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An Effective Traffic Signal Optimization Model for Intersections in Bangkok

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Abstract. 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 by 3.34%. Furthermore, when optimal cycle length is utilized as an upper bound of the model, the overall vehicle flow rate improves.

Keywords: Traffic Signal Optimization, Effective Green Time, Optimization

1. Introduction

In Bangkok, new roads with more lanes are built to increase the capacity of traffic networks. However, traffic congestion is still problematic because of the city's fast development. According to the Traffic Index, which covered 416 cities across 57 countries, the congestion level in Bangkok was 44% in 2020 and ranked 10th for the world traffic index [1]. Therefore, people in Bangkok often travel to the destination unpredictably slower than usual during rush hours. For instance, it would take approximately 10 minutes from the Pradiphat intersection to Tuk Chai at the normal situation. However, with congestion during rush hours, the traveling time often changes to 18 minutes due to traffic delays.

The congestion also causes many problems for the citizens. For example, because of the high concentration of diesel-fueled fleets, PM 2.5, particulate pollutants that are 2.5 microns or smaller, concerning people's health is detected [2]. In addition, excessive delay and increased traffic congestion could increase the frequency of crashes, especially rear-end collisions [3]. Furthermore, ambulances and emergency vehicles are unable to respond in an appropriate amount of time [4].

An ineffective traffic signal at an intersection is one of the major reasons causing disorderly traffic flow and congestion [5]. Bangkok's traffic signalling control and management system is currently not well planned [6]. Therefore, to sustainably solve the congestion traffic in Bangkok, an effective system to optimize the traffic flow is needed.

The objective of this research is to analyse and provide a suggestion of traffic signal management (e.g., the duration for green light at regular and rush hours) at an intersection in Bangkok by utilizing an optimization model.

The remainder of the article is organized as follows. Section 2 presents related work to this research. Then, section 3 describes the methodology. Section 4 presents the results from the experiments. Lastly, section 5 conclusions and discusses the future work directions.

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2. Related Work

2.1. Cycle Length

One of the well-known methods to determine the optimum cycle length for the intersection is the Webster theory. For example, the Webster theory has been utilized for optimizing traffic signal timing and coordination for oversaturated road networks [7]. The results show that a practical minimum intersection delay can be explained by Eq. (1).

$$C_0 = \frac{1.5L+5}{1-\sum_{i=1} Y_i} \quad (1)$$

Where C_0 is the optimum cycle length (second), L is the total lost time per cycle (second), and Y_i is the maximum value of the ratio of approach flow to saturation flow for all lanes groups using phase i.

Thiscycle length range can be set as an upper or lower bound limit in the optimization model to determine the suitable signal timing for an intersection.

In this study, the cycle length is considered an upper bound. On the other hand, the lost time is considered as a lower bound. Lost time is when no vehicle is able to pass through an intersection despite the traffic signal displaying green [8].

2.2. Traffic Optimization and Vehicle Flow Rate

In terms of traffic optimization, the concept of optimal signal timing is selected to maximize the vehicle flow rate of the current situation. This includes the effect of the vehicle crossing the street and the maximum allowable cycle length [8].

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 [8]. 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).

3. Methodology.

This section presents problem description of the studies. Subsequently, the mathematical optimization model is formulated to improve traffic flow at intersections.

3.1. Problem Description

In general, effective signal timing provides an orderly flow of the traffic vehicle at an intersection. However, it is possible to have traffic over-/under- flow cases due to an improper time setting [8]. The ineffective green light time in one approach of an intersection could cause the ineffective flow out of the vehicles in other approaches. In addition, traffic management becomes more challenging during rush hours due to high traffic density [10]. Therefore, the optimized green light time and cycle length at an intersection will maximize the vehicle leaving intersections, improving the flow condition.

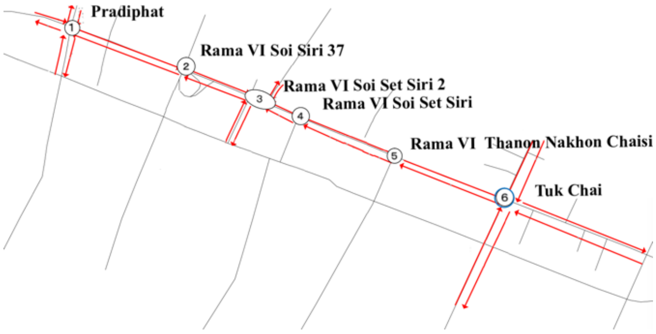

Fig. 1: Intersections of study

In this study, we focus on the following intersections, which are controlled by traffic control and traffic wardens: 1) Pradiphat ($Prad$), 2) Rama VI Soi Siri 37 ($RamaVI\_S37$), 3) Rama VI Soi Set Siri 2

($RamaVI\_SS2$), 4) Rama VI Soi Set Siri ($RamaVI\_SS$), 5) Rama VI Thanon Nakhon Chaisi ($RamaVI\_TNC$), and 6) Tuk Chai (TC) intersections as shown in Fig. 1. These intersections are regarded as busy during the peak period.

3.2. Mathematical Model.

3.2.1. Sets and Parameters

LT_i = Lost time, or additional amount of time for the first vehicle to begin moving and pass through the intersection at approach i.

YT_i = Time of yellow light signal for approach i of an intersection.

AR_i = Time of the all-red light signal for each approach$i$ of intersection.

SF_i = Saturation flow, or rate that vehicles can traverse an intersection approach i under prevailing conditions.

FI_i = Vehicle flows into the approach i.

FO_{ij} = Vehicle flows out of the approach i, where j is the piecewise step of flow rate.

STQ_i = Queue length of approach i before the green light.

BEQ_i = Breakpoint of approach i between the changed slope of effective and ineffective flow out.

3.2.2. Decision Variables

GT_{ij} = Time of green light for each approach$i$ of intersections, where $j$is piecewise step of flow rate.

CL= Time required to display all phases for each direction before returning to first phase of cycle.

TQ_{ij} = Total queue for each of approaches$i$, where j is the piecewise step of the flow rate.

3.2.3. Objective Function

$$\max\ Z = \sum_{i \in I} \sum_{j \in J} FO_{ij} GT_{ij} \tag{2}$$

3.2.4. Constraints

$$TQ_{i1} \leq BEQ_i; \forall i \in I \tag{3}$$

$$TQ_{i2} \leq TQ_{i1}; \forall i \in I \tag{4}$$

$$TQ_{i1} + TQ_{i2} \leq STQ_i; \forall i \in I \tag{5}$$

$$GT_{ij} = \frac{TQ_{ij}}{FO_{ij}}; \forall i \in I, \forall j \in J \tag{6}$$

$$\sum_{j \in J} GT_{ij} \geq LT_i; \forall i \in I \tag{7}$$

$$CL \leq \frac{1.5(\sum_{i \in I} LT_i) + 5}{1 - \sum_{i \in I} \frac{FI_i}{SF_i}} \tag{8}$$

$$CL = \sum_{i \in I} \left(\sum_{j \in J} GT_{ij} + YT_i + AR_i \right) \tag{9}$$

The objective is to maximize the vehicles leaving from intersections, which can be mathematically described in Eq. (2) or the flow out of the vehicles multiplied by the green light of different approaches. The more the vehicles leave the intersection, the more delay will potentially drop. This causes a better overall traffic condition to flow out of the intersection.

Constraints (3) and (4) are the piecewise constraints. As shown in Fig. 2, the total queue 1 is considered as an effective queue while total queue 2 is regarded as an ineffective queue, at approach i. Note that total queue 1 has to be less than or equal to the Break point. Constraint (5) ensures the condition of the total queue 1 and 2 must be less than or equal to the start total queue for each approach. Constraint (6) ensures that each approach's green light timeequals the total time. (The arrangement of green light time for different approaches should equal the time that vehicles are discharged in all approaches.) For boundaries, constraint (7) is the lower bound constraint (green time for each approach has to be greater than or equal to the lost time). Constraint (8) is the upper bound constraint(optimum time limit for the optimum cycle length). Constraint (9) is the combination of time for green, yellow, and all-red light (signals in all approaches are limited within the cycle length). The reason for constraint (9) is because of a larger traffic volume condition. During rush hour, opening the green light for a long time for clearing the queue is impossible since the time exceeds the limit of proper cycle length. The green light needs to be open until it reaches the limit of the appropriate cycle length.

Mathematical equations are modeled with approach i at the intersection. In the case of a four-way intersection, the traffic signal at each approach i is denoted by$i = \{1, 2, 3, 4\}$. In the case of a three-way intersection, approach$i$ is denoted by$i = \{1, 2, 3\}$. j is the piecewise step of the flow rate, which is denoted by 1 and 2 (as shown in Fig. 2).

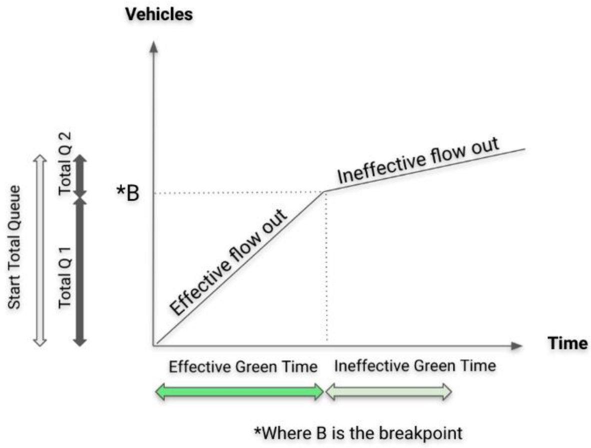

Fig. 2: The piecewise constraints.

4. Results.

In this section, the data used in the experiments are displayed. Also, the computational results are presented.

4.1. Data Collection.

The input data is collected by recording the number of vehicles entering and exiting the selected intersections (i.e., $Prad$, $RamaIV\_S37$, $RamaVI\_SS2$, $RamaVI\_SS$, $RamaVI\_TNC$, and TC intersections) from each approach. The data (i.e., flow rates) were averaged and used as input parameters. The data are measured during a rush hour (5 p.m. to 6 p.m.).

4.2. Computational Results.

The OPL programming was used to solve the optimization model. Table 1 presents results from thesix intersectionsduring rush hour traffic. The number of vehicles that leave an intersection per cycle length, or vehicle flow rate, has improved (by 3.34% on average) when utilizing the optimization model, indicating that more vehicles leave intersections with the same amount of time.

Furthermore, $Prad$ is selected for deeper investigation. Two cases, with and without cycle length boundary, are investigated to understand the effect of cycle length.

Table 1: An overview results from OPL

Intersections of Study Results			
Intersections	Vehicle Flow Rates (vehicles/hour)		
	Current	Optimization Model	% Improvement
$Prad$	3,337.87	3,425.47	2.62%
$RamaIV\_S37$	2,444.57	2,528.08	3.42%
$RamaIV\_SS2$	3,305.63	3,442.75	4.15%
$RamaIV\_SS$	2,179.87	2,275.76	4.40%
$RamaIV\_TNC$	3,339.17	3,442.75	3.10%
TC	3,169.22	3,242.81	2.32%

4.2.1. Case 1:Optimization Model without Cycle Length Boundary

The results from case 1 are presented in Table 2and Fig. 3. In this case, constraint (8) is eliminated. Flow in is the flow input value from each approach of intersection. The effective and ineffective flow out is the flow output value from each approach of intersection. The flow in and flow out values are presented in average value. When the number of vehicles reaches the average value of the breakpoint queue amount, the flow out rate becomes ineffective. Hence, green light time is the same as a total queue, which contains effective and ineffective queues at each approach.

During rush hour, we can see that the flow in values is high, meaning a high traffic density. By inspection, the cycle length is 227.57 seconds, and the number of vehicles leaving the intersection is 211 vehicles. The flow rate, in this case, is 211 vehicles per 215.57 seconds, which is approximately 0.927 vehicles per second (or 3,337.87 vehicles per hour).

Table 2: OPL results from Pradiphat intersection during the rush hour (Case 1)

Case 1 Results	Approaches			
	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Parameters				
Flow in	1,520	2,010	620	780
Effective Flow out	3,900	3,900	3,800	3,800
Ineffective Flow out	3,000	3,000	2,800	2,800
Start Total Queue	65	75	32	39
Decision Variables				
Effective Total Queue	50	50	32	39
Ineffective Queue	10	20	0	0
Effective Green	46	46	30	37
Ineffective Green	12	24	0	0
Objectives				
Number of Vehicle(s) Leave		211		
Cycle Length (seconds)		227.57		
Vehicle Flow Rates (vehicles/hour)		3,337.87		

4.2.2. Case 2:Optimization Model with Cycle Length Boundary

For case 2, the upper bound of cycle length is added. This case consisted of the optimum limit for the cycle length. The model has been run with the same data of flow in approach.

After adding the optimal cycle length (180.69 seconds),the number of vehicles leaving the intersection increases to 171.93. In addition, if we accumulate all the cycle lengths in total, more vehicles leave the intersection compared to case 1. The flow rate in case 2 is 171.93 vehicles in 180.69 seconds, which is 0.951

vehicles per second (or 3425.47 vehicles per hour). The results show that the flow rate has improved when the optimum cycle length is added to the model.

The results can be summarized in Table3 and Fig. 3. Note that the ineffective flow out is reduced because of the upper bound constraint.

Table 3: OPL results from Pradiphat intersection during the rush hour (Case 2)

Case 2 Results	Approaches			
	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Parameters				
Flow in	1,520	2,010	620	780
Effective Flow out	3,900	3,900	3,800	3,800
Ineffective Flow out	3,000	3,000	2,800	2,800
Start Total Queue	65	75	32	39
Decision Variables				
Effective Total Queue	50	50	32	39
Ineffective Queue	0.93	0	0	0
Effective Green	46	46	30	37
Ineffective Green	1.11	0	0	0
Objectives				
Number of Vehicle(s) Leave	171.93			
Cycle Length (seconds)	180.69			
Vehicle Flow Rates (vehicles/hour)	3,425.47			

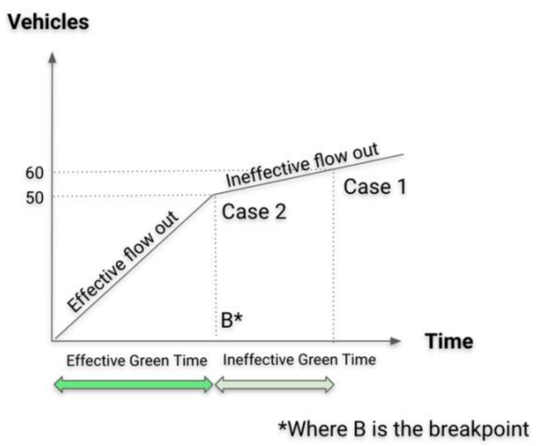

Fig. 3: The results for Case 1 and Case 2.

5. Conclusion and Future Work.

Traffic congestion has caused many issues in Bangkok. Effective traffic signal management is considered as one of the critical elements to alleviate the problem in long term. Hence, to systematically solve the congestion problem in Bangkok, in this research, the mathematical model is developed to manage traffic signals at the intersections. The objective of the mathematical model is to maximize the number of vehicles discharged from the intersection by having effective green time in specific approaches. Experiments have been conducted with the data of the six selected intersections in Bangkok to validate the model. The results indicate that the mathematical model outperforms the current practice by increasing the number of vehicles leaving the intersections (by 3.34% on average). Furthermore, when a deeper investigation has been conducted, it shows that the optimal cycle length plays an important role in increasing the vehicle flow rate.

In the future, further data collection will be performed, and more research should be expanded by applying the model to more intersections to examine the correlation on a larger scale. Furthermore, researchers can consider the situation where different vehicle types have different speeds.

6. Acknowledgment

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