IJARSE
ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

MEASURING CONTROL DELAY AT SIGNALIZED INTERSECTIONS: CASE STUDY FROM SOHAG, EGYPT

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ABSTRACT

Control Delay is considered the most important measure of effectiveness (MOE) at signalized intersections because it is used in the estimation of level-of-service (LOS) and intersection design. Thus, this paper presents a methodology to analyze and estimate the delay times at signalized intersections in Egypt, using the Global Positioning System (GPS) devices. GPS was used to identify critical points along the intersection using speed and acceleration profiles associated with each delay component. Speed profiles were used for the identification of stopped time periods, and acceleration profiles were used for detecting deceleration starting points and acceleration ending points. After applying the methodology at the selected intersection, 51 sampled runs were collected from GPS-equipped instrumented vehicles at peak and off peak hours. Data analysis showed that total stopped delay is considered the most influential variable on control delay and comprises about 50% of the total control delay. Also, the average control delay of non-stopped runs is small, and it is about 17% and 23% of the total delay at peak and off peak hours respectively. These results are comparable with the most studies reported in the literature. Regression models between control delay and delay components were developed. Such models might help traffic engineers to estimate the LOS for signalized intersections using criteria that reflect the local conditions in Egypt. In addition, the delays obtained from the models can be used in both design and evaluation practices.

Keywords: Signalized Intersections; Control Delay; Gp, Speed Profiles; Stopped Delay, Acceleration and Deceleration Delays

I. INTRODUCTION

Delay at signalized intersections is the time lost to a vehicle and driver because of the operation of the signal and the geometric and traffic conditions present at the intersection [1]. According to Olszewski [2] and HCM [3], it is defined as the difference between the actual travel time to traverse the intersection and the travel time in the absence of traffic signal control and geometric delay at the desired speed. It is the most important parameter used by transportation professionals to evaluate the performance of signalized intersections [4]. The HCM [3] defines intersection Level-Of-Service (LOS) based on control delay that includes initial deceleration delay, queue move-up time, stopped delay and final acceleration delay. Consequently, the identification of acceleration

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ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

and deceleration delays as well as stopped delay is significant to be able to analyze the performance of signalized intersections [5]. Measuring different control delay components, especially deceleration and acceleration delays, is not easy without using advanced devices such as GPS. The device provides high resolution speed and acceleration profiles which can be used to detect the critical points (i.e. when a vehicle begins/stops to decelerate/accelerate) [6]. In contrast, stopped delay is relatively easy to measure in the field using a number of methods such as test car observation or recording of arrival and departure times on a cycle-by-cycle basis. This explains the reason for using the measured stopped delay for a long time to estimate the control delay [7] despite the fact that stopped delay does not only reflect every aspect of intersection performance affected by traffic signals [8]. Three significantly different relationships concluded in the previous studies between control delay and stopped delay [9-11]. Such differences may be attributed to different driving behaviors, intersection characteristics and signal timings in the specific country/site under study. For these reasons, the main objective of this paper is to analyze and model the delay times at signalized intersections in Egypt. The delay components at an isolated intersection, in Sohag City, Egypt, having 60Km/h posted speed and 80 s cycle lengths were measured in the field using GPS. The findings could be integrated with previous results to develop more general conclusions.

II. LITERATURE REVIEW

Vehicle delay at signalized intersections is commonly used as a measure for quantifying intersection performance in both design and evaluation practices. It reflects the inconvenience caused by traffic signals to the road users. It is also can be used to estimate the fuel consumption, noise, and vehicle emissions [11]. The total delay at a signalized intersection is measured by subtracting the travel time without delay from the actual travel time. The travel time without delay is estimated, when a vehicle is unaffected by the signalized intersection, over a distance between an unaffected point upstream of the intersection and a similar point downstream of the intersection. The actual travel time is then measured by observing the total time taken over the selected distance [12]. This delay includes lost time due to vehicle deceleration, acceleration and stopped.

The actual travel time can be measured using the test vehicle technique, or by measuring the entrance and exit times of vehicles already in the travel stream. It seems that there are few studies in the literature concerning the estimation of control delay in the field. Examples of such studies and the methods used to estimate this delay are presented in the following subsections.

One of the methods of estimating vehicle delay is based on measuring the entrance and exit times that known as "path tracing" method. It depends on tracing vehicle trajectories. This method is very laborious and time consuming [11]. The path tracing method was applied for the research efforts of Olszewski [2] and Mousa [11]. Olszewski [2] measured vehicle crossing times at three intersections in Singapore using two screen lines. Control delay in this research was measured by subtracting the average travel time of unaffected vehicles from the actual travel times between the two screen lines. Mousa [11] used the same method for measuring and analyzing the delay components and identified critical delay points using a speed difference threshold of 5.4 km/h at an isolated intersection, with pre-timed signal, in Muscat City (the capital of the Sultanate of Oman), having a posted speed 60 km/h, a cycle length 80 s. The method in this study was based on selecting a distance

IJARSE
ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

covering 250 m upstream and 120 m downstream of the intersection. This distance was divided into 12 screen lines, then, the crossing times of each vehicle are observed at these lines.

Quiroga and Bullock [10] and Ko et al. [8] provided a methodology that applied the test car technique, which measures the components of control delay based on the GPS data. Quiroga and Bullock [10] conducted the methodology on two arterials in Florida. The common posted speed limit at both arterials was 80 km/h and signals were pre-timed with 150 s cycle length. The main components of delay were determined by analyzing the distance-time, speed-time and acceleration-time diagrams of a travel time run. Ko et al. [8] stated that this methodology seems to have three defects: it requires several points to identify the critical points. Also, it assumes all the data points considered for averaging have the same weight. Moreover, it relies primarily on changes in accelerations to locate critical points, even when detecting stopped time intervals. Therefore, Ko et al. [8] identified control delay components based on vehicle speed profiles obtained from GPS devices at one second time intervals at a signalized intersection in Atlanta. The proposed approach by Ko et al. [8] utilizes both speed and acceleration profiles for capturing critical points associated with each delay component.

III. CASE STUDY

The scope of this research is focused on analyzing and modeling of delay times at signalized intersections. To achieve the target, a T-signalized intersection was selected at an important location in Sohag city, Egypt. The site selected for this study has a high degree of importance and considered as a Central Business District (CBD) area. The basic data collected from the studied intersection are categorized into two categories: geometric, and signal phasing data. The geometric data includes number of lanes and lane widths. Figure 1 shows the existing geometric characteristics of the selected site. Field measurements were made on the through traffic, as shown in Figure 2, in which, the solid line indicates the studied direction. The traffic signal was operating in a fixed-timed mode with a total cycle length of 85 s. The signal phasing for the through traffic movement consisting of 36, 4, and 45 s for the green, yellow and red indications respectively.

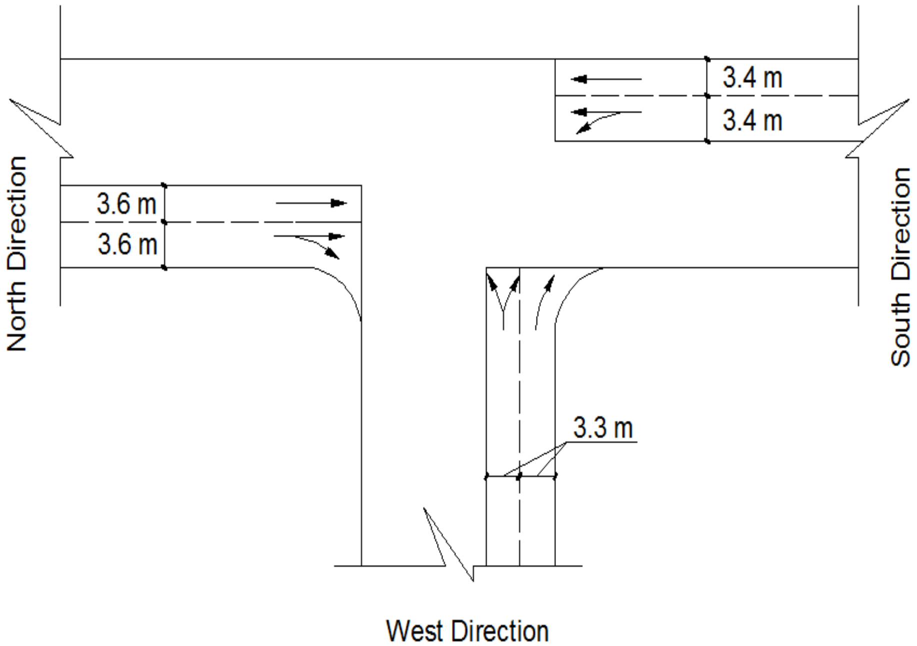

Figure 1: The Layout of the Studied Intersection

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ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

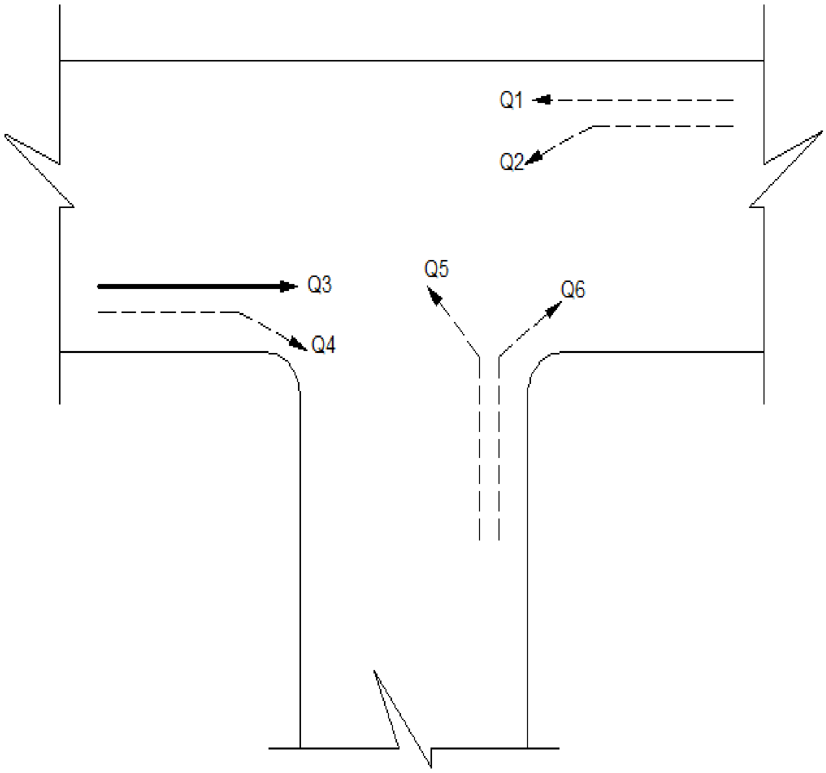

Figure 2: IIustration of the Direction under Study

IV. DELAY TIMES COLLECTION METHODOLOGY

4.1 GPS Methodology

The methodology, used in this research to identify control delay components, is based on second-by-second vehicle speed profiles obtained from GPS devices. The developed methodology depends on using test car technique with GPS equipment.

The equipment included GPS receiver SOKKIA GRX-2 and data collector. The receiver is installed on the board of the passenger car (the test car), but the researcher holds the data collector in hand. Speed profile and acceleration profile can be used to detect critical points along the intersection, as shown in Figure 3. Speed profiles are used for the identification of stopped time periods, and acceleration profiles are used for detecting deceleration onset points and acceleration ending points.

As in Figure 3, it is observed that, all the critical points associated with the delay components have zero acceleration, indicating that acceleration changes can be good indicators of critical points.

International Journal of Advance Research in Science and Engineering
Vol. No.5, Issue No. 11, November 2016
www.ijarse.com
IJARSE
ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

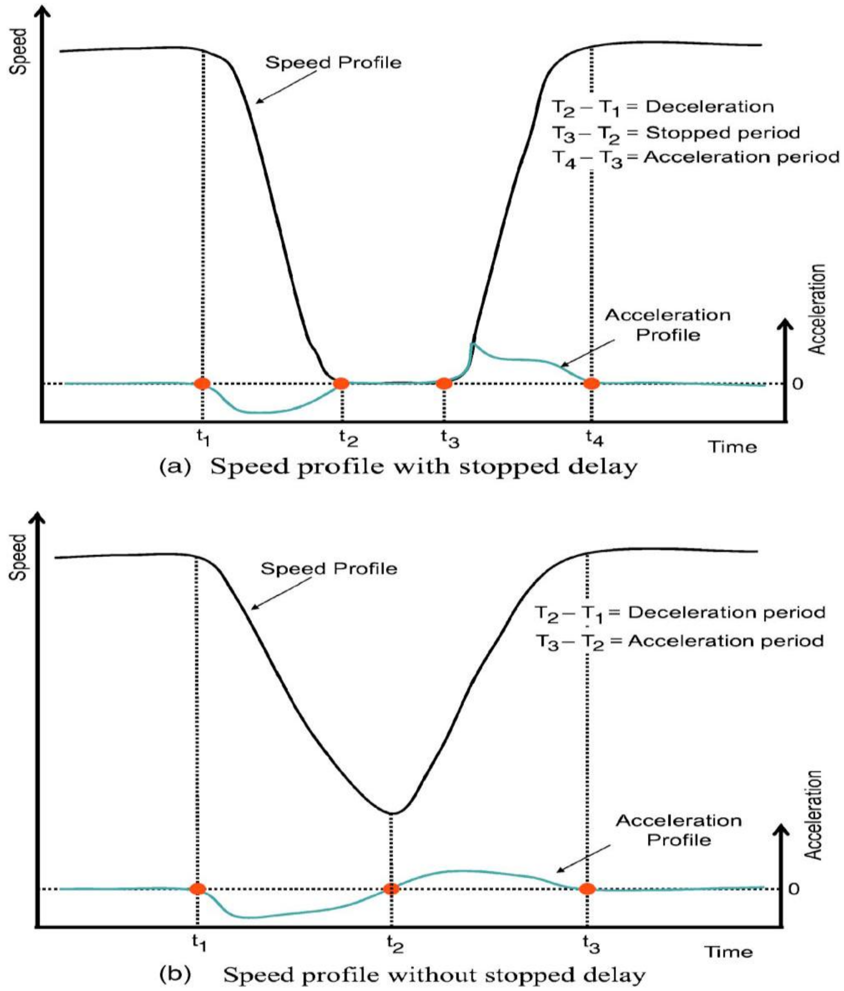

Figure 3: Vehicle Speed and Acceleration Profiles near an Intersection [8]

4.2 Components of Delay

The intersection control delay can be defined as the sum of three components, as depicted in Figure 4, as follows:

- Stopped Delay: is the time during which the vehicle is at stationary position and obtained from the difference in time between points 3 and 2.
- Deceleration Delay: is the component between points 1 and 2, where point 2 is the average location at which vehicles stop upstream of the stop line from a normal speed.
- Acceleration Delay: is the component between points 3 and 4 that occurs as the vehicle is returning to a normal speed.
- Thus, the computation of control delay components requires the identification of the critical delay points when a vehicle begins to decelerate, stops or starts moving, and reaches its normal speed (t1–t4).

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ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

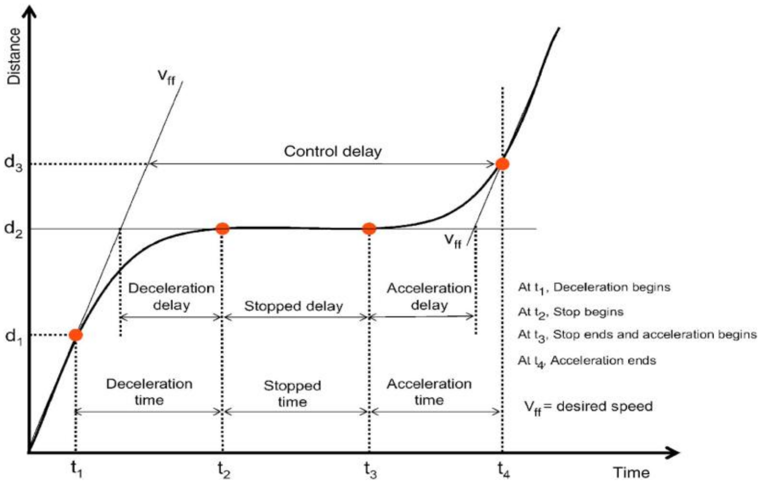


Figure 4: IIustration of Control Delay Components [8]

4.3 Computation of Delay

Most existing research efforts have used the posted speed limit as the desired speed or the free flow speed. Delay components can be easily calculated from the following equations for which the definitions of symbols can be found in Figure 4.

Deceleration delay = $$(t_2 - t_1) - \frac{d_2 - d_1}{V_{ff}}$$

Stopped delay = $$(t_3 - t_2)$$

Acceleration delay = $$(t_4 - t_3) - \frac{d_3 - d_2}{V_{ff}}$$

Then, Control delay = $$(t_4 - t_1) - \frac{d_3 - d_1}{V_{ff}}$$

4.3 Application of Methodology

Pilot Survey

The developed methodology was tested on the through traffic of two signalized intersection approaches in Sohag city. The data obtained from the GPS provide an opportunity to measure the performance of intersections on the basis of computed control delay. However, it was noted that the distance between the consecutive intersections is short, hence, the delay induced by downstream traffic operations on an upstream intersection might be significant. This result occurs only at closely spaced signalized intersections. This type of intersections differs from isolated intersections at which the developed methodology should be conducted. Thus, another intersection was selected to execute the formal survey.

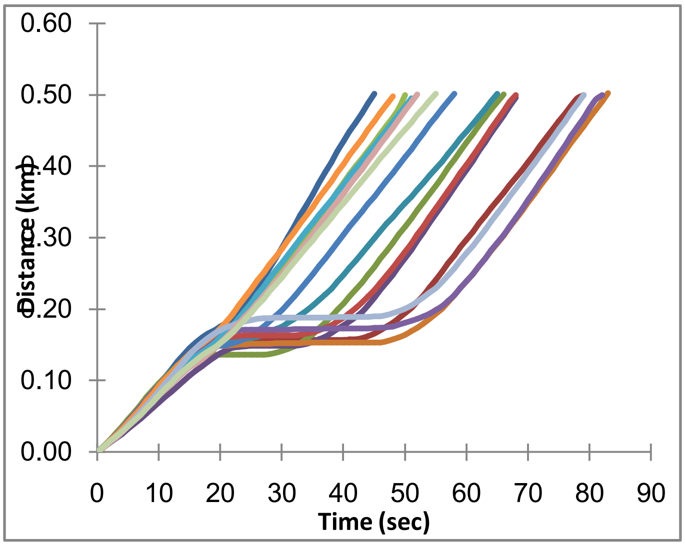
Formal Survey

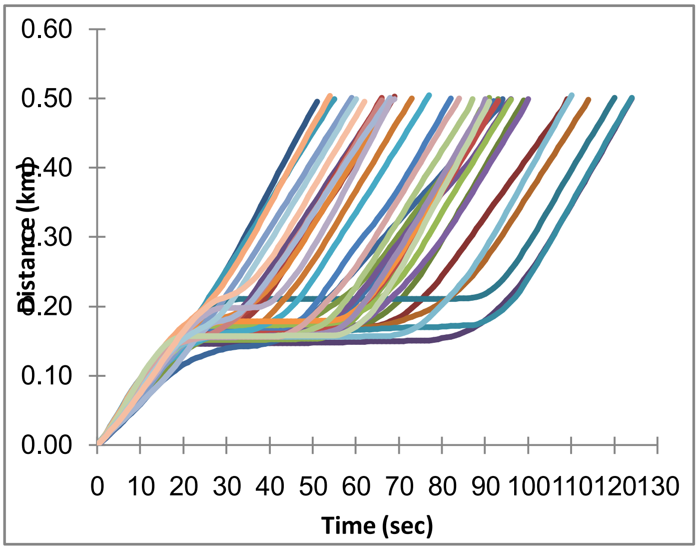
As test cases, 51 GPS runs were executed over 0.5 km roadway segment which consists of one signalized intersection with posted speed limit 60 km/h. Most of the previous studies that estimated the delay time in the field were conducted on one intersection such as [11, 8], accordingly, the current study was done on one intersection as well. These runs were conducted between 6:00 a.m. and 9:00 a.m. (through movements only; containing no significant GPS errors).

In addition to GPS runs, traffic count was performed to differentiate between peak and off-peak hours using 2 observers at each approach of the intersection in which everyone recorded the traffic volume existed in each direction. Such data was collected on Monday (i.e. working day). The cars is only permitted at this site.

Based on traffic count results, the sampled runs are divided into: 36 runs at peak hour (8:00 a.m. to 9:00 a.m.) and 15 runs at off peak hour (6:00 a.m. to 7:00 a.m). The 51-runs in this study mediate the number of trials made in the literature, resulting in acceptable results. Figures 5 and 6 show the time-space diagrams developed from the 51 sampled runs. Each line in the diagrams represents the trajectory of each run over the roadway segment, illustrating that some runs include stopped time. The stopped delay is a function of other parameters including the signal timing, traffic volume, traffic mix, and saturation flow rate of the traffic stream in subject. This delay varied over a wide range, depending on the arrival of individual vehicles with respect to the start of the red signal period [13]. From the Figures, it can be noticed that the total travel time over the segment varies from 45 to 83 s at off peak hour and from 51 to 124 s for runs at peak hour. Thus the total travel time at peak hour is leading to higher control delay than at off peak hour.

Figure 5: Time–Space Diagram of Sampled Runs at off Peak Hour, Figure6: Time–Space Diagram of Sampled Runs at Peak Hour





V. RESULTS OF GPS SURVEY

5.1 Assumptions Used in Surveys

A higher speed threshold 4.8 km/h was applied to allow for the identification of vehicles crawling forward in a queue according to Ko et al. [8] and Colyar and Rouphail [14]. Several drivers seemed to select 47 km/h as their desired speed. This speed is at the moment when a vehicle begins to decelerate or stop accelerating. The acceleration computation method in this research follows the central difference scheme commonly used in other research efforts such as Quiroga and Bullock [10] and Mousa [11], as shown in the following equation:

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ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

$$a_i = \frac{V_{i+1} - V_{i-1}}{t_{i+1} - t_{i-1}}$$

Where:

a_i = acceleration associated with GPS Point i;

V_{i+1}, V_{i-1} = speeds associated with GPS Points i+1 and i-1, respectively; and

t_{i+1}, t_{i-1} = time stamps associated with GPS Points i+1 and i-1, respectively.

5.2 Vehicle Delays

Examples of the results of the computed delays were presented in Tables 1 and 2. Figure 7 presents the speed profiles, the time–space diagrams, and the acceleration profiles for two runs: one at off-peak hour and the other at peak hour.

Table 1: Examples of the Results for the Sampled Runs at off-Peak Hour At off-Peak Hour

At off-Peak Hour				
Sample No.	Deceleration Delay (sec)	Stopped Delay (sec)	Acceleration Delay (sec)	Control Delay* (sec/veh)
1	2.34	0.00	0.45	2.79
2	7.11	20.00	6.57	33.68
3	5.64	10.00	8.74	24.38
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15	3.87	0.00	3.17	7.04
Sum	84.96	122	86.77	293.72
Average				19.58

Table 2: Delay Computation Results for Sampled Runs at Peak Hour

At Peak Hour				
Sample No.	Deceleration Delay (sec)	Stopped Delay (sec)	Acceleration Delay (sec)	Control Delay* (sec)
1	0.7	0.00	1.17	1.87
2	6.34	42.00	11.04	59.38
3	7.34	37.00	9.28	53.62
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36	8.34	0.00	8.28	16.62
Total	291.83	700	342.98	1335.81
Average				37.11

*Control Delay = deceleration delay + stopped delay + acceleration delay

Based on the results, the average control delay of non-stopped vehicles is small, and it is about 17% and 23% of the total delay at peak and off peak hours respectively. Runs contain stopped time are resulting in much larger control delays than the other trips. Total stopped delay for the sampled runs is 700 s and 122 s at peaks and off peak hours respectively, which represents about 50% of the total control delay. At peak hour, the stopped delay ranges from 9 to 65 s, and the minimum and maximum control delays are 1.87 and 81.38 s respectively.

Figure 7 contains the critical points and these points are marked as an asterisk. The first two runs have only three critical points as they do not include complete stops, whereas the second runs have four critical points. As suggested by the principles adopted in the methodology, critical points are located on the points at which the signs of acceleration change.

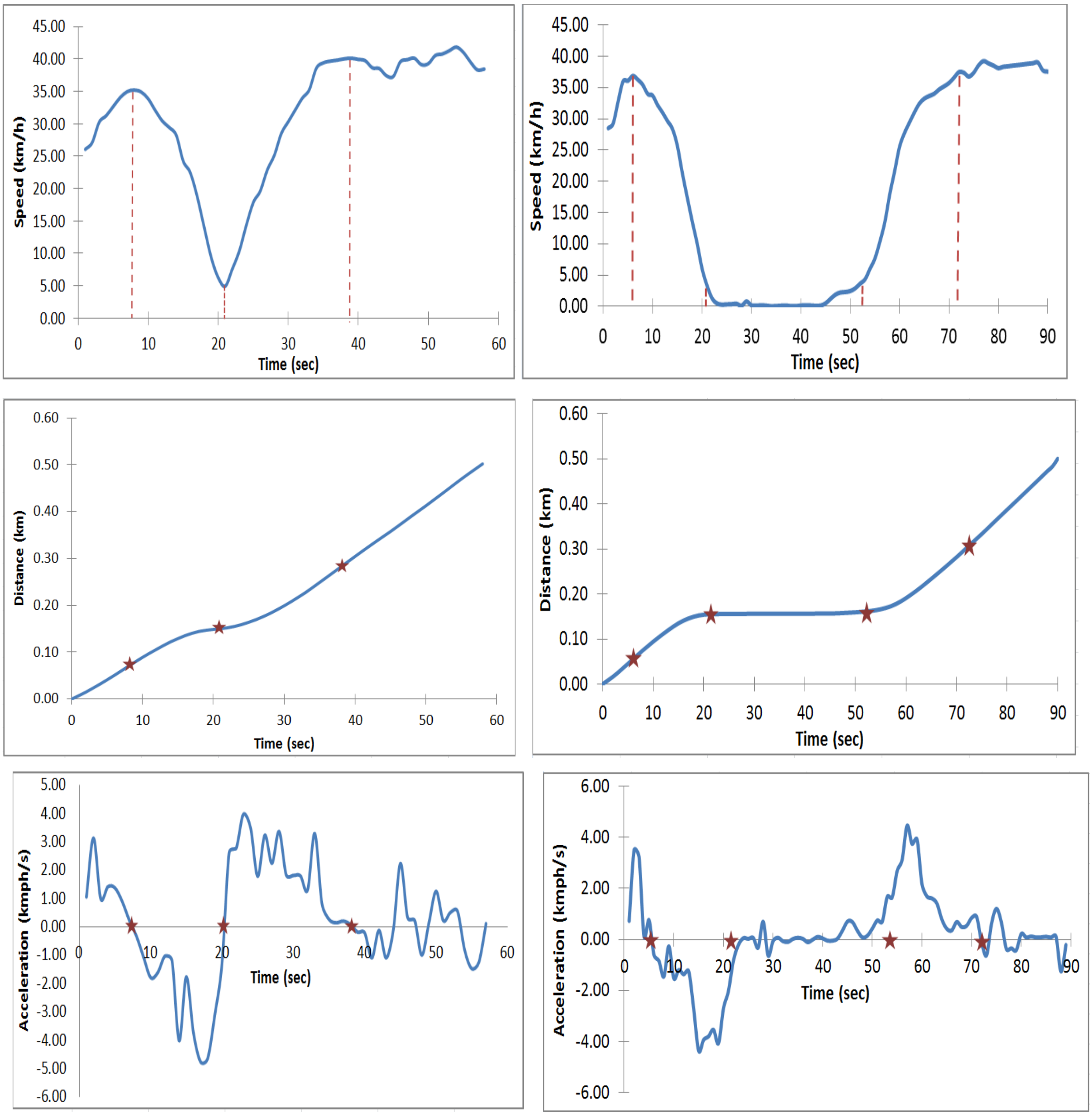

Figure 7: Examples of Speed Profile, Time–Space Diagram, and Acceleration Profile with Identified Critical points (a) at off- Peak Hour – (b) at Peak Hour

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ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

The compositions of delay components for the 36 sampled runs at peak hour are illustrated in Figure 8. This figure indicates that deceleration delays tend to be larger than acceleration delays for non-stopped vehicles such that the average deceleration delay is 8.7 s, while for acceleration delay is 7.7 s. This could be due to an increase of caution among drivers slowing down before entering the intersection. In contrast, for stopped vehicles, the average acceleration and deceleration delays are 10.7 s and 7.8 s, respectively. Similarly, Mousa [11] and Ko et al. [8] reported that the average acceleration delay (11.4 s and 8.7 s) is higher than the average deceleration delay (7.2 s and 7.8 s) respectively, for the sampled stopped vehicles. Additionally, the average deceleration–acceleration delay in the current study is 18.5 s, which is very close to the 20 s associated with Quiroga and Bullock [10] model and the 18.6 s obtained by Mousa [11] when the data were analyzed for the stopped vehicles only. At off peak hour, the results were found to be in agreement with the findings concluded at peak hour.

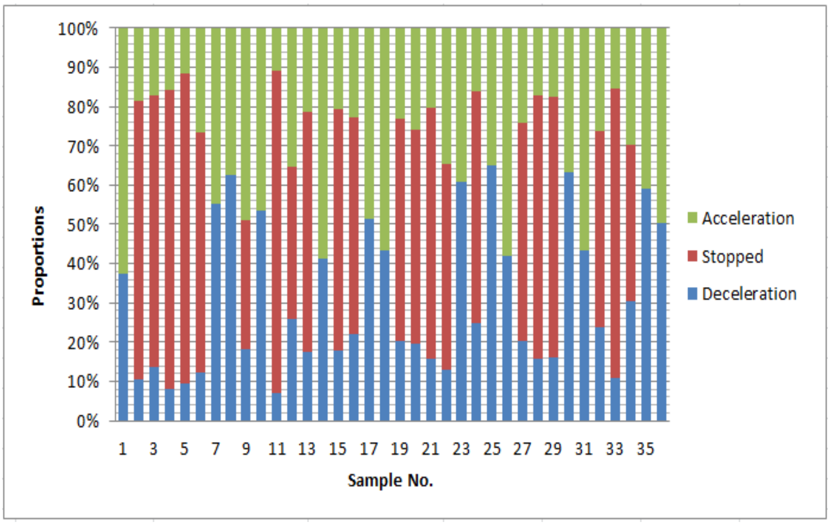

Figure 8: Composition of Deceleration, Stopped and Acceleration Delays for the 36 Runs at the Peak Hour

VI. DEVELOPMENT OF DELAY MODELS

6.1Correlation Analysis

The large variation calculated for delay components makes it inadequate to use the mean value to describe these delays. For this reason, a regression analysis was performed on computed delays to model the relationships between delay components. SPSS statistical computer program was used to perform the analysis [15]. Details of correlation analysis between control delay and delay components at peak and off-peak hours are shown in Table 3.

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ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

Table 3: Correlation Coefficients between Control Delay and Delay Components Control

	Multiple Comparisons (Significance)	Deceleration Delay		Stopped Delay		Acceleration Delay		Control Delay	
		Peak	Off-Peak	Peak	Off-Peak	Peak	Off-Peak	Peak	Off-Peak
Deceleration Delay	Correlation	1.000							
	Sig. (2-tailed)	-							
Stopped Delay	Correlation	0.152	0.568*	1.000					
	Sig. (2-tailed)	0.375	0.027	-					
Acceleration Delay	Correlation	0.411*	0.921**	0.297*	0.587*	1.000			
	Sig. (2-tailed)	0.013	0.000	0.078	0.021	-			
Control Delay	Correlation	0.112*	0.774**	0.959**	0.956*	0.522**	0.794**	1.000	
	Sig. (2-tailed)	0.532	0.001	0.000	0.000	0.001	0.000	-	

*Correlation is significant at the 0.05 level (2-tailed).

**Correlation is significant at the 0.01 level (2-tailed).

From that table, it could be noted stopped delay has the highest correlation with control delay at peak and off peak hours. Generally, the signs of the correlation coefficients are in the expected direction, meaning that the control delay tends to increase as the delay components increase.

6.2 Regression Analysis

To get the best relationships between control delay and its components, linear regression analysis was conducted using data from the field measurements. The control delay was the dependent variable and the delay components were the independent variables. Two types of regression analysis were used (single variable and multi-variable). Details of the developed regression models are shown in Tables 4 and 5 for peak & off-peak hours.

From these tables, it was found that the resulting coefficients of determination (R2), in all models, are considered good and comparable to that found in other studies. They are also found significant at the 95% confidence level as the significance of F statistic < 0.001. Also, it was observed that the stopped delay has the highest t-value of all independent variables at peak and off peak hours. Thus, the stopped time component is considered the most influential independent variable and has the most contribution in all models.

International Journal of Advance Research in Science and Engineering
Vol. No.5, Issue No. 11, November 2016
www.ijarse.com
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ISSN (O) 2319 - 8354
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Table 4: Details of the Regression Analysis between Control Delay and Delay Components at off-Peak Hour

Model Type	Independent Variable	Coefficients	t	Sig.	R^2	Sig. of F statistic
Single	Constant	9.096	6.514	0.000	0.914	< 0.001
	Stopped Delay	1.289	11.774	< 0.001		
Multi-variable	Constant	2.24	4.679	0.001	0.997	< 0.001
	Stopped Delay	1.008	37.205	< 0.001		
	Acceleration Delay	1.58	17.655	< 0.001		
	Constant	0.002	0.472	0.646	1.000	< 0.001
	Stopped Delay	1.000	5535.705	< 0.001		
	Acceleration Delay	1.001	795.168	< 0.001		
	Deceleration Delay	0.998	521.673	< 0.001		

Table 5: Details of the Regression Analysis between Control Delay and Delay Components at Peak Hour

Model Type	Independent Variable	Coefficients	T	Sig.	R^2	Sig. of F statistic
Single	Constant	17.027	11.873	0.000	0.920	< 0.001
	Stopped Delay	1.033	19.819	< 0.001		
Multi-Variable	Constant	5.147	3.927	0.000	0.981	< 0.001
	Stopped Delay	0.949	36.135	< 0.001		
	Acceleration Delay	1.417	10.662	< 0.001		
	Constant	0.090	0.961	0.344	1.000	< 0.001
	Stopped Delay	0.999	606.740	< 0.001		

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ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

	Acceleration Delay	0.996	110.315	< 0.001		
	Deceleration Delay	0.998	96.385	< 0.001		

The proposed models might help traffic engineers to estimate the LOS for signalized intersections using criteria that reflect the local conditions of the area under study. In addition, the delays obtained from the proposed models can be used in both design and evaluation practices. For example, delay minimization is frequently used as a primary optimization criterion when determining the operating parameters of traffic signals at isolated intersections.

6.3 Comparison with Previous Models

From Tables 4 and 5, it is obvious that the relationship between control delay and stopped delay appeared linear at peak and off peak hours. The single variable models between control delay and stopped delay, developed in the current study (for peak and off peak hours), were compared with: the HCM [9] relationship; the model developed by Quiroga and Bullock [10] for two arterials in Florida (QBF Model); and the model introduced by Mousa [11]. The following equations present the comparative models:

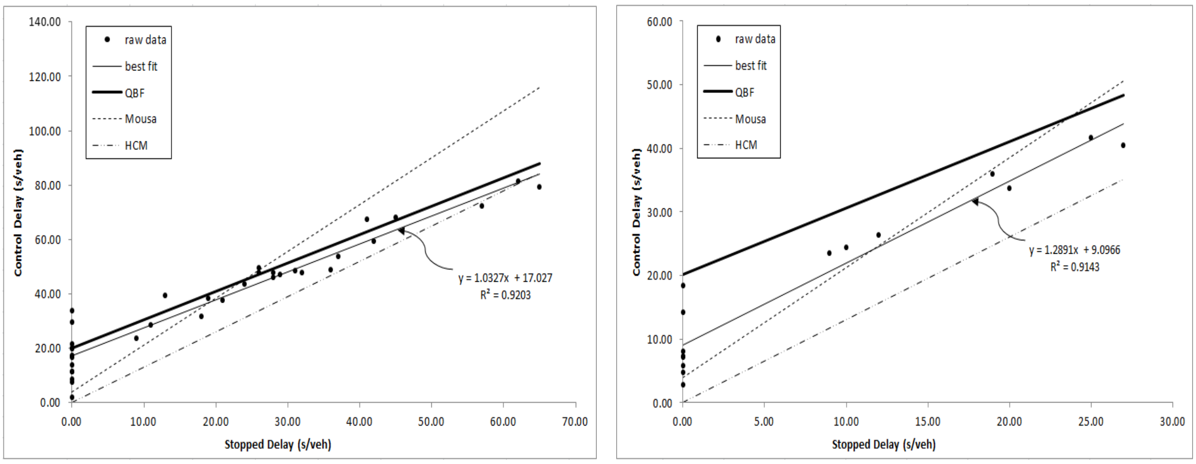
- QBF Model $d_c = 1.043\ d_s + 20.125$ ($R^2 = 0.917$)
- HCM Model $d_c = 1.3\ ds$
- Mousa Model $d_c = 1.724\ d_s + 3.983$ ($R^2 = 0.86$)
- Current Study Peak Hour Model $d_c = 1.033\ d_s + 17.027$ ($R^2 = 0.92$)
- Current Study Off-Peak Hour Model $d_c = 1.289\ d_s + 9.096$ ($R^2 = 0.914$)

Where:

d_c= Control delay (sec/veh); and

d_s = Stopped delay (sec/veh).

The models along with the raw data of the current study (for peak and off peak hours) are shown in Figure 9.



(a) At Peak Hour (b) At off-Peak Hour

Figure 9: Comparison with Previous Studies

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ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

From this figure, it could be noticed that neither QBF model nor Mousa and HCM models are appropriate for the data collected in the current study, and the developed models obtained in this study generally lie between these models.

For example, at peak hour, QBF model gives about 20 s control delay when the stopped delay is almost zero, while Mousa model gives about 4 s. These values compared to about 17 s in the current study. The large intercept in QBF model might be due to the absence of non-stopped vehicles in the data used in this model. At off peak hour, it was noticed that the value of delay time in the current study is about 9 s, which is slightly close to Mousa value, and this is due to the ratio of non-stopped vehicles.

In all models, it was also noticed that the impact of stopped delay (ds) on control delay (dc), as reflected by the coefficients of the independent variable (dc), is different from country/region to another. This could be attributed to different driving attitudes and behaviors of drivers from country to another.

VII. CONCLUSIONS

Based on the results presented in this paper, the following conclusions were drawn:

- The used approach, GPS-based, can provide an automation process for the analysis of large-scale instrumented vehicle data, revealing the components of control delay. In addition, researchers by using the results can understand drivers' behavior near intersections, and can analyze intersection performance. Furthermore, the automation process provides consistent results unlike the manual process.
- Based on the comparison between relative magnitudes of delay components at peak hour, it was found that deceleration delay tends to be larger than acceleration delay for vehicles with zero stopped delay and vice versa for stopped vehicles.
- The average control delay of non-stopped vehicles is small, about 17% and 23% of the total delay at peak and off peak hours respectively. The runs contain stopped time showed much larger control delays than other trips.
- The stopped delay component has the highest correlation of other components with control delay. The stopped delay represents about 50% of the total vehicular delay.
- The control delay of the current study at peak hour is close to QBF model, but at off peak hour, the current study is close to Mousa value. This is due to the ratio of non-stopped vehicles in these studies; for the current study the ratio is 39% at peak hour and 53% at off peak hour, for QBF model zero%, and for Mousa model 45%.
- The study emphasis that the magnitude of delay components differ from country to country according to local characteristics of these countries (i.e. the behavior of drivers).
- The proposed models, between control delay and delay components, might help traffic engineers to estimate the LOS for signalized intersections using criteria that reflect the local conditions in Egypt. In addition, the delays obtained from the proposed models can be used in both design and evaluation practices.
- Future research should be performed on different types of intersections such as four leg intersections and multi-leg intersections with a wide range of traffic and geometric conditions.

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ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

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