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How to Design Traffic Signals at Multiple Coordinated Intersections

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Abstract

Traffic signals at signalized intersections are effective tools to safely control the movement of traffic through the intersections word-wide. The conflicts arising from movements of traffic in different directions are addressed by time sharing between the intersection approaches. The advantages of traffic signals include an orderly movement of traffic, reduce probability of accidents by minimizing possible conflict points, and an increased capacity of the intersection, while stopping delays are the major disadvantage. This paper presents a prototype traffic signal design of four virtual fixed-time signalized intersections that addresses a coordinated design system. The major movements are assumed to occur along the Northbound and Southbound, and their optimal coordination through these intersections is achieved by changing their split times, cycle lengths, offsets, and left-turn phasing types in order to reduce the average delay, average number of stops, and travel time. Intersection 1, 3, and 4 are assumed to have the standard four-approaches, while intersection 2 is assumed to be a T-intersection with three-approaches. The simulation is conducted using VISSIM to make the final selections of the timing parameters.

Keywords

Signal Design, Signalized Intersections, Cycle Length, Offsets, Splits

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1. Introduction

Traffic signals play an important role in the transportation networks and they could sometimes be a source for frustration for the public when not operated efficiently. Outdated traffic signal design accounts for a portion of traffic delay on urban networks and traffic signal retiming is one of the most cost effective ways to improve traffic flow and is one of the most basic strategies to help mitigate congestion [1-9]. Traffic signals should be designed to serve both operational efficiency and safety based on the conditions. A traffic signal that is properly designed and timed can be expected to provide one or more of the following benefits [1, 2, 7, 10]:

a) Manage the efficient movement of people.

b) Maximize the volume movements served at the intersection.

c) Reduce the frequency and severity of certain types of crashes.

d) Improve the level of service at intersections.

e) Improve the level of accessibility for pedestrians and side traffic.

The extent to which these benefits are achieved is based partly on the design of the traffic signal. A poorly designed signal timing plan or an unneeded signal may make the intersection less efficient, less safe, or both. There are many signal timing parameters that affect intersection efficiency including the cycle length, the minimum and maximum green time, and clearance intervals. Increasing a traffic movement's green time may reduce its delay and the number of vehicles

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that stop. However, an increase in one movement's green time generally comes at the expense of increased delay and stops to another movement. Thus, a good signal timing plan is one that allocates time appropriately based on the demand at the intersection and keeps cycle lengths to a minimum [10-12]. The relationship between signal timing and safety is also addressed with specific timing parameters and the design of the intersection. For instance, the intent of the yellow time change interval is to facilitate safe transfer or right-of-way from one movement to another. The safety benefit of this interval is most likely to be realized when its duration is consistent with the needs of drivers approaching the intersection at the onset of the yellow indication. This need relates to the driver's ability to perceive the yellow indication and proceed to stop before the stop line, or to travel through the intersection safely. Their decision to stop, or continue, is influenced by several factors, most notably speed. Appropriately timed yellow change intervals have been shown to reduce intersection crashes. Signal timing plans that reduce the number of stops and minimize delays may also provide additional safety benefits [2, 4, 6, 9, 10-16].

2. Phasing and Timing Parameters

The signal timing for intersection 1, intersection 3, and intersection 4 was selected to be the standard eight phase, four-approach intersections. The minimum green time was set to be 5 seconds for the left-turn (LT) and 10 seconds for the through (TH) movement, with a vehicle extension time of 2 seconds. Yellow time was 3 seconds accompanied by an All-Red time of 2 seconds. With this setup, max green time was equal to each individual split minus the Yellow and All-Red time of 5 seconds. Splits were determined using a critical movement analysis (CMA) at each intersection. The signal timing for intersection 2 was selected to be a four phase, T-intersection. The phasing and traffic volumes of the four intersections are shown in Figures 1, 2, 3, and 4.

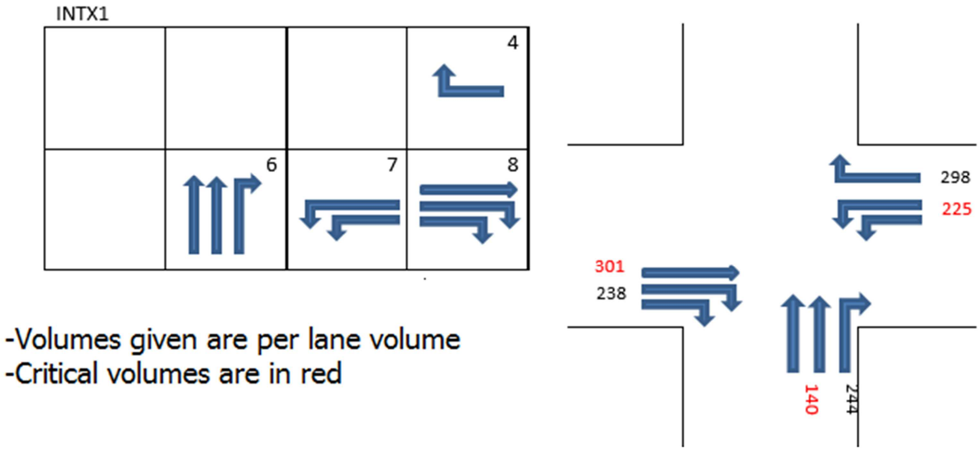

Figure 1. Intersection 1.

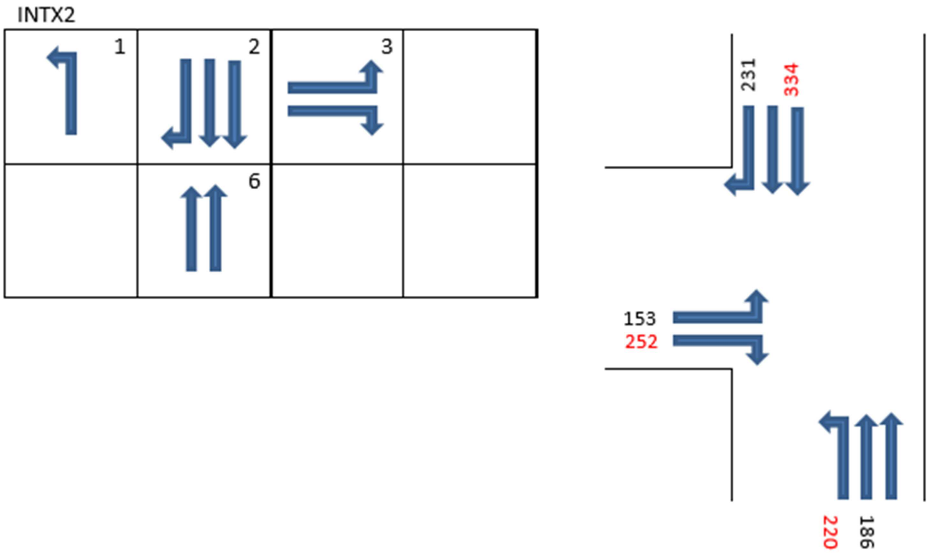

Figure 2. Intersection 2.

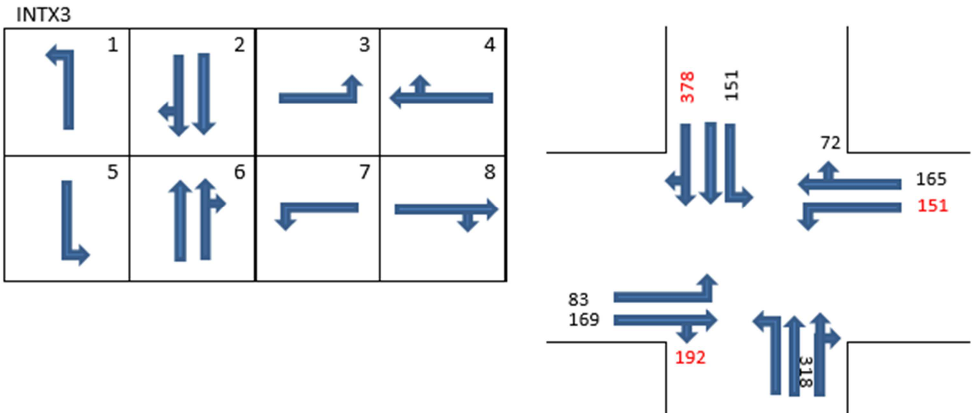

Figure 3. Intersection 3.

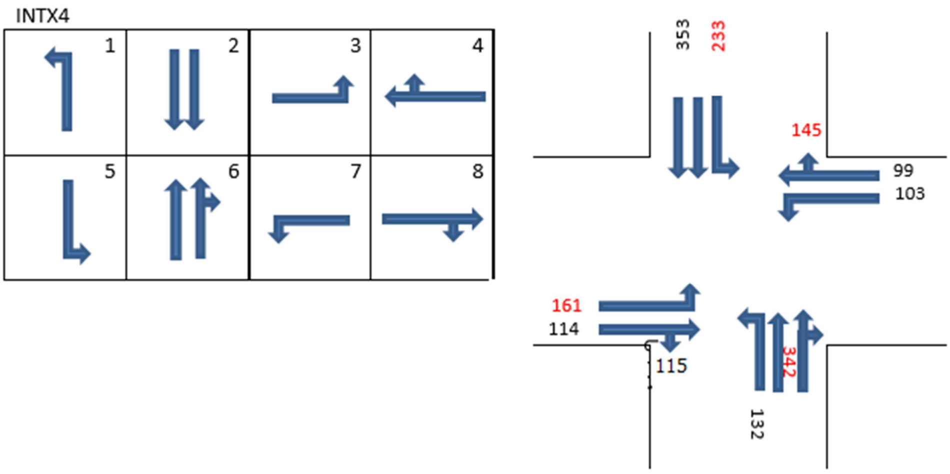

Figure 4. Intersection 4.

3. Methodology

Four fix-time virtual signalized intersections were used in the traffic signal design in order to optimize the major Northbound and Southbound Through (NBT, SBT) movements. The initial base case was chosen to be the peak afternoon hour using VISSIM. The design steps included the split times, cycle length, offsets, and left turn (LT) phasing for each intersection. The main factors that were used to evaluate the system were the amount of delay, number of stops, and travel time for all vehicle types in the system. The evaluation was based on four stages, as described below:

a) Splits: A critical movement analysis of each intersection is performed to determine the amount of time allocated to each movement at each intersection based on the proportion of each critical vehicle volumes to the critical sum of all the critical vehicle volumes. New splits were found and incorporated into the base case of timing parameters. The simulation was run using VISSIM and all performance data were collected.

b) Cycle lengths: With the new split times, the simulation was run at different virtual cycle lengths of 60, 70, 80, 90, 100, and 110 seconds. The cycle length that produced the minimum delay was chosen and a new critical movement analysis was conducted based upon this new cycle length. The new parameters obtained from this step were incorporated into the initial base case's timing parameters. Again the simulation was run using VISSIM and all relevant data were collected.

c) Offsets: The simulation was run with an assumed offset of zero seconds for the first intersection and systematically tried offsets of 0 -60 seconds (at 10 second increments) between intersections 1 & 2, 2 & 3, and 3 & 4. As each offset was evaluated, the optimal offset was included in the model for the next offset's evaluation. The offsets that produced the least average delay, average number of stops, and least travel time were kept. All relevant data was recorded after each evaluation using VISSIM.

d) Phasing: The optimal phasing was determined by completing a critical movement analysis assuming only through movements and then changing the phasing plan and changing the new split times. The average delay, number of stops, and travel time data was compared to that of the protected phasing plan.

4. Split Evaluation

Split timing was based on the critical movement analysis (CMA) of each intersection. By comparing the added volumes of vehicles from conflicting movements (e.g. 1+2, 3+4, 5+6, and 7+8), the highest combined volumes were determined, which presented the critical movements for that intersection. Dividing each of these critical movement sums by the critical sum (total sum of the critical movements in the intersection) provided the proportion of the cycle length that each critical movement should be allotted. Multiplying these proportions by the cycle length yielded the exact number of seconds for each split. All new split times were checked against the required minimum green times. After incorporating these new splits in VISSIM, multiple runs were conducted to determine the delay and #stops data. Pedestrian crossing time was ignored for simplicity and not included as part of the splits. The CMA for the permitted left turn (LT) phasing was carried out by ignoring the LT volumes, using only the volumes of the through (TH) and right turn (RT) movements. Table 1 shows the decrease in delay between the initial basic case and the new split times case for the movements identified in the base case.

Table 1. The decrease in Delay (sec).

Intersection and movement		Delay (sec) Base Case	New Splits
INTX1	WBL	104	29
INTX2	NBL	135	63
	NBT	51	8
INTX3	NBL	113	57
	NBT	69	35
	NBR	61	34
INTX4	SBL	120	42
Average		93	38

5. Cycle Length Evaluation

Using the optimal split times from previous step, the ideal cycle length was determined by conducting multi runs in VISSIM at virtual cycle lengths of 60, 70, 80, 90, 100, and 110 seconds. Plotting the average delay vs. cycle length for both the northbound through (NBT) and the southbound through (SBT) movements at each intersection, the overall average delay for the entire system was determined, as shown in Figure 5.

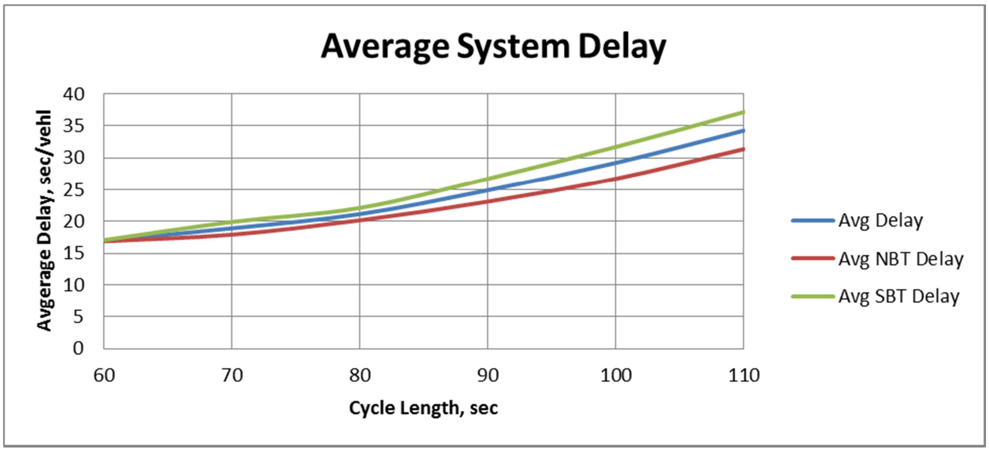

Figure 5. Average System Delay.

From Figure 5, it can be seen that the best cycle length for the entire system would be 60 seconds since it shows clearly that with the increasing cycle length, delay for the system is increased. For example, looking at the base case (C = 100 sec) and C = 60 sec for the major NBT and SBT movements, there is a 12.1 second drop in delay for the system from 29.2 seconds to 17.1 seconds respectively (41% decrease from base case). The cycle length of C = 60 seconds was optimal for all through movements at all intersections.

6. Offset Evaluation

Using the platoon dispersion, it was found that the approximate platoon length at startup would be approximately 30 seconds and 50 seconds at the next intersection. Using these numbers in the time space diagram, the optimal offsets of 0, 15, 45, and 0 seconds for intersection 1-4 respectively were chosen (offsets measured relative to intersection 1). Comparing these values with those calculated from VISSIM data, they were found reasonable. To find the optimal offsets, delay and #Stops were evaluated using a three-step process. First, the NBT at intersection 1 and the SBT at intersection 2 at offsets of 0, 10…60 were compared and found that the optimal offset was 20 seconds. Using this new off set in VISSIM, the NBT at intersection 2 and the SBT at intersection 3 at offsets of 0, 10…60 as before were compared, and the optimal offset was found to be 0 seconds, which is equivalent to one full cycle length of 60 seconds. Similarly, the NBT at intersection 3 and the SBT at intersection 4 were compared, and found that its optimal offset to be 50 seconds. The best offset was chosen to be the offset that minimized delay for the SBT movement since it has the highest volume during peak afternoon traffic. Comparing Delay and number of Stops from the VISSIM for these offsets (0, 20, 0, 50) to those found with the platoon dispersion model and time space diagram (0, 15, 45, 0) showed very similar results. Figure 6 shows typical optimal offset comparison between intersection 2 and intersection 3.

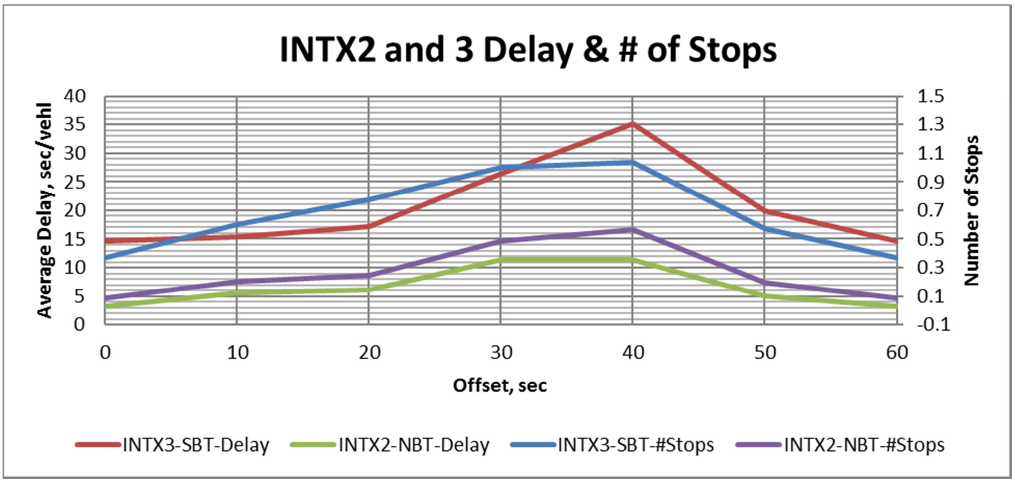

Figure 6. Optimal offset between Intersection 2 and 3.

7. Left Turn Evaluation

After determining the best offset for each intersection, the last parameter to test was protected vs. permitted let-turn (LT) phasing. This was done by changing all of the LT's in the system to permitted by assigning them the same signal group as the TH movement from the same approach. After recalculating the split times with a new critical movement analysis, the results showed that the permitted LT caused increases in delay, number of Stops, and travel time. The only improvement it made in the system was a slight drop in the travel time of the SBT movement by 7 seconds. This improvement, however, was not significant enough to keep the permitted phasing plan given the other objections. Observation of the model confirmed this and showed that by the end of the simulation period, the NBL queue at intersection 2 had largely grown. Therefore, the protected LT was selected in the final plan. Table 2 shows comparison results between permitted and protected LT.

Table 2. Permitted vs. protected left turn (LT).

Network Total	Protected	Permitted
Avg. Delay, s (system)	23.9	34.5
Avg. #Stops (system)	0.73	1.23
Avg. # Vehicles (system)	8471	7750
Travel Time, s (NB)	171	184
Travel Time, s (SB)	145	137

8. The Final Plan

The final plan was selected based on evaluations of the split, cycle length, offset, and left-turn movement. Table 3 summarizes the increase in system performance at the final plan of each signal timing parameter. Table 4 shows the initial base case timing plan parameters. Table 5 shows the final case timing plan parameters.

9. Conclusion

Traffic Signals are vital tools used to safely and manage vehicle, bicycle and pedestrian traffic on highways. To achieve optimum efficiency, traffic signals must be designed to serve changing traffic patterns. Signals that are insufficiently designed often generate an increase in vehicle stops, traffic delays, fuel consumption, traffic accidents and non-compliance. Closely spaced signals are inter-connected, creating coordinated signal systems that work together so that cars moving through the group will make the least number of stops possible. Coordinated signals try to provide green lights for the major vehicle flow on a street. This requires gathering data on the volume, speed, distance between signals, and the timing of individual intersections. When the data has been collected a study is done to determine the best timing and coordination of all intersections involved. This paper presented a prototype traffic signal design of four virtual fixed-time signalized intersections that addresses a coordinated design system. The design steps included the split times, cycle length, offsets, and left turn (LT) phasing for each intersection. The optimal coordination through these intersections was achieved by changing their split times, cycle lengths, offsets, and left-turn phasing types in order to reduce the average delay, average number of stops, and travel time. The simulation was conducted using VISSIM to make the final selections of the timing parameters.

Table 3. System performance improvement.

NBT & SBT	Protected LT Phasing				Permitted LT Phasing	Final Plan	% Performance Improvement
	Base Case	New Splits	Cycle Length	Offsets			
Avg. Delay, seconds	52.1	29.2	17.0	15.6	17.9	15.6	70
Avg. #Stops	1.06	0.75	0.60	0.52	0.60	0.52	51
NB Travel Time, sec	278	233	163	171	184	171	38
SB Travel Time, sec	364	221	155	144	137	144	60

Table 4. The initial base case plan parameters.

INTX #	Mvmt	LT Phasing	Min. Green Time (sec)	Yellow Time (sec)	All-Red Time (sec)	Splits	Max Green Time (sec)	Offset (sec)	Cycle Length (sec)
INTX1	WBR	-	5	-	-	50	45	0	100
	NBT	-	5	3	2	50	45		
	WBL	Protected	5	3	2	15	10		
	EBT	-	5	3	2	35	30		
INTX2	NBL	Protected	5	3	2	15	10	0	100
	SBT	-	5	3	2	35	30		
	EBR	-	5	3	2	50	45		
	NBT	-	5	3	2	50	45		
INTX3	NBL	Protected	5	3	2	15	10	0	100
	SBT	-	5	3	2	35	30		
	EBL	Protected	5	3	2	15	10		
	WBT	-	5	3	2	35	30		
	SBL	Protected	5	3	2	15	10		
	NBT	-	5	3	2	35	30		
	WBL	Protected	5	3	2	15	10		
	EBR	-	5	3	2	35	30		
INTX4	NBL	Protected	5	3	2	15	10	0	100
	SBT	-	5	3	2	35	30		
	EBL	Protected	5	3	2	15	10		
	WBR	-	5	3	2	35	30		
	SBL	Protected	5	3	2	15	10		
	NBT	-	5	3	2	35	30		
	WBL	Protected	5	3	2	15	10		
	EBT	-	5	3	2	35	30		

Table 5. The final plan parameters.

INTX #	Mvmt	LT Phasing	Min. Green Time (sec)	Yellow Time (sec)	All-Red Time (sec)	Splits	Max Green Time (sec)	Offset (sec)	Cycle Length (sec)
INTX1	WBR	-	5	-	-	45	40	0	60
	NBT	-	5	3	2	15	10		
	WBL	Protected	5	3	2	19	14		
	EBT	-	5	3	2	26	21		
INTX2	NBL	Protected	5	3	2	16	11	20	60
	SBT	-	5	3	2	25	20		
	EBR	-	5	3	2	19	14		
	NBT	-	5	3	2	41	36		
INTX3	NBL	Protected	5	3	2	12	7	0	60
	SBT	-	5	3	2	23	18		
	EBL	Protected	5	3	2	10	5		
	WBT	-	5	3	2	15	10		
	SBL	Protected	5	3	2	12	7		
	NBT	-	5	3	2	23	18		
	WBL	Protected	5	3	2	10	5		
	EBR	-	5	3	2	15	10		
INTX4	NBL	Protected	5	3	2	14	9	50	60
	SBT	-	5	3	2	21	16		
	EBL	Protected	5	3	2	10	5		
	WBR	-	5	3	2	15	10		
	SBL	Protected	5	3	2	14	9		
	NBT	-	5	3	2	21	16		
	WBL	Protected	5	3	2	10	5		
	EBT	-	5	3	2	15	10		

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