The Investigation of the Effect of Saturation Flow on the Average Vehicle Delay at Signalized Intersections

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Abstract

Saturation flow (*s*) is one of the most important parameters used for determining of signal timings at signalized intersections. Therefore, this parameter directly affects the various intersection performance criteria such as queue length, average delay, the level of service and capacity. In this study, determination of the effect of saturation flow rate on the average vehicle delay is aimed.

In the scope of the study, firstly, an optimization model which minimizes the average vehicle delay at the intersection is set. Then, a software which optimizes the signal timings at the intersection by using Differential Evolution Algorithm (DEA) is prepared in MATLAB environment. In the second stage, 15 traffic volume scenarios which have different total traffic volume from each other for a four-leg signalized intersection are created in order to test different traffic cases. Created scenarios are classified in 3 groups as Low Volume (LV), Moderate Volume (MV) and High Volume (HV). In the next stage, each scenario is analyzed considering 9 different saturation flow rates (*s*=1600, 1650, 1700, 1750, 1800, 1850, 1900, 1950, 2000 vehicle/hour/lane), separately. In case of implementing of these saturation flow rates, obtained signal optimum timings and average vehicle delay for each scenario are evaluated in details. In the last stage of the study, the average vehicle delays obtained by using s=1800 vehicle/hour/lane which is frequently encountered in many studies in the literature are compared with the average vehicle delays obtained by using other saturation flow rates, relatively.

As a result of the comparisons, it is determined that the differences between average vehicle delays are quite low (between -0.9% and +1.2%) in case of Low Volume. In case of Moderate Volume, differences between -20.8% and +37.2% are seen. In case of High Volume, it can be said that the differences change between -41.4% and +116.3%. This situation clearly demonstrate that accurate and faultless measurement of saturation flow rate is quite important in terms of the performance of the intersection, especially in case of moderate and high volume.

Keywords: Saturation flow, Delay, Differential evolution algorithm, Signalized intersection, Capacity

1. INTRODUCTION

Intersections are the critical areas of the road networks. Therefore, management of the traffic at these areas is a quite difficult issue. Especially at the intersections which have high traffic volumes, the movements of traffic flows are managed with signalization systems in generally. Effective and sustainable intersection management can be achieved by the proper and reasonable determination of the signal timings at the intersection. Average vehicle delay, noise pollution, exhaust emission and fuel consumption at the intersection may be decreased and the capacities of existing intersection approaches may be increased with an effective traffic signal control [1].

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One of the most important parameters used for determining of signal timings at signalized intersections is also saturation flow (s). Highway Capacity Manuel (HCM) defines saturation flow as the equivalent hourly rate at which previously queued vehicles can cross an intersection approach under prevailing conditions, assuming that; a green signal is available it all times and no lost time is experienced [2]. HCM assumes that after the fourth vehicle of a queue, vehicles have similar and stable headways. The average headway of vehicles after the fourth vehicle is used to compute saturation flow. The relationship between headway and vehicles in queue is presented in Figure 1.

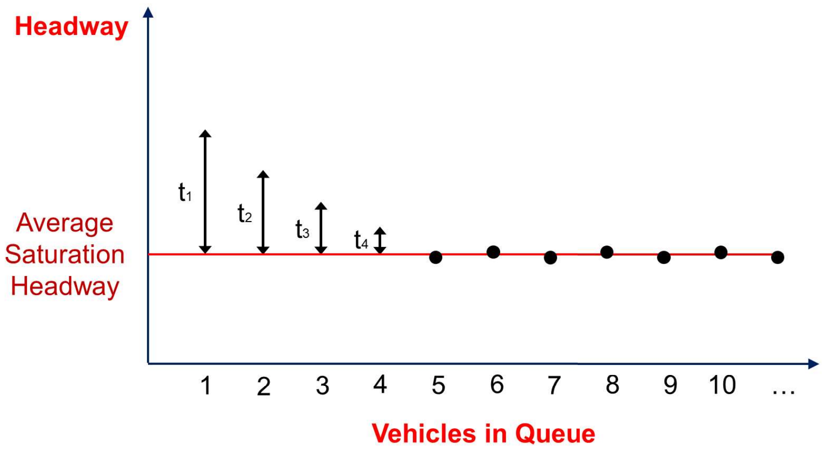

Figure 1. The Relationship between Headway and Vehicles in Queue [3]

As can be seen from the Figure 1, average saturation headway and saturation flow can be calculated by using the Eq. (1) and Eq. (2).

$$h = \frac{T_N - T_4}{N-4} \quad (1)$$

$$s = \frac{3600}{h} \quad (2)$$

In Eq. (1) and Eq. (2);
N : Last vehicle in a queue,
T_N : Time at which cross the stop line of the last vehicle in the queue,
T_4 : Time at which cross the stop line of the fourth vehicle in the queue,
h : Average saturation headway (sec.),
s : Saturation flow (veh/h/lane).

Saturation flow directly affects the various intersection performance criteria such as average vehicle delay, queue length, level of service and capacity. The measurement of the saturation flow in the field is difficult and tedious task. In generally, it is determined based on the field observations. Saturation flow is affected by some factors. The factors which are affecting the saturation flow are listed in Table 1.

Table 1. The Factors which are affecting the Saturation Flow [4-5]

Road Factors	Lane width
	Longitudinal grade
	Intersection design

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Traffic Factors	Vehicle type (heavy-light vehicle, motorcycle)
	Right-turn vehicles
	Left-turn vehicles
	Opposing straight traffic
	Crossing pedestrian
Surrounding Factors	Area characteristics
	Parking and stopping
	Bus stops

In the literature, various saturation flow values are suggested by different researchers or studies. When these studies are investigated carefully, it can be seen that saturation flow values show differences from the country to country. Even, these values can also show the big differences from an intersection to another intersection in the same country. Suggested saturation flow values by different researchers or studies are listed in Table 2.

Table 2. Suggested Saturation Flow Values by Different Researchers or Studies

Researchers or Studies	Country	Saturation flow (veh/h/lane)
Webster and Cobbe [6]	England	1800
Miller [7]	Australia	1710
Shoukry and Huizayyin [8]	Egypt	1617
HCM [2]	USA	1800 – 1900
Dundar and Ogut [9]	Turkey	1894
Hussain [10]	Malaysia	1945
Hamad and Abuhamda [11]	Qatar	2323
Potts et al. [12]	USA	1736 – 1913
Caliskanelli and Tanyel [13]	Turkey	1720
Nııttymaki and Pursula [14]	Finland	1800 – 2475
Shao et al. [15]	China	1450 – 1800
Transportation Research Board [5]	USA	1800
Coeyman and Meely [16]	Chili	1603
Aoyama et al. [17]	Japan	1800 – 2000
Joseph and Chang [18]	USA	1850 – 1950

From the Table 2, it is seen that the saturation flow value per lane change between 1600 veh/h and 2000 veh/h, in generally. Therefore, 9 different saturation flow rates (s=1600, 1650, 1700, 1750, 1800, 1850, 1900, 1950, 2000 veh/h/lane) within this range are considered in the analyses made in the scope of this study. In this way, the effect of saturation flow on the average vehicle delay at signalized intersections is researched.

This study consists of five parts. In the next part, performance criteria (delay) is explained in details. In the third part, firstly, created optimization model is presented. Then, differential evolution algorithm is introduced in briefly. Analyses and analyses results are included in the fourth part. In the last part, the findings obtained from the results are evaluated and interpreted.

2. PERFORMANCE CRITERIA: DELAY

Experienced lost time by the drivers at the intersections can be described as Delay. Delay is one of the most important parameters used for determining the level of services and performances of signalized intersections [19]. The main components of this parameter is shown in Figure 2.

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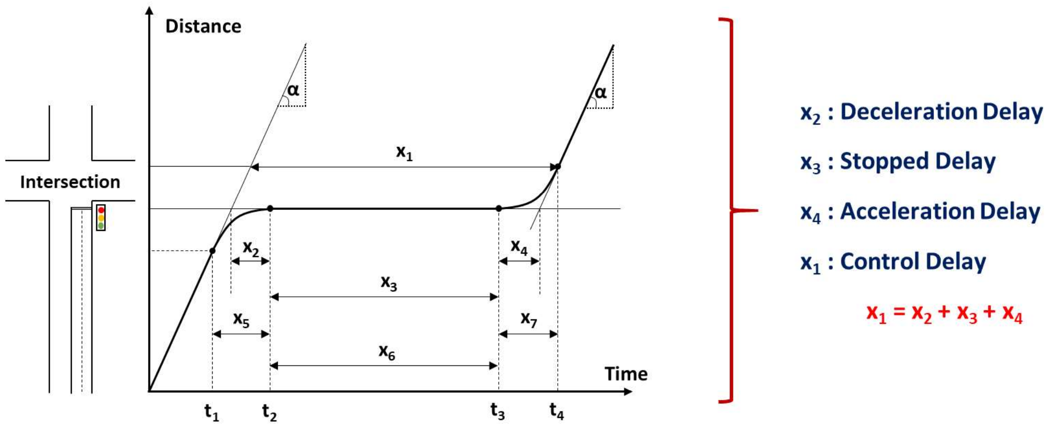

Figure 2. The Main Components of Control Delay

Webster, Highway Capacity Manuel (HCM) and Australian (Akcelik) delay models are most used and well-known delay models. In Webster and HCM models, optimum signal timings are determined considering phase-based approach. Whereas, in Akcelik delay model, optimum signal timings are determined considering movement (lane)-based approach. In this study, lane-based traffic volumes are taken into account for the optimization of signal timings. Therefore, Akcelik delay model is used in optimization process. In Akcelik delay model, total delay, average overflow queues and average vehicle delay can be calculated by using Eqs. (3) – (5), respectively.

$$TD = \frac{qC \times (1-\alpha)^2}{2 \times (1-y)} + N_o \beta \tag{3}$$

$$N_o = \begin{cases} \frac{QT_f}{4}\left(z + \sqrt{z^2 + \frac{12(\beta - \beta_o)}{QT_f}}\right), & \beta \geq \beta_o \\ 0 & , \quad \beta < \beta_o \end{cases} \; ; \; z = \beta - 1 \; ; \; \beta_o = 0.67 + \frac{sg}{600} \tag{4}$$

$$d = \frac{TD}{q} \tag{5}$$

In Eqs. (3) – (5);
TD : Total delay (sec.),
q : Flow (veh/sec.),
C : Cycle time (sec.),
α : Green time ratio,
y : Flow ratio,
s : Saturation flow (veh/h/lane),
β : Degree of saturation,
N_o : Average overflow queue,
Q : Capacity (veh/sec.)
T_f : Flow period,
β_o : Degree of saturation below which the average overflow queue is approximately 0,
g : Effective green time (sec.),
d : Average vehicle delay (sec./veh).

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3. OPTIMIZATION MODEL AND DIFFERANTIAL EVOLUTION ALGORITHM

3.1 Optimization Model

In this study, firstly, a signalized intersection model which have four approaches is created for the analyses. This model includes a total of ten lanes. The created signalized intersection model plan is depicted in Figure 3.

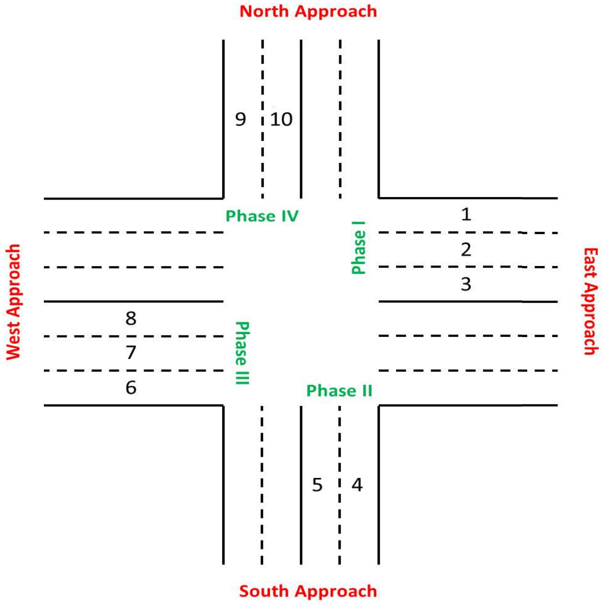

Figure 3. The Created Signalized Intersection Model Plan

In the next stage, an optimization model which minimizes average vehicle delay at the intersection is set. Objective function, decision variables, green time constraints, cycle length constraint and degree of saturation constraints for this optimization model is presented in Table 3 in details.

Table 3. Created Optimization Model for the Minimization of Average Vehicle Delay

Objective Function $t = 1,2,....,10$ (t : Total number of traffic flows at the intersection)	$f = \min\left(d = \dfrac{\sum_{a=1}^{t} TD_a}{\sum_{a=1}^{t} q_a} \right)$
Decision Variables $c = 1,2,....,4$ (c : Phase no)	g_c : Green time of phase c (sec.)
Green Time Constraint $c = 1,2,....,4$ (c : Phase no)	$7 \le g_c \le 45$ (sec.)
Cycle Length Constraint	$48 \le C \le 200$ (sec.)
Degree of Saturation Constraint $t = 1,2,....,10$ (t : Total number of traffic flows at the intersection)	$0 \le \beta \le 1.25$

As can be seen from Table 3, green signal timings are constrained between 7 sec. and 45 sec. In addition to this, the degree of saturation value for each lane is constrained with a maximum of 1.25 to investigate the oversaturated traffic conditions [19].

3.2 Differential Evolution Algorithm

Optimization problems can be solved by using deterministic and stochastic techniques. Because stochastic techniques (meta-heuristic optimization algorithms) are easy, effective and flexible, they are used for solving of the many engineering problems [20]. Therefore, in this study, Differential Evolution Algorithm which is one of the evaluation based meta-heuristic algorithms is preferred. The basic steps of Differential Evolution Algorithm are shown in Figure 4.

Initialization
Evaluation
Repeat
    Mutation
    Recombination
    Evaluation
    Selection
Until
Termination criteria is met

Figure 4. The Basic Steps of Differential Evolution Algorithm

There are four control parameters in Differential Evolution Algorithm. They are population size, mutation factor, crossover rate and maximum iteration number. In this study, these parameters are selected as: 50, 0.8, 0.8 and 1000 considering the previous studies in the literature [21].

4. ANALYSES

In this part of the study, firstly, 15 traffic volume scenarios which have different total traffic volume from each other for a four-leg signalized intersection are created in order to test different traffic cases. It is assumed that the traffic volume for each lane is the same. Total traffic volumes for created scenarios are shown in graphically in Figure 5.

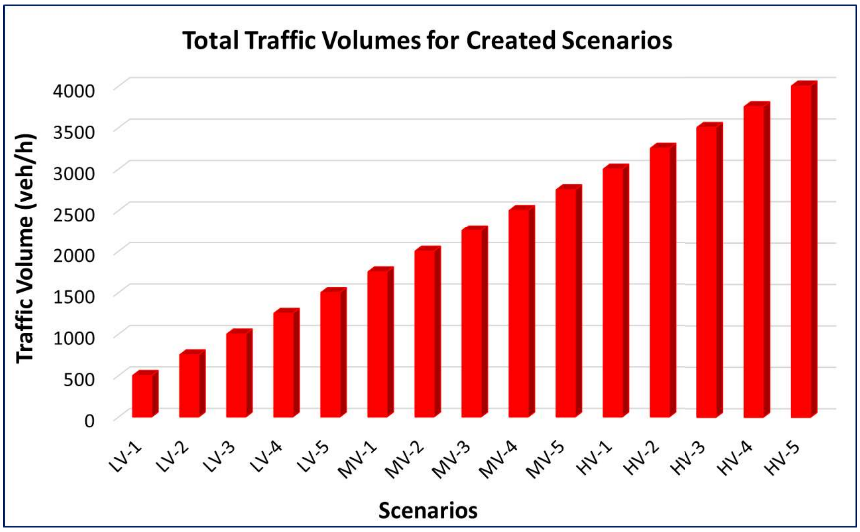

Figure 5. Total Traffic Volumes for Created Scenarios

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As can be seen from the Figure 5, created scenarios are classified in 3 groups as Low Volume (LV), Moderate Volume (MV) and High Volume (HV). In this way, it becomes possible to make an assessment on a group basis.

In the second stage, each scenario is analysed considering 9 different saturation flow rates (s=1600, 1650, 1700, 1750, 1800, 1850, 1900, 1950, 2000 vehicle/hour/lane), separately. For some sample cases and scenarios, in case of implementing of these saturation flow rates, obtained optimum signal timings are shown in Table 4.

Table 4. For Some Sample Cases and Scenarios, Obtained Optimum Signal Timings

Saturation Flow Rate (*s*)		**1650**	**1750**	**1850**	**1950**
Signal Timings (sec.) PI – PII – PIII – PIV – Cycle T.	**LV-1**	7-7-7-7-48	7-7-7-7-48	7-7-7-7-48	7-7-7-7-48
	LV-4	7-7-7-7-48	7-7-7-7-48	7-7-7-7-48	7-7-7-7-48
	MV-2	12-12-12-12-68	10-10-10-10-60	9-9-9-9-56	8-8-8-8-52
	MV-5	21-20-21-20-102	19-18-19-18-94	16-15-16-15-82	15-14-15-14-78
	HV-2	34-33-34-33-154	28-27-28-27-130	24-23-24-23-114	21-20-21-20-102
	HV-4	45-43-45-43-196	45-44-45-44-198	37-36-37-36-166	30-29-30-29-138

PI: Phase I / **PII**: Phase II / **PIII**: Phase III / **PIV**: Phase IV
Yellow time: 2+2=4 sec. (at start and finish of each phase)
All red time: 1 sec. (at each phase transition)

In the third stage, the average vehicle delay values for all scenarios considering 9 different saturation flow rates are obtained. The results are demonstrated in Figure 6.

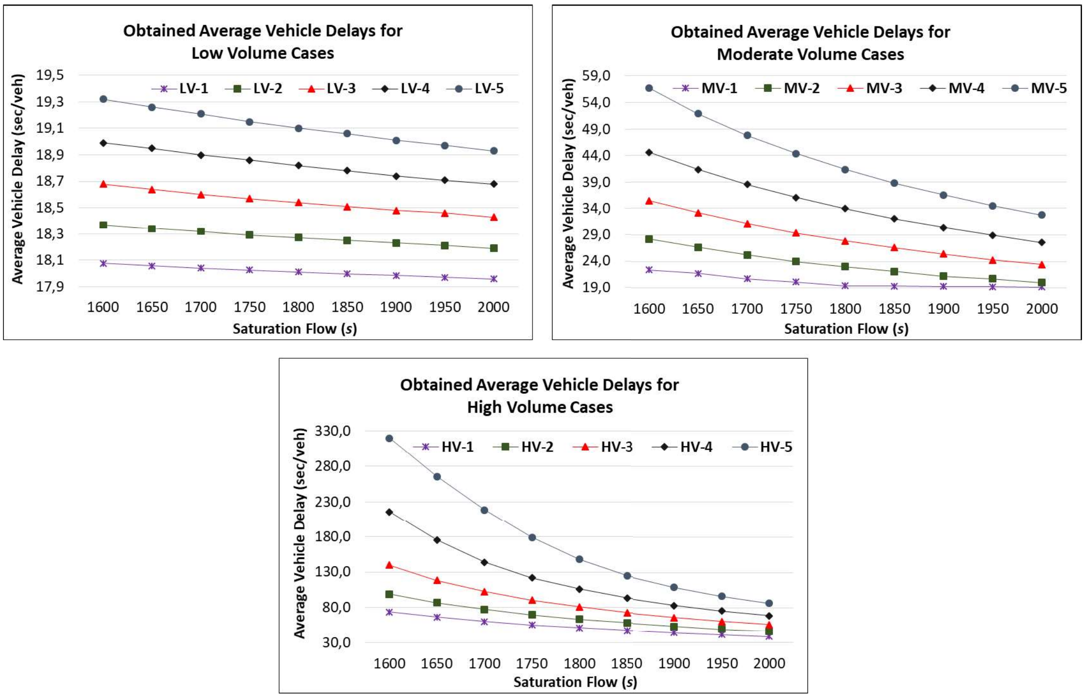

Figure 6. Average Vehicle Delays for Low, Moderate and High Volume Cases

In the last stage of the study, the average vehicle delays obtained by using *s*=1800 veh/h/lane which is frequently encountered in many studies in the literature are compared with the average vehicle delays obtained by using other saturation flow rates, relatively. The comparison results are shown in Figure 7.

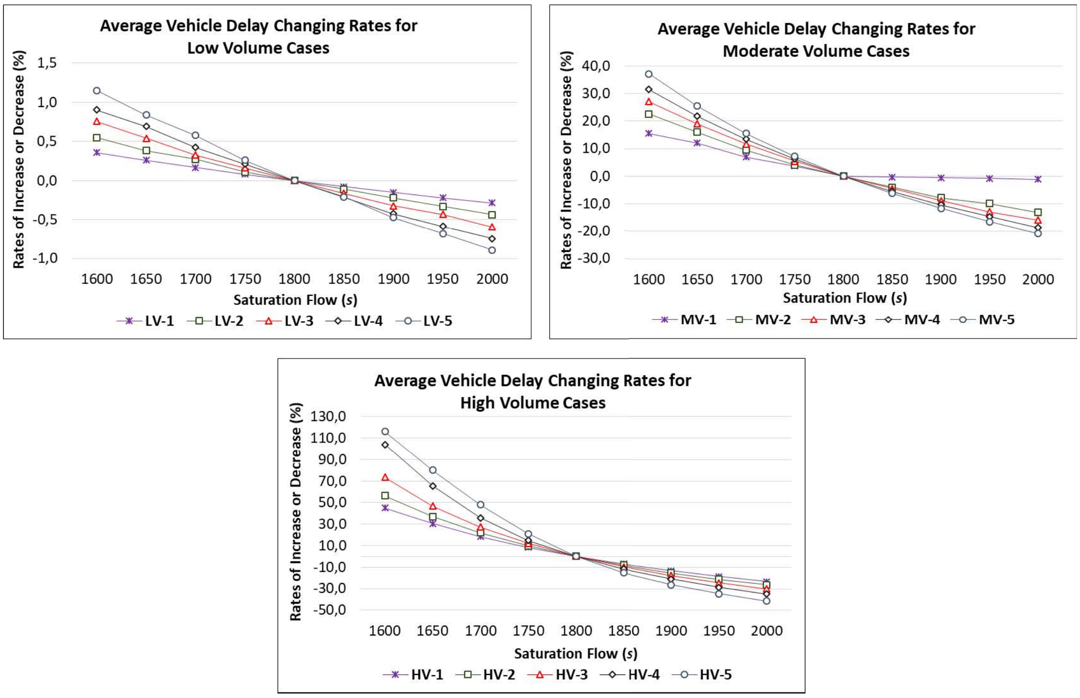

Figure 7. Average Vehicle Delay Changing Rates for Low, Moderate and High Volume Cases

5. RESULTS AND DISCUSSION

In this study, the effect of saturation flow rate on average vehicle delay is investigated. As a result of the comparison, it is determined that;

- For Low Volume cases, the differences between average vehicle delays are quite low. They are between -0.9% and +1.2%.
- For Moderate Volume cases, the differences between average vehicle delays are between about -20.8% and +37.2%.
- For High Volume cases, the differences between average vehicle delays are quite high. They are between -41.4% and +116.3%.

From the obtained numerical results, it can be understood that the differences also increase when the total traffic volume at the intersection increase. This situation clearly demonstrate that accurate and faultless measurement of saturation flow rate is quite important in terms of the performance of signalized intersections, especially in case of moderate or/and high volume cases.

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