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Comparison of Delay Time Models for Over-Saturated Traffic Flow Conditions at Signalized Intersections

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Abstract

Delays at the signalized intersections the most important parameters of the signal timing optimization and level of service (LOS) estimations. The determination of the delays at the signalized intersections has a significant importance for the evaluation of the performance and travel time of the transportation modes. The optimization of the travel time delays at the signalized intersections provides a better fuel economy. This study compared these delays in the scope of the various model studies in Turkey and other countries considering the signalized intersection approaches controlled in fixed-time and operated in a range of conditions. This study also specifically focused on the differences between Iran and Turkey considering the modal approaches and the driver behavior variations.

Keywords: *Signalized Intersection Approaches; Delay Time; Travel Time; Over-Saturated Flows; Signal Timing*

1. Introduction

Despite the fact that, traffic congestion is becoming more and more prominent problem in urban areas of many cities in the world. Signalized intersections are designed and operated still under the oversaturated traffic flow conditions. Although a significant amount of study investigated the rule-of-thumbs to operate the oversaturated traffic signal systems at signalized intersections, our knowledge about the characteristics of the oversaturation (and even description of oversaturation) is still too narrow [1]. In their study, Wu et al. [1] defined the oversaturated intersection as an intersection which the traffic demand exceeds the road capacity and proposed the degree of the saturation as follows;

$$X_i = \frac{v_i}{c_i} \quad (1)$$

Where: X_i is the degree of the saturation for lane group "*i*"; respectively v_i and c_i are demand flow rate and capacity for lane group "*i*". Referring to the Eq. 1, a lane group is considered as oversaturated when X_i>1. This notion was expanded by Gazis [2] for the oversaturation and a single intersection with two competing traffic streams by suggesting the inequality as follows;

$$\frac{q_a}{s_a} + \frac{q_b}{s_b} > 1 - \left(\frac{L}{C}\right) \quad (2)$$

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Where: q_a and q_b are arrival rates for two conflicting directions; s_a and s_b are saturation flow rates for two directions; L is the total lost time and C is the length of the cycle.

2. Delay at Signalized Intersections

Delay is a key parameter governing the effectiveness of the Level of Service (LOS) at a signalized intersection. The calculation of the real delay time has a significant importance for the design and evaluation applications at a signalized intersections. As an example, delay minimization is frequently used at isolated and coordinated intersection as initial optimization criteria to determine the operating parameters of traffic signals. Also average control delay was used in Highway Capacity Manual (HCM) to determine the level of service at signalized intersection sited at the downstream-end of these approaches [3].

Delay time can be calculated by site observations or analytical models. In analytical models, according to entrance or exit characteristics of traffic flows, delay time can be defined as deterministic, steady state or time dependent model respectively. First two models are commonly implemented to calculate the under-saturated and over-saturated traffic flow delays at the signalized intersections [4]. Among them, the deterministic model calculates infinite delay when saturated degree equals to 1. However, the steady state model calculates zero delay for this value. As a result of this, these models are considered as inadequate for modelling the signalized intersection capacity condition (Figure 1). Hence, it was suggested to take into account all these three models in calculations with using time dependent model transformation methods [5, 6]. The estimation of the delay time is quite difficult. In his study, Teply [7] stated that, a perfect match for the calculation of delay between analytical method and field measurements could not be expected. The difficulty of the delay estimation at signalized intersections has been reported by many studies. Delay time at signalized intersections can be defined as in Figure 1.

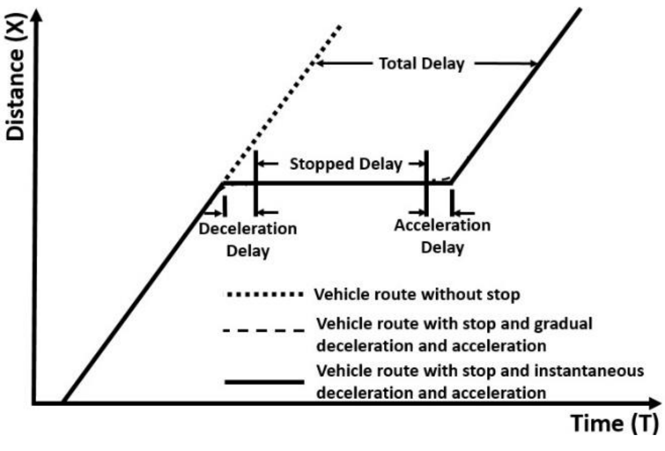

Figure. 1. Definition of the Total, Stopped, Deceleration and Acceleration Delays [8]

Figure 1 shows that the total delay of a vehicle can be categorized as three cases as: deceleration, stopped and acceleration delays. Deceleration and acceleration delays are defined as “The time that is elapsed while a vehicle is slowing from its operation speed to stop at a signalized intersection and the time passed in order for a vehicle to accelerate back to its operation speed after the departure” [9]. Stopped delay is defined as the incurred when a vehicle is fully immobilized [8]. In some special cases, stopped delay may also be considered while a vehicle moving at a lower operation speed. For instance, the Canadian Capacity Guide for Signalized Intersections defines the stopped delay as any delay incurred while moving at a speed that is less than the average speed of a pedestrian (1.2 m/s) [10].

3. Delay Models for Signalized Intersections

HCM [6] proposed a time dependent model was suggested for the calculation of delays of vehicles at signalized intersections. This suggested model was extensively implemented in many studies in Turkey [11, 12]. In this study, developed time dependent analytical models by Akçelik [13], Akgöngör and Bullen [14], Akgöngör [15], HCM [6] and Nassiri and Nadernejad [16] were compared with each other and their usability and effectiveness were investigated.

3.1. Time Dependent Delay Model

The general time dependent delay (TDD) model was originally suggested by Robertson [17] developed by Kimber and Hollis [5] using the Coordinate Transformation Technique (CTT) as demonstrated in Figure 2. CTT transforms the equation describing a steady-state stochastic delay so that model equation becomes asymptotic to the deterministic over-saturation model. Although there is no particular basis considering this approach [4], outcomes of the empirical study shows that these models give adequate results. This situation explains why generally the time dependent delay formulas based on the CTT have been suggested over the years [18-22] and have been incorporated into a number of capacity guides, such as United States [23, 3], Australia [18] and Canada [10].

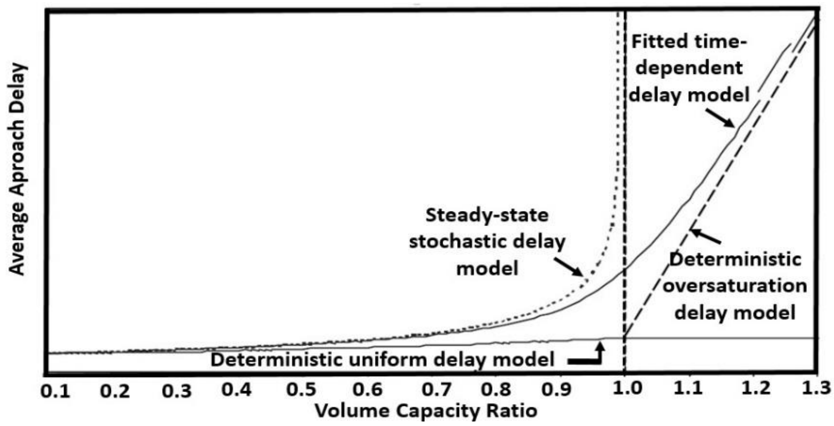

Figure 2. Stochastic Time-Dependent Delay Model Concept [8]

TDD Model is used to predict the delay for under-saturated and over-saturated conditions. The model parameters are defined with the three variables as follows.

$$d_{total} = d_{uniform} + d_{over-saturated} + d_{initial} \quad (3)$$

Where: d_{total} is the average delay in sec., $d_{uniform}$ is the uniform delay, $d_{over-saturated}$ is the sum of random and continuous over-saturated flow delays and $d_{initial}$ is the delay time at the beginning of analysis period caused by vehicles at intersections.

3.1.1. Uniform Flow Delay: Uniform delay can be defined as a traffic flow's delay that has discrete and deterministic arrival depending on queueing theory at a signalized intersections. Uniform delay can be calculated by using Eq. 4 or Eq. 6 [24, 6]. In HCM [6] uniform delay value is defined as follows.

$$d_{uniform} = PF \frac{C(1-\frac{g}{C})^2}{2\left[1-\min(1,x)\frac{g}{C}\right]} \quad (4)$$

Where: C is cycle time (sec.), g is the green time (sec.), x is degree of saturation, "PF" is progress correction factor calculated with the following equation

$$PF = \frac{(1-p)f_{PA}}{1-\frac{g}{c}} \quad (5)$$

Where: f_{PA} is an addition correction factor for the group arrivals at green time and p is ratio of vehicles for green time arrivals. According to Webster [24] model, uniform delay is calculated by using given formula:

$$d_{uniform} = \frac{C(1-\frac{g}{C})^2}{2\left[1-x\frac{g}{C}\right]} \quad (6)$$

In this formula, in over-saturated flows (x>1), uniform delay calculation degree of saturation is taken 1.

3.1.2. Over-Saturated Flow Delay: An over-saturated flow condition is satisfied if the traffic demand exceeds the capacity [1]. Also according to [6] over-saturated flow is defined as "The delay that it is formed by temporary or continuous traffic flow in every observed cycle period". In HCM [6], it is named also "increased delay". It is formed by random delay and continuous delay and calculated using Eq. 7-10 where this is the generalized form of over flow delay model.

$$d_{over-saturated} = d_{random} + d_{continous} \quad (7)$$

$$d_{continous} = 1800T(X-1) \quad (8)$$

$$d_{Random} = 900T\left[-(X-1) + \sqrt{(x-1)^2 + \frac{m(x-x_0)}{CT}}\right] \quad (9)$$

$$d_{Over-Saturated} = 900T\left[(X-1) + \sqrt{(x-1)^2 + \frac{m(x-x_0)}{CT}}\right] \quad (10)$$

Where: C is the capacity (veh/hr), X is degree of saturation (q/c), T is analysis period, m is delay parameter or calibration parameter (Table 1), x_0 is the degree of saturated value for the overcapacity approximately equals 0 (See Table 1).

Table 1. m and x_0 Values Compared for Models

Model Name	m	x_0	k	I
Akçelik [13]	12	$0.67 + \frac{sg}{600}$	-	-
HCM [6]	8kl	0	0.5(x>1)*	0.9(x>1)*
Akgüngör & Bullen [14]	8k	0	$0.8x^2 - 1.4x + 1.1$	-
Akgungor [15]	8k	0	$0.6923T^{0.0844}$	-

*In HCM [6] for the over-saturated flows k and l parameters were taken as constant value.

Initial delay is defined as the required time to charge queue formed by signalization and saturated traffic flow. This delay is examine and it can be calculated with the help of

Eq. 11 [6]. In specific models, "there is no queue" assumption is made when analysis period started $d_{initial}=0$.

$$d_{initial} = \frac{1800 Q_b (1+u) t}{cT} \tag{11}$$

Where: Q_b is the queue length at beginning flow (vehicle), "u" is the delay parameter [$if\ t < T$: u=0], "c" is the group capacity for the corrected lanes (veh/hr), T is analysis period (hr) and "t" is uncovered demand at time T (hr) [For over-saturated flow $t = T$].

3.2. Empirical Model

In the scope of the study, models were examined considering the usability of saturated delay empirical models suggested by Nassiri and Nadernejad [16] for over-saturated traffic flow. In their study, data were obtained from video recordings at different signalized intersection which they have saturation degree more than one and a constant cycle period. From the observed data, Nassiri and Nadernejad [16] obtained entry and exit traffic flow and they calculated delay values by using regression method. Models and model parameters obtained from regression analysis were given in Table (2-5). As can be seen from the Table 7 different models were examined. In Table 2, Table 3 and Table 4, models were taken respectively X and (X-1) as 2 type depending on objective function.

Table 2. Model Type 1 and 2 [16]

Model No	Models	Coefficient. a	t-stat	R^2
1	$\frac{(c-g_e)}{2} + aX$	141.15	45,48	<0
2	$\frac{(c-g_e)}{2} + aX^2$	96.65	64.13	0.51
3	$\frac{(c-g_e)}{2} + aX^3$	65.39	68.74	0.79
4	$\frac{(c-g_e)}{2} + aX^4$	43.75	51.57	0.77
5	$\frac{(c-g_e)}{2} + a(X-1)$	447.26	64.55	0.78
6	$\frac{(c-g_e)}{2} + a(X-1)^2$	876.04	26.60	0.59
7	$\frac{(c-g_e)}{2} + a(X-1)^3$	1609.37	16.52	0.23
8	$\frac{(c-g_e)}{2} + a(X-1)^4$	2748.75	11.65	<0

Table 3. Model Type 3 and 4 [16]

Mode l No	Models	Coefficients			t-stat			R^2
		a	***b***	***c***	***a***	***b***	***c***	
9	$\frac{(c-g_e)}{2} + (aX^2 + bX)$	159.35	-92.22	-	7.29	-2.88	-	0.75
10	$\frac{(c-g_e)}{2} + (aX^3 + bX^2 + cX)$	54.39	2.18	24.06	7.27	0.35	1.48	0.76
11	$\frac{(c-g_e)}{2} + (aX^3 + cX)$	54.39	-	24.06	7.27	-	1.48	0.75
12	$\frac{(c-g_e)}{2} + [a(X-1)^2 + b(X-1)]$	-136	529.81	-	-2.8	14.32	-	0.75

13	$\frac{(c-g_e)}{2}+[a(X-1)^3+b(X-1)^2+c(x-1)]$	18.18	-184.5	533.42	0.03	-0.32	4.18	0.76

Table 4. Model Type 5 and 6 [16]

Model No	Models	Coefficients *a*	*b*	t-stat *a*	*b*	R^2
14	$\frac{(c-g_e)}{2}+aX^b$	75.63	2.63	10.38	11.43	0.75
15	$\frac{(c-g_e)}{2}+ae^{(bX)}$	14.83	1.79	4.26	11.35	0.75
16	$\frac{(c-g_e)}{2}+aLog(X)$	1262.60	-	69.84	-	0.75
17	$\frac{(c-g_e)}{2}+a(X-1)^b$	290.30	0.815	17.65	11.13	0.75
18	$\frac{(c-g_e)}{2}+ae^{[b(X-1)]}$	59.24	1.79	12.65	11.35	0.75
19	$\frac{(c-g_e)}{2}+aLog(X-1)$	-513.89	-	-13.51	-	<0

Table 5. Model Type 7 [16]

Model No	Model 7	Coefficient *a*	t-stat	R^2
20	$\frac{(c-g_e)}{2}+a\left[(X-1+\sqrt{(X-1)^2+\frac{4X}{C}})\right]$	222.68	66.11	0.79

Where: *a*, *b*, *c* parameters are obtained coefficients from regression models. In the next step, among these models statistically significant 4 models were chosen. Then delay values collected by 4 different signalized intersections were compared each other and Eq. 12-14 were suggested given below [16]:

$$d_{total}=\frac{(c-g_e)}{2}+a\left[(X-1)+\sqrt{(X-1)^2+\frac{4X}{C}}\right] \quad (12)$$

$$d_{total}=\frac{(c-g_e)}{2}+a(X-1) \quad (13)$$

$$d_{total}=\frac{(c-g_e)}{2}+aX^4 \quad (14)$$

In the equations above, uniform delay constitutes the first part of the models ant the remaining parts of the equations define the saturated delay. Eq. 8 was proposed by using the HCM models. Model 7 and 8 have objective function X and (X-1) and they are among between Type 1 and Type 2.

4. Comparison of Studies

According to the Figure 2, saturated delay value of the models were investigated for duration 0.25 hour and capacity of 500 veh/hr, saturated flow of 1500 veh/hr and 30 sec., green time in 90 sec., cycle period as 1 and degree of saturation as 1,7 at the corresponding signalized intersection

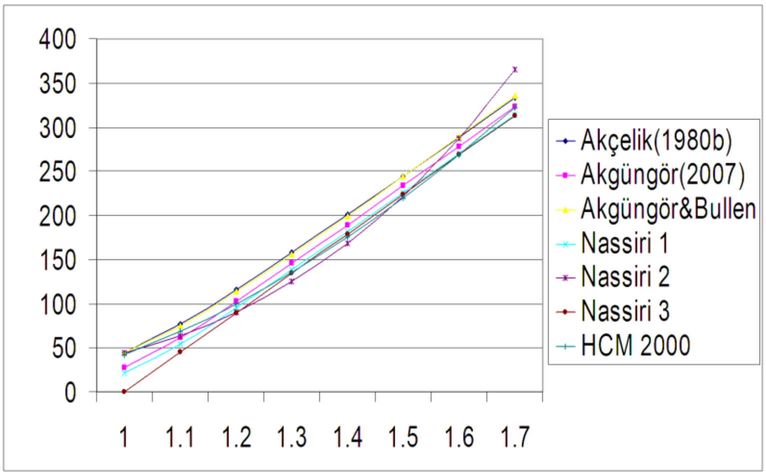

Figure 2. Graph of Saturation Delay Value (Sec.) vs. Saturation Degree

According to the proposed models of Nassiri and Nadernejad [16], vehicles arrive to a signalized intersection in the middle of the effective green time for the process of average uniform delay calculation. In their model the use of the extra PF factor distinct from the [6] model. On the other hand, in their models, it was assumed that there is no queue in the beginning of the analysis. Also only saturated delay value was considered and examined in these analysis [16].

Time dependent models are depend on analysis duration. Because of this reason if analysis duration increase, also delay times will increase. For this condition, Akçelik [18] model suggested a coefficient value for X_0 and he assumed that over-saturated delay starts before reaching to saturated degree. Eq. 10 can be examined with Eq. 9 (m=1, T_f=0.25, x_0=0). From the analysis results, it can be seen that obtained "a" coefficient is relatively close to the duration coefficient 900T of the analysis. In the same time, it can be considered as m/Tf=4.

In this situation, it can be said that "m" value was taken as unity by Nassiri and Nadernejad [16]. Model proposed by Nassiri and Nadernejad was compared with the time dependent models. It is concluded that, corresponding model gives similar results with the model represented with Eq. 6 because, the obtained "a" coefficient has approximate values according to the results of (1800 T_f) value. Therefore, it can be said that this equation describes continuous saturated delay more accurately. Moreover, evaluation of the Eq. 12 considering the function structure of the increase of saturated degree also resulted higher values. In the model evaluations, Eq. 12 model was not able to calculate delay saturated degree over "1.7".

5. Conclusion and Suggestions

In this study various delay models suggested in five different studies for the over-saturated traffic conditions were investigated at signalized intersections. Model results conclude that, the suggested model by Nassiri and Nadernejad [16] gave relatively same results suggested by HCM [6] and Akçelik [13] model. Also the model evaluations showed that, performance properties of the signalized intersections were almost same for over saturated traffic flow conditions at signalized intersections. According to the results, approximately the same delay times were obtained for different driver characteristics at the signalized intersections. Therefore signal duration and similarity of used systems should be taken into the account in the analysis of delay time for over-saturated flow at signalized intersections.

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