

CONTROL DELAY VARIABILITY AT SIGNALIZED INTERSECTION BASED ON HCM METHOD

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Abstract: The 2000 Highway Capacity Manual (HCM) designates mean control delay as the primary performance measure for signalized intersections. Considering the variability of delay, more reliable signal control strategies may be generated resulting in improved LOS of signalized intersections. This research was to determine the set of variables that affect control delay at signalized intersection. SIDRA and Transyt-7F, the widely used capacity software which determine the delay based on HCM methods was utilized in this study. At $\alpha = 0.05$, the research indicated that only cycle time, intergreen time, no. of phasing, no. of lane and LTOR have a significant correlation. LTOR type of turning movement if allowed will significantly reduce the intersection control delay.

Key Words: Delay Variability, Signalized Intersection, SIDRA, TRANSYT-7F, HCM

1. INTRODUCTION

Most of traffic signal studies focus on the estimation of delays and queue lengths that result from the adoption of a signal control strategy at individual intersections, as well as on a sequence of intersections. Traffic delays and queues are principal performance measures that enter into the determination of intersection level of service (LOS), in the evaluation of the adequacy of lanes, and in the estimation of fuel consumption and emissions. Since numerous transport authorities decided that an acceptable LOS is one of the basic parameters to be fulfilled in signal control design, the obtained minimum delay being the foremost goal to the traffic engineers.

Delays estimation at signalized intersections has been extensively studied in the literature and several methods for estimating vehicle delay at signalized intersections have been widely used.

However, it seems that the exploration on the method for estimating the delay is still continuously conducted. This is may be due to the consideration of various variables which could affect the delays.

As an example, the 1994 Highway Capacity Manual (HCM) stated that the stopped delay can be multiplied by a factor of 1.3 to obtain an approximate estimate of the total delay. Whereas several studies have found that this factor should be variable rather than just a constant value (Olszewski, 1993; Quiroga and Bullock, 1999; Mousa, 2002). The change of the primary factor for measuring the LOS at signalized intersection from stopped delay (HCM1994) to control delay (HCM1997 and 2000) also depicts the continuing improvement by incorporating current research findings.

Dion *et al* (2004) illustrated five delay models for signalized intersection: deterministic queuing model, shock wave delay model, steady-state stochastic delay model, time-dependent stochastic delay model, and finally, microscopic simulation delay model. The time-dependent stochastic delay model have been proposed over the years and have been incorporated into a number of capacity guides, such as those from the United States (TRB 1994, 1997, 2000), Australia (Akcelik, 1981) and Canada (ITE, 1995).

Unfortunately, the vast majority of the study has focused on developing models for estimating the mean delay and much less work has been done to quantify the variability of delay at a signalized approach. While knowing the variability of the delay has a number of useful applications, such as developing more accurate signal timing plans and providing a more complete and statistically significant comparison of different signal timing or roadway geometric improvements. Moreover, considering the variability of delay, more reliable signal control strategies may be generated resulting in improved LOS of signalized intersections.

Accordingly, it is necessary to identify the significant variables affecting the control delay. Having established the variables, a simple and quick approach for designing optimal intersection layout and signal timings is achieved. Besides reducing the time consuming during intersection analysis and planning as well as the project costing, the optimum results is obtained.

The purpose of this research was to determine the set of variables that affect significantly the control delay at signalized intersections. This list of variables will provide improved understanding of the applicability of past research and such variation may have important implications to practitioners for the planning, design and analysis of signal controls.

1.1 SIDRA and TRANSYT-7F Capacity Software

The Signalized and Unsignalized Intersection Design and Research Aid (SIDRA) software is used as an aid for design and evaluation of signalised intersection (fixed-time/pretimed and actuated), roundabouts, two-way stop sign control, all-way stop sign control, and give-way (yield) sign-control (Akcelik *et al*, 2002). SIDRA uses detailed analytical traffic models coupled with an iterative approximation method to provide estimates of capacity and performance statistics (delay, queue length, stop rate, etc).

TRANSYT-7F is an acronym for TRAFFIC Network Study Tool, version 7F and it is a microcomputer-based system for traffic simulation and signal timing optimization program. TRANSYT-7F optimizes signal timing by performing a macroscopic simulation of traffic flow within small time increments while signal timing parameters are varied. Design includes cycle length, offsets, and splits based on optimizing such objective functions as increasing progression opportunities; reducing delay, stops, and fuel consumption; reducing total operating cost; or a combination of these.

2. DELAY AT SIGNALIZED INTERSECTIONS

Delay in the realm of signalized intersections is associated with the time lost to a vehicle and/or driver because of the operation of the signal and the geometric and traffic conditions present at the intersection (Click, 2003). While delay in the HCM 2000 context is defined as the difference between the travel time actually experienced and the reference travel time that would result during ideal conditions; in the absence of traffic control, in the absence of geometric delay, in the absence of any incidents, and when there are no other vehicles on the road.

There are several different types of delay that can be measured at an intersection, and each serves a different purpose to the transportation engineer. The signalized intersection capacity and LOS estimation procedures are built around the concept of average control delay per vehicle. Control delay is the portion of the total delay attributed to traffic signal operation for signalized intersections (TRB, 2000).

Control delay (overall delay) can be categorized into deceleration delay, stopped delay and acceleration delay. Stopped delay is easier to measure, while overall delay reflects better the efficiency of traffic signal operation (Olszewski, 1993). Typically, transportation professionals define stopped delay as the delay incurred when a vehicle is fully immobilized, while the delay incurred by a decelerating or accelerating vehicle is categorized as deceleration and acceleration delay, respectively.

Various components of vehicular delay at signalized intersection, including control delay used in the HCM, are shown in Figure 1 (Quiroga and Bullock, 1999). In the 2000 version of the HCM, control delay is comprised of initial deceleration delay, queue move-up time, stopped delay, and final acceleration delay, though in earlier versions it included only stopped delay.

In the figure, it is first observed that several vehicles reaching the intersection come to a complete stop. These vehicles need to stop either as a consequence of their arrival during the red interval or during the green interval when the queue of vehicles that had formed during the previous red interval has not yet fully dissipated. While it is further observed that the rest vehicles only experience deceleration and acceleration delay, as these vehicles reach the intersection when all previously queued vehicles have already started to move and therefore only need to slow down to maintain a safe distance with the vehicles ahead of them.

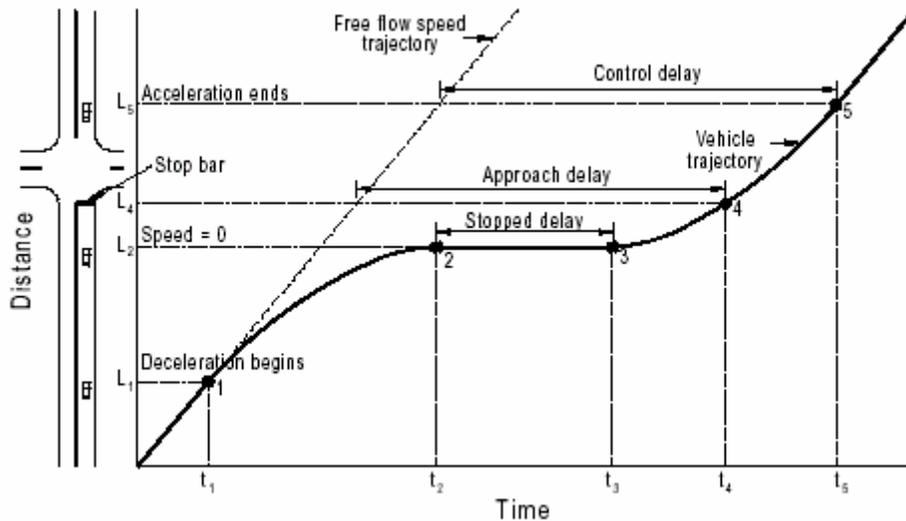


Figure 1. Delay Terms at a Signalized Intersection

Besides the control delay, there is another type of delay which vehicles experienced at signalized intersection. This type of delay is identified as geometric delay. Luttinen and Nevala (2002) define geometric delay as the time lost due to the intersection geometry. Geometric delays may be large for turning movements. Total delay of a vehicle is the sum of control delay and geometric delay.

On the other hand, the drivers perception and reaction time to the changes of the signal display at the beginning of the green interval and during yellow interval to mechanical constraints and to individual driver behavior also contribute to the traffic delay at signalized intersection. Husch and Albeck (2004) explain that during simulation process using SimTraffic micro simulation software, there are input parameters called as driver parameters. These parameters involve yellow deceleration, yellow reaction time, green reaction time, headways and gap acceptance factor. All these driver parameters depend on driver type.

Green reaction time is the amount of time it takes the driver to respond to a signal changing to green. More aggressive drivers will have a shorter reaction time to green lights. This value ranges from 0.8 to 0.2 seconds. While headways are the amount of time between vehicles drivers try to maintain. When traveling at 30 ft/s a vehicle with a 1-second headway will try to maintain 30ft between it and the leading vehicle. Gap acceptance factor is an adjustment to the approach gap times. This is the gap vehicles will accept at unsignalized intersections, for permitted right turns, and for left turns on red. These values range from 1.15 to 0.85 second. The higher values represent more conservative drivers (Husch and Albeck, 2004).

To account for the additional delays due to driver reaction time and vehicle acceleration constraints, the operation of a signalized intersection is usually defined in terms of effective signal intervals instead of actual intervals in delay estimation models, as shown in Figure 2. Instead of explicitly considering green, yellow and amber intervals and attempting to model variable departure rates, delay calculations are typically performed by dividing the signal cycle into effective periods of stopped and moving traffic within which constant traffic characteristics

can be assumed. The amount of difference between the actual and effective timings will thus depend on the assumptions regarding driver reaction time at the beginning of the green interval and vehicle accelerations.

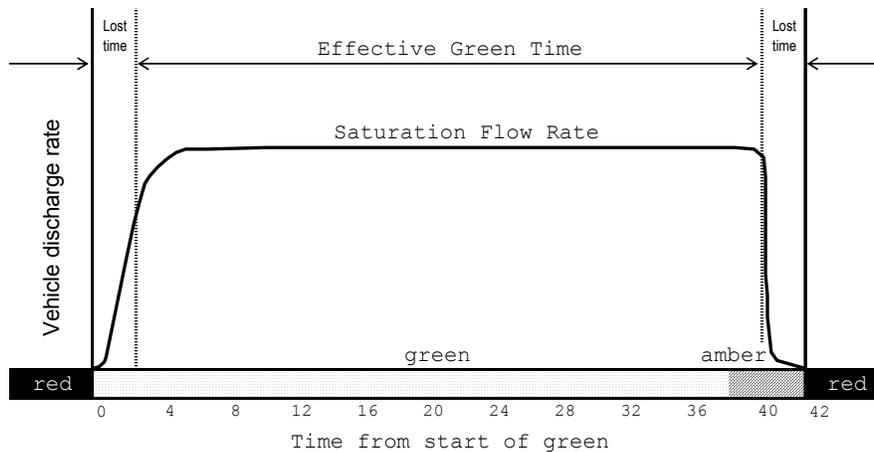


Figure 2. Queuing Model under Deterministic Queue Analysis

A final element that may affect the delays incurred at intersection approaches is the randomness in vehicle arrivals. If vehicles were to arrive at uniform intervals, the delays incurred by vehicles within successive signal cycles would be identical, as there would then be an exact replication of the arrival and departure patterns. However, under random arrival patterns, the number of arrivals may fluctuate from one cycle to the other, thus resulting in different queue lengths. This may in turn result in arrival demands that occasionally exceed the approach capacity, and therefore, in higher delays. Finally, platooned arrivals may also occur in coordinated traffic signal systems. In this case, the delay incurred by vehicles will depend on the degree to which the signals at successive intersections are timed to provide a green indication during the periods of high arrival flow rate (Dion *et al*, 2004).

3. DELAY MODEL IN HCM2000

After the release of the Highway Capacity Manual 1994, numerous researches have been undertaken to assess the changes that were made in the delay estimation model with respect to the 1985 version of the manual. Using the 1994 HCM version of the equation, traffic engineers were unable to: a) discriminate between fixed time and actuated control operation; b) evaluate oversaturated intersections or variable-length analysis periods; c) evaluate intersections using variable demand profiles on the intersection approaches; d) consider the filtering and metering effects of upstream signals; and e) fully consider the effects of progression on delay (Troutbeck and Kittelson, 1998).

Prevedouros and Koga (1996) compared the 1985 and 1994 delay models using field data. In another research project, Akcelik (1996) extended the 1994 HCM delay progression factor to account for the prediction of queue length, queue clearance time, proportion of stopped vehicles in a queue, and queue move-up rate. Fambro and Roupail (1997) proposed a generalized delay

model that corrected some of the problems found in the 1994 HCM model and that is now the delay model found in the HCM 2000.

In the HCM 2000, the average delay per vehicle for a lane group is given by Equations 1 to 4 (TRB, 2000).

$$d = d_1 \cdot f_{PF} + d_2 + d_3 \cdot f_r \quad (1)$$

with:

$$d_1 = 0.5C \frac{\left(1 - \frac{g}{C}\right)^2}{\left(1 - \min(X, 1.0) \cdot \frac{C}{g}\right)} \quad (2)$$

$$d_2 = 900T \left[(X-1) + \sqrt{(X-1)^2 + \frac{8kIX}{cT}} \right] \quad (3)$$

$$f_{PF} = \frac{(1-P)f_p}{1 - \frac{g}{C}} \quad (4)$$

where:

- d = average overall delay per vehicle (seconds/vehicles),
- d_1 = uniform delay (seconds/vehicles),
- d_2 = incremental, or random, delay (seconds/vehicles),
- d_3 = residual demand delay to account for over-saturation queues that may have existed before the analysis period (seconds/vehicles),
- PF = adjustment factor for the effect of the quality of progression in coordinated systems,
- C = traffic signal cycle time (seconds),
- g = effective green time for lane group (seconds),
- X = volume to capacity ratio of lane group,
- c = capacity of lane group (vehicles/hour),
- K = incremental delay factor dependent on signal controller setting (0.50 for pretimed signals; vary between 0.04 to 0.50 for actuated controllers),
- I = upstream filtering/metering adjustment factor (1.0 for an isolated intersection),
- T = evaluation time (hours),
- P = proportion of vehicles arriving during the green interval,
- fp = progression adjustment factor.

In this delay model the residual delay components d_3 make use of vehicles instead of passenger car units to quantify traffic flows. The period analysis T is reported in hours instead of minutes, but this change is reflected in the use of a different multiplication factor in each term involving

the variable T. In Equation 3, parameters k and I are introduced in the last term of the equation, and this term reduces to 0.5 and 1.0 when the values associated with pre-timed traffic signal control at an isolated intersection are used respectively.

4. RESEARCH METHODOLOGY

The tasks taken in the study involves the selection process for the variables to be considered and the levels at which they will be considered. This selection process is a key step in identification of those variables that have an effect on the control delay. Each of the potential variables that were identified will be submitted to a test using SIDRA and TRANSYT-7F to determine the magnitude of its impact on the control delay.

4.1 Summary of Potential Variables Identified

Table 1 summarizes the variables identified above as candidates for consideration. Through investigating individually, variables that do not have an effect, or whose effects are considered marginal, can be eliminated from the experimental design, reducing the difficulty in determining the source of differences in the data. Also, once the experimental design is reduced to those variables that are known to have an effect, then additional levels for the included variables can be considered as needed.

4.2 Variables Selected for Testing

The variables selected for testing were chosen based on systematic and practical reasons. The variables highlighted in HCM2000 were to be the most referred variables. Table 2 summarizes the variables to be tested and their levels.

Table 1. Summary of Potential Explanatory Variables

No.	Descriptions	Variables
1	From Delay Definitions	Cycle length
		Effective green time
		Volume to capacity ratio
		Duration of analysis period
		Capacity
		Ideal saturation flow rate
2	From Signal Design	Control type
		Intergreen time
		Phasing plan & sequence
		Main vs. side street split
3	From Geometric Conditions	Number of lanes
		Treatment of turning movements
		Exclusive LT and/or RT lanes
		Length of exclusive lane storage bay
4	From Traffic Conditions	Approach length
		Speed limit (approach speed)

Table 2. Summary of Tested Variables and Their Levels

No.	Variables	No. of levels	Levels to be considered
1	Controller type	2	Pretimed and actuated
2	Cycle length	3	60, 120, and 180 seconds
3	Ideal saturation flow rate	2	1500 and 2000 vph
4	Intergreen interval	2	4 and 5 seconds
5	Phasing plan	4	2-phase 4-phase 4-phase with lagging RT 4-phase with leading RT
6	Ratio of main street to side street volumes and splits	3	50-50, 60-40, and 70-30
7	Number of approaches lanes	2	1, 2 and 3 lanes
8	LTOR with exclusive lane	2	Allowed and not allowed
9	Approach length	2	1/3 rd , 2/3 rd and 1.0km
10	Speed limit	3	40, 60, and 80 km/hr

4.3 Methods and Testing of Variables

The first step that was done in testing the variables is to develop the basic test junction because it is important to understand the characteristics of the test junction. The basic test junction is the intersection with basic layout and parameters. Thus, the testing of all potential variables will be done by substituting the test junction variables with the testing variables. Table 3 displays these characteristics.

Each of the potential variables was submitted to a test using TRANSYT-7F and SIDRA to determine the magnitude of its impact on the control delay. The disparities of the control delay values after executing the testing variables will be the main target of the measurement in this study.

The paired samples t-test method was utilized in this test to determine the significant variables that affect the control delay at signalized intersection. The t and sig. 2-tailed parameters also illustrate how far the relationship between variables and control delay.

Table 3. Characteristics of Test Junction.

No.	Parameter	Value
I Controller Properties		
1	Type of controller	Actuated
2	Number of phases	4-phase
3	Minimum Cycle length	30 seconds
4	Maximum Cycle length	240 seconds
5	Clearance interval (yellow + all red)	5 seconds
II Approach Characteristics		
1	Number of approaches	4 (EB, WB, NB and SB)
2	Number of lane per approach	2, 3 (for testing RT and LT)
3	Ideal saturation flow rate	1500 vph
4	Speed limit	40 km/hr
5	Approach length	1/3 rd km

5. RESULTS OF VARIABLE TESTING

The basic test junction as stated in Table 3 is the first input variables with twelve (12) replications of the design v/c ratios and three (3) main to side volume ratios (50-50, 60-40 and 70-30). Then, by substituting each tested variable, the junction new control delay was determined. As an example, Figure 3 and 4 illustrate the average delays of test junction utilizing all tested variables using SIDRA and TRANSYT-7F with main to side street volume ratio 70-30. The paired samples test results which consist of t-value and sig. 2-tailed parameters are given in Table 4 and 5.

Referring to the figures, the obtained control delay from both capacity analysis softwares (SIDRA and TRANSYT-7F) appears to have similar pattern. Several tested variables result in lower average delay whereas some have higher delay compared to basic test junction delays. Amongst the fifteen levels of tested variables, the test junction with 2-phase phasing plan has the lowest average delay. However, the operation of 2-phase at four-legged intersection is inappropriate if the intersection experience high turning volumes and pedestrian volumes. In contrary, the test junction with period of analysis 60 minutes has the highest average delay for relatively high v/c ratios. The additional lane to the junction approach also results in lower average delays.

In terms of difference between average delay from SIDRA and TRANSYT-7F, Figure 5 shows that at relatively low design v/c ratios the delays have only slight differences. Nevertheless, at higher v/c ratios the differences seem tend to be significantly different. This is probably due to the overflow approaches of both utilized capacity software.

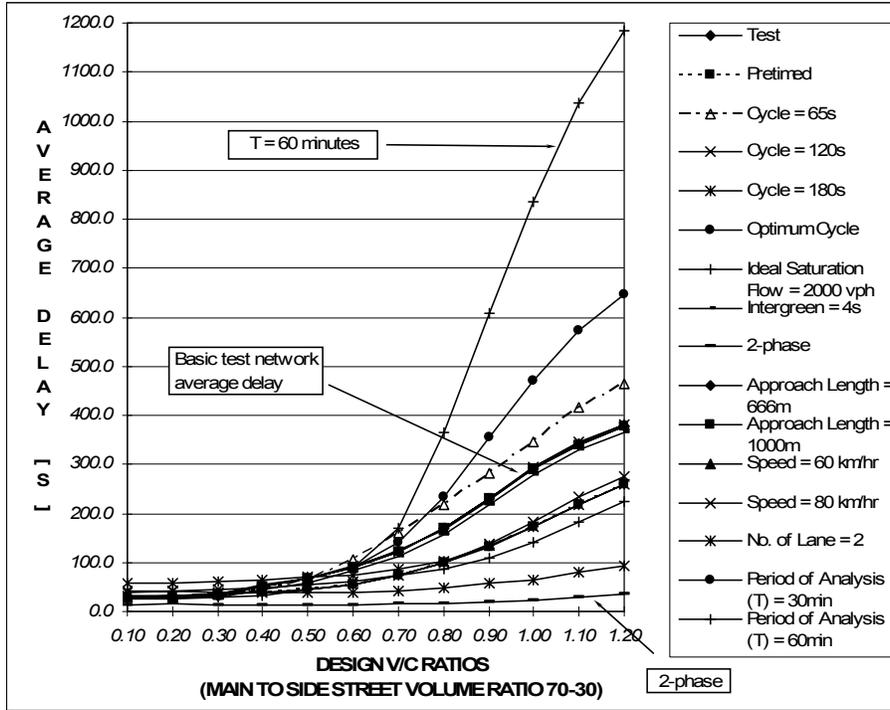


Figure 3. SIDRA Test Junction Average Delays

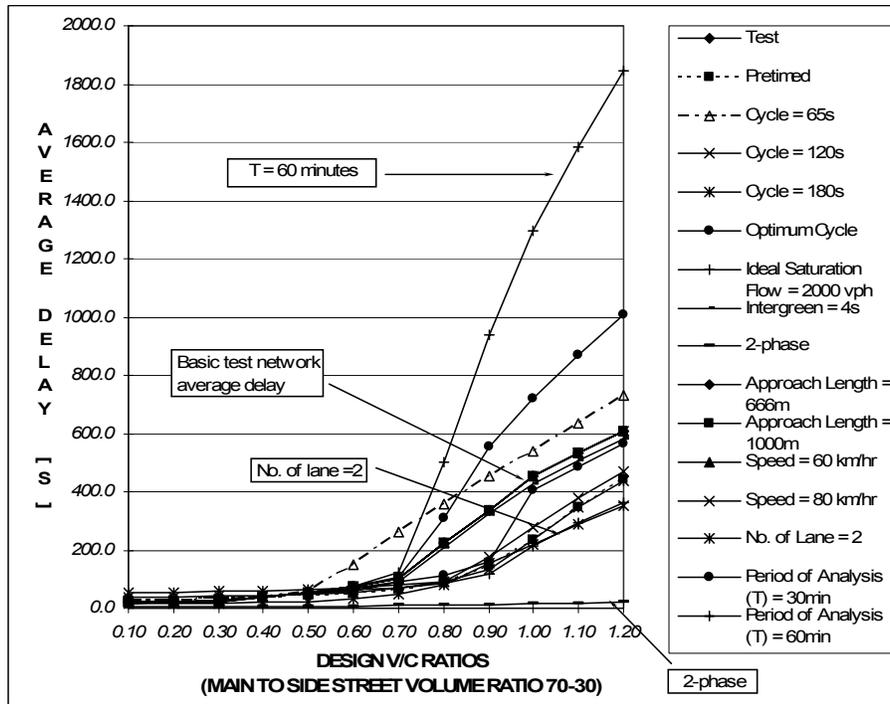


Figure 4. TRANSYT-7F Test Junction Average Delays

Based on statistics analysis results as depicted in Table 4 (SIDRA average delays), it is seen that tested variable approach length do not have t and sig. (2-tailed) values. Referring to the statistics analysis output, this is because the average delays from test junction have difference equal to zero. In other words, there is no difference of average delay from basic test junction and test junction after substituting the approach length to be 666m and 1000m. Moreover, for TRANSYT-7F output (see Table 5), it could be seen that beside approach lengths the substitution of various speed limit also do not change the junction average delays.

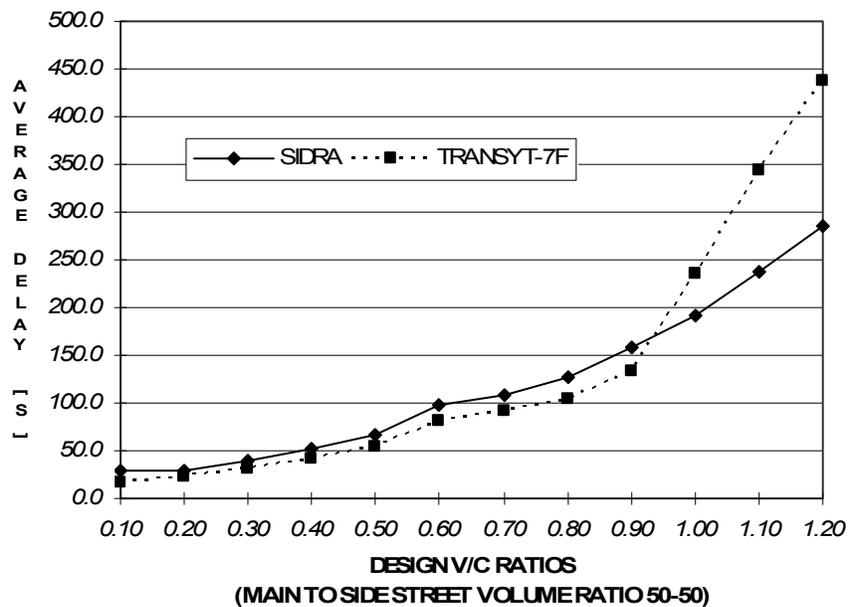


Figure 5. SIDRA and TRANSYT-7F Basic Test Junction Average Delays

Referring to t-value and sig. (2-tailed) parameters obtained from SIDRA analysis, controller type, cycle time, ideal saturation flow, intergreen time, no. of phasing, no. of lane, and left turn on red (LTOR) are significant variables affecting the control delay at signalized intersection. While speed limit and period of analysis effect are dependent on volume ratio of major to side street of the intersection. Approach length and combination of leading or lagging right turn are not significantly affecting the average delay.

On the other hand, referring to TRANSYT-7F analysis results, it is only cycle time, intergreen time, no. of phasing, no. of lane, and left turn on red (LTOR) that significantly affect the control delay at signalized intersection. Meanwhile control type, ideal saturation flow and period of analysis effect are dependent on volume ratio of major to side street. The approach length and speed limit are absolutely not effecting the average delay of the intersection. Table 6 summarizes the significant variables affecting control delay at signalized intersection based on SIDRA and TRANSYT-7F analysis.

Table 4. Paired Samples Test Results of Test Junction Average Delays Using SIDRA

Basic Test Network Vs. Network with Tested Variable	Volume Ratio 50-50		Volume Ratio 60-40		Volume Ratio 70-30	
	t	Sig. (2-tailed)	t	Sig. (2-tailed)	t	Sig. (2-tailed)
Test - Pretimed	5.2219	0.0003	5.3308	0.0002	3.7632	0.0031
Test - Cycle = 65s	-1.5774	0.1430	-1.5610	0.1468	-3.1457	0.0093
Test - Cycle = 120s	1.6837	0.1204	2.9900	0.0123	3.1345	0.0095
Test - Cycle = 180s	0.2432	0.8124	1.3787	0.1954	2.1837	0.0515
Test - Optimum Cycle	5.2219	0.0003	5.3308	0.0002	3.7632	0.0031
Test - Ideal Saturation Flow = 2000 vph	3.5513	0.0045	3.8006	0.0029	3.6131	0.0041
Test - Intergreen = 4s	6.2809	0.0001	7.5015	0.0000	6.8023	0.0000
Test - 2-phase	4.4454	0.0010	4.3061	0.0012	3.8647	0.0026
Test - Approach Length = 666m	N/A	N/A	N/A	N/A	N/A	N/A
Test - Approach Length = 1000m	N/A	N/A	N/A	N/A	N/A	N/A
Test - Speed = 60 km/hr	-11.0659	0.0000	-6.0631	0.0001	-1.3760	0.1962
Test - Speed = 80 km/hr	-15.5640	0.0000	-8.9112	0.0000	-3.2978	0.0071
Test - No. of Lane = 2	3.3849	0.0061	3.3980	0.0059	3.2071	0.0083
Test - Period of Analysis (T) = 30min	-2.0203	0.0684	-2.3537	0.0382	-2.5403	0.0275
Test - Period of Analysis (T) = 60min	-1.9804	0.0732	-2.3327	0.0397	-2.5271	0.0281
Test - 4-phase with lagging RT	-1.3812	0.1946	-1.2254	0.2460	-0.1066	0.9170
Test - 4 phase with leading RT	-1.3812	0.1946	-1.2254	0.2460	-0.1066	0.9170
Test - LTOR is allowed	5.3673	0.0002	5.2238	0.0003	4.4281	0.0010

Table 5. Paired Samples Test Results of Test Junction Average Delays Using TRANSYT-7F

Basic Test Network Vs. Network with Tested Variable	Volume Ratio 50-50		Volume Ratio 60-40		Volume Ratio 70-30	
	t	Sig. (2-tailed)	t	Sig. (2-tailed)	t	Sig. (2-tailed)
Test - Pretimed	0.9376	0.3686	3.4304	0.0056	3.0734	0.0106
Test - Cycle = 65s	-2.5937	0.0250	-2.7911	0.0176	-3.8660	0.0026
Test - Cycle = 120s	-1.9108	0.0824	1.3955	0.1904	2.7574	0.0186
Test - Cycle = 180s	-2.1016	0.0594	1.3268	0.2115	2.2334	0.0472
Test - Optimum Cycle	2.9727	0.0127	2.5716	0.0260	2.4895	0.0301
Test - Ideal Saturation Flow = 2000 vph	2.1383	0.0558	2.6649	0.0220	2.9147	0.0141
Test - Intergreen = 4s	2.9455	0.0133	3.6455	0.0039	3.5543	0.0045
Test - 2-phase	3.2122	0.0083	3.3629	0.0063	3.1859	0.0087
Test - Approach Length = 666m	N/A	N/A	N/A	N/A	N/A	N/A
Test - Approach Length = 1000m	N/A	N/A	N/A	N/A	N/A	N/A
Test - Speed = 60 km/hr	N/A	N/A	N/A	N/A	N/A	N/A
Test - Speed = 80 km/hr	N/A	N/A	N/A	N/A	N/A	N/A
Test - No. of Lane = 2	3.2816	0.0073	3.6644	0.0037	3.4650	0.0053
Test - Period of Analysis (T) = 30min	-1.8587	0.0900	-2.2594	0.0451	-2.4921	0.0299
Test - Period of Analysis (T) = 60min	-1.8241	0.0954	-2.2755	0.0439	-2.4784	0.0307
Test - 4-phase with lagging RT	-1.7775	0.1031	-2.1074	0.0588	0.4403	0.6683
Test - 4 phase with leading RT	-1.9916	0.0718	-2.0075	0.0699	1.1010	0.2944
Test - LTOR is allowed	3.6853	0.0036	3.8434	0.0027	3.5481	0.0046

Moreover, pretimed traffic signal control has lower average delays compare to vehicle actuated traffic signal, particularly at relatively high v/c ratios. In addition, although not all of transport authorities accept the implementation of left turn on red (LTOR) due to safety reasons, however, it appears that this type of turning movement if allowed will significantly reduce the intersection control delay.

Table 6. Significant Variables Affecting Control Delay

No.	Capacity Tool	Significant Variables Affecting Control Delay
1	SIDRA	Control type Cycle time Ideal saturation flow rate Intergreen time Number of phasing Number of lane LTOR
2	TRANSYT-7F	Cycle time Intergreen time Number of phasing Number of lane LTOR

6. CONCLUDING REMARKS

Based on findings of the study, the following remarks maybe considere:

- Amongst the fifteen (15) levels of tested variables which are considered to affect control delay at signalized intersection, only cycle time, intergreen time, no of phasing sequence, no. of lane and LTOR have a significant correlation;
- The variation of approach lengths are absolutely not effecting the average delay of the intersection;
- LTOR type of turning movement if allowed will significantly reduce the intersection control delay;
- Of all input variables for SIDRA and TRANSYT-7F, basically only the variables related to signal timing and v/c ratio would significantly affect the control delay.

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