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Optimization of vehicle delay and exhaust emissions at signalized intersections

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Abstract

Traffic signals at intersections have a significant effect on traffic emissions. They interrupt traffic flow and create additional acceleration and deceleration driving modes. Therefore, the objective of this paper is to perform the optimization process of vehicle delay and exhaust emissions at isolated signalized intersections. Three-leg intersection located in Kafr El-Sheikh City, Egypt was selected in this study. Field delay times were estimated based on vehicle speed and acceleration profiles using GPS device. On-road measurements of vehicle speeds and emissions were collected simultaneously for all movements of all approaches at the selected intersection. The micro-simulation software VISSIM was used to model and analyze the selected intersection. The model was calibrated and validated using the collected data. Signal timing model was developed for the selected intersection and used for optimization of delay time and vehicle emissions. It was found that the changing of signal timing was effective in improving the operational and environmental performance of the traffic signal under study. Also, the results indicated that when the traffic flow rate is higher, the optimal cycle time corresponding to the performance index function increases. Optimization of the delay times and exhaust emissions gives traffic engineers the option of minimizing vehicle emissions in the designing of the signalized intersections or timing a signal system.

Keywords - delay time, exhaust emissions, optimization, traffic signals, VISSIM

1. Introduction

Road traffic sector is one of the main sources of exhaust emissions in urban areas. Vehicle emissions represent about one-third of total hydrocarbon (HC) emissions, one-third of total nitrogen oxides (NO_X) emissions, and two-thirds of total carbon monoxide (CO) emissions [1]. Therefore, a direct link can be shown between vehicle emissions and societal health.

Urban intersection cannot be considered a node of urban traffic network only, but also a traffic congestion spot. Major intersections along arterials typically involve the highest traffic density, the longest vehicle idling time, and the most deceleration and acceleration rates. They are often “hot spots” of air pollution and have negative environmental and health effects on vital buildings such as hospitals and schools in the vicinity. Therefore, the demand for more efficient intersection designs is a high priority [2].

Traffic signals at intersections affect traffic emissions significantly. They interrupt traffic flow and create additional deceleration, idle and acceleration driving modes to the otherwise cruise driving mode. Traffic emissions are very sensitive to the driving modes. For example, accelerating vehicles produce higher values of vehicle emissions than those in the cruise driving mode [3]. Therefore, the objective of this paper is to reduce the delay times and exhaust emissions at signalized intersections through optimization process.

2. Previous studies

Many studies have focused on the effect of signal coordination on exhaust emissions. Rakha et al. [4] indicated that signal coordination strategy can reduce vehicle emissions up to 50% in a highly simplified scenario. Madireddy et al. [5] investigated a signal coordination measure that reduces exhaust emissions by about 10% on a signalized arterial.

Studying the optimization process of vehicle delay and exhaust emissions at signalized intersections has been carried out by several authors. In a study conducted by Li et al. [6], the authors investigated the relationships between the signal cycle time and vehicle delay, fuel consumption, and exhaust emissions. They developed signal timing model for an intersection in Nanjing city. The study concluded that the developed model is effective in signal timing optimization using the collected data.

Park et al. [7] proposed signal timing optimization models to reduce vehicle emission based on microscopic simulation. The results of this study indicated that the proposed models were effective in reducing emission with moderate relationship in delay and stops.

Ma and Nakamura [8] developed an analytical procedure to obtain the optimized cycle length against vehicle emissions for isolated intersections. The study concluded that the cycle length that minimizes emission is recommended to be applied on conditions with high cruise speed or high heavy vehicle percentage.

Lv [2] developed an optimization methodology for signal timing at intersections to reduce delay and vehicle emissions. The methodology development includes four levels: the vehicle level, the movement level, the intersection level and the arterial level. The simulation results indicate that the benefit of emission reduction becomes more and more significant as the number of intersections along the arterial increases.

Lin et al. [9] investigated the relationship between vehicular emissions and delay. They developed the traffic signal control model for Changchun intersection using VISSIM software. The results of this study showed that the proposed model can significantly reduce vehicle delay and traffic emissions simultaneously.

Although many signal timing optimization approaches are currently available in the literature, it is noteworthy that these approaches depend mainly on analytical procedure or microscopic models. In this paper, the optimization process is conducted using microscopic models calibrated and validated using field delay times and on-road exhaust emissions measurements. Using the simulation, various values of performance index function (PI) are generated for different signal design parameters (e.g. cycle length); then, the minimum value of PI is selected as the optimum design.

3. Methodology

3.1. Measuring of exhaust emissions

In this paper, on-road vehicle emissions technique is employed for measurement of real-world traffic conditions. This technique is based upon instrumentation of individual vehicles and measurement of tailpipe emissions. Its advantage is providing second-by-second vehicle activity and emissions data, which enables characterization of emissions at any time or location during a route. Gas analyzer instrument is used for measuring exhaust emissions at the selected intersection. It is the most powerful and advanced portable emissions analyzer. Furthermore, it is a complete, portable tool for Environmental Protection Agency (EPA) compliance level emissions monitoring of boilers, engines, and other combustion equipment [10].

In urban areas in Egypt, most of vehicles with engine sizes range from approximately 1.3 liters to 1.6 liters with both automatic and manual transmission systems [11]. Therefore, the vehicles for which measurements have been obtained include three different vehicle types: a 2012 Kia Cerato, 2007 Daewoo Lanus and 2005 Mitsubishi Lancer. The fuel type of these vehicles is gasoline. These vehicle types are approximately representative of new technology cars and the most common types in Egypt.

Exhaust emissions measurements were carried out at the selected intersection using gas analyzer instrument. Figure 1 illustrates the placement of the gas analyzer instrument on a seat inside the vehicle. Figure 2 shows the emission sampling probe and hose, which are routed into the vehicle. Figure 3 illustrates the vehicle fully equipped with the gas analyzer and ready for on-road testing.

3.2. Definition of control delay components

Control delay at a signalized intersection is generally defined as the delay attributed to the traffic signal operation. As illustrated in Figure 4 the control delay can be determined as the sum of deceleration delay, stopped delay and acceleration delay.

Most existing studies 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.

$$\text{Deceleration delay} \quad = (t_2 - t_1) - \frac{d_2 - d_1}{v_{ff}} \quad \ldots\ldots\ldots\ldots \quad (1)$$

$$\text{Stopped delay} \quad = t_3 - t_2 \quad \ldots\ldots\ldots\ldots \quad (2)$$

$$\text{Acceleration delay} \quad = (t_4 - t_3) - \frac{d_3 - d_2}{v_{ff}} \quad \ldots\ldots\ldots\ldots \quad (3)$$

Fig. 1 - Gas analyzer instrument installed in a vehicle

Fig. 2 - Sampling probe routed from vehicle tailpipe into vehicle

Fig. 3 - Vehicle fully equipped with gas analyzer and ready for testing

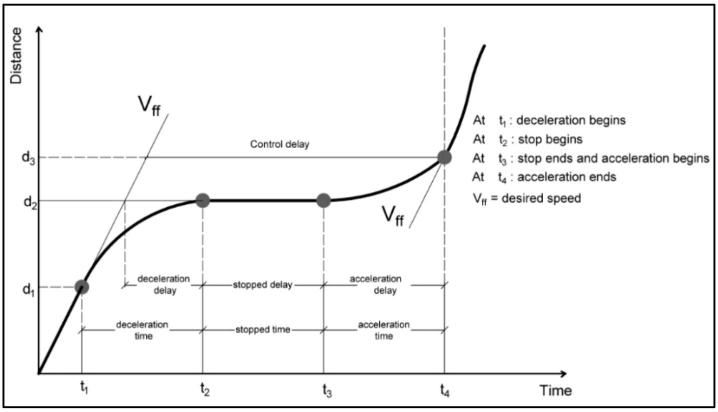


Fig. 4 - Diagram of intersection delay components [12]

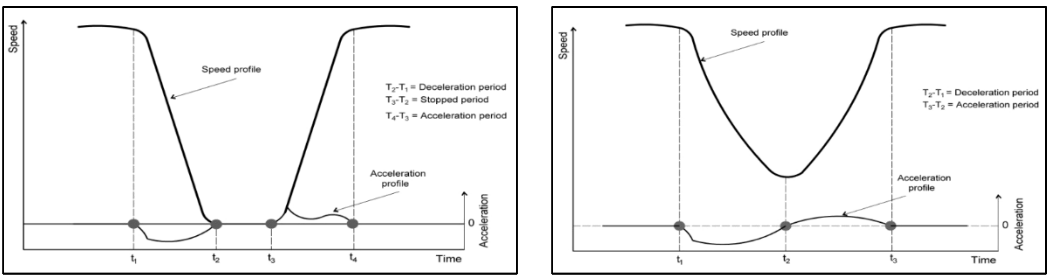
3.3. Measuring of field control delay

There are a number of techniques for measuring field control delay based on speed profiles of individual vehicles. These techniques include: path tracing technique; video image technique; and test car using GPS technique. In this research, on-road vehicle data measurements technique is used for estimating control delay from second-by-second speed profile data obtained from GPS device. Figures 5 (a) and (b) represent two different potential speed and acceleration profiles of a vehicle passing an intersection. 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. Noteworthy is that, all the critical points associated with the delay components have zero acceleration, indicating that acceleration changes can be good indicators of critical points [13].

3.4. Development of micro-simulation model

In this study the micro-simulation software VISSIM was used to model and simulate the studied intersection. VISSIM is versatile and provides the modeler with the ability to model a wide range of traffic operations in both the interrupted and uninterrupted traffic environment [14].

Model calibration and validation are two necessary steps to ensure the reliability of the developed model. Model calibration and validation processes were conducted based on a trial-and-error method.



(a) Speed profile with stopped delay (b) Speed profile without stopped delay

Fig. 5 - Vehicle speed and acceleration profiles near an intersection [13]

The delay and emissions data of eastbound approach were used in the calibration process while, the data of westbound approach were used for validation purpose. The desired speed distribution is one of the most influential parameters of a VISSIM simulation model. Therefore, the desired speed was chosen as the calibration parameter in the current analysis.

3.4.1. Model calibration

Model calibration is the process of modifying the model parameters so that the model outputs match the real data. In general, the target of calibration is to ensure that the simulation outputs of the evaluation variable match the observed data. Instead of calculating average errors to assess the quality of the calibration, a more robust approach is applied where the "matching" is evaluated using a suitable hypothesis statistical test. If the simulation output fits the observed data statistically then the model is said to be calibrated. Otherwise, the calibration variable would need further fine tuning [15].

3.4.2. Model validation

Validation of a simulation model is the next stage after ensuring that the model is well-calibrated. Validation is defined as the process of matching the output of the calibrated simulation model with a different set of real world observations that were not used in the calibration. The evaluation measures used in this process should be different from the measures used in the calibration process. Alternatively, the measurements of the same variable can be utilized but for different locations, time periods, and/or traffic conditions [16].

3.5. Optimization of delay time and vehicle emissions

The objective of optimization for delay time and vehicle emissions is to reduce the delay time of vehicles and emissions at the signalized intersections. This objective can be achieved by optimization of the signal cycle time and green time.

3.5.1. Signal timing model

The first step for a multi-objective optimization problem is to determine how to combine and achieve different objectives. The performance index (PI) function is used to transform the multi-objective programing problem into a traditional single-objective programing problem. The average delay per vehicle and the total amount of vehicle emissions at the intersection are defined as indexes. The initial values of the delay of the signal timing and the initial values of vehicle emissions are used for normalization as the units of these indexes are different [6]. The signal timing model is thus:

$$PI = \alpha \times \frac{D}{D_I} + \beta \times \frac{E}{E_I} \tag{4}$$

where:

PI = the performance index function;
α, β = the weight of delay and emissions, respectively;
D, E = the average delay per vehicle and total amount of emissions, respectively; and
D_I, E_I = the initial values of the delay of the signal timing and the emissions, respectively.

The weights α, β reflect the relative significance of the two indexes. They are based on the views of a group of experts [6]. In this study, three values of relative weights are considered: α = 0.5, β = 0.5; α = 0.6, β = 0.4; and α = 0.7, β = 0.3.

3.5.2. Optimization of signal cycle time

A proper cycle time can ensure that vehicles move through an intersection in an orderly and smooth manner. When traffic flow is low, the cycle length should be small (i.e., generally no less than 15n, where n is the number of signal phases of the intersections) because a short period of time can cause vehicles to queue in the intersection, thus affecting traffic safety. When traffic flow is high, the capacity should be the highest priority, and the cycle time should be long but not more than 100 seconds, considering the psychology of driver to accept the longer red light without too much impatience [9]. Shorter cycle time for an isolated intersection should be considered to minimize vehicle queues on the streets. Preferably, it ranges between 35 and 60 seconds. Although, when approach volumes are very high, it is necessary to use longer cycle time. However, cycle times should not be exceeded 120 seconds, since very long cycle times will result in excessive delay [17]. As a result, the value of the cycle time should be defined as follows:

$$15n \leq C \leq 100 \text{ sec} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

The optimized cycle time (C_0) can be obtained by minimizing the performance index function (PI). The optimization process used in this study is shown in Figure 6.

After the optimization process, the cycle time which meets the minimum value of PI can be obtained. Next, the principle of equal saturation is adopted to determine the signal timing design for the intersection and choose the optimized timing instead of the original timing [17]. This principle is expressed as follows:

$$\frac{g_n}{\sum_{n=1}^{N} g_n} = \frac{y_n}{\sum_{n=1}^{N} y_n} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

where n is the n[th] critical signal phase; g_n is the effective green time in second; y_n is the flow ratio; and N is the number of critical phases.

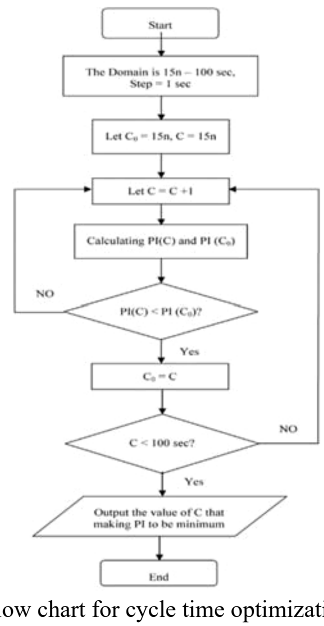


Fig. 6 - Flow chart for cycle time optimization [9]

4. Data collection and preliminary analysis

In addition to the field delay time and vehicle emissions, other basic data were collected for calculating theoretical delay time. These data are: geometric characteristics, traffic volume and signal phasing and timing.

4.1. Site selection

Three-leg (T) intersection is the most common intersection design in Egypt [18]. Therefore, the objective of this paper is focused on the impact of delay times on emissions at signalized intersections in Egypt. To achieve this objective, a three leg-signalized intersection was selected at an important location in Kafr El-Shekih City. The selected intersection is presented in Figure 7.

4.2. Geometry data

Geometric characteristics of the selected intersection are given in Table 1. Geometric characteristics include intersection type, number of lanes, lane width, median width and sidewalk width.

4.3. Traffic counts and composition

Traffic volumes for the intersection must be specified for each movement on each approach. Data collection was carried out in working days during the daylight hours. During data collecting periods, the weather was clear and the pavement was dry. Traffic counts were collected manually from 8.00 A.M. to 4.00 P.M. for every 15-minute time intervals. Traffic was classified into two vehicle classes: passenger cars which included private cars and taxis and light good vehicles which contained light trucks (pick up) and microbuses.

From count survey, it can be noticed that most traffic is composed of cars. The traffic volumes data of the selected intersection for all approaches are given in Table 2.

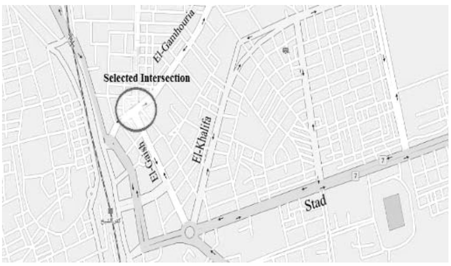


Fig. 7 - The selected intersection for the study (From Google Maps)

Tab.1 - Geometric characteristics of the selected intersection

Approach	Movement	No. of Lanes	Average Lane Width (m)	Average Median Width (m)	Average Sidewalk Width (m)
Eastbound	Left-turn	1	3.50	4.00	1.35
	Through	1			
Westbound	Right-turn	1	3.50	2.55	1.35
	Through	1			
Southbound	Left-turn	1	3.25	2.00	1.70
	Right-turn	1			

Tab. 2: Traffic volumes of the selected intersection for all approaches

Time Period	Traffic Volume (Veh/hr)								
	Eastbound Approach			Westbound Approach			Southbound Approach		
	Total	Left-turn	Through	Total	Right-turn	Through	Total	Left-turn	Right-turn
08:00 AM : 09:00AM	824	105	719	412	87	325	388	174	214
09:00 AM : 10:00AM	876	112	764	514	95	419	462	172	290
10:00 AM : 11:00 AM	908	136	772	495	80	415	433	180	253
11:00 AM: 12:00 PM	984	94	890	704	81	623	539	197	342
12:00 PM : 01:00 PM	822	101	721	608	91	517	502	184	318
01:00 PM : 02:00 PM	845	109	736	618	88	530	515	181	334
02:00 PM : 03:00 PM	782	115	667	584	84	500	485	175	310
03:00 PM : 04:00 PM	702	109	593	455	79	376	412	168	244
PHV*	1102	155	947	719	96	623	539	197	342
PHF**	0.908	0.901	0.915	0.848	0.889	0.807	0.880	0.879	0.881

*PHV = Peak-hour Volume
**PHF=PHV/Qmax, (Q_{max} = 4 × highest volume/interval of 15min.).

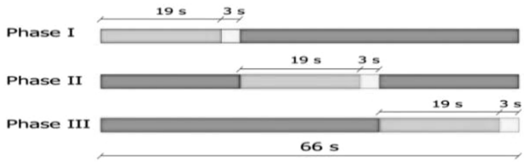


Fig. 8 - Existing timing plan of the selected intersection

4.4. Signal phasing and timing

In Kafr El-Sheikh City, to control the traffic operations, traffic signals are operating in a fixed-timed mode. The traffic signal is operating in a fixed-timed mode with a total cycle time of 66 s. Three phases are used at the selected intersection. The existing timing plan of the selected intersection is illustrated in Figure 8. The signal phasing is consisting of 19, 3, and 44 s for the green, yellow and red indications respectively.

5. Vehicle delays and exhaust emissions

The study used GPS device to record second by second vehicle activity such as instantaneous speed and acceleration. The emissions data obtained using Gas analyser instrument include CO, NO_X and HC. Figures 9 and 10 show examples of speed profile, time-space diagram, acceleration profile and vehicle emissions without stopped delay and with stopped delay for left-turn movement of eastbound direction at the selected intersection respectively. Examples of the results of delay components and exhaust emissions at the selected intersection are presented in Tables 3 and 4 respectively. Furthermore, Table 5 presents the descriptive statistics for the exhaust emissions and control delay component.

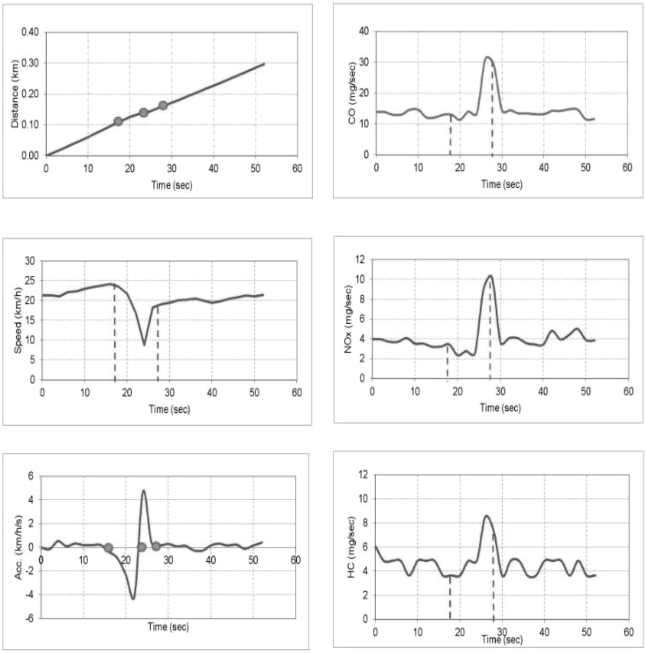


Fig. 9 - Example of speed profile, time–space diagram, acceleration profile and vehicle emissions without stopped delay for left-turn movement of eastbound direction at the selected intersection

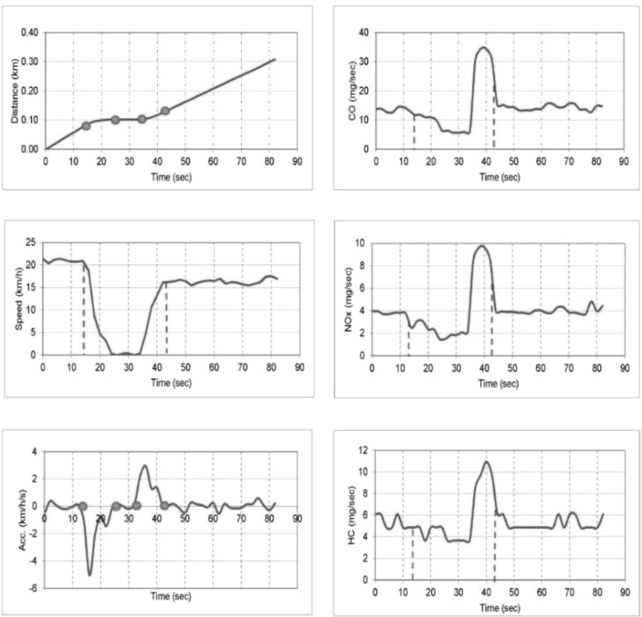


Fig. 10 - Example of speed profile, time–space diagram, acceleration profile and vehicle emissions with stopped delay for left-turn movement of eastbound direction at the selected intersection

Tab. 3 - Examples of delay computation results for sampled runs of eastbound approach at the selected intersection

Sample No.	Deceleration Delay (sec)	Stopped Delay (sec)	Acceleration Delay (sec)	Control Delay* (sec)
Left-turn Movement				
1	6.4	10.0	5.4	21.8
2	4.4	21.0	3.6	29.0
3	1.2	0.0	0.2	1.4
4	7.2	8.0	7.0	22.2
5	2.2	0.0	0.2	2.4
6	4.0	0.0	2.6	6.6
7	7.4	45	4.4	56.8
8	2.4	0	0.6	3.0
9	7.0	9	5.4	21.4

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

Tab. 4 - Examples of vehicle emissions results for sampled runs at eastbound approach

Sample No.	During Delay Events			During Non-Delay Events		
	CO (mg/sec)	NO_X (mg/sec)	HC (mg/sec)	CO (mg/sec)	NO_X (mg/sec)	HC (mg/sec)
Left-turn Movement						
1	14.81	4.05	5.68	14.04	3.92	5.32
2	14.26	4.05	4.55	14.06	3.90	4.48
3	19.86	5.37	5.85	13.50	3.83	4.45
4	19.96	5.63	6.09	14.27	3.93	4.74
5	16.59	4.02	5.12	13.43	3.93	4.30
6	17.28	4.14	5.36	13.63	3.98	4.36
7	14.65	4.10	5.27	13.84	3.87	5.11
8	19.82	5.84	6.09	13.74	4.07	4.32
9	16.03	4.55	5.71	13.97	3.88	5.03

Tab. 5 - Descriptive statistics of exhaust emissions per vehicle and control delay components

	Variable	Sample Size	Mean	SD	Max.	Min.
Exhaust Emissions	**CO (mg/sec)**	56	19.79	3.08	25.22	14.10
	NO_X (mg/sec)	56	5.10	0.77	6.94	3.70
	HC (mg/sec)	56	5.89	0.58	7.31	4.55
Control Delay Components	**Stopped Delay (sec)**	56	3.82	9.29	46.00	0.00
	Deceleration Delay (sec)	56	4.69	2.56	10.60	0.60
	Acceleration Delay (sec)	56	4.93	2.95	11.20	0.20

6. Development of signal timing model

The geometric characteristics, signal timing plan and traffic flow data of the selected intersection were used as inputs into the micro-simulation software VISSIM V. 7.00 [13] to model and evaluate the traffic signal control performance and the average vehicle emissions.

6.1. Model calibration and validation

Initially, simulation runs were executed with the default parameters of VISSIM (i.e. with no calibration) for the selected intersection. The delay and vehicle emissions values resulted from simulation were determined and compared with the observed data. The values of percent error for the initial simulation runs are presented in Table 6. The results indicated that, running the model with the default parameters would not be appropriate and hence, the speed distributions of all vehicle classes had to be edited in the simulation model.

To calibrate the model, the desired speed distribution was manually edited for all vehicle classes to closely match the observed data. The model was re-run again and the simulated delay and vehicle emissions of the calibrated model were determined. Again, percent errors were computed for the calibrated model; the results are presented in Table 6. From this table, it was found that, the percent error measurements were below 10% indicating a reasonable matching between the simulated and the observed data. The model calibration was considered to be successfully completed. Validation of the simulation model is the next step to make sure that the model replicates field conditions for another approach of the selected intersection.

To validate the model, the simulated delay and vehicle emissions of the calibrated model for westbound approach were compared to the observed data. Percent error measurements were computed and presented in Table 7. As shown in this table, the percent error measurements were below 10% indicating a reasonable matching between the simulated and the observed data. Therefore, it can be concluded that, the model is successfully calibrated and validated.

Tab. 6 - Results of percent error measurements of delay and vehicle emissions per vehicle of eastbound approach for model calibration

Movements	**Observed**	**Simulated**	**Error (%)**	**Observed**			**Simulated**			**Error (%)**
	Average Delay (sec)			**CO mg/sec**	**NO_X mg/sec**	**HC mg/sec**	**CO mg/sec**	**NO_X mg/sec**	**HC mg/sec**	
Before Calibration										
Through	6.56	5.62	14.33	20.89	5.29	6.03	26.76	4.97	6.49	18.64
Left-turn	18.29	18.36	0.38	17.03	4.64	5.52	20.52	3.81	4.99	7.83
After Calibration										
Through	6.56	6.09	7.16	20.89	5.29	6.03	23.69	4.39	5.76	5.07
Left-turn	18.29	18.50	1.15	17.03	4.64	5.52	20.49	3.80	4.98	7.64

Tab. 7 - Results of percent error measurements of delay and vehicle emissions per vehicle of westbound approach for model validation

Movements	**Observed**	**Simulated**	**Error (%)**	**Observed**			**Simulated**			**Error (%)**
	Average Delay (sec)			**CO mg/sec**	**NO_X mg/sec**	**HC mg/sec**	**CO mg/sec**	**NO_X mg/sec**	**HC mg/sec**	
Through	19.84	19.21	3.18	19.86	5.11	5.97	23.37	4.34	5.67	7.89
Right-turn	8.38	8.49	1.31	20.70	5.32	6.07	22.65	4.20	5.50	0.82

6.2. Optimization process results

After conducting the calibration and validation processes, the proposed model was applied to obtain the initial delay and vehicle emissions of the intersection. The initial average delay per vehicle and the initial total vehicle emissions of the intersection were calculated at initial cycle time equals 15n (45 sec). The values of initial average delay per vehicle and initial total vehicle emissions were determined to be 9.71 sec and 1521.36 gm respectively.

To perform the optimization process of signal cycle time (C), the calculation procedure for performance index function (PI) were repeated several times. Next, the cycle time that meets the minimum value of PI can be obtained. Figure 11 shows the changes in PI as the cycle time changes ($\alpha = 0.6$, $\beta = 0.4$). For more illustration of the convergence pattern of the optimization process, the PI values were calculated starting from cycle time with 40 sec instead of 45 (15n) sec.

From Figure 11, it can be noticed that C = 46 sec yields the minimum PI. Also, the other different values of relative weights gave that C = 46 sec yields the minimum PI. This cycle time is less than the original (66 sec) and within the limits defined earlier, that allows the driver to accept the longer red light without too much impatience.

After that, the principle of equal saturation was used to determine the optimal timing plans. Figure 12 shows the optimized timing plan of the selected intersection.

6.3. Comparison of delay and emissions before and after optimization

To determine the effect of optimizing the delay and vehicle emissions, the selected intersection was simulated before and after changing the timing plans of signals. Table 8 shows the comparison of the delay and vehicle emissions based on the simulations before and after changing the timing plans of signals.

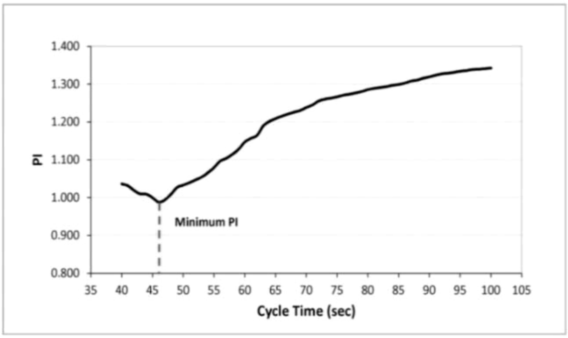


Fig. 11 - Changes of PI with the cycle time ($\alpha = 0.6$, $\beta = 0.4$)

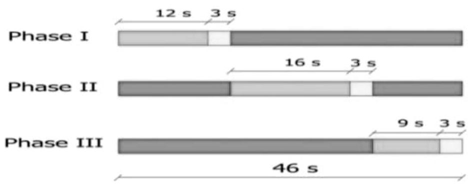


Fig. 12 - Optimized timing plan of the selected intersection

Tab. 8 - Average delay per vehicle and total vehicle emissions of the intersection before and after optimization

	Delay (sec/veh)	CO (gm)	NO_X (gm)	HC (gm)
Before	9.13	1038.56	202.10	240.70
After	9.11	1020.96	198.64	236.62
Improvement %	0.22	1.69	1.71	1.70

Tab. 9 - Impact of traffic flow on optimum cycle time

Traffic Flow	Delay (sec/vehicle)	Exhaust Emissions			Optimum Cycle Time (sec)
		CO (gm)	HC (gm)	NO_X (gm)	
80% of Actual	8.51	1019.97	198.43	236.39	41
90% of Actual	8.72	1029.23	200.24	238.54	44
Actual	9.13	1038.57	202.06	240.70	46
110% of Actual	9.62	1048.10	203.90	242.89	51
120% of Actual	10.20	1068.61	207.91	247.66	54

From Table 8, it was found that there is an improvement for both the delay and vehicle emissions after optimization. The delay values are calculated per vehicle, consequently the aggregated improvement for total number of vehicles is significant. Such findings agree with those reported by other researchers, such as Lin et al. [9]. It can be concluded that, the changing of signal timing is effective for improving the operational and environmental performance of the traffic signal under study.

6.4. Impact of traffic flow on optimum cycle time

To quantify the impact of traffic flow on optimum cycle time four different percentages of traffic flow were analyzed; 80%, 90%, 110% and 120% of the actual traffic flow. Table 9 shows the values of delay, exhaust emissions and optimum cycle time for different percentages of traffic flow. From this table, it was found that when the traffic flow rate is higher, the optimal cycle time corresponding to the performance index function increases.

7. Conclusions and recommendations

This paper described the optimization process of delay times and exhaust emissions at signalized intersections. A three leg signalized intersection was selected at an important location in Kafr El-Sheikh City, Egypt. Field delay times and vehicle emissions were measured simultaneously for all movements of all approaches at the selected intersection. The micro-simulation model was developed for the selected intersection. Then, it was calibrated and validated using the collected data. The developed model was used to reduce vehicle delays and exhaust emissions. The signal cycle time and green time were optimized using the developed model based on performance index function. There is an optimum cycle time that corresponding to minimum performance index function, when the signal cycle time increases from 40 to 100 sec. Finally, the optimization of signal timing is effective in improving the operational and environmental performance of the traffic signal under study. Furthermore, optimum cycle time increased with the increase of traffic flow. Optimization of the delay times and exhaust emissions gives traffic engineers the option of improving traffic quality and reducing exhaust emissions. A future extension of this work should be conducted on different types of intersections with a wide range of traffic and geometric conditions.

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