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Traffic Simulation Models to Enhance Signal Timing in an Oversaturated Network: A Comparative Study of Optimizing Individual Intersections versus the Entire Network

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Abstract. The objective of this study is to investigate the variations in performance of a network with multiple oversaturated intersections—particularly delays and queue lengths—generated by two different signal timing approaches, namely (*i*) the classical isolated signal timing approach that aims to optimize each intersection's signal timing independently and (*ii*) the network optimization approach that focuses more on the network's holistic performance. In doing so, two signal timing models are herein developed using Synchro—a powerful traffic simulation tool—based on the information of a real oversaturated network with six consecutive intersections located on a major arterial street of Bangkok, Thailand, during the weekday evening peak period. The results of this simulation indicate that optimal cycle lengths and the allocation of green intervals are two key success factors that help reduce average delays and queue lengths at these intersections. To this end, excessive green intervals tend to result in greater delays and queue lengths, as the remaining approaches would experience excessively long red intervals. Furthermore, the key factor that helps enhance the network's holistic performance is the allocation of coordinated green intervals considering vehicular flows on all traffic corridors. In this regard, we find that the network optimization approach is considerably more efficient, as it could help reduce average delays and queue lengths by 43.5% and 61.9% compared to the base case scenario—which is 9.7% and 9.4% better than the isolated signal timing approach, respectively.

Keywords: Delay; Isolated intersection; Network optimization; Signal timing; Traffic simulation queue length

1. Introduction

It is well known that traffic congestion—and its environmental impacts—could be mitigated by making land development more compact, along with increasing public transit density and accessibility (Verbavatz and Barthelemy, 2019). Unfortunately, in large urbanized areas—in which land use development and public transit systems are not well planned—motorized traffic on roadways usually becomes a prevalent problem

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(Thaithatkul *et al*., 2011). To this end, severe traffic congestion usually occurs at at-grade multiple-leg intersections, largely due to their respective numbers of conflict points, coupled with diverse vehicular traffic flows on intersections' approaches. To avoid such conflicts and road accidents, especially in dense urban areas (Mustakim *et al*., 2023), signal controllers are thus employed at these intersections.

While important, these traffic controllers generally mandate vehicles to stop—which, in turn, results in an accumulation of queues on some of the intersection's approaches. This situation might be worse in a network with multiple intersections, as excessive queues forming at one intersection could dampen vehicular flows on nearby intersections (or roads), which eventually leads to widespread congestion (Al-Selwi *et al*., 2023). To maintain the greatest levels of safety and mobility of motorists at these at-grade intersections, intelligent traffic signal controllers—under different signal timing schemes depending on traffic control technologies and transport policies (Tang and Nakamura, 2008)—are therefore needed.

According to Akgungor and Korkmaz (2018), a complete rotation of different signal intervals—namely the green interval, the change interval (yellow time), the clearance interval (all-red time), and the red interval—normally referred to as a cycle length, has played an important role in reducing traffic congestion, particularly delays and queue lengths, as well as other nontraditional transport issues like greenhouse gas (GHG) emissions. Practically, the cycle length is designed to last from 40.0 seconds to 150.0 seconds, depending on the number of phase sequences, lost time, and vehicular flow rates.

While it is somewhat intuitive to give a longer green interval—and so a longer cycle length—to an intersection's approach with higher arrival rates, this does not necessarily shorten the overall queue lengths at the intersection, due to the accumulated queues on the remaining approaches. On the contrary, we might be unable to discharge accumulated queues at an intersection if the cycle length is far too short, as there would be a relatively large proportion of inefficient green time, *i.e*., start-up lost time and red time (Roess, Prassas, and McShane, 2011), in each cycle (Akgungor and Korkmaz, 2018; Eriskin et al., 2017; Srisurin and Singh, 2017). These problems are especially worse at oversaturated intersections, as queue lengths at the main and minor corridors are quickly formed, due to comparatively high vehicular flow rates.

To better optimize signal timing at an intersection, a number of research studies have therefore been conducted under different problem settings, objectives, and solution methodologies. In terms of problem settings, most research in this domain typically involves signal timing optimization at an isolated intersection. Yet, the research objectives may vary depending on the selected performance metrics, such as delays (Alhajyaseen *et al*., 2017; Zakariya and Rabia, 2016; Liu and Xu, 2012; Webster, 1958), queue lengths (Srisurin and Singh, 2017; Babicheva, 2015; Sutarto *et al*., 2015; Teo, Kow, and Chin, 2010), throughput flows (Wang *et al*., 2020a; Eriskin *et al*., 2017), or multiple objectives combined (Ma *et al*., 2020; Li *et al*., 2013; Robles, 2012; Hewage and Ruwanpura, 2004; Li *et al*., 2004). Regarding the solution approaches, Teo, Kow, and Chin (2010) and Manh *et al*. (2020) utilized the concept of genetic algorithm (GA) to determine the optimal signal timing at an isolated intersection, while Wang *et al*. (2020a), Hewage and Ruwanpura (2004), Robles (2012), Li *et al*. (2013), and Ma *et al*. (2020) instead used simulation modeling for the same purpose. A deterministic optimization model and a queuing model were also introduced to help determine optimal signal timing at an isolated intersection by Li *et al*. (2004), Babicheva (2015), and Srisurin and Singh (2017).

In addition to the aforementioned approaches, the solution methodologies adopted by recent studies were rather complex yet interesting, such as the elimination pairing system by Eriskin *et al*. (2017), the differential evolution bacteria foraging algorithm by Liu and Xu

(2012), the regression analysis by Zakariya and Rabia (2016), the lane-based method by Alhajyaseen *et al.* (2017), and the parabolic interpolation method by Sutarto *et al.* (2015).

Besides optimizing signal timing at an isolated intersection, there is also a set of complementary research that focuses more on a network with multiple intersections. Bargegol *et al.* (2015), Dixit *et al.* (2020), Wang *et al.* (2020b), Gu *et al.* (2021), and Wang *et al.* (2021), for instance, investigated signal timing of networks with multiple intersections that resulted in minimum overall delays. Liu and Chang (2011) and Li and Chen (2018), on the contrary, put more emphasis on the development of signal timing schemes that resulted in minimum overall queues. In addition to the traditional transport performance metrics, some have further included other transport concerns—such as greenhouse gas emissions (Shen, 2018) and total travel times (Tang and Friedrich, 2016; Guo *et al.*, 2019)—or even combined various performance measures into one single framework (Lee *et al.*, 2022; Park *et al.*, 2021; Zhou *et al.*, 2021; Wong and Liu, 2019; Armas *et al.*, 2017; Hu and Smith, 2017; Li, Xu, and Zhang, 2017; French and French, 2006).

Regarding the solution methodology, classical methods—like the genetic algorithm (Guo *et al.*, 2019; Li and Chen, 2018; Bargegol *et al.*, 2015; Liu and Chang, 2011) and simulation modeling (Shen, 2018; French and French, 2006)—were mainly applied to this problem setting. Yet, machine learning (Wang *et al.*, 2021) and deep reinforcement learning approaches (Lee *et al.*, 2022; Gu *et al.*, 2021; Park *et al.*, 2021; Li, Xu, Zhang, 2017) were among recent popular techniques that have been widely utilized, due to the advancement in tracking technologies (*e.g.*, GPS data).

Unlike previous research that applied the so-called isolated signal timing approach to optimize the signal timing of a network with multiple intersections, Hu and Smith (2017), Nesheli, Puan, and Roshandeh (2009), Adacher (2012), and Xie, Smith, and Barlow (2012) proposed quite an interesting signal timing concept that aimed to maintain vehicular flows along the main corridors, called the signal timing coordination approach. In this approach, the green intervals between successive intersections are coordinated so that vehicles can traverse along the main corridor without stopping. According to Roess, Prassas, and McShane (2011), this approach was found superior when the distance between two adjacent intersections on major arterial roads was less than 1.6 *km* and the volumes on the main corridor were higher compared to those of minor streets. Nonetheless, the performance of the signal timing coordination approach may be inferior in practice, as traffic on minor streets of oversaturated intersections may be slightly lower than that of the main corridor.

As has been illustrated, the majority of previous research studies generally address issues related to the performance of isolated intersections. While a few studies have focused on optimizing the signal timing of networks with multiple intersections—either by locally optimizing each intersection's signal timing independently or coordinating the signal timing of all intersections based on green time offsets—none has focused on the holistic performance of an oversaturated network with different intersection configurations.

In light of this gap, this paper thence aims to (*i*) investigate the performance of a network optimization approach that focuses more on overall network performance rather than that of isolated intersections or the main corridor and (*ii*) compare it with the classical isolated signal timing approach. For practical reasons, our study is based on the information of a real oversaturated network with six consecutive intersections (with both at-grade three-leg and four-leg intersections) located on Rama VI Street, Bangkok, Thailand, during the evening peak period. To systematically compare and assess the performance of these two approaches, two simulation models representing these two settings are herein developed, calibrated, and run using Synchro with the same input data. Based on our conduct of simulation, we find that shorter cycle lengths and optimal allocation of green intervals are two key success factors that help reduce average delays and queue lengths at these six isolated intersections. Furthermore, excessive green intervals tend to result in greater delays and queue lengths, as green intervals are not well utilized to their fullest potential. On the other hand, the key factor that helps enhance the performance of the whole network is the coordination of green intervals—not only on the main corridor but also on minor streets with relatively high vehicular flows.

The remainder of this paper is organized as follows. Section 2 provides a thorough discussion regarding the models of both classical isolated signal timing and network optimization approaches. The results to these models, in terms of delays and queue lengths, from simulation runs are then reported and compared with those of the current traffic data—or the base case scenario—in Section 3. Finally, Section 4 concludes this present work and suggests some future research directions.

2. Methodology

2.1. Data collection and phase plan formulation

This research adopts a road network with six consecutive intersections, located in Bangkok, the capital city of Thailand, as a test case. The reason for this is that Bangkok is one of the most congested cities in Southeast Asia. According to TomTom's 2023 ranking of the most congested cities (TomTom, 2024), Bangkok ranks 46th in the world and 13th among Asian cities in terms of road congestion. Additionally, signal timing at intersections in Bangkok is mostly manually controlled, using a pretimed system that cannot precisely respond to fluctuations in vehicular demands at different time periods. To better improve the performance of traffic control in Bangkok, a more efficient signal timing scheme is therefore needed; and this will be investigated based on the underlying road network.

Regarding data collection, the traffic data used in this study are provided by a Japanese infrastructure development agency, in which real-time traffic data of six consecutive intersections located on Rama VI Street, Bangkok, are collected—primarily between 5:00 p.m. and 6:00 p.m. (evening peak period) on 23 weekdays in March 2022. For ease of discussion, Figure 1 illustrates an abstraction of the underlying network, comprising four at-grade four-leg intersections (denoted by int-1, int-2, int-4, and int-6) and two at-grade three-leg intersections (denoted by int-3 and int-5). The distances between intersections (in meters, m) and average vehicular flow rates on different intersections' approaches (in passenger cars per hour, pc/h) derived from the dataset are also shown in Figure 1.

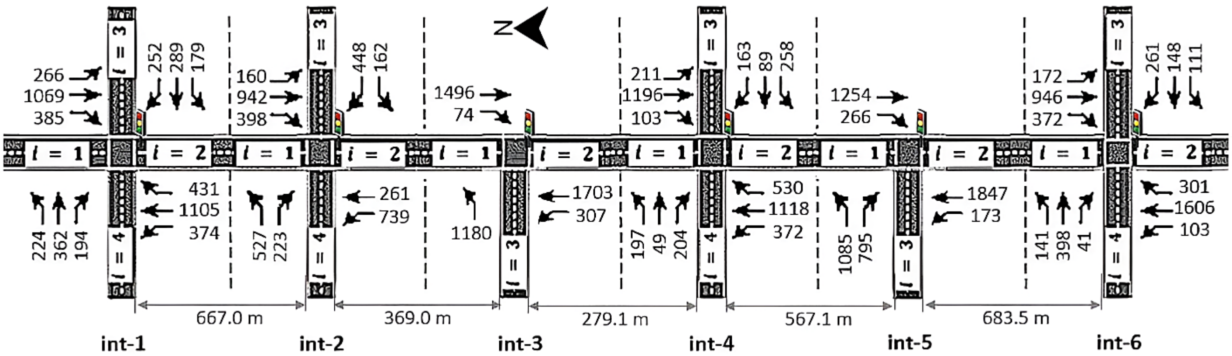

Figure 1 Layout of the underlying network with average vehicular flows (pc/h)

In addition to vehicular flow rates, information pertaining to throughputs, saturation flow rates, turning movements, maximum queue lengths, estimated proportion of heavy vehicles, cycle lengths, split green intervals, and offsets for each intersection are also derived from the dataset and, later, used as input (if needed) for all models.

Regarding the phase plan formulation, pretimed traffic signal phasing is separately assigned to each intersection as shown in Figure 2, using left-hand traffic (LHT)—in which traffic keeps left—as the rule of the road. Furthermore, the phase plan of both four-leg and three-leg at-grade intersections is assigned with a through-right turn phase in order to simultaneously accommodate through and right-turn movements on each intersection's approach (represented by the thick black arrows). The underlying reason that we prevent the application of exclusive right-turn phasing lies in the geometric design of intersections that makes exclusive right-turn phasing unsafe for vehicles turning in opposite directions. From Figure 2, left turn on red (LTOR) is also applied at some of the intersections, as represented by the thin grey arrows. The thick grey arrow, on the contrary, represents the permissive right-turn movement, while the numbers in small boxes (*e.g.*, Ø1 and Ø2) denote phase numbers, according to the ring-and-barrier diagram (Koonce, 2008).

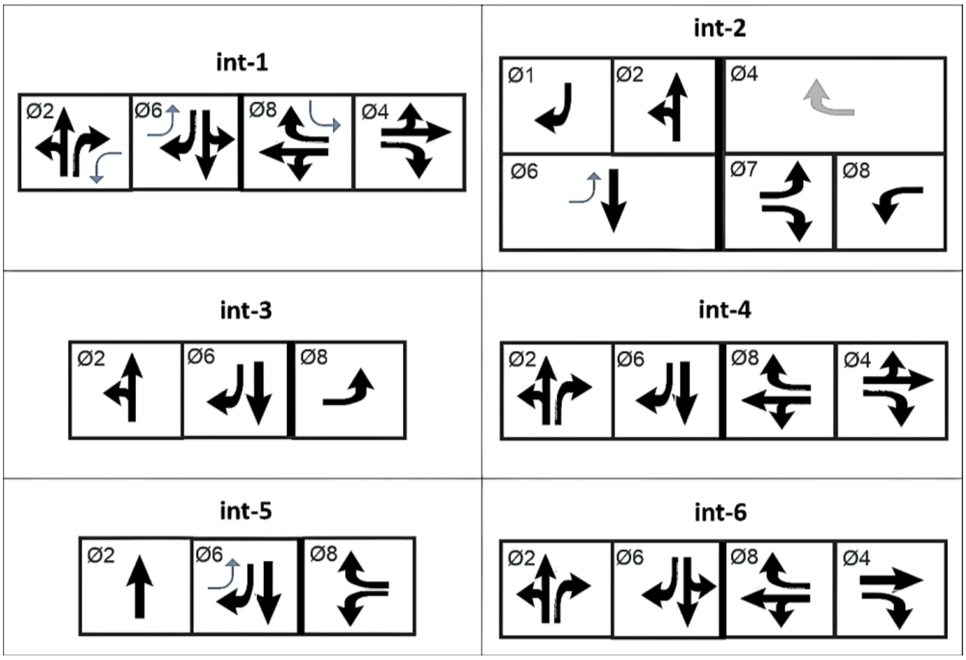

Figure 2 Phasing diagrams of all six intersections

According to the U.S. Federal Highway Administration's Traffic Signal Timing Manual, a ring-and-barrier diagram consists of two rings and one barrier that divides phases into left (phases Ø1, Ø2, Ø5, and Ø6) and right ones (phases Ø3, Ø4, Ø7, and Ø8). Based on this notation, Intersections 1, 4, and 6 (four-leg intersections) have about four phases, while Intersections 3 and 5 (three-leg intersections) have only three phases. Moreover, these phases run in a sequence from left to right.

2.2. Isolated signal timing model

In the isolated signal timing approach, Webster's method (Webster, 1958), as shown in Equation (1), is adopted as a foundation for determining the optimal cycle length (CL) that minimizes total delays and queue lengths, at each intersection.

$$CL = \frac{1.5 \times (\sum_{i \in I} LT_i) + 5}{1 - (\sum_{i \in I} V_{ci}/SF_i)}, \tag{1}$$

where i denotes the i^{th} approach of an intersection (*e.g.*, for a four-leg at-grade intersection, $i \in \{1, 2, 3, 4\}$); LT_i represents the total lost time on the i^{th} approach, which is the sum of the start-up lost time and clearance lost time per phase; V_{ci} represents the critical flow volume on the i^{th} approach, which is defined by the maximum flow rate less the available turning movements on red; and SF_i represents the saturation flow rate on the i^{th} approach, which is the capacity of a lane group assuming that the signal indication is always green.

Some modifications are further made and included in the simulation model of the isolated signal timing approach so that the devised model properly reflects the current traffic operations of these six intersections. The default value of total lost time per phase, for example, is set at five seconds—instead of four seconds as recommended by the Highway Capacity Manual (National Research Council, 2016)—to compensate for unexpected extra lost time due to congestion. Additional restrictions concerning phases, cycle lengths, minimum splits, queue lengths, and green intervals are also included, as supplementary sets of constraints in the model, whose detailed information is provided as follows.

2.2.1. Phase and cycle length constraints

An intersection's cycle length (CL) can be computed by the summation of three different intervals on all of an intersection's approaches—namely the green interval (G_i), the change interval or the yellow time (Y_i), and the clearance interval or the all-red time (AR_i), as elaborated by Equation (2).

$$CL = \sum_{i \in I}(G_i + Y_i + AR_i) \tag{2}$$

Note that the yellow time and the all-red time in this study are set at three seconds and two seconds, respectively, according to the existing conditions. And, for consistency, these durations are also preserved as the default values for the network optimization model.

Furthermore, the lower cycle length limit is slightly lifted to 50.0 seconds, while the upper cycle length limit is set at the nominal value of 200.0 seconds, due to congestion, as described by Inequality (3).

$$50.0 \leq CL \leq 200.0 \tag{3}$$

2.2.2. Minimum split constraint

The minimum split in each phase sequence—*i.e.*, the shortest amount of time allowed for an intersection's approach—is justified at 25.0 seconds to accommodate pedestrians crossing streets and provide a reasonable proportion of green interval per total lost time, as mandated by Inequality (4).

$$(G_i + Y_i + AR_i) \geq 25.0 \quad ; \forall i \in I \tag{4}$$

2.2.3. Minimum split constraint

The maximum queue length on each intersection's approach is restricted to 90% of the street length—for safety, as well as to prevent chances of spillbacks occurring at the entrance of the approach—as stated by Expression (5), where Q_i and L_i denote the maximum queue length and roadway length on approach $i \in$ I, respectively.

$$Q_i \leq 0.90\, L_i \quad ; \forall i \in I \tag{5}$$

2.2.4. Green interval splitting

To properly allocate green intervals, the green interval in each phase is proportionate to the ratio of phase-wise critical flow volume per saturation flow ratio (V_{ci}/SF_i) and the sum of critical flow volumes per total saturation flow ratio, multiplied by the sum of green intervals from all phases ($\Sigma_{i\in I} G_i$), as shown in Equation (6).

$$G_i = \frac{(V_{ci}/SF_i)}{(\sum_{i \in I} V_{ci}/SF_i)} \times \Sigma_{i\in I} G_i \tag{6}$$

By adding Expressions (1)–(6) into the model, we can simulate and determine the optimal green time on each of the intersection's approaches, as well as the optimal cycle length, that minimizes total delays and queue lengths, from the simulation runs, as reported in Section 3.

2.3. Network optimization approach

Unlike the isolated signal timing approach that aims to independently optimize the optimal green time—and so the cycle length—of each isolated intersection, the purpose of the network optimization approach is to enhance the network's holistic performance, taking into account traffic flows on both main corridors and minor streets. This is in contrast to the signal timing coordination approach that maintains only the vehicular flows along the main corridor—which could lead to extremely long queues and more delays on the minor streets of an oversaturated intersection.

Similar to the previous model, Expressions (1)–(6) are also included in the network optimization model, along with the same set of parameters, for the simulation conduct in Synchro.

2.4. Traffic simulation

To systematically compare and assess the performance of these two approaches, two simulation models representing these two settings are constructed and run in Synchro with the same input data. The justification of Synchro in this study is based on its advantages that allow users to adjust the speed limit and lane width of every road segment, as well as the ability to calibrate the lost time and headway on every approach. More importantly, Synchro is specifically designed to simulate traffic at intersections. This makes it a flexible and suitable platform for simulating complex traffic scenarios, including our underlying network.

In this regard, a simulation framework that represents the current geometric design of traffic facilities is initiated using field data. The existing vehicular flows, turning movements, turn penalties, roadway lengths, lane widths, geometric design of the traffic facilities, cycle lengths, and split green intervals are then applied to develop a simulation model of the existing system (*e.g.*, using the pretimed signal operation at all intersections). In addition to these parameters, the percentage of heavy vehicles is assumed to be 1.0%, while the average standstill passenger car length of 5.0 *m* is utilized, along with the speed limit of 60 *km/h* and the peak-hour factor of 0.92, according to the field data. Lastly, the estimated saturation flow rate of 1,900 passenger cars per hour per lane (*pc/h/ln*) is adopted in the models, as recommended by the Highway Capacity Manual (National Research Council, 2016).

It should be remarked that, as the real queue lengths and vehicular flows within the network generally vary across the passage of time, the model is thence calibrated using the maximum queue length and flow of each intersection's approach, as observed from the field data. Based on this calibration procedure, the finalized simulation model representing this so-called base case scenario provides the maximum errors of 6.0% and 8.8% in terms of total queue lengths and vehicular flows, respectively.

With this simulation model, the simulation of both isolated signal timing and network optimization approaches could be conducted—the results of which are compared and thoroughly discussed in Section 3. For further reproducibility, the information related to the simulation models, as well as the illustrations of all important metrics, is made available at www.github.com/orcchula.

3. Results and Discussion

3.1. Delay

Figure 3 below shows the simulation results of the isolated signal timing and the network optimization approaches, compared to those of the base case scenario, while Table 1 reports the percentage reduction of delays by these two approaches at each intersection separately.

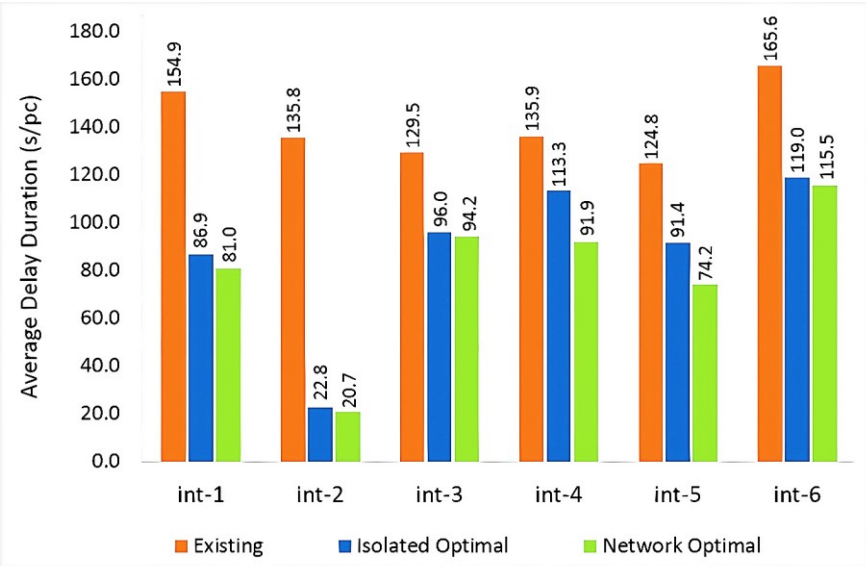

Figure 3 Comparison of delays between the base case scenario (existing), the isolated signal timing approach (isolated optimal), and the network optimization approach (network optimal)

From Figure 3, it could be seen that network optimization is the most effective approach in reducing delays at all six intersections—although it only slightly outperforms the isolated signal timing approach at some intersections, *i.e.*, Intersections 2 and 3. Furthermore, Intersection 2 seems to be the one that most benefits from both signal timing approaches, followed by the first intersection, whereas the least improvements by these two approaches are found at Intersections 4 and 3, respectively. In terms of network performance, by adopting the network optimization approach, the average delay per vehicle in the entire network could be significantly reduced from 140.5 seconds per passenger car unit (*s/pc*) in the base case scenario to 79.3 *s/pc*, or equivalently a 37.5% reduction.

Based on these results, it could be inferred that the current cycle lengths and green times used to regulate traffic in this network are excessively long—as issuing shorter green times seems to significantly aid in lowering overall delays and queue lengths. Furthermore, the network optimization approach is found to be superior to the isolated signal timing approach, as its overall delays are around 9.7% better than those of the other approach. The underlying reason is that the network optimization approach aims to minimize overall delays by treating the entire network as one single system, whereas the isolated signal timing approach merely focuses on minimizing delays at individual intersections. Due to a more myopic scope, the isolated signal timing approach may not reduce overall delays. Rather, it may create higher vehicular demands at adjacent intersections, thereby increasing burdens on such intersections in an uncooperative manner.

Table 1 Percentage reduction of delays by isolated signal timing (denoted by isolated) and network optimization approaches (denoted by network)

Intersection	Percentage Delay Reduction (%)		
	Isolated vs. Existing	Network vs. Existing	Network vs. Isolated
int-1	-43.9%	-47.7%	-6.8%
int-2	-83.2%	-84.8%	-9.2%
int-3	-25.9%	-27.3%	-1.9%
int-4	-16.6%	-32.4%	-18.9%
int-5	-26.8%	-40.5%	-18.8%
int-6	-28.1%	-30.3%	-2.9%
Overall	-37.5%	-43.5%	-9.7%

3.2. *Queue length*

Similar to total delays, both isolated signal timing and network optimization approaches are found useful in shortening queue lengths at these six intersections, when compared to the base case scenario, as reported in Table 2. Furthermore, Intersection 2 is among the intersections that most benefits from these two signal timing approaches, with an average queue length reduction of over 80%, followed by Intersection 1, with about a 60% queue length reduction.

Table 2 Percentage reduction of delays by isolated signal timing (denoted by isolated) and network optimization approaches (denoted by network)

Intersection	Percentage Difference in Average Total Queue Length (%)		
	Isolated vs. Existing	Network vs. Existing	Network vs. Isolated
int-1	-63.2%	-62.9%	0.8%
int-2	-83.9%	-85.1%	-7.8%
int-3	-52.1%	-55.1%	-6.2%
int-4	-26.6%	-57.9%	-42.7%
int-5	-59.3%	-49.1%	25.1%
int-6	-54.3%	-58.9%	-9.9%
Overall	-58.0%	-61.9%	-9.4%

It should be remarked that, although the overall queue lengths yielded by these two signal timing approaches are comparable at the intersection level, the granular results at the approach level may vary greatly (see Tables 3–8 for more details). At Intersection 1 (see Table 3), for instance, both signal timing approaches produce quite similar queue lengths at the intersection level—although the queue length generated by the network optimization approach on the westbound (i = 3) approach is slightly longer. Similarly, at Intersection 2 (see Table 4), the queue lengths on the eastbound and the westbound approaches generated by these two signal timing schemes are almost identical. Yet, the queue length on the southbound approach (i = 1), generated by the network optimization approach, is a lot shorter—about 49.4%—which is opposite to its queue length on the northbound approach (i = 2), which is inferior to that of the isolated signal timing approach around 34.5%.

Besides these two intersections, the network optimization approach is found to be superior to the isolated signal timing approach on every approach at Intersections 3, 4, and 6, whereas the isolated signal timing approach outperforms the network optimization approach on all Intersection 5's approaches.

In addition to queue lengths, the maximum queue per street length ratio (maximum Q/L ratio) on each intersection's approach is further explored, the results of which are reported in Tables 3–8. According to Tables 3–8, it is evident that the base case scenario is worse in terms of not only delays and queue lengths but also the maximum Q/L ratio—especially on the northbound approach (i = 2) of Intersection 3 and the southbound approach (i = 1) of Intersection 4, with the maximum Q/L ratios over 100% (*i.e.*, spillbacks likely occur on these approaches).

By adopting the isolated signal timing approach, spillbacks are less likely to be found, with the greatest maximum Q/L ratio of 82% on the southbound approach (i = 1) of Intersection 4. The corresponding number is a lot lower in the case of network optimization, that is, 52% on the northbound approach (i = 2) of Intersection 3.

Table 3 Simulation results of Intersection 1

Measure	Existing				Isolated Signal Timing				Network Optimization			
	i = 1	i = 2	i = 3	i = 4	i = 1	i = 2	i = 3	i = 4	i = 1	i = 2	i = 3	i = 4
Flow (pc/h)	1869	2076	783	847	1869	2076	783	847	1869	2076	783	847
Sat. Flow (pc/h)	6960	6651	5034	5208	6960	6651	5034	5208	6960	6651	5034	5208
Delay (s/pc)	156.5	152.9	169.3	143.1	88.1	86.8	83.6	87.3	88.1	67.4	100.1	80.9
Max. Queue (m)	364.6	391.5	184.9	228.5	136.2	142.2	62.9	89.0	136.2	142.0	69.0	86.5
*MQ/SL (%)	53%	59%	17%	99%	20%	21%	6%	39%	20%	21%	6%	38%

*MQ/SL denotes the proportion of the maximum queue length per length of street.

Table 4 Simulation results of Intersection 2

Measure	Existing				Isolated Signal Timing				Network Optimization			
	i = 1	i = 2	i = 3	i = 4	i = 1	i = 2	i = 3	i = 4	i = 1	i = 2	i = 3	i = 4
Flow (pc/h)	1631	2174	663	815	1631	2174	663	815	1631	2174	663	815
Sat. Flow (pc/h)	5283	7862	4841	4578	6960	6651	5034	5208	5283	7862	4841	4578
Delay (s/pc)	121.3	175.9	129.1	63.1	17.6	18.5	54.5	18.9	9.5	19.6	54.5	18.9
Max. Queue (m)	314.4	359.2	120.8	154.8	69.0	42.0	20.0	22.2	34.9	64.1	20.0	22.2
*MQ/SL (%)	47%	97%	62%	50%	10%	11%	10%	7%	5%	17%	10%	7%

*MQ/SL denotes the proportion of the maximum queue length per length of street.

Table 5 Simulation results of Intersection 3

Performance Measure	Existing			Isolated Signal Timing			Network Optimization		
	i = 1	i = 2	i = 3	i = 1	i = 2	i = 3	i = 1	i = 2	i = 3
Flow (pc/h)	1706	2185	2043	1706	2185	2043	1706	2185	2043
Sat. Flow (pc/h)	5125	5986	3808	5125	5986	3808	5125	5986	3808
Delay (s/pc)	155.2	160.6	74.6	101.6	93.1	94.6	96.1	86.6	100.6
Max. Queue (m)	313.5	358.7	270.2	146.2	160.2	145.1	138.9	145.0	139.7
*MQ/SL (%)	85%	129%	82%	40%	57%	44%	38%	52%	43%

*MQ/SL denotes the proportion of the maximum queue length per length of street.

Table 6 Simulation results of Intersection 4

Measure	Existing				Isolated Signal Timing				Network Optimization			
	i = 1	i = 2	i = 3	i = 4	i = 1	i = 2	i = 3	i = 4	i = 1	i = 2	i = 3	i = 4
Flow (pc/h)	1641	2195	554	489	1641	2195	554	489	1641	2195	554	489
Sat. Flow (pc/h)	5048	6651	4740	3255	5048	6651	4740	3255	5048	6651	4740	3255
Delay (s/pc)	127.8	153.3	128.0	94.4	139.1	99.9	92.0	111.3	116.0	69.1	100.4	104.4
Max. Queue (m)	300.3	251.8	70.4	89.8	229.7	171.1	44.0	78.2	54.6	141.3	39.0	64.9
*MQ/SL (%)	108%	44%	39%	46%	82%	30%	24%	40%	20%	25%	22%	34%

*MQ/SL denotes the proportion of the maximum queue length per length of street.

Table 7 Simulation results of Intersection 5

Performance Measure	Existing			Isolated Signal Timing			Network Optimization		
	i = 1	i = 2	i = 3	i = 1	i = 2	i = 3	i = 1	i = 2	i = 3
Flow (pc/h)	1652	2196	2043	1652	2196	2043	1652	2196	2043
Sat. Flow (pc/h)	4423	4956	6212	4423	4956	6212	4423	4956	6212
Delay (s/pc)	167.5	129.7	85.0	113.3	98.6	65.9	99.3	59.8	69.5
Max. Queue (m)	283.8	356.9	184.5	110.2	144.1	81.8	138.4	180.2	101.8
*MQ/SL (%)	50%	52%	60%	19%	21%	27%	24%	26%	33%

*MQ/SL denotes the proportion of the maximum queue length per length of street.

Table 8 Simulation results of Intersection 6

Measure	Existing				Isolated Signal Timing				Network Optimization			
	i = 1	i = 2	i = 3	i = 4	i = 1	i = 2	i = 3	i = 4	i = 1	i = 2	i = 3	i = 4
Flow (pc/h)	1619	2185	566	631	1619	2185	566	631	1619	2185	566	631
Sat. Flow (pc/h)	8256	9748	5034	4642	8256	9748	5034	4642	8256	9748	5034	4642
Delay (s/pc)	162.1	157.3	183.9	186.6	112.3	113.5	127.5	147.7	109.4	107.4	122.5	153.1
Max. Queue (m)	325.2	379.8	155.3	167.6	144.7	168.2	75.4	81.2	135.6	147.6	66.7	73.0
*MQ/SL (%)	48%	44%	16%	48%	21%	20%	8%	23%	20%	17%	7%	21%

*MQ/SL denotes the proportion of the maximum queue length per length of street.

In terms of network performance, by adopting the network optimization approach, the overall queues could be substantially reduced from 255.8 m/approach (base case scenario) to 97.3 m/approach, or equivalently a 61.9% reduction, which is 10.1 m/approach, or about 9.4%, better than that of the isolated signal timing approach.

3.3. Cycle length and split green interval

Figure 4 shows a comparison of results pertaining to cycle lengths of the two signal timing approaches versus those of the base case scenario. From Figure 4, it is evident that the current cycle lengths at all intersections are comparatively longer than those of the two signal timing approaches, especially at Intersection 2. Furthermore, the network optimization approach's cycle lengths seem to be more consistent across intersections, with the exception of Intersection 2, whose cycle length is only 75.0 seconds, due to the offsets between green initiation times. The cycle lengths of the isolated signal timing approach, on the other hand, vary between 120.0 seconds and 180.0 seconds.

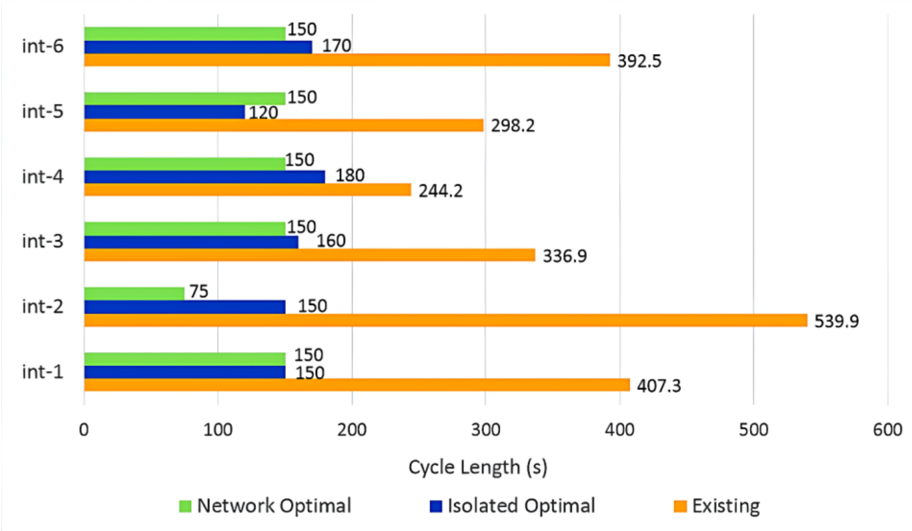

Figure 4 Comparison of cycle lengths between the base case scenario (existing), the isolated signal timing approach (isolated optimal), and the network optimization approach (network optimal)

In terms of the split green interval at the approach level, as illustrated by Figure 5, the current split green intervals are obviously excessive on all intersections' approaches—which, in turn, results in excessive red times, longer accumulated queues, and greater delays. Instead of issuing longer green intervals, the isolated signal timing and the network optimization approaches aim to utilize shorter green times to their fullest potential so that accumulated queues on the remaining approaches could be timely discharged with fewer delays.

In sum, the implementation of shorter green times could effectively reduce overall delays and traffic queues. Furthermore, extending green times excessively for specific intersections' approaches is less efficient, particularly in oversaturated intersections, as it could lead to disproportionately long red times for other approaches. These findings align well with previous research (*e.g.*, Akgungor and Korkmaz, 2018; Eriskin *et al.*, 2017; Srisurin and Singh, 2017), highlighting inefficiency in the traditional signal timing strategies.

It should be remarked that the split green intervals at an intersection's approach are not generally proportionate to each other. To properly evaluate the efficiency of green time on each approach, based on its respective flow, flow per G/C ratio, defined by Equation (7), is therefore adopted for the green time assessment.

$$Flow\ per\ G/C = \sum_{i \in I} \left(\frac{q_i}{(G_i/CL) \times 3600}\right), \tag{7}$$

where q_i is the hourly flow rate (pc/h).

As the flow per G/C ratio measures the total number of passenger cars per second of green (pc/s of green) passing through all approaches of an intersection, the higher the flow per G/C ratio, the better the efficiency of green time is.

Table 9 summarizes the resulting flow per G/C ratio at each intersection, as generated by the isolated signal timing and the network optimization approaches, and compares them with the base case scenario. From Table 9, it is clear that both signal timing approaches are marginally superior to the base case scenario, despite their relatively shorter green intervals. Although the network optimization approach seems to outperform the other approach at four out of six intersections, such improvements are not that substantial—less than 5%. We can, therefore, infer that both signal timing approaches are comparable in terms of flow per G/C ratio.

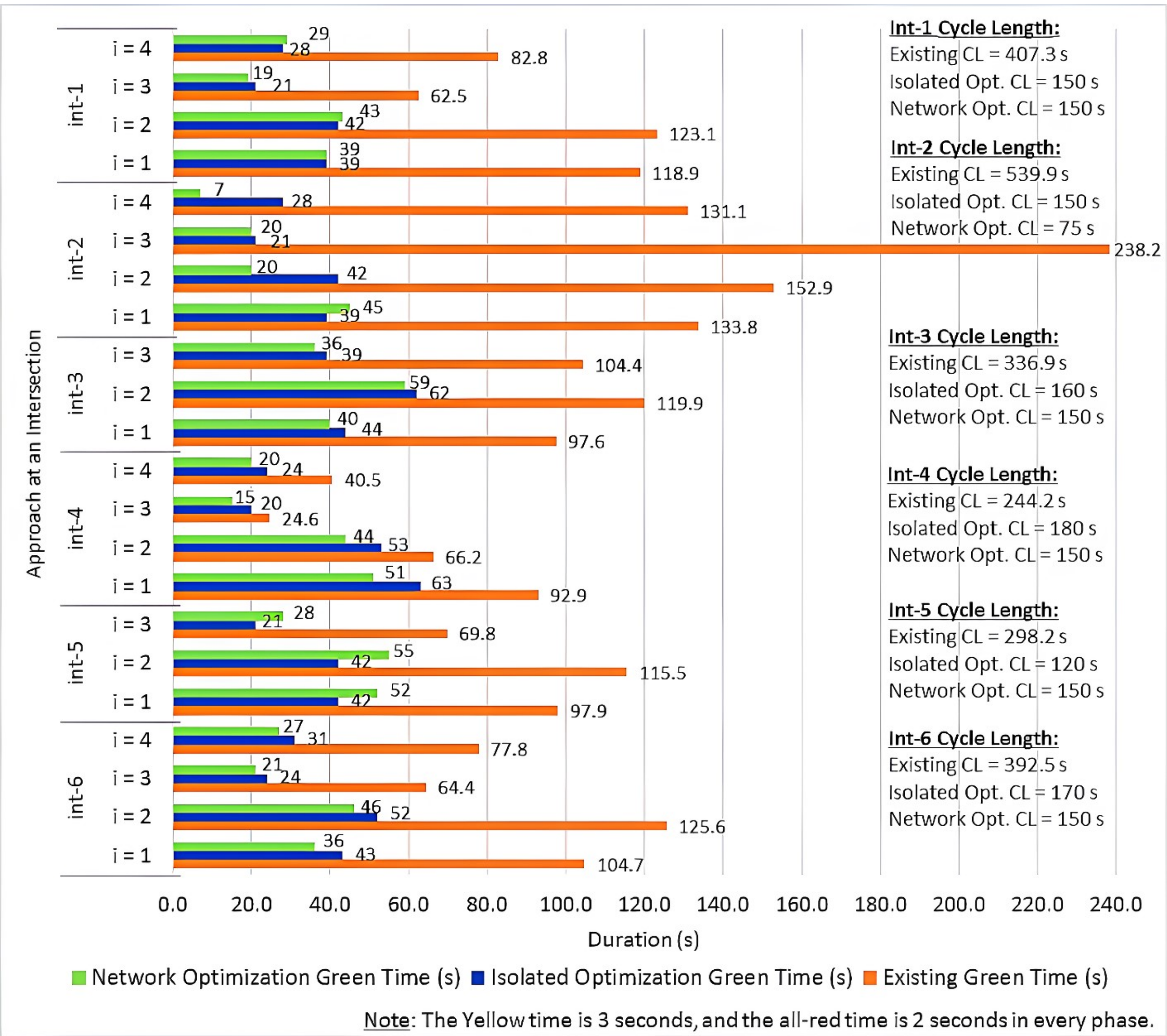

Figure 5 Comparison of split green times between the base case scenario, the isolated signal timing approach (isolated optimal), and the network optimization approach (network optimal)

Table 9 A summary of flow per G/C ratio at each intersection

Intersection	Flow per G/C (pc/s of green)			Difference (%)		
	Existing	Isolated	Network	Isolated vs. Existing	Network vs. Existing	Network vs. Isolated
int-1	6.26	6.87	6.94	9.7%	10.9%	1.1%
int-2	5.31	6.43	6.14	21.0%	15.5%	-4.5%
int-3	5.17	5.62	5.68	8.6%	9.9%	1.2%
int-4	5.79	5.78	5.98	-0.3%	3.2%	3.5%
int-5	5.40	6.30	6.03	16.7%	11.7%	-4.3%
int-6	5.43	5.84	5.95	7.6%	9.7%	1.9%

3.4. Vehicle trajectory under the network optimization approach

To visualize the interrelationship of these six intersections' signal timing under the network optimization approach, Figure 6 shows the trajectory of vehicles traversing the main corridor in the northbound direction, from Intersection 6 through Intersection 2. Note that, in Figure 6, an optimal cycle length of 150.0 seconds is applied at Intersections 3 through 6, whereas a shorter cycle length of 75.0 seconds is applied at Intersection 2.

According to the collected data, traffic in the northbound direction is heavily platooned. The proportion of traffic in the platoon ranges between 0.82 and 0.99, with sufficiently high numbers of passenger cars per hour, *i.e.*, between 3,707 *pc/h* and 3,826 *pc/h*. By adopting the network optimization approach, motorists on the northbound approach are prioritized, taking into account traffic on minor streets. As a result, the issued green intervals are not perfectly aligned.

Although the issued green intervals on the main corridor are not perfectly aligned, the network optimization approach tends to prioritize the overall vehicular delays from the network's perspective, leading to a better traffic flow on the network level.

This implies that the conventional signal coordination approach that gives priority to the vehicular flow on the main corridor may fail to provide the best results in terms of network delays for oversaturated networks. This is largely due to the considerably high demand volumes on the minor streets that impede both accessibility and the mobility of other road users at nearby intersections, thereby inducing widespread network congestion.

By properly aligning green time intervals without overlooking traffic on minor streets, the whole network's performance could be enhanced. This highlights the practical benefits of the network optimization approach in real-world applications.

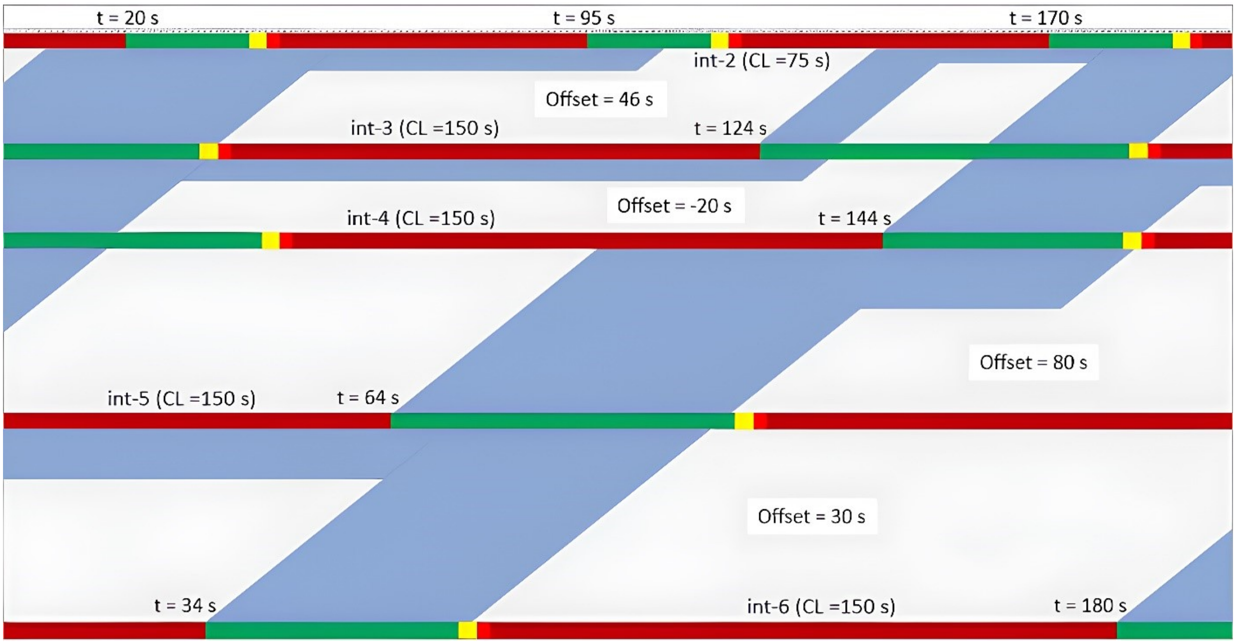

Figure 6 Time-space diagram showing the results of the network optimization approach in the northbound direction (*i.e.*, from Intersection 6 through Intersection 2)

4. Conclusions

Determining optimal signal timing in a network with multiple intersections is rather complex, largely due to the interrelationships among different intersections' approaches that impact one another's performance—and so the whole network at the same time. This is especially an issue in dense urban areas where intersections are closely aligned, coupled with the oversaturated vehicular demands on both main corridors and minor streets during the peak periods. To address this issue, this study aims to investigate and compare the variations in performance of an oversaturated network with six consecutive intersections located on a major arterial road in Bangkok, Thailand, during the weekday evening peak period, by two main approaches: (*i*) the isolated signal timing approach that issues optimal signals to each intersection independently and (*ii*) the network optimization approach that optimizes the network's holistic performance based on traffic on both the main corridor and minor streets. According to our simulation conduct, we find that optimal cycle lengths and proper allocation of green intervals are vital to reduce delays and queue lengths at an isolated intersection. We also find that, while both isolated signal timing and network optimization approaches can significantly reduce the overall delays at all intersections, the average delays produced by the network optimization approach turn out to be lower. The reason for this is the fundamental difference between these two approaches. Particularly, the isolated signal timing approach focuses on minimizing delays at individual intersections, whereas the network optimization approach considers the whole network as a single system. By properly aligning green intervals, taking into account minor streets' vehicular flows, the whole network's performance could be enhanced, highlighting the practical benefits of the network optimization approach in real-world applications. It should be remarked that, while our study is primarily based on a network with six consecutive oversaturated intersections in Bangkok, Thailand, we expect that the proposed framework could be further applied to other oversaturated networks with different configurations—*e.g.*, signalized multi-leg intersections and roundabouts—at different time periods. We also expect that, with advanced data collection processes (such as AI traffic cameras that are capable of classifying various vehicle types), a more dynamic/precise signal timing approach could be further developed; and, it would be interesting to see how to include all of the abovementioned aspects in future research studies.

5. Nomenclature

The following symbols are used in this paper:
Int-1 = Intersection 1 (northernmost);
Int-2 = Intersection 2;
Int-3 = Intersection 3;
Int-4 = Intersection 4;
Int-5 = Intersection 5;
Int-6 = Intersection 6 (southernmost);
CL = Cycle length (s);
G = Green time (s);
Y = Clearance or yellow time (s);
AR = All-red time (s);
LT = Total lost time per phase (s);
V_{ci} = Critical flow volume on the i^{th} approach, which is defined by the maximum flow rate less the available turning movements on red (pc/h);
SF_i = Saturation flow rate on the i^{th} approach (pc/h);
Q_i = Queue length on the i^{th} approach (m);
MQ_i = Maximum queue length on the i^{th} approach (m);
SL_i = Street length on the i^{th} approach (m);
q_i = Hourly flow rate on the i^{th} approach (pc/h);
G/C ratio = Ratio of total green time to the cycle length (unitless);

pc/h = Unit of flow rate (passenger car unit per hour);
pc/h/ln = Unit of flow rate per lane (passenger car unit per hour per lane);
s/pc = Unit of average delay per vehicle (seconds per passenger car unit).

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Conflict of Interest

The authors declare no conflicts of interest.

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