VERIFICATION OF HCM 2000 DELAY EQUATION ON A IDEAL SIGNALIZED JUNCTION IN BANDUNG (JUNCTION OF ASIA AFRIKA AND TAMBLONG)

Aloysius TJAN
Associate Professor
Civil Engineering School
Parahyangan Catholic University
Jl. Ciumbuleuit 94
Bandung 40141
Indonesia
Fax: +62-22-2033692
E-mail: aloysius@home.unpar.ac.id

Ria SUJOTO
Civil Engineer
Alumnus of Civil Engineering School
Parahyangan Catholic University
Jl. Ciumbuleuit 94
Bandung 40141
Indonesia
Fax: +62-22-2033692
E-mail: aloysius@home.unpar.ac.id

Abstract: One criterion to determined level of service of a junction is average stopped time delay (HCM 1994) or control delay (HCM 2000) to passing vehicles. HCM 2000 provides a method to predict control delay. It is relatively easy to use, however it requires some level of confidence on the accuracy of the predicted control delay before it is applied at a particular intersection.
Stopped time delay is measured directly to the traffic at a closely ideal major urban arterial roads in Bandung, i.e. an intersection of Asia Afrika Street and Tamblong Street. The predicted and measured control delay is compared. In most cases, the measured delay is clustered around the predicted delay. The rasio of measured to predicted delay are between 0.35 to 2.5. As the differences are widely varied, one single adjustment factor for the HCM delay procedure cannot be developed. The results show that predicted delay cannot be used at this particular junction.

Key Words: control delay, stopped time delay, signalized junction, HCM 2000

1. INTRODUCTION

In urban area, there are a lot of intersections. Most of them are heavily traffic and are controlled by traffic signal. Road users, i.e. drivers, almost always find their traverse movement experience some level of delay at intersections. At the earlier stage of technology, traffic signal system is based on pretimed signal. The system is simple, cheap and reliable. The cyclic fluctuation of traffic volume, as peak and off peak volume is accomodated by setting the green time and cycle time for those two traffic conditions. However, some time the length of green time may still not be appropriate to the traffic demand. By an improvement and suuport of the available technology, it is become more common that traffic signal is based on full or semi traffic actuated signal. This system is supposed to minimized delay experienced by drivers through the intersection, as the cycle length and the green time is adjusted to the real traffic demand.

Level of service of an signalized intersection is determined by average stopped time delay. As this parameter is important to evaluate level of service of a signal system, the accuracy of predicted average stopped delay – which is obtained from traffic capacity manual such as HCM – is an absolute necessity. One way to evaluate the accuracy of the manual prediction is to make field measurement. For the same prevailing traffic condition, delay is predicted by manual. The comparison of the results will show whether the manual is applicable to the surveyed intersection, and to its traffic conditions.

2. RESEARCH OBJECTIVES

1. To obtain average stopped delay at an fully actuated signalized intersection as measured directly in the field, and then adjusted the value to control delay.

2. To compare the measured control delay to the delay prediction based on HCM 2000 procedure.

3. To draw a conclusion about applicability of the predicted control delay of HCM at this particular intersection, with all the prevailing traffic condition.

3. THEORETICAL BACKGROUND

Intersection is nodes within an interrupted highway system. The quality of operation, or level of service (LOS), within the interrupted highway system is more difficult than the uninterrupted highway system. In an interrupted highway system, intersection is a kind of bottleneck to the system. Level of service of traffic in an interrupted highway system with a closely spaced intersections is determined by the level of service of traffic of the intersection. Level of service for drivers while traversing the intersection can be expressed as the length time of delay imposed to the driver.

Delay describes the length of time consumed while driver traverses through intersection. There are several different ways to define delay (Roess, et al., 1998), i.e. stopped time delay, approach delay, travel time delay, and time-in-queue delay. Stopped time delay is total time a vehicle is stopped while waiting to pass through the intersection. Approach delay includes stopped time delay as well as the time lost when a vehicle decelarates as to prepare to stop or accelerates as to prepare to reach an expected traffic flow speed after passing the intersection. Travel time delay is the difference between driver's desire total time to traverse the intersection and the actual time required to traverse it. Time-in-queue delay is total time from a vehicle joining an intersection queue to its discharge accross the stop line.

In 1994 HCM defined LOS of an intersection based on stopped time delay. Later in HCM 2000, the parameter is changed to control delay. Control delay is defined as the difference between the time for drivers to traverse through the intersection and the time is required to traverse the same length of section as an uncontrolled condition. LOS criteria for those two HCM versions is shown in Table 1. Based on these LOS criteria, Figure 1 shows the difference between control delay to stopped time delay. The difference will be used as to correlate between these two different delays.

Table 1. LOS Criteria for Signalized Intersection

Level of Service, LOS	AD, Stopped Delay per Vehicle[1)] (sec)	CD, Control Delay per Vehicle[2)] (sec)
A	≤ 5.0	≤ 10
B	5.1-15.0	10-20
C	15.1-25.0	20-35
D	25.1-40.0	35-55
E	40.1-60.0	55-80
F	≥ 60.1	> 80

Note:
[1)] based on HCM 1994
[2)] based on HCM 2000

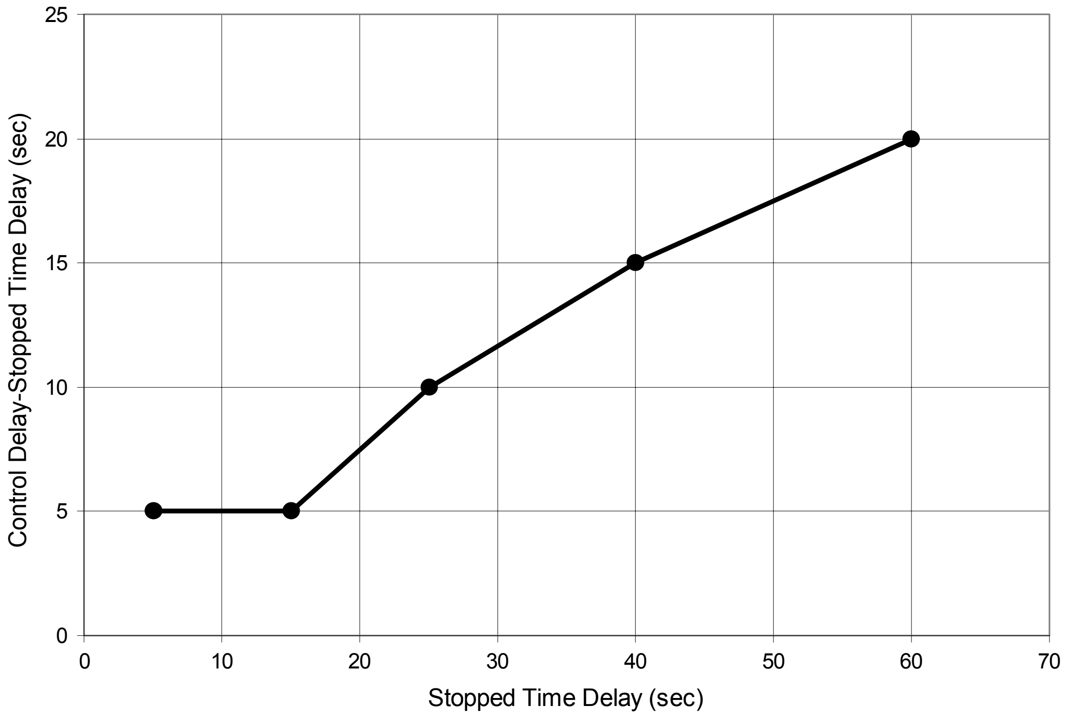

Figure 1. The Difference between Control Delay to Stopped Time Delay Based on LOS Criteria in HCM

4. RESEARCH PROGRAM

4.1. An Ideal Intersection

There are a lot of intersections in Bandung metropolitan area which controlled by traffic signal, most of them are coodinated and fully traffic actuated signal. However, it is very difficult to choose an ideal intersection for this research. Research at an ideal intersection means to minimize the needs of adjustment factors when using the HCM. There is no opposing flow, and there is no any requirement for adjustment factors to incorparate the effect of either protected or opposed flow. One of the most closed to ideal intersection in CBD area, is an intersection at Asia-Afrika Street and Tamblong Street (Figure 2). They are one way four lane streets, crossed perpendicular, no curbed parking allowed, with a properly designed and constructed pedestrian sideways. Side friction due to pedestrian activities is minimum. The surface of the pavement is longitudinally level (grades = 0%), no observed unmotorized vehicles, with majority of the traffic are passanger cars, however there is some small number of buses, and small trucks. In addition to all of these, the traffic volume is adequately high but it never achieves a condition where the traffic is overflow. However, the lane width for each lane is not ideal, as each lane's width is 2.5 m.

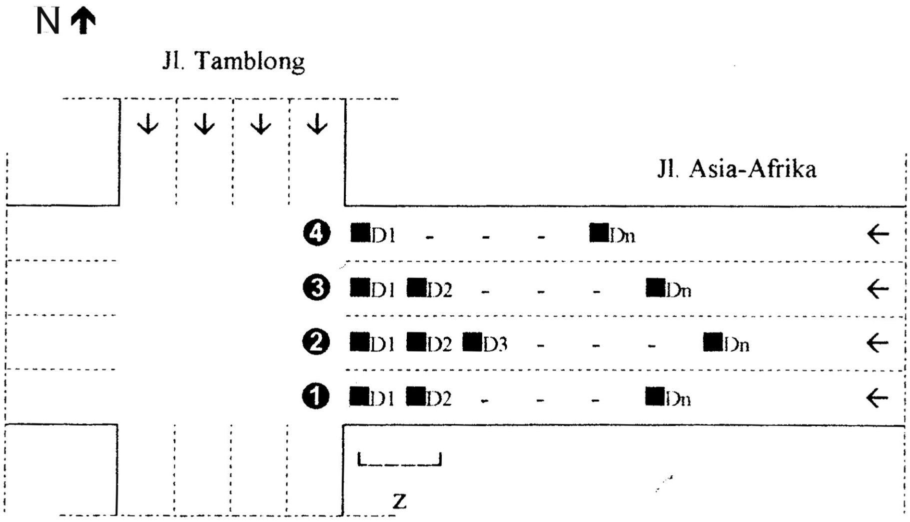

Figure 2. Location of Asia-Afrika and Tamblong Streets Junction

4.2. Stopped Time Delay Measurement and Control Delay

New criteria of delay for defining LOS is understood as a better way to express the effect of an intersection as compared to the basic element of a highway. However, as intersections in Bandung are closedly spaced, it is impossible to obtained the travel time (or travel speed) of vehicle in a basic element as to compare to the segment under the influence of intersection phenomenon. If vehicle speed is measured outside the area of intersection, and it is assumed equal to vehicle speed at basic segment, then control delay equals to approach delay. In this research, the measured delay is the stopped time delay, rather than control delay or approach delay. However, control delay is then calculated from the measured stopped time delay, by applying the difference of the delays as on Figure 1. At the surveyed intersection, vehicles can almost always go through the section with at the most one stop. With this current traffic flow, the stopped time delay is very similar to time-in queue delay.

A video camera is used to record traffic flow. The view of camera covers one approach of interest, i.e. Westbound traffic at Asia-Afrika approach. The view covers from the stop line and all queuing vehicles for all the four lanes at the Asia-Afrika approach. There are four days of survey, i.e. Thursday 11 April, Friday 19 April, Tuesday 23 April, and Wednesday 24 April 2002.

As this junction, especially at the interest approach, traffic is classified as underflow. It is rarely vehicle stop more than once to discharge from the intersection. The method of delay measurement is as the following:

a. At the beginning of measurement, it starts at the red light. The first vehicle in queue is recorded the time it stops and the time it passes the stop line. The time difference is defined as delay for the first vehicle.
b. In the mean time, vehicles are piled up, and extent the queue. It is also recorded delay of the last vehicle that stop in that particular cycle.
c. Number of vehicles in the queue is recorded for that particular cycle.
d. The measurement is for each traffic lane.
e. Stopped time delay for other vehicles in between (the first and the last) is linearly interpolated, as calculated by Eq. 1.

$$D_{ij} = D_{1j} - (i-1)\frac{D_{1j} - D_{Nj}}{N-1} \qquad \text{.............(1)}$$

f. Total delay is the sum of stopped time delay from all vehicles in a particular lane, and cycle as calculated by Eq. 2.

$$TD_j = \sum_{i=1}^{N} D_{ij} \qquad \text{.............(2)}$$

g. The average stopped time delay is total delay divided to total volume based on each cycle counting, as calculated by Eq. 3 for delay on lane j, or Eq. 4 for delay of total lanes.

$$AD_j = \frac{TD_j}{n_j} \qquad \text{.............(3)}$$

$$AD = \frac{\sum_{j=1}^{m} TD_j}{\sum_{j=1}^{m} n_j} \qquad \text{.............(4)}$$

Based on the difference between control delay and stopped time delay, when HCM defined LOS criteria (see Figure 1), the measured stopped time delay can be mathematically correlated to control delay. These control delays is called as measured control delay.

4.3. Predicted Control Delay Based on HCM 2000

Delay based on HCM 2000 is calculated as precribed on the manual. The are four worksheets used, i.e. Input Worksheet, Volume Adjustment and Saturation Flow Rate Worksheet, Capacity and LOS Worksheet, and Supplemental Uniform Delay Worksheet for Left Turn Exclusive Lanes with Protected and Permitted Phases. As traffic movements are in the left hand side, as the opposite of the US, all applicable left and right turn is changed accordingly. Find detail calculation of delay at HCM 2000.

5. RESEARCH RESULTS

5.1. Measured Stopped Time Delay, Measured and Predicted Control Delay

The result of the first day survey is compiled and is shown in Table 2. There are 8 vehicles passing the stop line during the first green time (first cycle), while six of them are vehicles in queue. The first standing vehicle in queue has a stopped delay of 68 sec., and the sixth has stopped for 17 sec. Those two vehicles are vehicles that their stopped delay are recorded. Stopped time delay of other four vehicles are calculated as assumed the vehicles' headway is the same. Stopped time delay of the second vehicle is calculated by using Eq. 1:

$$D_{21}(\text{sec}) = \frac{D_{11} - D_{61}}{6-1} = 68 - (2-1)\frac{68.0-17}{5} = 57.8$$

Delay of other vehicles are shown in Table 1. Lane 1 has a special characteristic it is used as left turn vehicles as well as through vehicles. In addition to that, city bus service uses this lane. For this reason, stopped time delay of Lane 1 is analysed separately. The other three lanes are used as for through vehicles. The total stopped time delay for the first lane as calculated by Eq. 2, TD_1 = 255 sec. Average stopped time delay is total delay divided by total number of vehicles pass the stop line for that particular cycle, as calculated by Eq. 3, AD_1=255/8 = 31.9 sec. For the other lanes, it is used the same procedure. Finally average stopped time delay for a combine lanes (2, 3, dan 4) is 22.3 sec. If different lane characteristics are ignored, average stopped time delay, AD, of this four lanes is 23.3 sec.

Table 2 shows all cycles surveyed on the 11th April 2002. Table 3 shows all stopped time delay obtained from survey. By following the procedure of HCM 2000, the delay for each cycle is also shown in Table 3.

For further analysis, especially the measured stopped time delay is adjusted as Figure 1 to obtain control delay. This control delay is called in this research as measured control delay. For example AD_1 = 31.9 sec. CD_1 = 31.9 + 10 + (31.9 – 25.0)/15*5 = 44.2 sec. The rest of measured control delays are shown in Table 3.

Table 2. Stopped Time Delay Surveyed on 11 April 2002 11:06-11:19 am

Cycle	Lane	Total Veh. Discharge	Total Veh. in Queue	Stopped Time Delay of Vehicle in Queue (sec)																					
				1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th	14th	15th	16th	17th	18th	19th	Total	Avarage	All Lanes
1	1	8	6	68	57.8	47.6	37.4	27.2	17.0	x	x	x	x	x	x	x	x	x	x	x	x	x	255	31.9	23.3
	2	25	16	67	63.2	59.4	55.6	51.8	48.0	44.2	40.4	36.6	32.8	29.0	25.2	21.4	17.6	13.8	10.0	x	x	x	616	22.3	
	3	21	10	68	61.6	55.1	48.7	42.2	35.8	29.3	22.9	16.4	10.0	x	x	x	x	x	x	x	x	x	390		
	4	17	11	68	61.6	55.2	48.8	42.4	36.0	29.6	23.2	16.8	10.4	4.0	x	x	x	x	x	x	x	x	396		
2	1	13	9	66	58.4	50.8	43.1	35.5	27.9	20.3	12.6	5.0	x	x	x	x	x	x	x	x	x	x	320	24.6	24.3
	2	21	15	66	62.4	58.7	55.1	51.4	47.8	44.1	40.5	36.9	33.2	29.6	25.9	22.3	18.6	15.0	x	x	x	x	608	24.3	
	3	23	14	67	62.2	57.5	52.7	47.9	43.2	38.4	33.6	28.8	24.1	19.3	14.5	9.8	5.0	x	x	x	x	x	504		
	4	16	9	66	59.1	52.3	45.4	38.5	31.6	24.8	17.9	11.0	x	x	x	x	x	x	x	x	x	x	347		
3	1	8	8	64	57.4	50.9	44.3	37.7	31.1	24.6	18.0	x	x	x	x	x	x	x	x	x	x	x	328	41.0	25.2
	2	15	9	66	58.3	50.5	42.8	35.0	27.3	19.5	11.8	4.0	x	x	x	x	x	x	x	x	x	x	315	22.9	
	3	24	13	65	60.6	56.2	51.8	47.3	42.9	38.5	34.1	29.7	25.3	20.8	16.4	12.0	x	x	x	x	x	x	501		
	4	17	13	65	60.2	55.3	50.5	45.7	40.8	36.0	31.2	26.3	21.5	16.7	11.8	7.0	x	x	x	x	x	x	468		
4	1	8	8	69	63.1	57.3	51.4	45.6	39.7	33.9	28.0	x	x	x	x	x	x	x	x	x	x	x	388	48.5	30.3
	2	22	15	70	65.5	61.0	56.5	52.0	47.5	43.0	38.5	34.0	29.5	25.0	20.5	16.0	11.5	7.0	x	x	x	x	578	28.0	
	3	23	16	69	64.9	60.7	56.6	52.5	48.3	44.2	40.1	35.9	31.8	27.7	23.5	19.4	15.3	11.1	7.0	x	x	x	608		
	4	18	15	69	64.6	60.3	55.9	51.6	47.2	42.9	38.5	34.1	29.8	25.4	21.1	16.7	12.4	8.0	x	x	x	x	578		
5	1	14	12	63	58.6	54.3	49.9	45.5	41.2	36.8	32.5	28.1	23.7	19.4	15.0	x	x	x	x	x	x	x	468	33.4	30.6
	2	19	14	69	64.8	60.5	56.3	52.1	47.8	43.6	39.4	35.2	30.9	26.7	22.5	18.2	14.0	x	x	x	x	x	581	29.9	
	3	21	18	64	60.8	57.6	54.5	51.3	48.1	44.9	41.8	38.6	35.4	32.2	29.1	25.9	22.7	19.5	16.4	13.2	10.0	x	666		
	4	18	12	68	63.0	58.0	53.0	48.0	43.0	38.0	33.0	28.0	23.0	18.0	13.0	x	x	x	x	x	x	x	486		
6	1	10	10	69	63.0	57.0	51.0	45.0	39.0	33.0	27.0	21.0	15.0	x	x	x	x	x	x	x	x	x	420	42.0	35.7
	2	15	13	66	62.4	58.8	55.3	51.7	48.1	44.5	40.9	37.3	33.8	30.2	26.6	23.0	x	x	x	x	x	x	579	34.6	
	3	22	19	65	62.6	60.2	57.8	55.4	53.1	50.7	48.3	45.9	43.5	41.1	38.7	36.3	33.9	31.6	29.2	26.8	24.4	22.0	827		
	4	20	16	66	62.0	58.0	54.0	50.0	46.0	42.0	38.0	34.0	30.0	26.0	22.0	18.0	14.0	10.0	x	x	x	x	570		

Table 3. Surveyed Delay and Predicted Delay

Date of Survey	i th Cycle	v/C for Lane			Peds (pers on/hr)	Measured Stopped Time Delay for Lane (sec)			Measured Control Delay for lane(sec)			Predicted Control Delay-HCM for Lane (sec)		
		1	2,3,4	All		1	2,3,4	All	1	2,3,4	All	1	2,3,4	All
Th-11 April 2002 (11:06-11:19 am)	1	0.4	0.9	0.8	130	31.9	22.3	23.3	44.2	30.9	32.5	31.9	22.3	23.3
	2	0.6	0.8	0.8	137	24.6	24.3	24.3	34.4	34.0	34.0	24.6	24.3	24.3
	3	0.4	0.8	0.7	141	41.0	22.9	25.2	56.3	31.9	35.2	41.0	22.9	25.2
	4	0.4	0.9	0.8	135	48.5	28.0	30.3	65.6	39.0	42.6	48.5	28.0	30.3
	5	0.7	0.9	0.9	115	33.4	29.9	30.6	46.2	41.5	42.4	33.4	29.9	30.6
	6	0.5	0.9	0.8	117	42.0	34.2	35.3	57.5	47.8	49.6	42.0	34.2	35.3
Fr-19 April 2002 (11:28-11:42 am)	1	0.4	0.8	0.7	112	22.1	23.2	23.1	31.2	32.4	32.2	22.1	23.2	23.1
	2	0.4	0.9	0.8	128	46.0	34.4	35.5	62.5	47.5	49.4	46.0	34.4	35.5
	3	0.5	0.8	0.7	118	25.4	26.5	26.3	35.5	36.9	36.7	25.4	26.5	26.3
	4	0.3	0.7	0.6	136	28.3	22.3	23.0	39.4	31.0	32.0	28.3	22.3	23.0
	5	0.5	0.9	0.8	122	20.3	23.6	23.2	28.0	32.9	32.2	20.3	23.6	23.2
	6	0.7	0.9	0.9	130	30.3	29.9	30.0	42.1	41.6	41.7	30.3	29.9	30.0
Tue-23 April 2002 (11:21-11:35 am)	1	0.2	0.9	0.7	128	16.8	29.5	28.6	24.1	41.0	39.8	16.8	29.5	28.6
	2	0.3	0.8	0.7	120	34.5	21.1	22.6	47.7	29.2	31.4	34.5	21.1	22.6
	3	0.4	0.7	0.6	125	28.8	28.7	28.7	40.0	39.9	39.9	28.8	28.7	28.7
	4	0.2	0.9	0.7	125	43.5	24.9	26.0	59.4	34.8	36.3	43.5	24.9	26.0
	5	0.6	0.8	0.8	119	23.8	23.8	23.8	33.4	33.2	33.2	23.8	23.8	23.8
	6	0.6	1.0	0.9	123	24.4	27.1	26.7	34.1	37.8	37.3	24.4	27.1	26.7
Wed-24 April 2002 (10:42-10:56 am)	1	0.4	0.8	0.7	138	33.3	20.9	22.4	46.0	28.9	31.0	33.3	20.9	22.4
	2	0.4	1.1	0.9	123	17.3	17.9	17.8	24.8	24.3	24.2	17.3	17.9	17.8
	3	0.4	0.9	0.8	117	26.8	25.2	25.4	37.4	35.2	35.5	26.8	25.2	25.4
	4	0.5	1.0	0.9	116	29.2	30.5	30.3	40.6	42.4	42.1	29.2	30.5	30.3
	5	0.3	0.8	0.7	112	35.0	28.2	28.8	48.3	39.2	40.0	35.0	28.2	28.8
	6	0.4	0.8	0.7	135	13.4	16.3	16.0	18.4	21.9	21.5	13.4	16.3	16.0
	7	0.5	0.8	0.7	126	10.5	8.5	8.8	15.5	13.5	13.8	10.5	8.5	8.8

5.2. Adjustment Factor of Control Delay

At lane 1, measured control delay varies as compared to the predicted control delay. The results is shown in Figure 3. Measured control delay is randomly spread over the predicted control delay, some of them are smaller and the others are bigger. In order to obtain adjustment factor for the predicted control delay to match the measured control delay, a rasio of measured to predicted control delay (y) is expressed as a function of predicted control delay (x). This relationship is shown in Figure 4. A linear regression analysis to these data shows that y = -0.0657x + 3.3329; R^2 = 0.284. Statistically, there is a weak relationship between the control delay and the rasio. It is suggested that there is no single adjustment factor available to traffic flow in Lane 1, in order to get the predicted control delay matched the measured control delay.

For the case lanes 2, 3, and 4 are combined, the results are shown on Figure 5 and 6. For this case, the adjustment factor is also not available, as regression analysis gives relationship as y = -0.0166x + 1.5519; R^2 = 0.248. When all lanes are combined, regression analysis suggests no adjustment factor as well. The regression is y = -0.0191x + 1.6772; R^2 = 0.262. Visual data are shown on Figure 7 and 8.

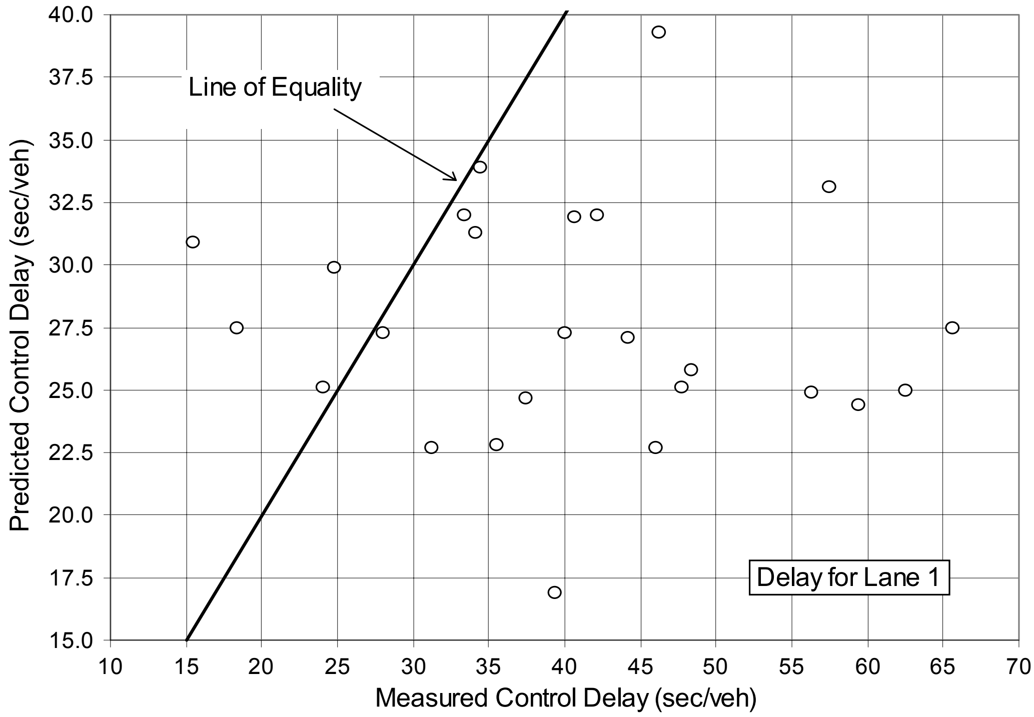

Figure 3. Comparison of Measured to the Predicted Control Delay for Lane 1

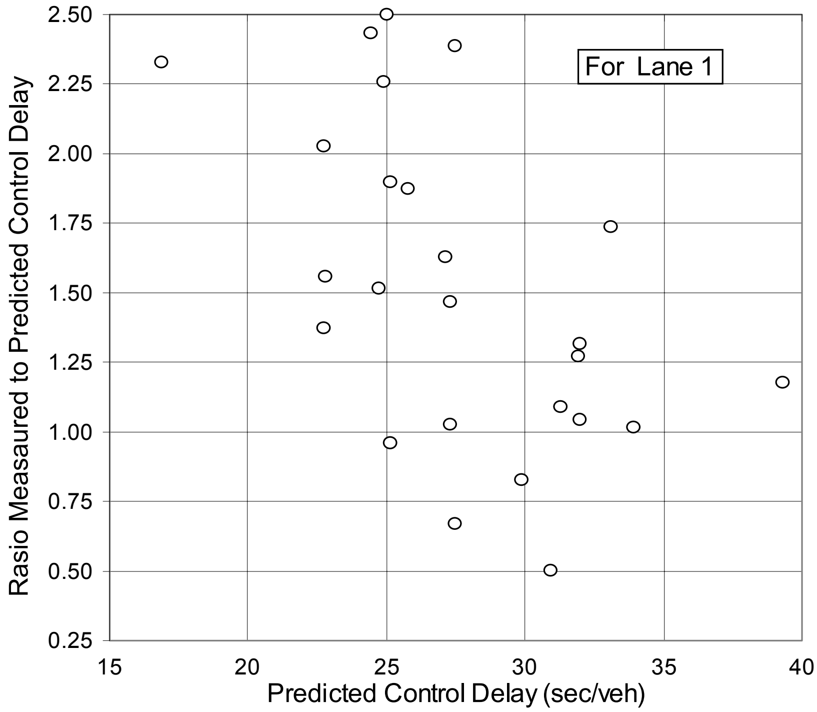

Figure 4. Rasio of Measured to Predicted Control Delay for Case Lane 1

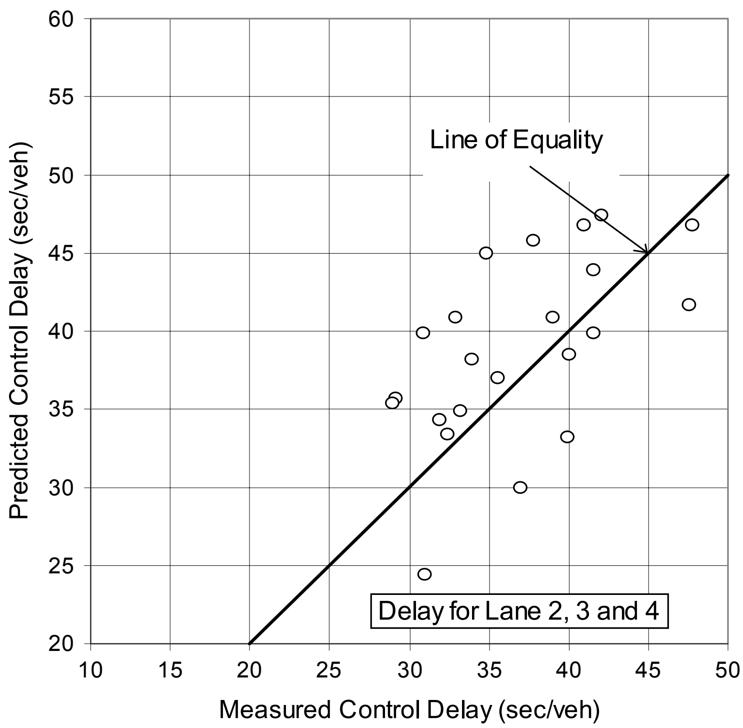

Figure 5. Comparison of Measured to the Predicted Control Delay for a Combined Lanes 2-3 and 4

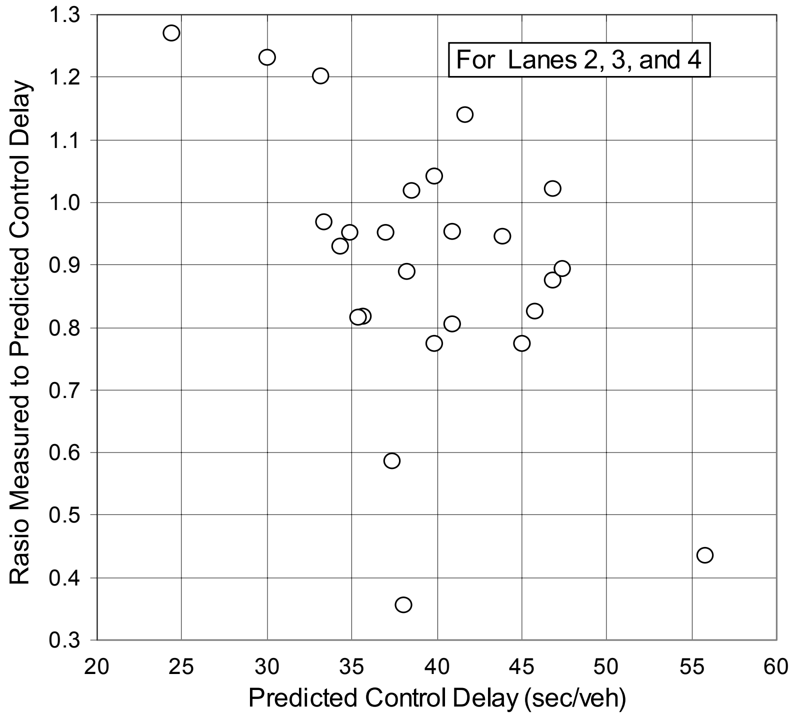

Figure 6. Rasio of Measured to Predicted Control Delay for Case Lanes 2-3-4

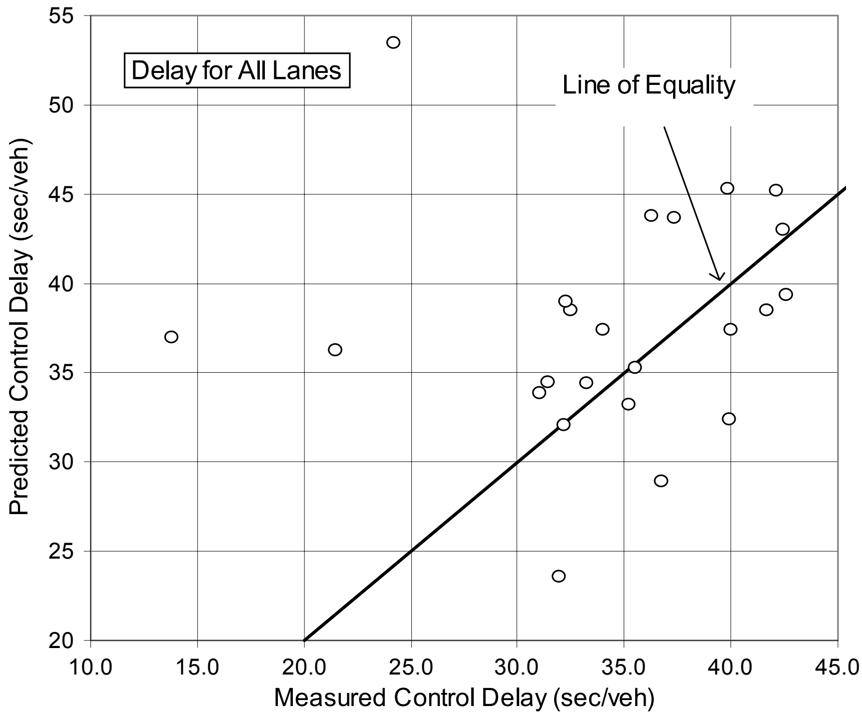

Figure 7. Comparison of Measured to the Predicted Control Delay for a Combined All Lanes

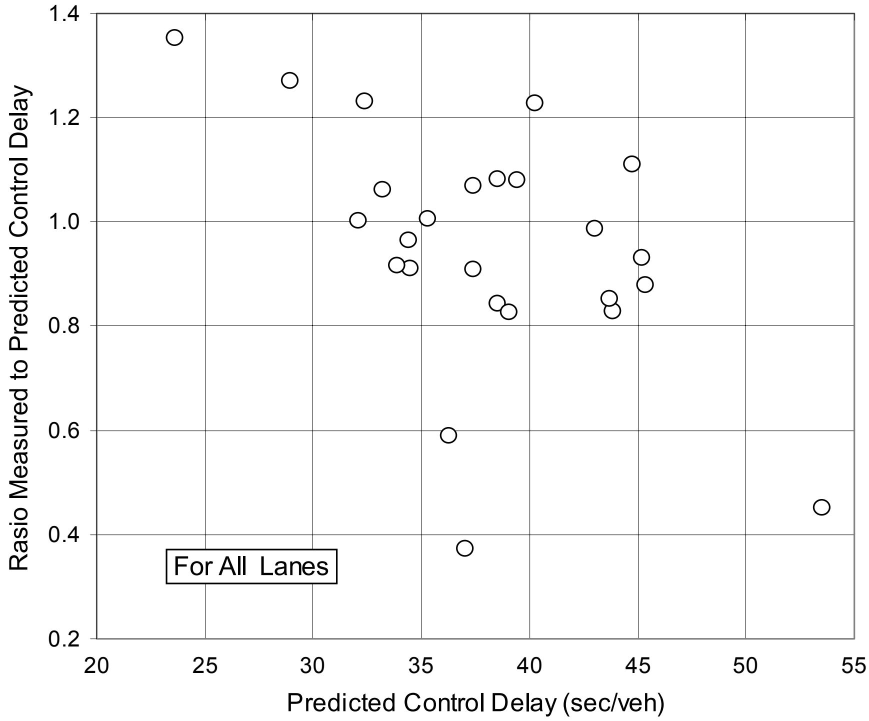

Figure 8. Rasio of Measured to Predicted Control Delay for Case All Lanes

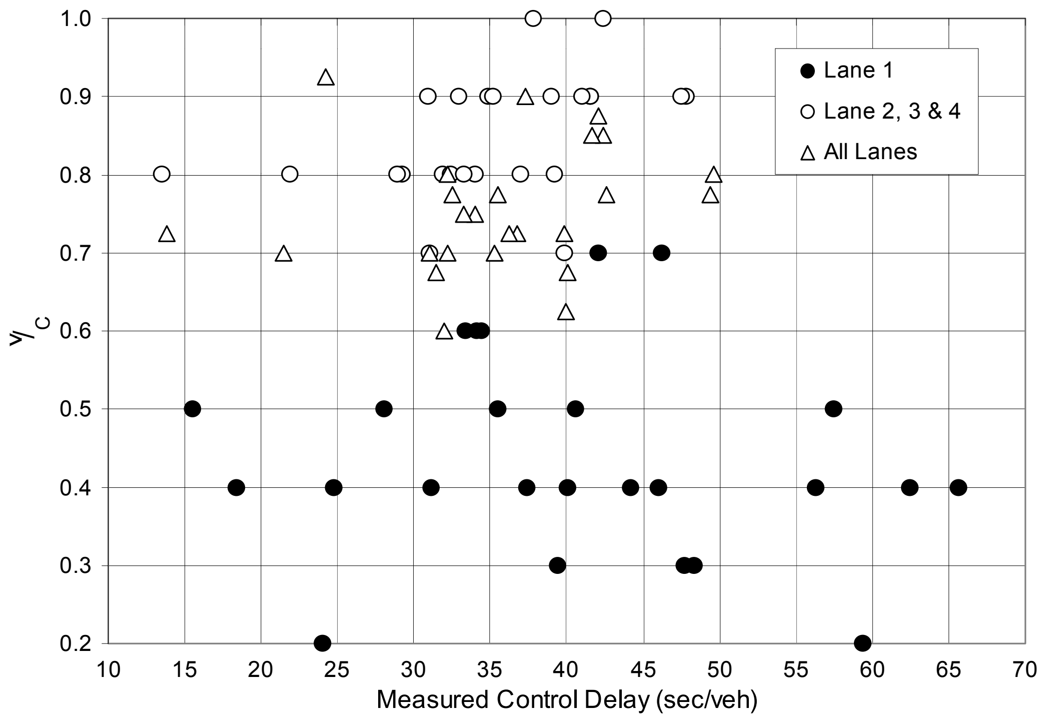

Figure 9. The Effect of Degree of Saturation to Surveyed Stopped Time Delay

5.3. The Effect of Degree of Saturation to Stopped Time Delay

As the data is available, Figure 9 shows data points of measured control delay that occur at a particular degree of saturation. In no case (lane 1, combined of lanes 2-3-4, or combined of all lanes), the measured control delay is a function of degree of saturation. At this particular intersection and traffic prevailing conditions, it suggests that stopped time delay is due to something else rather than degree of saturation.

6. CONCLUSIONS

a. Lanes with through traffic, the measured control delay is spread over the predicted control delay. It can be either smaller or bigger than the predicted control delay.
b. For lane where it is being used for through or left turn traffic, the spread of measured control delay is much greater.
c. For a combined lanes of through and left turn traffic flow, the spread of measured control delay is about the same as through traffic.
d. In any case, there is no single adjustment factor available to be applied to control delay, in order to get a correct control delay.
e. The value of predicted control delay from HCM 2000 is not suggested to be used as control delay of a mix (left and through) traffic lane, while for through traffic, the predicted control delay should be used with cautious.
f. Degree of saturation at this particular junction shows no direct effect to the stopped time delay.

NOTATIONS

AD	average stopped time delay for all lanes
AD_j	average stopped time delay for particular lane
CD	control delay
D_{ij}	stopped time delay of i-th vehicle in queue on lane j (sec). The first vehicle in queue is the closest vehicle to the stop line.
N	number of vehicle standing in queue for a particular cycle in lane j
n_j	total number of vehicles discharged for a particular cycle through lane j
TD_j	total delay on lane j as a summation of stopped time delay within that lane for a particular lane
x	control delay
y	rasio of stopped time delay to control delay

REFERENCES

Roess, R.P., W.R. McShane, and E.S. Prassas (1998) **Traffic Engineering**. 2nd Edition. Prentice Hall. Upper Saddle River, NJ.
HCM 1994 (1994) Highway Capacity Manual. **Special Report 209**. 3rd Edition. Transportation Research Board. National Research Council. Washington, DC.
HCM 2000 (2000) **Highway Capacity Manual**. Transportation Research Board. National Research Council. Washington, DC.