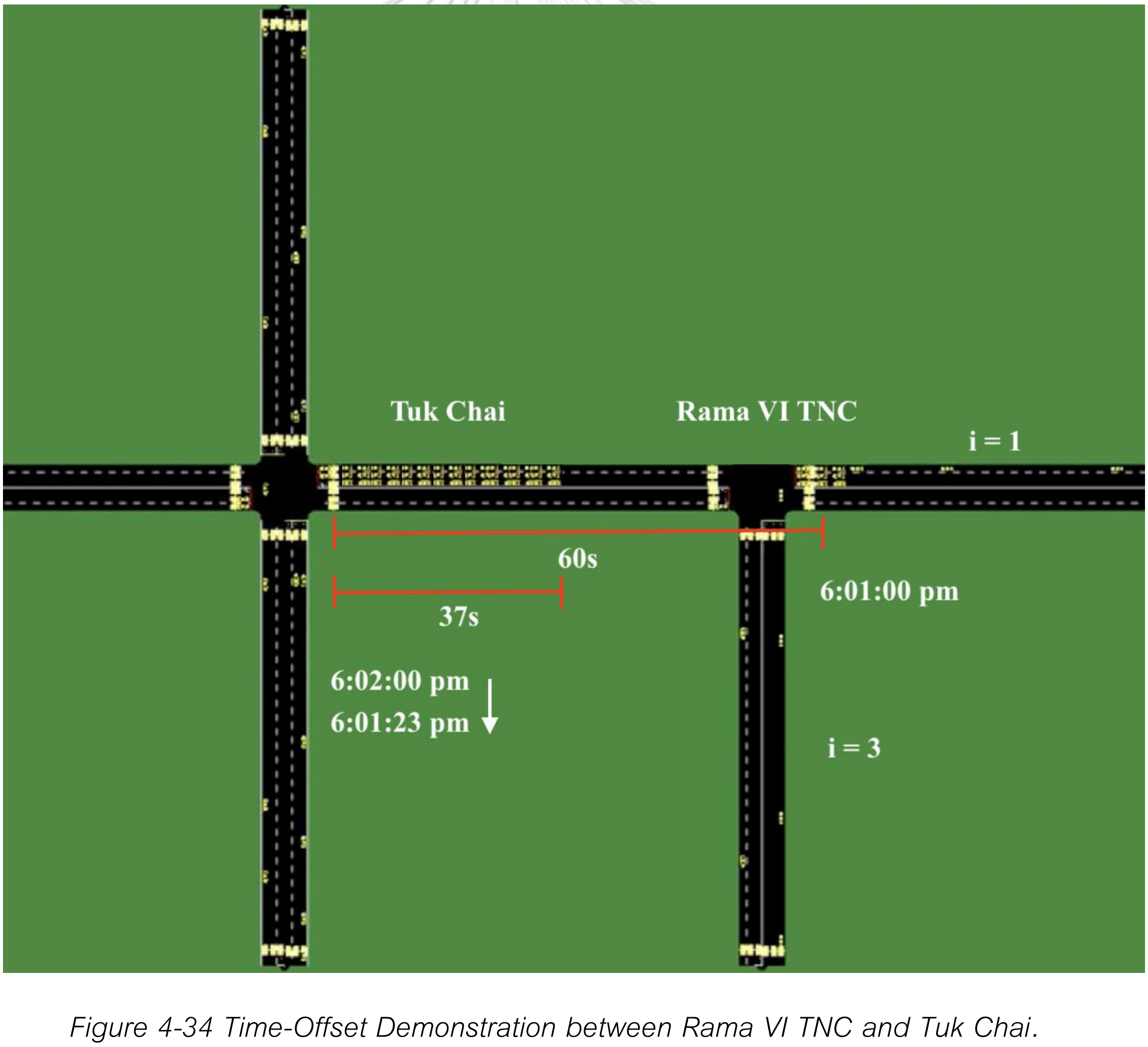

Figure 4-34 Time-Offset Demonstration between Rama VI TNC and Tuk Chai.

Table 4-25 OPL Result from Tuk Chai Intersection.

Tuk Chai Intersection	Approaches			
	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Parameters				
Flow in	1,520	2,010	520	580
Effective Flow out	2,650	2,700	2,050	2,080
Ineffective Flow out	1,550	1,590	1,200	1,250
Start Total Queue	72	85	40	44
Decision Variables				
Effective Total Queue	48	50	4.2	20
Ineffective Queue	0	0	0	0
Effective Green	65.2	66.7	7.4	34.6
Ineffective Green	0	0	0	0
Objectives				
Number of Vehicle(s) Leave			122.22	
Cycle Length (seconds)			193.31	
Vehicle Flow Rates (vehicles/hour)			2,276.10	

4.4 Opposite Direction

Additionally, if we want to examine the opposite direction in terms of offset, then the following are observed.

4.4.1 Tuk Chai intersection

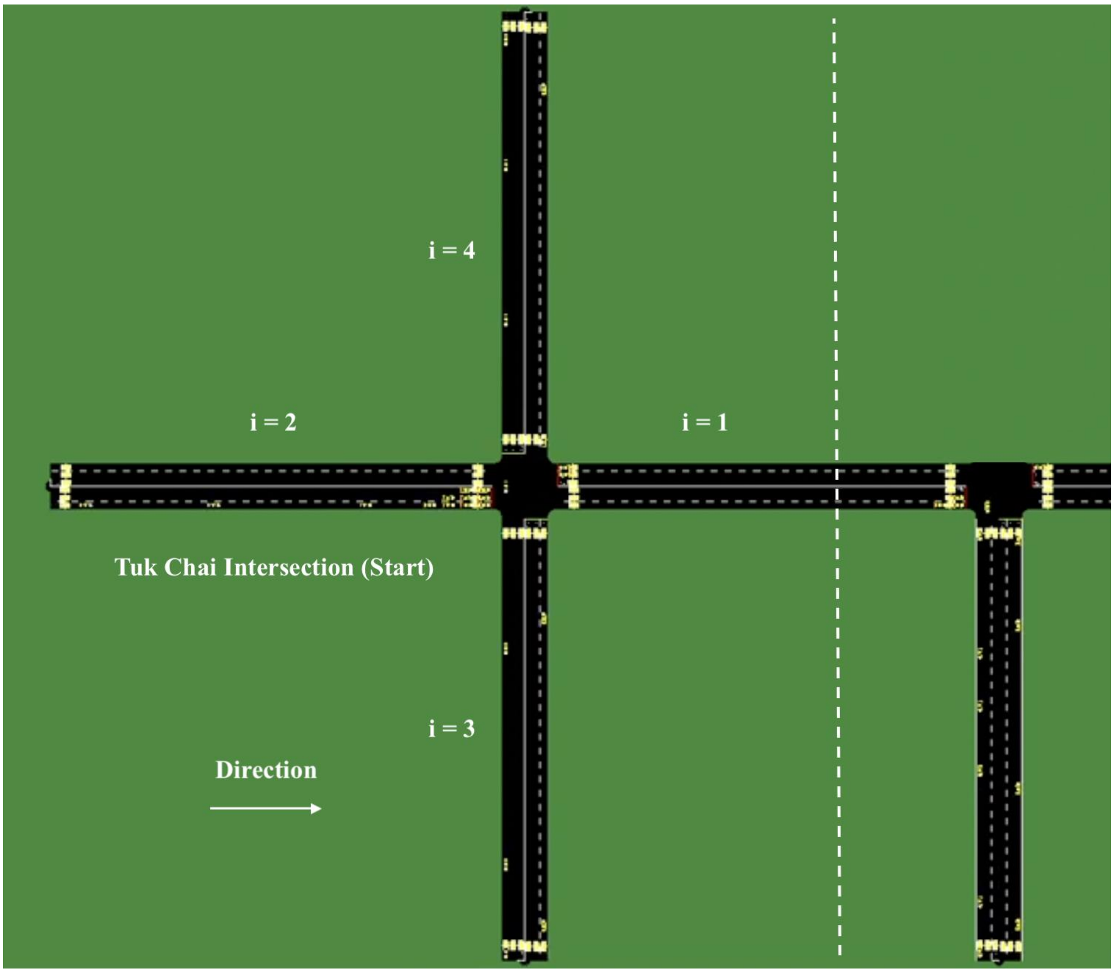

Figure 4-35 Visualization for Starter Intersection – Tuk Chai Intersection.

In Figure 4-17, it represents the visualization for Tuk Chai intersection. We can see the visualization along with different approaches of the intersections, where i is represented by the approach of that intersection. Note that i = 1 approach is not taken into account in terms of calculation. This is because the flow is from Tuk Chai to

Pradiphat intersection. In this case, Tuk Chai intersection is the starter intersection. Therefore, no offset is required.

4.4.2 Rama VI TNC intersection

With the similar concept, approach $\boldsymbol{i} = \mathbf{1}$ is ignored in order to calculate from Tuk Chai to Rama VI TNC intersection. The vehicles from the previous intersection are 73 are added to the queue. The value of vehicles from previous intersection are accumulated by vehicle leave at each approach from Tuk Chai intersection (including $\boldsymbol{i} = \mathbf{2, 3, 4}$). Note that the percentage of vehicles added to the queue length from previous intersection approaches varies. According to Table 4-22, 80% of vehicle leave at approach 2, 8% of vehicle leave at approach 3, and 5% of vehicle leave at approach 4. Note that each vehicle leaving at different approaches times with different percentages, because this depends on how much the vehicles are leaving at that point. In this case, the value at $\boldsymbol{i} = \mathbf{1}$ for Tuk Chai intersection is ignored, because the flow is at reverse direction (from Tuk Chai to Rama VI TNC). The effective flow out rate is recorded as 2550 vehicles per hour, conferring to OPL Table 4-19. In this case, the offset would have to shift by 49.51 seconds. This is because 5 seconds (or the queue length at start calculation) divided by 2550 (or the flow rate) is approximately 6 (in seconds). The traveling time from Tuk Chai intersection to Rama VI TNC intersection is 56 seconds. If we subtract 56 seconds with 6 seconds, or the time it takes to clear the old queue, then this is equivalent to 50 seconds. Therefore, at Rama VI TNC intersection, the green time for $\boldsymbol{i} = \mathbf{2}$ would have to be open at 50 seconds in advance, in order to clear the previous and the new queue. This would allow the flow consistency from Tuk Chai to Rama VI TNC. Therefore, as a demonstration from Figure 4-18, the green time should offset by 50 seconds at 6pm in advance.

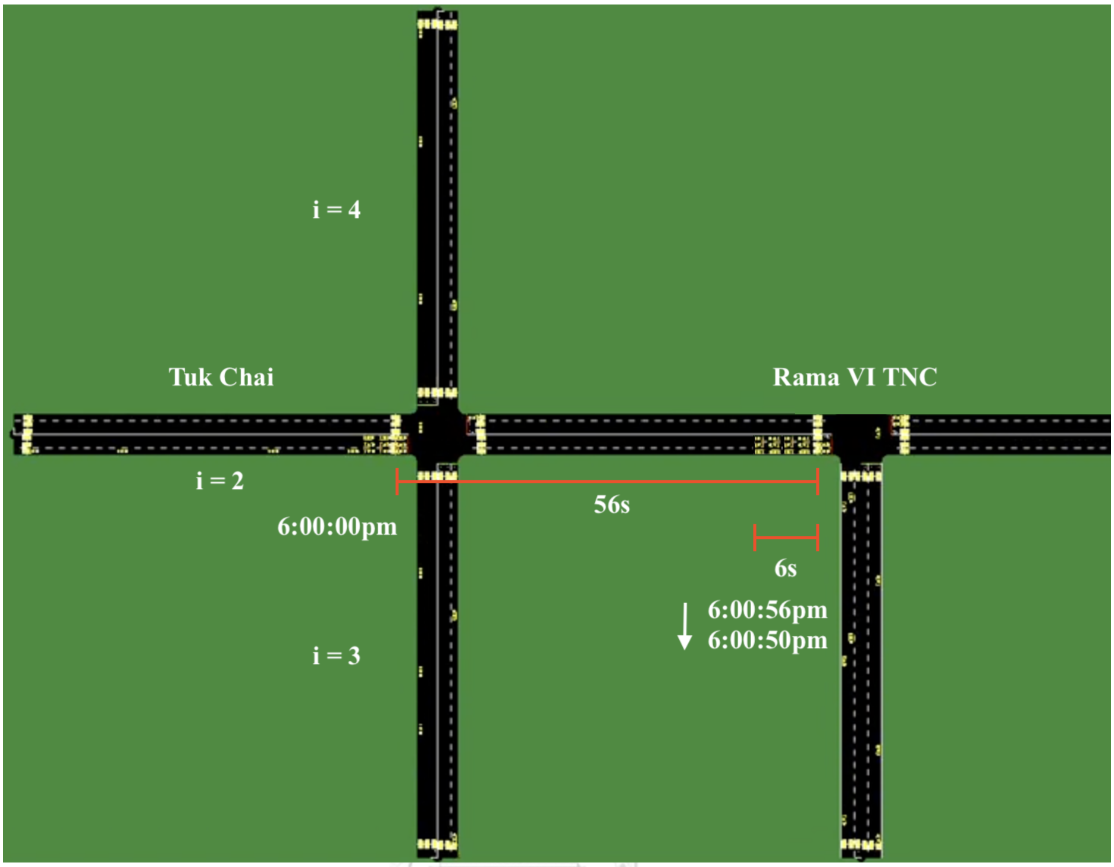

Figure 4-36 Time-Offset Demonstration between TC and Rama VI TNC.

4.4.3 Rama VI SSS intersection

For next coordinated intersection, the vehicles from the previous intersection are 73 are added to the queue. The value of vehicles from previous intersection are accumulated by vehicle leave at each approach from Rama VI TNC intersection. In this case, 81% of vehicle leave at approach 2 and 8% of vehicle leave at approach 3 from Rama VI TNC including $\boldsymbol{i} = \mathbf{2, 3, 4}$. Again, the approach $\boldsymbol{i} = \mathbf{1}$ for Rama VI SSS intersection is ignored, because the flow is from Rama VI TNC to Rama VI SSS. The effective flow out rate is recorded as 2720 vehicles per hour. In this case, the offset would have to shift by 49.51 seconds. This is because 5 seconds (or the queue length at start calculation) divided by 2720 (or the flow rate) is equivalent to 15.2 (seconds). The traveling time from Rama VI TNC intersection to Rama VI SSS intersection is 38 seconds.

If we subtract 38 seconds with 15 seconds, or the time it takes to clear the old queue, then this is equivalent to 23 seconds. Therefore, at Rama VI SSS intersection, the green time for $\boldsymbol{i} = \mathbf{2}$ would have to be open at 23 seconds in advance, in order to clear the previous and the new queue. This would allow the flow consistency from Rama VI TNC to Rama VI SSS. Therefore, as a demonstration from Figure 4-19, the green time should offset by 23 seconds at 6pm 50 seconds.

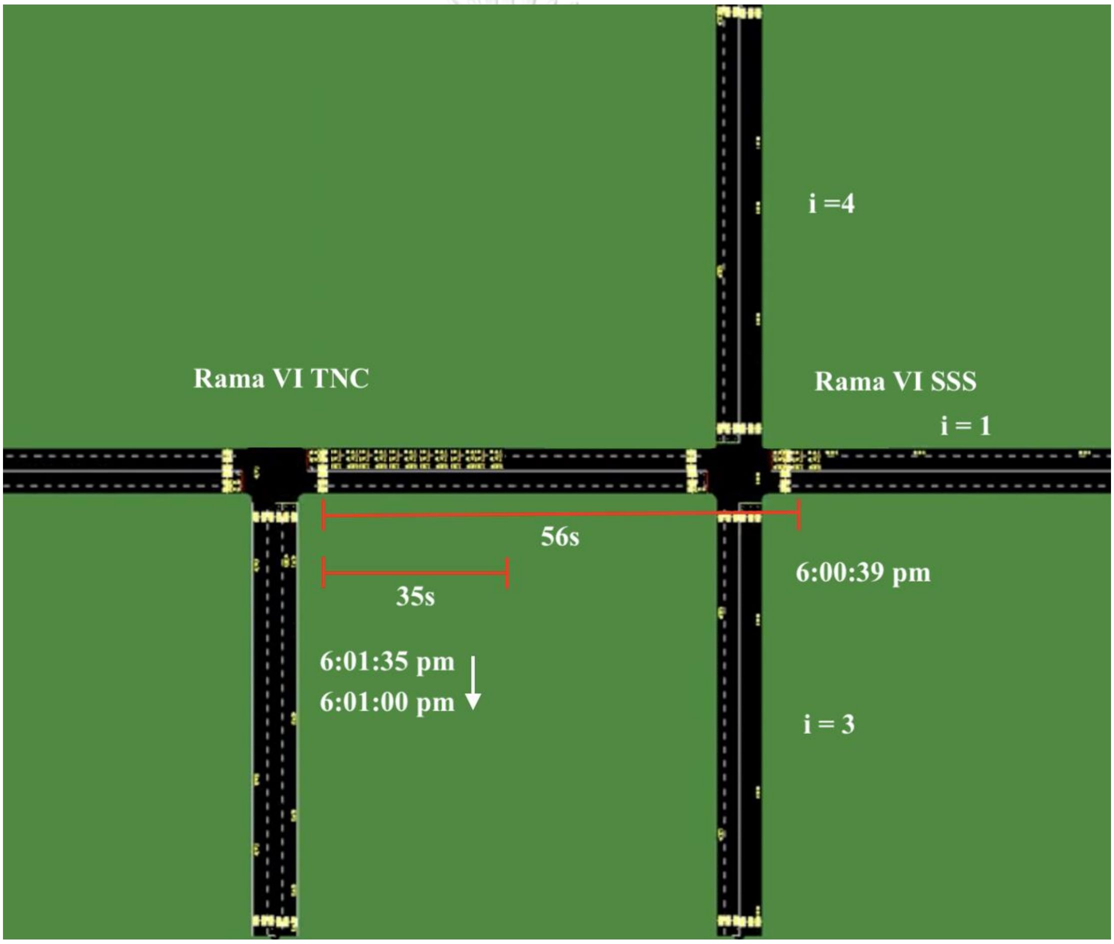

Figure 4-37 Time-Offset Demonstration between Rama VI TNC and Rama VI SSS.

4.4.4 Rama VI SSS2 intersection

For subsequent intersection, the vehicles from the previous intersection are 66 is added to the queue. In this case, 81% of vehicle leave at approach 2 and 8% of vehicle leave at approach 3 for Rama VI SSS intersection. The effective flow out rate is recorded as 2560 vehicles per hour. To calculate the time of clearing the previous queue, 16 seconds (or the queue length at start calculation) divided by 2560 (or the flow rate) which is equivalent to 22.19 (seconds). The traveling time from Rama VI SSS intersection to Rama VI SSS2 intersection is 40 seconds. In this case, the offset would have to shift by 17.8 seconds. If we subtract 40 seconds with 22.19 seconds, or the time it takes to clear the old queue, then this is equivalent to 17.8, or 18 seconds. Therefore, at Rama VI SSS intersection, the green time for $\boldsymbol{i} = \mathbf{2}$ would have to be open at 18 seconds in advance, in order to clear the previous and the new queue. This would allow the flow consistency from Rama VI SSS to Rama VI SSS2. Therefore, as a demonstration from Figure 4-20, the green time should offset by 23 seconds at 6pm 13 seconds.

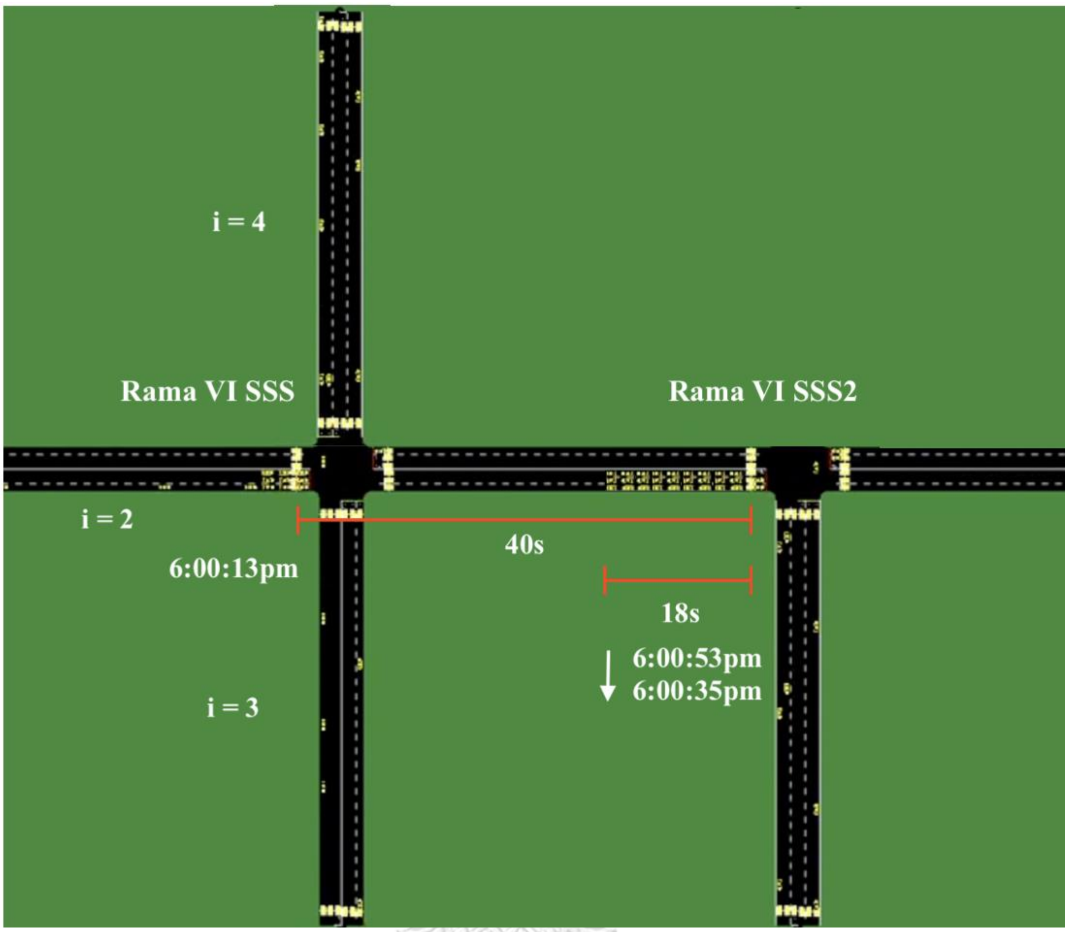

Figure 4-38 Time-Offset Demonstration between Rama VI SSS and SSS 2.

4.4.5 Rama VI SS37 intersection

The vehicles from the previous intersection are 72 is added to the queue. In this case, 83% of vehicle leave at approach 2 and 5% of vehicle leave at approach 3 from Rama VI SSS 2 three-way intersection (including $i = 2,3$). The effective flow out rate is equivalent to 2580. 13 seconds (or the queue length at start calculation) divided by 2580 (or the flow rate) is approximately equivalent to 18 (in seconds) in order to clear the previous queue. The traveling time from Rama VI SSS intersection to Rama VI SS37 intersection is 58 seconds. If we subtract 58 seconds with 18 seconds, or the time it takes to clear the old queue, then this is approximately equivalent to 40 seconds. Therefore, at Rama VI S37 intersection, the green time for $i = 2$ would have to be open at 40 seconds in advance at 6 pm 35 seconds, in order to clear the previous and the new queue.

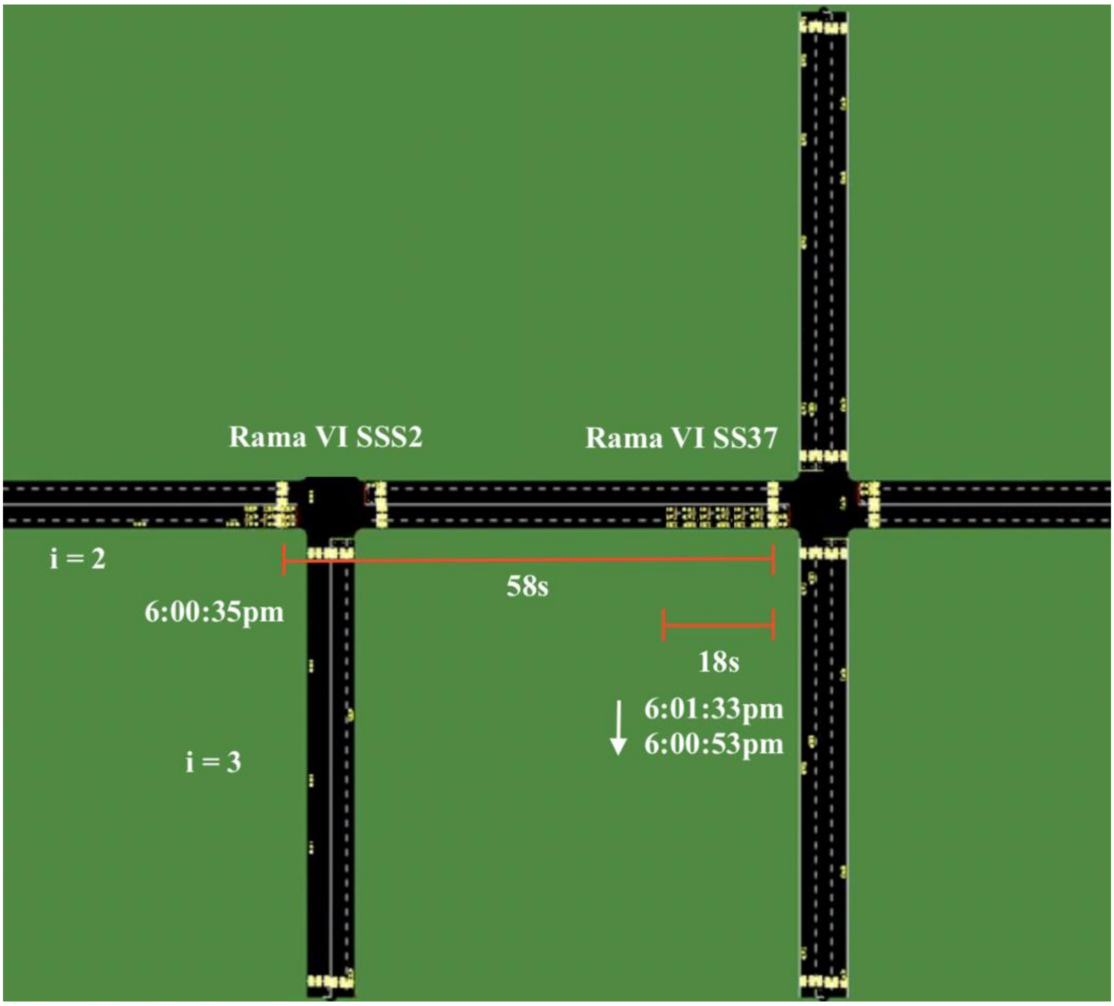

Figure 4-39 Time-Offset Demonstration between Rama VI SSS 2 and SS 37

4.4.6 Pradiphat Intersection

The vehicles from the previous intersection are 72 is added to the queue. The vehicles from previous intersection are accumulated by vehicle leave at each approach from Rama VI SS37 intersection (including $\boldsymbol{i} = \mathbf{2,3,4}$). In this case, 84% of vehicle leave at approach 2, 11% of vehicle leave at approach 3, and 6% of vehicle leave at approach

4. The effective flow out rate is equivalent to 2750. To calculate the time, 14 seconds (or the queue length at start calculation) divided by 2750 (or the flow rate) is approximately equivalent to 18 (in seconds) in order to clear the previous queue. The traveling time from Rama VI SS37 intersection to Pradiphat intersection is 58 seconds. If we subtract 42 seconds with 18 seconds, or the time it takes to clear the old queue, then this is approximately equivalent to 24 seconds. Therefore, at Pradiphat intersection, the green time for $\boldsymbol{i} = \mathbf{2}$ would have to be open at 24 seconds in advance at 6 pm 53 seconds, in order to clear the previous and the new queue.

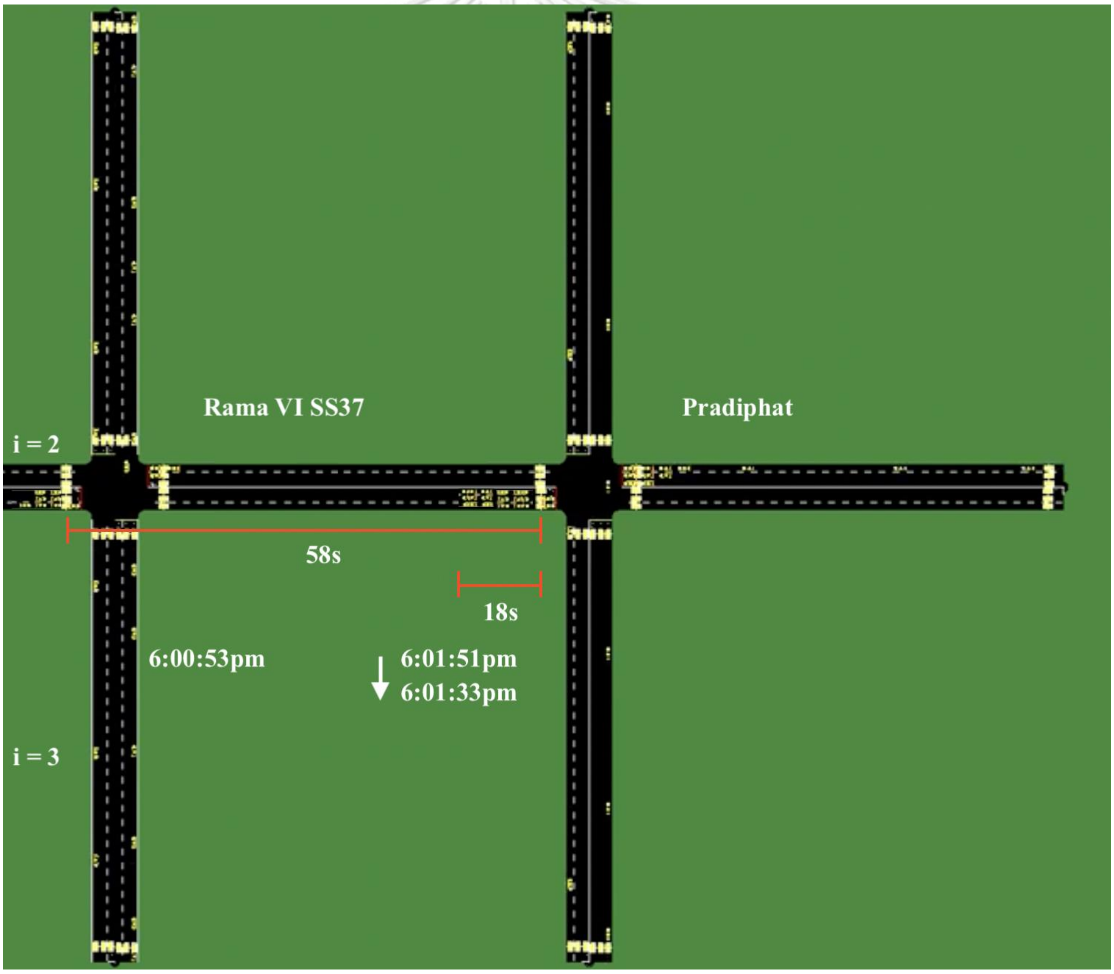

Figure 4-40 Time-Offset Demonstration between Rama VI SS 37 and Pradiphat.

4.5 Coordinated Intersections Result Summary

Table 4-26 Coordinated Intersections Result Summary – Pradiphat to Tuk Chai

Information(s)	Pradiphat	Rama VI SS37	Rama VI SSS2	Rama VI SSS	Rama VI TNC	Tuk Chai
Vehicle to add queue length from previous intersection	-	55	47	43	46	45
Start Total Queue	82	75	71	70	70	72
Flow rate	2680	2600	2540	2650	2500	2650
Optimized Green Time for approach 1	69.85	67.85	66.61	65.21	69.12	65.21
Vehicle Leaves at approach 1	52	49	47	48	48	48
Leaving Percentage for approach 1	0.92	88	0.90	0.89	91	-
Optimized Green Time for approach 3	64.53	55.39	14.07	28.10	15.81	7.42
Vehicle Leaves at approach 3	37.99	28	7.97	16	8.26	4.22
Leaving Percentage for approach 3	0.16	14	0.13	0.15	14	-
Optimized Green Time for approach 4	14.19	7.06	-	10.88	-	34.62
Vehicle Leaves at approach 4	8.12	3.43	-	6.07	-	19.99
Leaving Percentage for approach 4	0.10	12	-	0.10	-	-

Table 4-27 Coordinated Intersections Result Summary – Tuk Chai to Pradiphat

Information(s)	Tuk Chai	Rama VI TNC	Rama VI SSS	Rama VI SSS2	Rama VI SS37	Pradiphat
Vehicle to add queue length from previous intersection	-	73	66	68	72	11
Start Total Queue	85	78	78	84	85	93
Flow rate	2700	2550	2720	2560	2580	2750
Optimized Green Time for approach 2	66.7	71.47	71.47	73.13	72.56	69.85
Vehicle Leaves at approach 2	85	78	78	85	85	93
Leaving Percentage for approach 2	0.80	0.81	0.82	0.83	0.04	-
Optimized Green Time for approach 3	7.42	73.41	28.10	14.07	55.39	64.53
Vehicle Leaves at approach 3	40	41	33	54	42	53
Leaving Percentage for approach 3	0.08	0.08	0.08	0.05	0.11	-
Optimized Green Time for approach 4	34.62	15.81	10.88	-	7.06	14.19
Vehicle Leaves at approach 4	44	-	27	-	48	58
Leaving Percentage for approach 4	0.05	-	0.06	-	0.06	-

4.5.1 Coordinated Intersections Bandwidth

To clarify how bandwidth works, in Figure 4-23 represents the bandwidth result of Pradiphat intersection to Tuk Chai intersection. We can see the decent alignment in terms of the bandwidth. However, this does not necessary mean that there is a flow consistency for each intersection, or that every intersection will receive the consecutive green light.

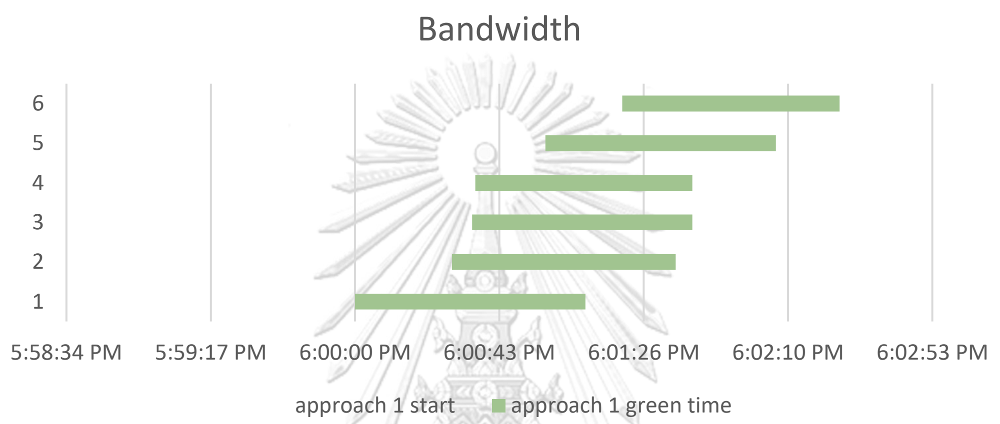

Figure 4-41 Bandwidth Visualization

If we examined the Figure 4-24 shows the green wave time for each of the intersection. When comparing with Figure 4-23, we can see some matches in terms of a pattern. Approximately the time between 18:00:00 and 18:01:26 pm range will receive the consecutive green light. Similarly, between 18:02:53 to 18:04:19 pm range will also receive the consecutive green light. However, in the middle time-span, the vehicles could receive a less consecutive green light, because the green wave time graph does not show the identical pattern with the bandwidth pattern.

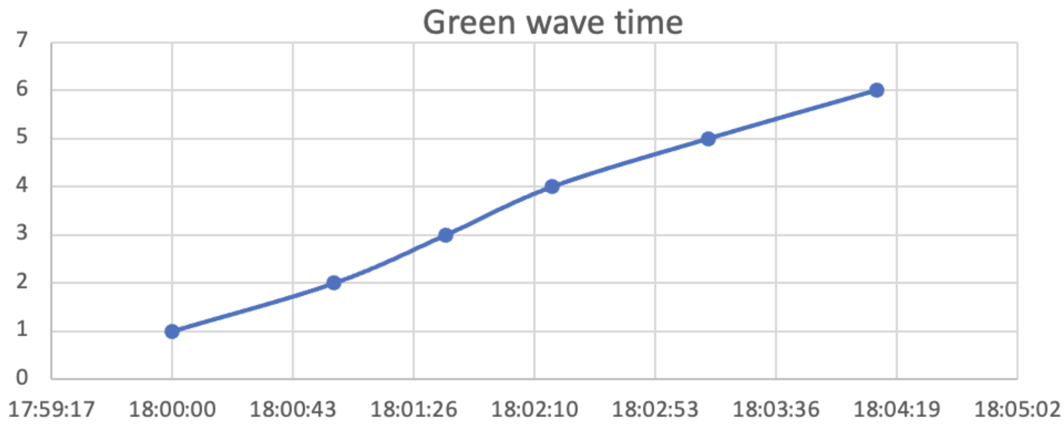

Figure 4-42 Green Wave Time

Note that the result with a very low or high alignment does not mean that this would give the consecutive green light. This depends solely on the green wave time. The more it shows the match in terms of a pattern, the better it is performing. However, this is regarded as ideal situation. In the real situation, this is really hard to achieved due to the inconsistent volume of traffic. Therefore, having that type of perfect scenario where everything goes as expected is very unlikely. Subsequently, for the Tuk Chai to Pradiphat intersection also gives the similar result. As a result, this is an example of visualization for the bandwidth and how it works to approximate the flow consistency.

4.6 Optimization Result Summary for Coordinated Intersection

In terms of analytical summary, overall intersection shows a percentage improvement of approximately 20% range after performing optimization and traffic coordination.

In Figure 4-24 represents the chart comparing the current traffic management with the optimized results. We can observe that the rate of vehicles per hour in current traffic management for Pradiphat, Rama VI SS37, Rama VI SS2, Rama VI SSS, Rama VI TNC, and Tuk Chai have improved of greater amount.

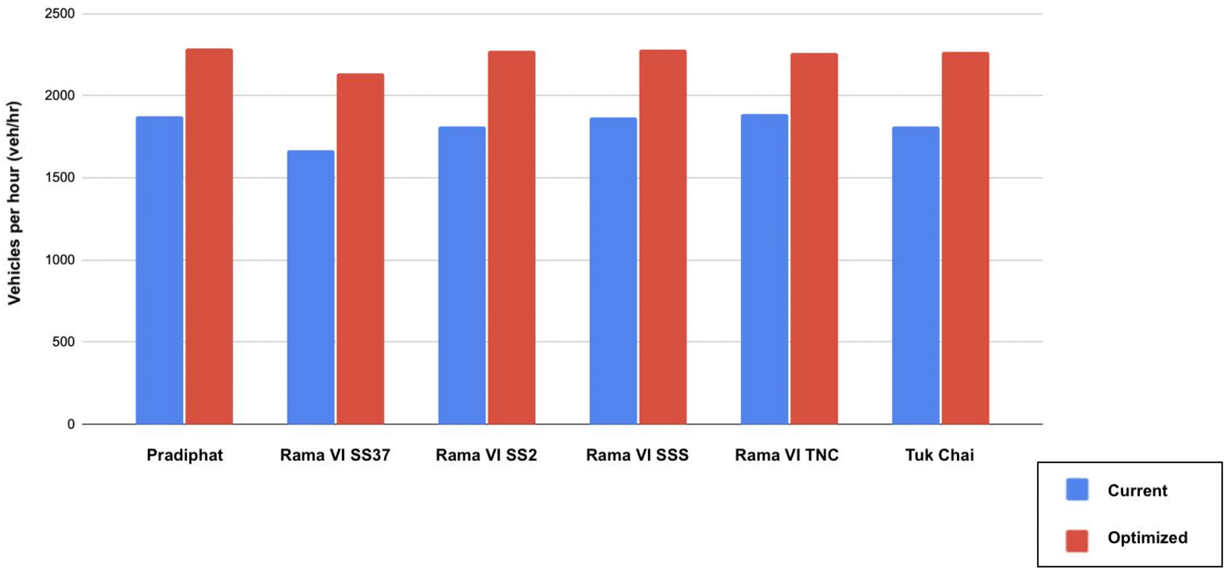

Figure 4-43 Charts comparing current and optimized result for the isolated intersections.

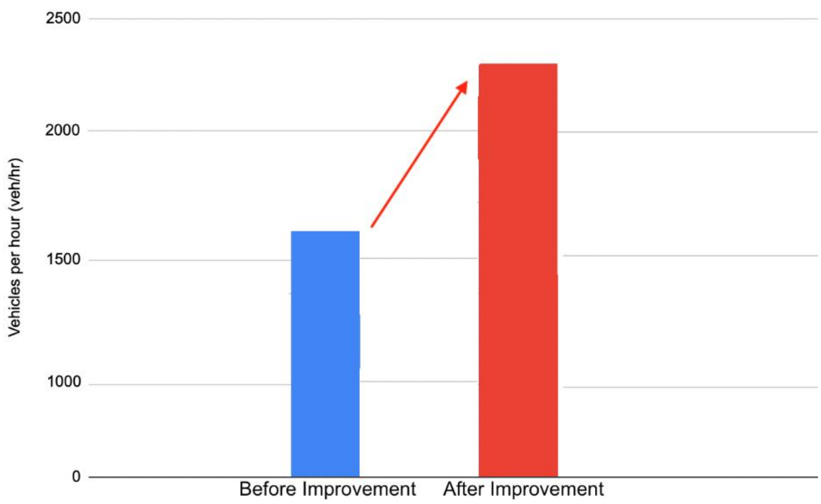

Figure 44 Charts comparing current and optimized intersections (On average)

In Table 4-23 summarizes the percentage improvement for each of the intersection. The intersections of study show a mean improvement of 23.04%. With maximum percentage improvement came from Rama VI S37 intersection, with the percentage improvement of 28.30%, and the minimum improvement came from Rama VI TNC intersection with the percentage improvement of 19.66%.

Table 4-28 Result Summary

Result summary for each intersection			
Intersection(s)	Vehicle Flow Rates (veh/hr)		
	Current	Optimized	Improvement
Pradiphat	1875.17	2291.36	22.19%
Rama VI SS37	1667.38	2139.32	28.30%
Rama VI SS2	1811.47	2275.39	20.94%
Rama VI SS	1870.58	2282.91	22.04%
Rama VI TNC	1888.95	2260.23	19.66%
TC	1813.61	2269.05	25.12%
Mean	1821.19	2253.04	23.04%
Max.	1888.95	2139.32	28.30%
Min.	1667.38	2291.36	19.66%

Table 4-29 Percentage improvement of different approach(s).

Intersection(s)	i = 1	i = 2	i =3	i = 4
Pradiphat	21.31	22.17	17.54	17.91
Rama VI SS37	22.36	22.39	18.59	24.70
Rama VI SS2	12.87	15.53	13.87	-
Rama VI SSS	18.00	17.94	24.61	24.84
Rama VI TNC	17.32	17.93	17.57	-
TC	19.13	22.32	36.19	24.92

4.7 Visualization

The results for the coordinated intersections cannot be tested in the real scenario because we do not have the right to do so. Therefore, the visualization can help us into certain extent for the ideal condition.

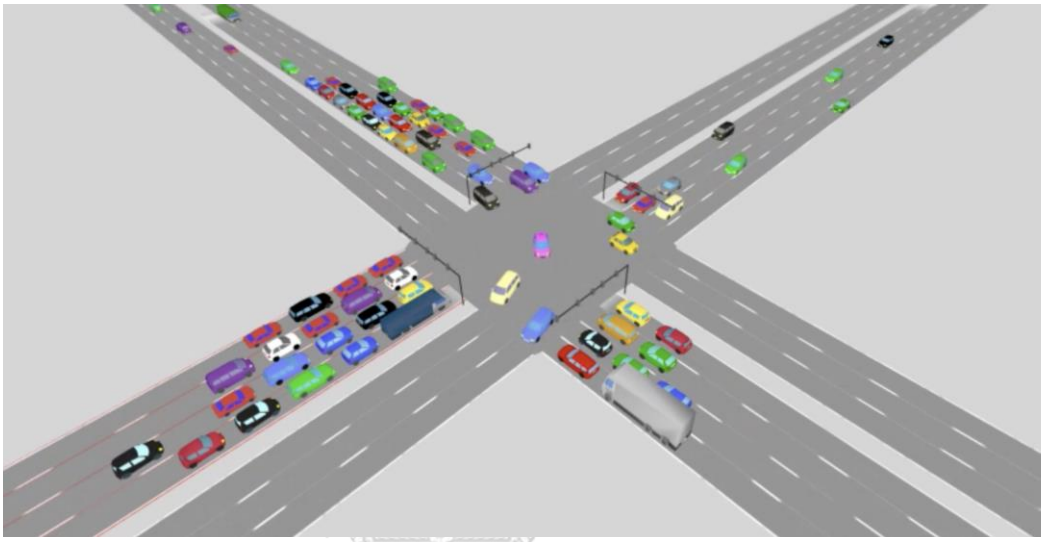

Figure 4-45 An example of traffic visualization illustrating the flow of the vehicle leaving the approaches with Pradiphat intersection configuration, or one of the intersections of study.

In Figure 4-27, represents the visualization for isolated intersection. It was found that the signal time responds to the total queue. Therefore, this shows the output of the effective green time because when there is a longer queue it serves the right amount of green time, and when there is less queue, it serves the less amount of green time signal. Therefore, the queueing management aligns with the green light signal. We can see that this will cause less in the delay and improve the traveler time and the flow of every approach, after the process of optimization. Another example can be found in Figure 4-23 below when performing the coordination.

In the video link will also show the visualization in terms of traffic coordination. Again, this can be examined in the video file. Through the visualization, the flow consistency for between these intersections is shown. For instance, Pradiphat, Rama VI SS37, Rama VI SSS2, Rama VI SSS, Rama VI S37, Rama VI TNC, Tuk Chai intersections receive a consecutive green light for all of their pathway. Both forward and reverse direction. No bottleneck is observed from the visualization. Conferring to Figure 3-5, the example result can also be examined in the link. Note that some of the videos are licensed.

The visualization for Figure 3-5 and Figure 4-27:
https://drive.google.com/drive/folders/1n_x6ZF9dSrEhW2DTonbbDkDGqdImKeyf?usp=sharing

4.8 Result Interpretation and Discussion

4.8.1 Optimizing the intersections

We can see that after the use of optimization, the average improvement is around 23.04%. The maximum improvement occurs at Rama VI SS37. On the other hand, the minimum improvement come from Rama VI TNC intersection. Conferring to the theory and current optimizer, the constraint should have greater effect on the traffic that has more saturated condition. When there are more vehicles, then the constraint will perform better. However, when less queue occurs, this would contain only the effective queue. The effective green time would only be given. We can say that more vehicles are flowing into the queue at these intersections.

By making a note, there is an effect for the upper bound constraint in the cases where there are more vehicles. According to Figure 4-29, case 2 turns out to be better than case 1, because it has the upper bound constraint. Making it to choose only the effective flow out. For case 1, it has both effective and ineffective flow out results. Therefore, overall flow out is worse than case 2. Hence, during rush hour the optimum cycle length helps reduces ineffective flow out.

4.8.2 Traffic Coordination

For traffic coordination, we consider the dynamic issue, and the fact that offset technique requires real-time information. Therefore, the real-time data is use. This shows the concept of how traffic coordination works before the real implementation. By applying the technique into the visualization, we can easily observe that all intersections of study receive the consecutive greenlight. For both forward and reverse direction of traffic. The offset technique allows the flow consistency, and no traffic bottleneck is observed in terms of visualization.

By inspection, the bandwidth from the result have shown that the offset technique from Pradiphat to Tuk Chai intersection has shown a greater improvement in this case.

However, since this a real-time, the opposite effect could occur. Currently, a detailed data cannot be obtained, since the traffic sensor still needs an improvement. Therefore, greater number of samples cannot be collected. However, these results already summarize the main ideology.

In practicality, one must still decide which side they want the flow consistency to be provide. Since different sides of the intersection will have different volume of traffic. In reality, different time may have different volume of the vehicles. In other words, one side of the traffic could be greater volume of traffic than the other side. In theory, when you let one side better, another side will have less effective flow. Therefore, it is better to let flow consistency from one side than another.

4.8.3 Covid-19 Effect

In this research, the data is collected after the peak of covid situation. That is why we can see a great improvement of approximately 20%. Before, the preliminary test was conducted. However, the result was not that satisfactory, because only 5% of improvement is achieved. Hence, the model works more effectively when there are more vehicles flowing into the queue.

Covid-19 traffic volume reductions was one of the issues that was face during data collection. This prevents a lot of valid performance. The previous levels of traffic volumes are approximately reduced by half of percentages from the regular baselines. Since Covid-19 significantly reduced traffic volumes, the data collection was performed again recently after the peak. Traffic volumes expected back up again fully in the near future. Nonetheless, this model still able to increase the productivity of transportation networks through its novel optimization algorithm. As observe at the case of Pradiphat, Rama VI SS37, Rama VI SSS2, Rama VI SSS, Rama VI TNC, Tuk Chai intersection, using the current optimization model was able to show a good improvement.

4.8.4 Model Sensitivity

For model sensitivity, this optimization model is sensitive in certain aspect. The effect of the optimization model has significant impact when there are more vehicles flowing into the queue. On the other hand, this model will not be effective when there are less vehicle flowing into the queue, or when there is less traffic volume. Therefore, the model does not have an effect during which the congestion does not occur, and the constraints should not have an effect during regular hours.

This is the reason why this research focus on only a certain hour, or during “rush hour”. Specifically, this model works well when there are more vehicles flowing in. In this section, we will focus on how the decision was made by mentioning the preliminary experiment that were found previously. Based on the experiments, the effect of the optimization model has less impact on the result, and is sensitive towards the regular traffic hour.

Table 4-25 represents case 1 or 2, shows an example result from Pradiphat intersection during the regular hour when there no optimization process was perform.

Table 4-30 - OPL Result with or without optimization during regular hour.

Case 1 or 2 Results	Approaches			
	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Parameters				
Flow in	1360	1800	550	650
Effective Flow out	3900	3900	3800	3800
Ineffective Flow out	3000	3000	2000	2000
Start Total Queue	25	30	12	14
Decision Variables				
Effective Total Queue	25	30	12	14
Ineffective Queue	0	0	0	0
Effective Green	23	28	11	13
Objectives				
Number of Vehicle(s) Leave			81	
Cycle Length (seconds)			95.4	
Vehicle Flow Rates (vehicles/hour)			2,276.10	

Results in case 1 and case 2 represents the process with and without optimization during regular hour respectively. In the first case, they release time is equivalent to the total queue. By inspection, the cycle length is 95.40 sec and the vehicle leaving from the intersection is 81 vehicles. In other words, the flow rate is 81 vehicles per 95.40 sec, or 0.849 vehicles per sec. If we examine the total queue approach row and the effective green approach row, the effective green time of each approach corresponds to the effective total queue of that approach. In other words, they release the vehicle or turn on the green light signal based on the queue.

For case 2, we undergo the optimization process. With the same data of flow in approach, the cycle length and the vehicle leave are the same. Hence, the traveling time is the same for all of the approaches. In other words, this means that when there are less vehicles that flow into the approaches, the constraints have no effect on the number of vehicles that leave from the intersection.

Table 4-31 OPL result without optimization during rush hour.

Case 3 Results	Approaches			
	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Parameters				
Flow in	1520	2010	620	780
Effective Flow out	3900	3900	3800	3800
Ineffective Flow out	3000	3000	2800	2800
Start Total Queue	60	70	32	39
Decision Variables				
Effective Total Queue	50	50	32	39
Ineffective Queue	10	20	0	0
Effective Green	46	46	30	37
Objectives				
Number of Vehicle(s) Leave			201	
Cycle Length (seconds)			215.57	
Vehicle Flow Rates (vehicles/hour)			2,276.10	

For Table 4-26, we have different recorded values for the rate of flow in approach. This is recorded during the peak period of rush hour in the evening. During rush hour, we can see that the values are higher this time for flow in approach, meaning that there is a higher traffic density during this hour. In this case, there is no maximum cycle length. This is the case of current traffic management. Since there is no limit, the cycle length increases to 215.57 sec, and the vehicle leaves are 201 vehicles. The flow rate in this case is 201 vehicles per 215.57 sec, which is 3355.2 vehicles per hour.

Table 4-32 OPL result with optimization during rush hour.

Case 4 Results	Approaches			
	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Parameters				
Flow in	1520	2010	620	780
Effective Flow out	3900	3900	3800	3800
Ineffective Flow out	3000	3000	2800	2800
Start Total Queue	60	70	32	39
Decision Variables				
Effective Total Queue	50	50	32	39
Ineffective Queue	0.93	0	0	0
Effective Green	46	46	30	37
Objectives				
Number of Vehicle(s) Leave			171.93	
Cycle Length (seconds)			180.89	
Vehicle Flow Rates (vehicles/hour)			2,276.10	

Table 4-27 represents when the optimization is applied. Therefore, the cycle length is now 180.69 seconds. And we can see that the vehicle leaves from the intersection of 171.93 vehicles. Conversely, this is just for one cycle length. This means that if we accumulate all the cycle length in total, there are more vehicles leaving the intersection compared to table 3. This can be proved by the flow rate of the intersection. When comparing to table 3, the flow rate for table 4 is 171.93 vehicles in 180.69 sec, which is 0.95 vehicles per sec (or 3425.469 vehicles per hour). We can see that the flow rate is better this time, when there is a maximum cycle length. When subtracting 3425.469 with 3355.2, the result is equivalent to 70.269 vehicles per hour. Meaning that there are approximately 70 more vehicles leaving the intersection each hour. Hence, after the process of optimization, the flow out rate of the approaches has improved especially during the rush hour.

By making a note on the previous cases without the upper bound constraint, the case 1 and 2 will give the same result. However, in the cases where there are more vehicles, there is an effect for the upper bound constraint. For instance, case 4 turns out to be better than case 3, because it has the upper bound constraint. Making it to choose only the effective flow out. But for case 3, because there is no upper bound constraint, this will make it have both effective and ineffective flow out results. Therefore, overall flow out is worse than case 4. Based on the result, we can tell that the optimization process has no effect on the regular hour. However, during rush hour the optimization helps reduces ineffective flow out.

Chapter 5
Conclusion

5.1 Conclusion

In conclusion, Bangkok traffic flow conditions are getting more and more saturated than before. The goal of this research is to alleviate the problem and improve Bangkok's current traffic signal system and management. By establishing an effective green light time at intersections in order to increase the vehicle flow rate. The mathematical model was designed to maximize the number of vehicles leaving intersections. Six Bangkok intersections are selected for the experiments. According to the experimental results, the optimization model outperforms current practice by increasing the number of vehicles leaving the intersection by 13.92% on average. After performing the traffic coordination, the percentage has improved by 23.04% on average. We can conclude that after the optimization process, the overall vehicle flow rate has significantly improved. Comparing with the old traffic management, we can see that this method is more effective.

From Pradiphat to Tuk Chai intersection, a traffic bottleneck often occurs at most in the evening at 6pm. With the proposed optimization model, and also combining with coordination, could potentially allow greater vehicle flow consistently in some degree. Furthermore, when webster's method is utilized as an upper bound of the model, the overall vehicle flow rate improves. In terms of traffic coordination, this process focuses on improving the traffic flow consistency. However, this is not to conclude that doing offset would always produce an effective result. This is because each cycle is different from time to time. This is the nature of offset implementation. However, in theory, this technique will most likely improve the traveler time for several groups of people from Pradiphat to Tuk Chai intersection, since they receive a consecutive green light from one intersection to another.

By applying the technique into the visualization, it was found that the signal time responds to the total queue. Therefore, this shows the output of the effective green time because when there is a longer queue it serves the right amount of green time, and when there is less queue, it serves the less amount of green time signal. The queueing management aligns with the green light signal. Hence, this will cause less in the delay and improve the traveler time and the flow of every approach, after the process of optimization. In the case of coordination, we can observe that all intersections of study receive the consecutive greenlight. The offset technique allows the flow consistency, and no traffic bottleneck is observed in terms of visualization.

5.2 Managerial Implication and Possible Policies

In terms of managerial, another point of view may concern regarding the human labor that could arise. Specifically, it could be burdensome to operate this optimizer from time to time, because the human labor has to operate this process. Therefore, additional policy could be implemented.

1. By inspection, a conclusion can be made that this model has shown an improvement and perform well when the overflowing queue occurred. In practice, the policy can be made that this optimizer could be operate specifically during the peak of rush hour (5:00pm – 6:00pm). This is to reduce the burdensome for labor usage.

2. Since uncertainty is still one of the issues that needs to be address, alternative choice can also be made depending on the traffic volume that occur at that instance.
3. There might be special occasion that occur; therefore, system recalibration might needed.
4. Consistently improve the previous policies to improve the future work process.

5.2.1 Operating Guidelines

This optimization model requires some knowledge regarding the fundamental background of traffic system. Some study on general traffic system at an intersection could be useful. Previously, in this thesis has explained the detail regarding the background knowledge before implementing the optimization model. Specifically, the objective of this optimization model that maximize the vehicle leave from the intersection. The following is the operating guideline:

- Use Optimization Programming Language (OPL)
    - Use OPL to generate the result of the optimization model.
    - The result should be separated into isolated and combined intersection.
- This required the computational data of the number of vehicles entering and exiting the intersection in certain hour, from each approach and intersections.
    - As explained previously, during the period of rush hour is the best time.
- Some calculations should be made before undergoing the operation.
- Cycle length can be calculated from accumulating signal time of green, yellow, all red of all approaches.
- The total queue is calculated by the flow in (vehicles per seconds) of the vehicle times the time of the red-light signal (in seconds).
- The vehicle leaving the intersections can be calculated by the time of the effective green light (in seconds) multiply by the flow out of the vehicles from each of the approaches (vehicles per second).
- Some uncertainty might arise based on observation. Depending on the traffic condition or the volume of traffic, the recalibration might needed in order to adapt to the environment.

5.3 Limitation and Future work

In terms of work limitation, there is a need for a technological advancement. On the other hand, it is very costly for this project to implement since this is a large-scale project, and additionally requires an authority permission to accomplish. No permission was able to obtained for controlling the traffic signaling, since this project considered as the individual thesis. Therefore, this project cannot be implemented in real situation yet because no right was able to obtained. For instance, a paper written by Deakin University have shown the effective and efficiency of controlling the traffic signal timing (Araghi et al., 2015). In this paper, they use a different learning method to find the appropriate green time by a given traffic environment. By using a computational learning method to improve the controller of a network of the intersections. Another journal written by a group of researchers has shown some the method for adaptive traffic modeling for traffic performance. The methodology and study location are different from the current implementation for this project. Their goal is to improve the efficiency of road networks create the adaptive traffic signal control (Abdulhai et al., 2003). In conclusion, there are many different methods to improve the traffic light signal control, and many more studies will be conducted by expertise researchers in the future.

It is to note that many researches have been conducted and traffic theories have been carefully examined. It is certain that that these methodologies will be effective in a certain degree. Specifically, the optimization programming results and the help of visualizations was able to moderately prove that this method does shows an efficiency when comparing to the current traffic management.

5.4 Contribution

In this thesis, the optimization model design and the Optimization Programming Language (OPL) experiment was carried out by the author of this thesis. Literature reviews has been conducted, and traffic theories have been examined. With some help of the traffic expert, the advice regarding the general traffic concept and design were given in order to make this thesis project possible.

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PUBLICATION	Tantipanichaphan, K., & Dusadeerungsikul, P. O. (2022). An Effective Traffic Signal Optimization Model for Intersections in Bangkok. In 2022 IEEE 9th International Conference on Industrial Engineering and Applications (ICIEA). IEEE.