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RESEARCH PAPER

Estimation of Time-Dependent Delay Models at Actuated Traffic Signals in Duhok City

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A B S T R A C T:

Duhok City, developed rapidly in recent years, leading to an increase in the traffic volume on its streets which are not sufficient for this increase resulting in traffic congestion. Therefore, this paper studied the delay as an important measure of effectiveness at traffic signals. The delay was measured and predicted (for saturated and under saturated conditions) to help in solving some underestimation problems by using the transportation system management (TSM) techniques. Five signalized intersections on Barzani major street in Duhok city was chosen. Vehicle delay was measured in these intersections directly from field, then it was calculated using the time-dependent equations recommended by three different official manuals, Highway Capacity Manual (HCM2000), Canadian Capacity Guide (ITE1995) and Australian Capacity Guide (ARRB1995). After that comparisons between the results of each theoretical method and the field result was made. Finally, the regression analysis technique was used to establish different relationships between the delay data obtained from the field and each of the theoretical methods to find the best applicable model to predict the vehicle delay at signalized intersections in Duhok City. It was proved that the logarithmic relationship between field and theoretical results obtained from the Canadian Capacity Guide is the best

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1.INTRODUCTION :

Vehicular delay at signalized intersections in Duhok City-Kurdistan-Iraq increases the total travel time through an urban road network, resulting in a reduction in the speed, increase in environmental pollutions and cost-effectiveness of the transportation system.

The scope of control of signalized intersections can be grouped into three categories:

1. Individual (isolated) intersection control;
2. Arterial (corridor) control; and
3. Network (down town) control.

The Individual (Isolated) Intersection Control is a single traffic signal operates without affecting the operation of other traffic signals and may be controlled as:

1 - pre-timed (fixed time)
2 - actuated (partial or full), or
3 - traffic responsive mode

Vehicle-Actuated Signals require actuation by a vehicle on one or more approaches in order for certain phases or traffic movements to be serviced. They are equipped with detectors and the necessary

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control logic to respond to the demands placed on them. Vehicle-actuated control uses information on current demands and operations, obtained from detectors within the intersection, to alter one or more aspects of the signal timing on a cycle-by-cycle basis. Timing of the signals is controlled by traffic demand. Actuated controllers may be programmed to accommodate variable green times for each phase and variable cycle length, caused by variable green times. Such variability allows the signal to allocate green time based on current demands and operations.

Delay in the Highway Capacity Manual (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 optimize the signal system to perform at a minimum delay".

Numerous equations have been developed for the estimation of delay. The use of steady state models during peak periods can introduce significant errors therefore, time dependent models are required for such periods.

The most frequently used manuals and guides for the estimation of vehicular delay using time dependent models are the American Highway Capacity Manual (HCM2000), the 1995 Australian Capacity Guide, and the 1995 Canadian Capacity Guide. The equations of these manuals and guides are a function of multiple input parameters arising from geometry, traffic and signal conditions.

Most signal intersection delay models fall into two categories, steady-state models and deterministic queuing models. the former are usually considered useful only for predicting delays at intersections with light loads, while the later do well only in the analysis of heavily loaded intersections where the volume is greater than the capacity (i.e. v/c >1). These models ignore the effect of random arrivals on queue lengths when intersections are slightly saturated. Because their assumptions are based on different v/c values, these two types of models are incompatible. However, when the load is heavy but v/c is still less than one, some good models are expected to produce excellent estimates.

The most frequently used manuals for the design of signalized intersection in developed countries assumes homogeneous and lane based traffic for analysis, which exists in those countries. But traffic flow in countries like Iraq consists of different classes of vehicles having no lane disciplined. There are no proper guidelines available to estimate saturation flow for non-lane based traffic conditions. The saturation flow has a direct great effect on the value of the capacity which has direct influence on the time dependent term (d_2) in delay equation in all theoretical methods that used in this research.

In 1958 Webster, (Webster F. V., 1958.) developed one of the fore most delay equations assuming practical distributions like Poisson (random) arrivals with uniform discharge headways. Webster introduced three terms to the delay equation: The first represents the delay when traffic is considered to arrive at a uniform rate, the second is a correction to the random nature of the arrivals and the third is empirical correction term with value of 5 to 15 percent of delay in most cases. But under some conditions Webster model may not be the right one (Gandhi Ganem Sofia, 1998).

In 1968 Miller developed an equation for delay estimation at signalized intersections. The guide developed by Miller became the basis of signalized intersection design in Australia during the 1960s and throughout the 1970s (Miller, A. S., 1968).

Time-dependent queuing models for oversaturated conditions started to interest the research field in 1977 from the work of Catling, who adopted equations of classical queuing theory for over saturated traffic conditions. He developed comprehensive queue length and delay formulas that may be used to represent the situation at the oversaturated intersections (Catling, 1977).

In 1978 Reilly, R and Gardner, C., used time- lapse photography to measure vehicle journey time from the moment the vehicle enters the approach to the moment of passing over the stop line. Data about the percent of vehicles stopped at 10 intersections were collected. The journey time was divided into 3 parts; the first part was the approach delay. This delay was defined as the time spent while vehicle decelerate to join the queue. The authors recommended that the point sample, stopped delay may be used for field measurement of delay (Reilly R. and Gardner C., 1977).

In 1979 Kimber and Hollis, developed a sophisticated time-dependent model for the prediction of vehicle delay. This model was found to provide reasonably accurate results over a wide range of operating conditions (Kimber, RM and Erica M. Hollis, 1979).

In 1985 James M. S. and Herbert S. L. analyzed delays at signalized intersections assuming “platoon” arrival flow. They estimated the average travel time delay using graphic analysis of vehicle platoon arrivals. The delay obtained was compared with delay obtained by three conventional methods: The Webster method, May’s continuum model method and the 1985 HCM method. The three conventional produced same results for v/c up to 0.75. For v/c from 0.75 to 1.0, Webster and HCM methods resulted in high values of delay than May’s method (James M.S. and Herbert S. L., 1985).

In 1988 Akçelik, in Australia, further developed the delay equation by utilizing the coordinate transformation technique to obtain a time-dependent equation that is applicable to signalized intersections. A generalized delay equation was developed that embraces the Australian and Canadian delay formulas (Akcelik, R., 1988).

In 1990 Olszewski, computed delay for a pre-timed signal when the arrival rate is non-uniform by utilizing the step arrival rate model. A significant finding of his research was that the progression affects the uniform delay term and not the overflow delay term in the HCM delay equation (Olszewski, P., 1990).

In 2000 in USA the Highway Capacity Manual (HCM) time-dependent delay equation is utilized in delay computations. The HCM 2000 propounds that delay be computed using the equations (1) to (3):

$$d = d_1 PF + d_2 + d_3 \qquad (1)$$

$$d_1 = \left(\frac{C}{2}\right) * \left\{\frac{(1-g/C)^2}{1-[min(1,X)*\frac{g}{C}]}\right. \qquad (2)$$

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

Where:

d = Control delay (s/veh),
d_1= Uniform delay component (s/veh),
PF = Progression adjustment factor,
d_2= Incremental delay component (s/veh),
d_3= Delay due to pre-existing queue (s/veh),
T = Analysis period (h),
X = Volume to capacity ratio for lane group (v/c),
C = Cycle length (sec),
k = Incremental delay factor for actuated controller settings; 0.50 for pre-timed controllers,
I = Upstream filtering/metering adjustment factor; 1.0 for individual intersection analyses,
c = Capacity of lane group (veh/h), and
g = Effective green tme for lane group (sec).

In 1995 the Australian Capacity Guide developed a time-dependent delay equation for the estimation of delay at traffic signals using equations (4) to (6):

$$d = d_1 + d_2 \qquad (4)$$

$$d_1 = \frac{0.5*C\,(1-g/C)^2}{1-[min(1,X)*\frac{g}{C}]} \qquad (5)$$

$$d_2 = 900.T.\left[(x-1) + \sqrt{(x-1)^2 + \frac{m.(x-x_0)}{c.T}}\right] \qquad (6)$$

Where:

$X_0 = 0.67 + \left(\frac{sg}{600}\right)$;
m =12 by assuming the uniform arrivals case;
T = analysis period, h;
x = degree of saturation, v/c ;
c = capacity, veh/h;
s = saturation flow rate, veh/sg, (vehs per second of green); and
g = effective green time, sec.
C = cycle length (sec).

In 1995 the Canadian Capacity Guide developed a time-dependent delay equation for estimation of delay at traffic signals using equations (7) to (9):

$$d= d_1 .\, k_f + d_2 \quad (7)$$

$$d_1 = \frac{0.5*C\,(1-g/C)^2}{1-[min(1,X)*\frac{g}{C}]} \quad (8)$$

$$d_2 = 15.T.\left[(x-1)+\sqrt{(x-1)^2+\frac{240.x}{c.T}}\right] \quad (9)$$

Where:

T = analysis period, h;
x = degree of saturation, v/c ;
c = capacity, veh/h;
k_f = progression adjustment factor;
g = effective green time, sec; and
C = cycle length (sec).

In 2006 Francesco Viti, in Delft city in Netherland, describes the progress made in the modelling of queues and delays at traffic signals and discusses the limitations of these models in describing the stochastic and dynamic behavior of these service systems. Starting from a well-established theory in operations research, the renewal theory of Markov Chains, which has been applied in the past to investigate and analyze the dynamic behavior of overflow queues at fixed time signals, he developed and integrated within this modelling framework a probabilistic formulation also for the queue behavior within each cycle. This model enables one to deal with queues using a continuous time approach, and it describes the effect of the variability of the arrivals in the service time process, which reflects into the variability of the delay caused by the signal operation. The flexibility of this modeling framework allows its application in more sophisticated service systems (Francesco Viti, 2006).

In 2006 Fang Zhao and Zhen Ding in Florida, developed intersection delay models to estimate highway and transit travel times. The objectives to be achieved in this research include; evaluating the appropriateness of different traffic engineering software for the purpose of determining intersection delays under different combinations of traffic conditions and intersection geometry, and developing models that are capable of predicting intersection delays based on traffic conditions and simplified intersection geometry (Frang Zhao, and Zhen Ding, 2006).

It can be drawn from the reviewed literature, that the delay is affected by a number of physical and operational features of the intersection. The intersection delay may be related to other factors seems to be site specific, or at least local in nature. The driver behavior is one of the mentioned above factors. The methods currently used in calculation of delay at intersection either ignore the way in which delays vary with time (which is useless in saturated conditions) or cope with variation using mathematical applications of common sense than mathematical models of traffic signal systems. To obtain accurate results better information about traffic patterns is needed.

The main objective of this study is to compute the time-dependent delay at actuated traffic signals by using theoretical models given in different official transportation manuals and guides and also computing delay by field observation methods for different time periods, and then make comparisons between the result of each theoretical method and the result of the field method.

Finally, the most practical models were chosen for the estimation of time-dependent delay at actuated traffic signals in Duhok city using regression analysis technique.

2. METHODOLOGY

To achieve the objective of this study a methodology includes the methods and equations which had been used to obtain the necessary elements for the data analysis was followed.

2.1 Passenger Car Equivalent (PCE)

HCM 2000 tables had been used to find Passenger Car Equivalents for trucks and buses as it reports PCEs according to percent and length of grade and proportion of heavy vehicles.

The terrain in the studied segments is a combination of horizontal and vertical alignment permits heavy vehicles to maintain approximately the same speed as passenger cars. Therefore, the terrain is assumed to be level terrain, and the value of PCE was selected as 1.5 for trucks and buses.

2.2 Link Speed

Moving vehicle method had been used to obtain average link travel speeds between intersections on the arterial streets. Also spot speed study at selected location in the mid-links were used to determine the Mid-Link spot speed using the stopwatch method, minimum necessary sample size of vehicles was usually obtained.

2.3 Traffic Volume

Traffic volume studies was conducted to determine the number, movements, and classification of roadway vehicles at study locations using Moving vehicle method to obtain link volume on arterial streets and video recording technique for the determination of intersection volumes at peak hours dividing the period of data collection into 5 minute intervals to obtain PHF.

2.4 Saturation Flow Rate

HCM2000 method was used for the determination of saturation flow rate which is used for the computation of both cycle time, capacity and traffic control delay for the signalized intersections.

2.5 Signal Timing

For the computation of delay at actuated traffic signals, the actuated signal timing was designed for each intersection. The average cycle length and effective green recommended by Highway Capacity Manual (HCM2000) was determined and used in this study.

2.6 Intersection Delay Estimations

Measurements of delays, stops, queue length etc. was done using video, and manual observations. Different theoretical and field methods for the estimation of vehicle delay at traffic signals was used.

2.6.1 Theoretical Delay

The HCM 2000, the Australian Capacity Guide (ARR 1995) and the Canadian Capacity Guide (ITE 1995) was used for the estimation of theoretical delay at studied intersections.

2.6.2 Field Delay

The travel time method is the most practical method for the determination of field delay because it accounts for the deceleration and acceleration delay times. In this study the travel time from a point in advance of the intersection to another point in or beyond the intersection was measured using the video recording technique. The travel time had been measured before the vehicle be influenced by presence of intersection and the other point at the place when the vehicle leaves the intersection and will not be influenced by presence of intersection again.

2.6.3 Time-Dependent Expressions for Field Delay

Simple regression analysis technique was used to establish different relationships between the field and the theoretical methods as it is the simplest relationship consists of a straight line.

The goal of using regression analysis is the development of statistical model that can be used to predict the value of the field (actual) delay in this research, based on the value of the theoretical delay. The models were obtained by using Statistical package for the social sciences (SPSS version 18) and Microsoft Office Excel (2007 Edition).

3. STUDY AREA AND DATA COLLECTION

The four important elements that should be considered when observing and collecting traffic data are site selection, measurement location, time of day for observation, and period of observation.

The study area selected for this study is Duhok City-Kurdistan Region-Iraq. The most important and congested arterial street in Duhok city is Barzani Street, therefore five successive intersections on this street was selected for this study as shown in Figures (1) to (6). Data collection was made by choosing different time periods from 7:30 AM to 7:30 PM according to the traffic activity in working days.

Data was collected on intersections and links geometry, approach counts, AM and PM peak hour counts, posted speed on all links and approaches, percent of heavy vehicles, all the data required for field studies of travel time and approach delay, signal timing and phasing data was collected

The manual Method was used to collect the intersection geometry, signal timing, detectors measurements, approach speed and mid link spot speed. The moving vehicle method was used to collect the speed and volume data for the links between the studied intersections, while video camera technique was used to collect classified approach counts (AM and PM peak hour counts), travel time, approach delay and all other data. The video camera data was abstracted using a computer program named EVENT (Al-Neami, A.H.K., 1995).

Figure (1): Google image of Barzani street showing the Five studied intersecions (Directorate of Traffic, Traffic Engineering Department, Duhok City, 2009)

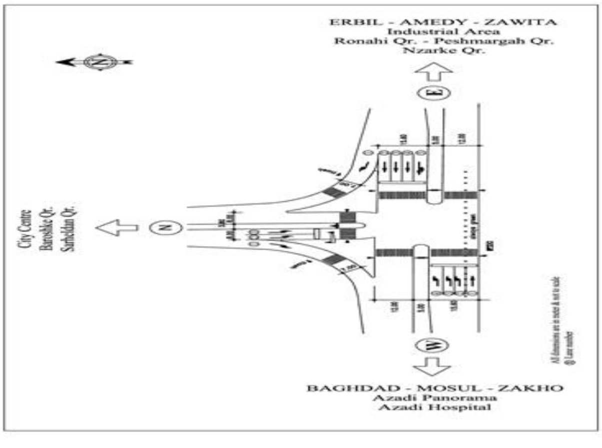

Figure (2): Peshmarga Intersection (P) Plan (Directorate of Traffic, Duhok City, 2009)

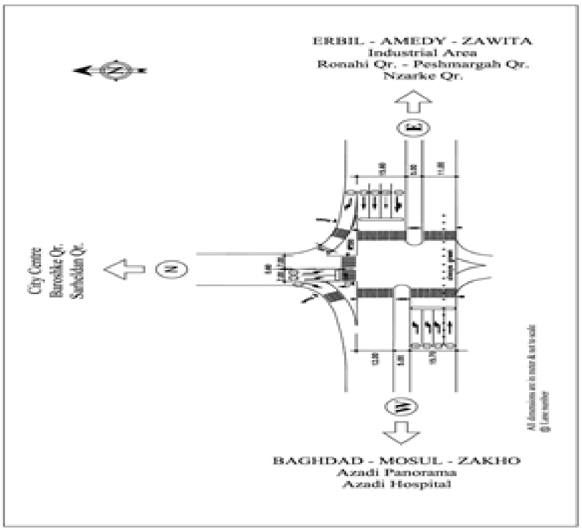

Figure (3): Sarsink Intersection (SRS) Plan (Directorate of Traffic, Duhok City, 2009)

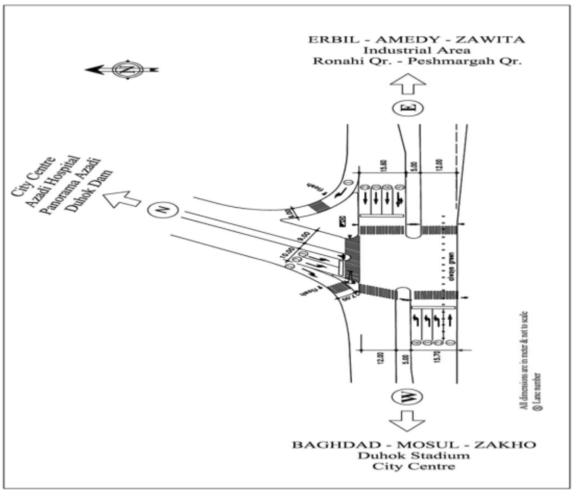

Figure (4): Silav Intersection (SIL) Plan (Directorate of Traffic, Duhok City, 2009)

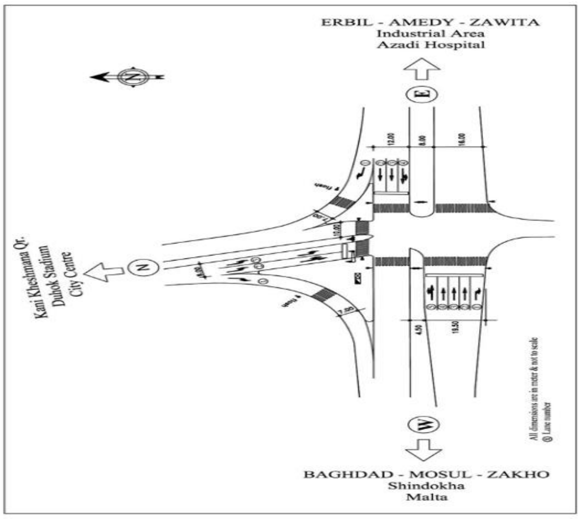

Figure (5): Raza Intersection (R) Plan (Directorate of Traffic Duhok City, 2009)

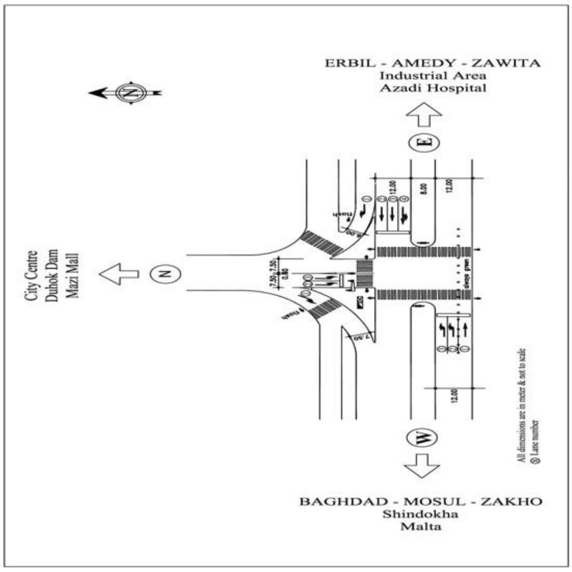

Figure (6): Sarok Intersection (SK) Plan (Directorate of Traffic, Duhok City, 2009)

4. DATA ANALYSIS

The collected data was analyzed for the determination of theoretical and field delays by using different official methods then developing time-dependent delay models for signalized intersections in Duhok City. Finally, the most practical models were chosen to use for the estimation of time-dependent delay at actuated traffic signals in Duhok city.

4.1 Link Volume and Speed

The volume and speed of each link between the intersections were counted as shown in Table (1).

Table (1): Link Speed and Volume Data on Barzani Street

Link	Link length (m)	Travel speed (km/h)	Running speed (km/h)	Mid-Link Spot Speed			Volume (vph)	Directional Distribution %
				Sample size (N)	Mean (km/h)	S.D		
P-SRS	1225	44.18	49.92	106	64.9	10.89	2492	49.90
SRS-P	1225	41.26	45.72	116	76.8	11.04	2502	50.10
SRS-SIL	1050	35.46	44.80	116	71.7	10.65	3125	50.80
SIL-SRS	1050	38.10	44.27	111	62.2	10.10	3019	49.20
SIL-R	305	13.76	28.75	105	48.4	9.33	2913	49.00
R-SIL	305	27.61	27.61	101	64.7	11.65	3024	51.00
R-SK	1100	42.20	47.96	109	78.2	11.24	2747	49.60
SK-R	1100	28.43	43.72	104	77.7	11.63	2782	50.40

4.2 Intersection Volume and Signal Timing Plan

The volume of each approach in all intersections was counted and recorded for each 15-minute interval in the peak hour. The volumes and PHF are shown in Table (2).

Table (2): Traffic Volumes, Saturation Flow Rate, Degree of Saturation and Capacity for Studied Intersections (pcph)

Intersection	Direction	Peak Hour Volume (pcph)	PHF (5 min)	Heavy Vehicle %	Degree of Saturation	Capacity (pcph)	Saturation Flow Rate(pcphg)
Peshmargah	East	2459	0.923	6.20	0.983	2502	1614
	West	1056	0.752	2.34	0.741	1424	1597
	North	504	0.841	1.94	0.684	737	1574
Sarsink	East	3191	0.844	6.91	1.091	2925	1615
	West	468	0.714	0	0.272	1720	1650
	North	60	0.433	0	0.194	309	1468
Silav	East	2592	0.797	7.90	1.237	2096	1438
	West	948	0.706	10.1	0.774	1225	1460
	North	1020	0.748	5.8	1.067	956	1708
Raza	East	2279	0.806	6.67	1.341	1700	1568
	West	2099	0.674	7.4	1.212	1733	1321
	North	1007	0.72	0	1.226	822	1746
Sarok	East	1956	0.915	9.01	1.047	1868	1607
	West	528	0.684	9.38	0.396	1332	1494
	North	540	0.733	5.14	0.775	697	1488

For the computation of delay at actuated traffic signals, the average cycle length and effective green must be used as recommended by Highway Capacity Manual (HCM2000). Therefore, the average cycle length and effective green are determined in field during peak hour period as shown in Table (3).

Table (3): Signal Timing plan for Studied Intersections

Int.	Direction	Average Cycle Length	Unit Extention	Yellow	All Red	Green Time		Average Effective Green
						Max.	Min.	
P	East	111	3	4	2	40	10	43
	West		3	4	2	30	10	33
	North		3	4	2	23	7	26
SRS	East	95	3	4	2	40	10	43
	West		3	4	2	30	10	33
	North		3	4	2	15	7	10
SIL	East	118	3	4	2	40	10	43
	West		3	4	2	30	10	33
	North		3	4	2	30	10	33
R	East	119	3	4	2	40	10	43
	West		3	4	2	36	10	39
	North		3	4	2	25	10	28
SK	East	111	3	4	2	40	10	43
	West		3	4	2	30	10	33
	North		3	4	2	23	8	26

4.3 Saturation Flow Rate and Approach Capacity

The saturation flow rate for each approach is computed and the results of all approaches are shown in Table (2).

The capacity of each approach is estimated by multiplying the saturation flow by effective green to cycle length ratio. All results are shown in Table (2).

4.4 Degree of Saturation (X)

The degree of saturation which is represented by volume to capacity ratio for each approach is computed for the peak hour as a whole, and also for each 15 minutes in peak hour separately as it's shown in Table (2) for all studied intersections.

4.5 Delay Calculations

4.5.1 Theoretical Delay Calculations

The delay for each approach are estimated using different time-dependent equations which are recommended by most frequently used manuals which are the American Highway Capacity Manual (TRB 2000), the Australian Capacity Guide (ARR 1995) and the Canadian Capacity Guide (ITE 1995).

4.5.1.1 Highway Capacity Manual (HCM 2000)

In the field analysis it can be noted that there is not large variability in arrival type in each cycle in peak hour period and its around between AT2 and AT4, therefore its assumed to be AT3 in this study as its recommended by HCM 2000 for non-coordinated traffic signals, and the value of PF will be equal to unity.

The incremental delay calibration factor (k) is determined from HCM2000 for all approaches of each intersection. The incremental delay adjustment factor (I) incorporates the effects of metering arrivals from upstream signals. For a signal analysis of an isolated intersection, the value of I is equal to unity as it is recommended by HCM2000.

The control delay was estimated for each 15 minutes' interval and also for the peak hour as a whole. All results are shown in Figure (7) for all approaches in each intersection.

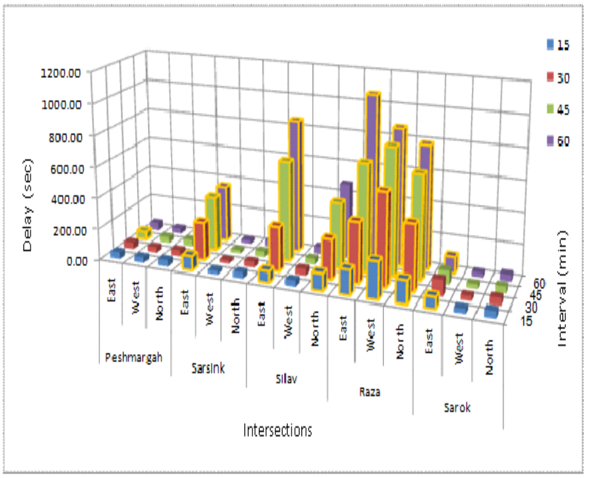

Figure (7): Approach Control Delay for All Intersections Using HCM

Note: The oversaturated intervals have yellow color in Scatter diagrams and also yellow border lines at its corners in the Histograms to be recognized from under-saturated intervals.

4.5.1.2 The Australian Capacity Guide (ARR 1995)

The Australian Capacity Guide does not consider a delay due to a positive initial queue and has the same expression for the uniform delay component d_1, but it does not consider the progression factor. The delay had been estimated for all approaches using equations of this manual. All results are shown in Figure (8) for all approaches in each intersection.

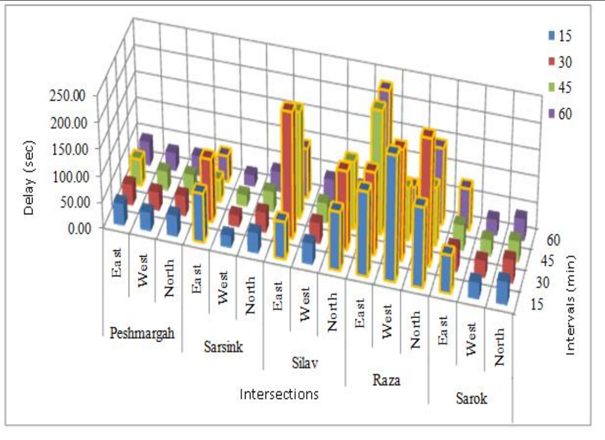

Figure (8): Approach Control Delay for All Intersections Using ARR

4.5.1.3 The Canadian Capacity Guide (ITE 1995)

Similarly, to the Australian Guide, the Canadian Capacity Guide considers only uniform and incremental delay components, while no initial queue delay is present. Therefore, it does not consider the delay due to a positive initial queue. The delay had been estimated for all approaches using equations that are recommended by this method. Results are shown in Figure (9) for all approaches in each intersection.

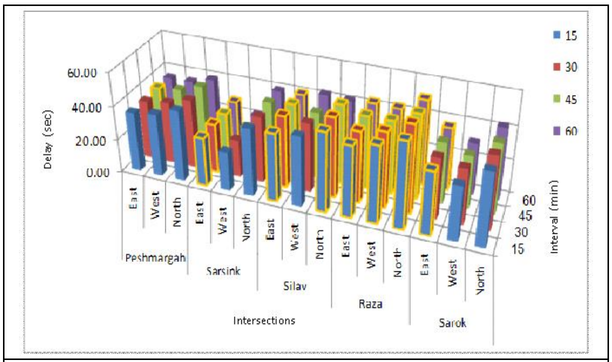

Figure (9): Approach Control Delay for All Intersections Using ITE

4.5.1.4 Field Computation of Intersection Delay

Travel times then the vehicles are crossing the intersection by free flow speed is shown in Table (4). The field measured delays in all approaches for each 15-minutes interval and for peak hour as a whole are shown in Figure (10) for all approaches in each intersection.

Table (4): Travel Times When the Vehicles are crossing the Intersection by Free Flow Speed

Intersection	Travel Time (sec)		
	East	West	North
Peshmargah	9.41	16.00	8.26
Sarsink	11.44	8.27	7.57
Silav	10.22	20.47	13.10
Raza	18.12	10.90	11.40
Sarok	5.30	14.90	6.45

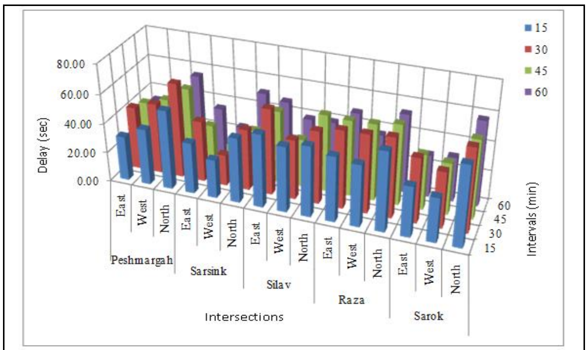

Figure (10): Field Approach Control Delay for All Intersections

4.6 Comparison Between Field Delay and Theoretical Delay

The comparison between field and theoretically computed delay using HCM2000, ARR1995 and ITE1995 manuals and also between the manuals themselves was made for one-hour design period as shown in Figure (11). Also to show the effect of the existence of initial queue at the beginning of analysis period the weighted average delay was taken between the four 15-minute intervals in the peak hour for each leg of each intersection as shown in Figure (12). All results are lower, except of the HCM value which is very higher in oversaturated cases because there is initial queue at the beginning of three intervals of these cases and the d_3 will have high value.

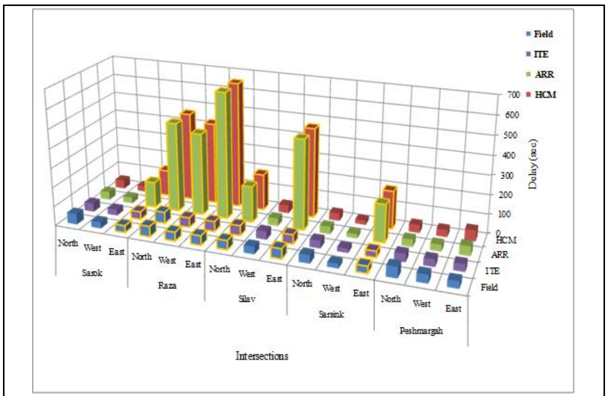

Figure (11): Comparison between Different Delays for One Hour Analysis Period

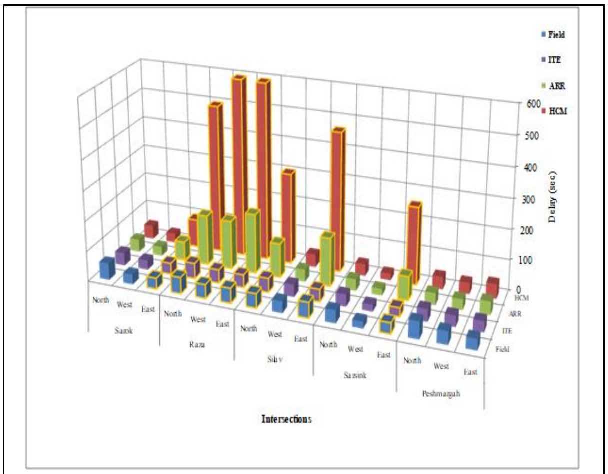

Figure (12): Comparison between Different Delays for Weighted Average Delay of four 15-Minute periods

4.6.1 HCM Method

Generally, in case of under-saturation conditions, or where the demand to capacity ratio (v/c) is smaller than 1.0 (X < 1.0), the field results of delay measurement are relatively close to that obtained theoretically from time-dependent equation in HCM2000. In such conditions the value of incremental delay (d_2) is very small because it is mainly depending on the degree of saturation value (X). The value of initial queue delay is zero in most cases of this condition because; usually there is no initial queue.

When the demand exceeds capacity, the condition changes to oversaturated (X > 1.0), the value of field measured delay will be very small compared to the theoretically estimated results, because the incremental delay (d_2) become very large due to the large value of degree of saturation. Also the initial queue delay (d_3) become very large, especially in last half of peak hour period due to the existence of initial queue and cumulative of this queue in last one or two analysis periods.

4.6.2 ARR 1995 Method

Generally, the field measured results are close to that obtained from Au
stralian Capacity Guide (ARR, 1995) when the demand is smaller than the capacity (X < 1.0). The ARR equation consist of two terms which are uniform delay term (d_1) and incremental delay term (d_2), and in case of under-saturated conditions the last term of equation have a small value when demand is near to the capacity (0.85 < X < 1.0), and negligible value when the demand is under 85 percent of capacity. The delay estimated using ARR1995 equation is very close to that estimated using HCM2000 equation in case of under-saturated conditions.

In the cases of oversaturated conditions, the ARR equation`s results are substantially overestimated field-measured values of delay, but not to the extent of HCM equation`s, because it is not including the initial queue delay term which cause extra overestimation of delay.

4.6.3 ITE 1995 Method

In general form, the field measured delay results are very close to that obtained from the Canadian capacity Guide (ITE, 1995) in all traffic conditions or when the demand is smaller, equal or higher than capacity (X ≤ 1.0, or X > 1.0).The Canadian Capacity Guide delay results are relatively close to that of Highway Capacity Manual and Australian Capacity Guide in under saturated cases only and it is very smaller in oversaturated cases, because the second term (d_2) of the ITE equation is not very sensitive to the degree of saturation.

4.7 Time-Dependent Expressions for Field Delay

Simple regression analysis technique was used to establish different relationships between the field and the theoretical methods. The simplest relationship consists of a straight line or linear relationship ($Y=B_o+B_1X$).

The goal of using regression analysis is the development of statistical models that can be used to predict the field (actual) delay based on the value of the theoretical delay, and also to select the best theoretical equation.

4.7.1 Field Delay with HCM Delay

The relationship had been determined between Field and HCM delay results using different forms of mathematical functions (linear, logarithmic, inverse, quadratic, and cubic), and then the best equation had been chosen which is the inverse form between Field and HCM. The scatter diagram and the best inverse fit is shown in Figure (13).

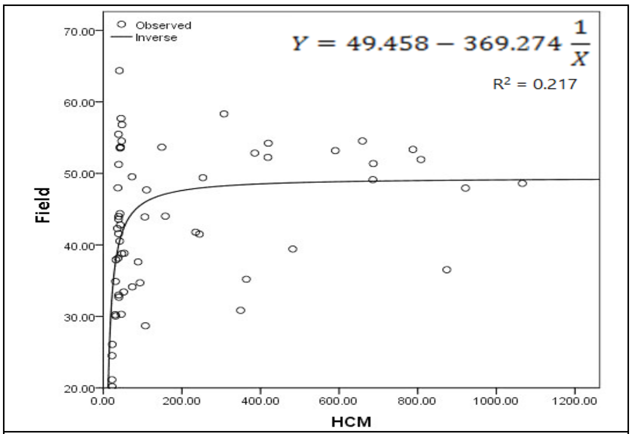

Figure (13): Inverse Relationship between

Field and HCM Delays **(sec/veh)**

The F-Test for the regression equation showed that the calculated F-Test value = 16.111 and the tabulated value at α = 0.05 and degree of freedom (df1= 1, df2=58) = 4.008. As the tabulated F-Test value is less than the calculated value for the same df1 and df2, this means that there is a statically significant Inverse relationship between the field delay and the theoretical (HCM) delay.

4.7.2 Field Delay with ARR Delay

The relationship had been determined between Field and ARR delay results using different forms of mathematical functions (linear, logarithmic, inverse, quadratic, and cubic), and then the best equation had been chosen which is the inverse form between Field and ARR. The scatter diagram and the best fit is shown in Figure (14).

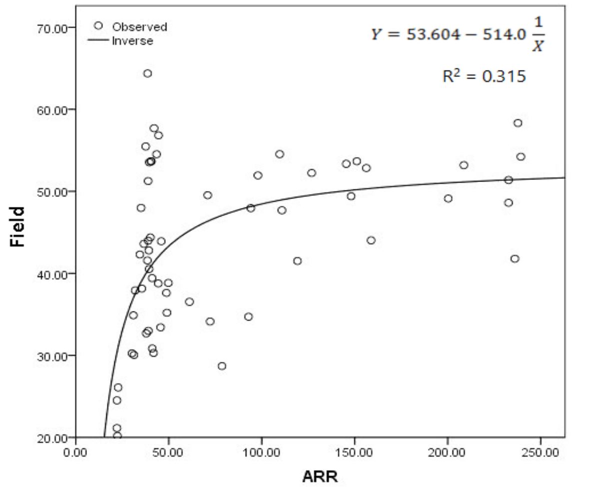

Figure (14): Inverse Relationship between Field and ARR

The F-Test for the regression equation showed that the calculated F-Test value = 26.708 and the tabulated value at α = 0.05 and degree of freedom (df1= 1, df2=58) = 4.008. As the tabulated F-Test value is less than the calculated value for the same df1 and df2, this means that there is a statically significant Inverse relationship between the field delay and the theoretical (ARR) delay.

4.7.3 Field Delay with ITE Delay

The relationship had been determined between Field and ITE delay results using different forms of mathematical functions (linear, logarithmic, inverse, quadratic, and cubic), and then the best equation had been chosen which is the logarithmic form between Field and ITE, see Figure (15).

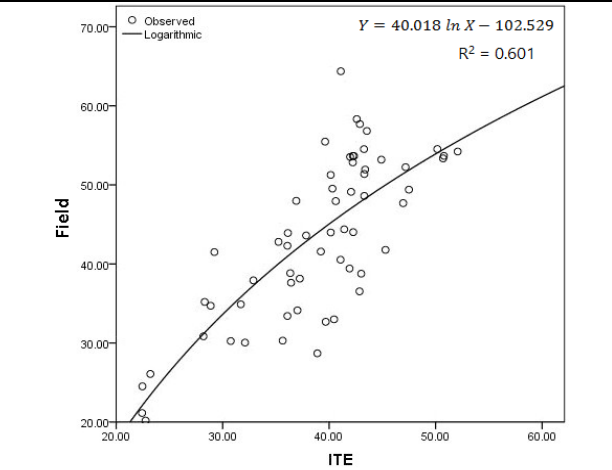

Figure (15): Logarithmic Relationship between Field and ITE

The F-Test for the regression equation showed that the calculated F-Test value = 89.644 and the tabulated value at α = 0.05 and degree of freedom (df1= 1, df2=58) = 4.008. As the tabulated F-Test value is less than the calculated value for the same df1 and df2, this means that there is a statically significant logarithmic relationship between the field delay and the theoretical (ITE) delay.

5. Conclusions

Based on the results of this study, it can be concluded that:

1. The range of intersection control delay was between (22.98) sec/veh on West approach of Sarsink Intersection and (56.79) sec/veh on North approach of Peshmargah Intersection, when the delay observed in field.
2. The range of intersection control delay was between (22.46) sec/veh on West approach of Sarsink Intersection and (594.80) sec/veh on West approach of Raza Intersection, when the delay computed by HCM equation.
3. The range of intersection control delay was between (22.38) sec/veh on West approach of Sarsink Intersection and (197.48) sec/veh on East approach of Raza

Intersection, when the delay computed by ARR equation.

4. The range of intersection control delay was between (22.75) sec/veh on West approach of Sarsink Intersection and (50.99) sec/veh on North approach of Raza Intersection, when the delay computed by ITE equation.
5. HCM has good delay results with respect to Field observed delay in under-saturated conditions but it has extra overestimate delay in oversaturation conditions.
6. ARR has good delay results with respect to Field observed delay in under-saturated conditions but it has overestimate delay in oversaturation conditions.
7. ITE has good delay results with respect to Field observed delay in under-saturated and oversaturation conditions too.
8. There was a good relationship between field measured delay and the control delay estimated by ITE equation, with (R^2=0.601) in case of logarithmic relationship.
9. There was a statically significant but relatively weak relationship between field measured delay and the control delay estimated by ARR equation, with (R^2_{adj}=0.303) in case of inverse relationship.
10. There was a statically significant but relatively very weak relationship between field measured delay and the control delay estimated by ARR equation, with (R^2_{adj}=0.204) in case of inverse relationship.

6. Recommendations

1. Due to high delay values on most approaches, there is a need to apply coordinated traffic signals for all the studied intersections in order to reduce delay, hence, reducing fuel consumption and vehicle emission.
2. HCM, ARR and ITE may be used to estimate delay for under saturated conditions because they have good delay results with respect to field observed delay.
3. The ITE may be used for the delay estimation for over saturated conditions as it has good delay results with respect to field observed delay.
4. The obtained regression equations between Field and ITE delay could be used for the prediction of field delay.

7. Further Research

Further studies on intersection delay is required for Duhok city street networks after signal coordination using ITE delay model.

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