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Investigation of the discharge flow rate patterns at real-time traffic signal control intersections

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Abstract

This study investigates the effects of variable queue lengths and green times on discharge flow rates at real-time managed intersections in Mersin, Turkey. For this purpose, traffic flow data were collected at two different signalized intersections during morning peak hours for two days. The traffic data including the time headways, queue lengths for each cycle were derived from video records via MATLAB coding while the signal timing data were obtained from Mersin Metropolitan Municipality. The impact of variable queue lengths and green times on discharge flow rate were evaluated separately via analysis of variance (ANOVA) tests. The results indicated that time headways of the first vehicles in the queue were statistically larger than the time headways of the remaining vehicles in the queue (p-value<0.05). On the other hand, the time headways of the remaining vehicles in the queue were not found statistically different at 95 confidence level (p-value>0.05). Furthermore, the effect of the variable green time on discharge flow rate revealed that the significant difference was only observed for the first twelve seconds of the green time.

1. Introduction

Traffic congestion has become one of the major problems of urban transportation as a result of the rapid increase in vehicle ownership. Geometrically well-designed signalized intersections and their appropriate management can reduce the consequences of this problem. Fixed-time and real-time signalization systems are used to manage the traffic flow in urban areas. However, fixed-time signalized systems have some drawbacks, when the traffic is oversaturated during the peak hours, which causes longer queue lengths. To eliminate these problems, traffic engineers have developed signalized systems that manage intersections with real-time traffic flow data. In these systems, the green times of the approach legs are determined by considering the instant traffic demand.

Discharge flow rate and saturation flow can be used to evaluate performance of the signalized intersections. The relationship of between these two parameters, green time, queue length and intersection geometry have been studied in many studies in the literature. Khosla and Williams [1] found that discharge flow rate tends to decrease after the 60 seconds of green time, but it is not statistically significant. Denney et al. [2] concluded that as the green time increases, the discharge flow rate decreases. On the other hand, Lin and Thomas [3] stated that the discharge flow rate increases with increase in effective green time. Stanić et al. [4] concluded that discharge flow rate of the first four vehicles in the queue is significantly lower than the discharge flow rate of the other vehicles in the queue. More specifically, it was observed that discharge flow rate increases 10% to 15% after the first four vehicles. Chaudhry and Ranjitkar [5] observed the increasing trend in discharge flow rate toward the back of the queue. This result was also supported by other studies [6-7]. On the other hand, some studies concluded that discharge flow rate decreases toward the back of the queue [8-10].

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A majority of these studies have been carried out on intersections managed with fixed-time signalization systems, however, it is very limited for real-time managed intersections which is the main motivation of this research. This study aims to make a discussion on the effect of variable queue lengths and green times on traffic flow at real-time managed intersections. For this purpose, traffic flow data were collected at two different real-time managed signalized intersections during morning peak hours in Mersin, Turkey. Relations between green time and queue length and discharge flow rate were statistically investigated.

2. Study Area

To examine the effect of the variable queue lengths and green times on the discharge flow rate, two isolated intersections were selected on major arterials located in Mersin, Turkey (see Figure 1). These intersections are fully actuated and the green times were allocated based on the arrival flow rates. One of them was 4-leg (namely CNR) and the other one was roundabout (namely Kipa) as shown in Figure 1. The following points were considered while selecting these intersections:

- Intersections with three lanes in each approach were selected to minimize the effect of right and left turning vehicles.
- Intersections with low heavy vehicle volume were selected to reduce negative effects of heavy vehicles.
- Intersections with lower pedestrian movements were selected to eliminate negative effects of pedestrian movements.
- Intersection with smaller approach slopes (i.e., less than 2%) were selected to reduce negative effects of high slopes.

Video camera data were collected during the morning peak hours of 7:30-9:30 on October 8-9, 2019. The approach legs with higher arrival flow rates were considered, since the effect of variable green times can be observable only if the approach leg was under saturation flow condition. Thus, east, west and north approach legs were taken into consideration for the Kipa intersection, while only west approach leg was considered for the CNR intersection. In addition, the right and left turning vehicles were not considered for this study; thus, only the middle lane of each approach leg was analyzed.

Figure 1. General view of Kipa and CNR intersections

3. Methodology

Figure 2 presents the proposed methodology of the study. For each approach leg of the Kipa and CNR intersections, traffic flow video data and signal timing data (green and red times) were obtained from Transportation Department of the Mersin Metropolitan Municipality. Time headway of the vehicles passing through the green time were calculated by deciphering video camera records in MATLAB® programming software, will be later converted to the discharge flow rate. Note that only cycles with queue length greater than 8 vehicles were considered based on the Highway Capacity Manual recommendations [11]. In overall, 337 cycles were analyzed from two intersections (254 cycles for Kipa intersection and 83 cycles for CNR intersection) (see Table 1).

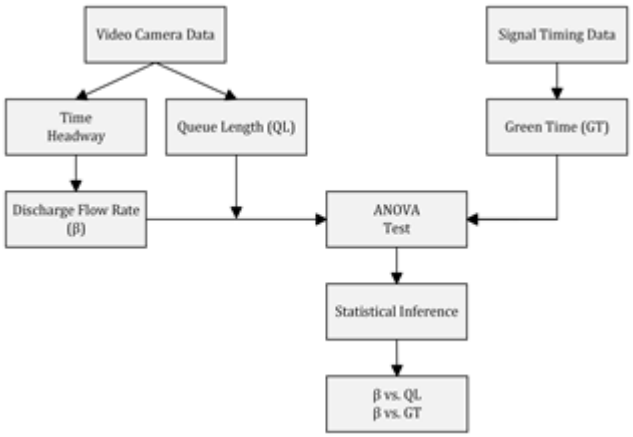

Figure 2. Methodological framework of the study.

Table 1. Traffic flow characteristics at Kipa and CNR intersections

Intersection		Kipa			CNR
Approach Leg		West	East	North	West
Number of Cycles		125	53	76	83
Green Time (sec.)	Min.	31	19	20	18
	Avg.	56	32	24	22
	Max.	72	35	30	33
Red Time (sec.)	Min.	30	48	54	63
	Avg.	46	67	76	69
	Max.	78	77	91	90
Cycle Time (sec.)	Min.	76	76	77	84
	Avg.	105	101	102	94
	Max.	130	114	120	111
Queue Length (veh./cycle/lane)	Min.	8	8	8	8
	Max.	25	15	15	13
Arrival Cycle Volume (veh./cycle/lane)	Min.	9	8	8	8
	Max.	33	15	15	16
Traffic Composition (%)	Car	94	91	95	93
	Minibus	5	3	3	5
	Others	1	6	2	2

To study effect of queue lengths, vehicles in the queue were grouped with four vehicles. Number of vehicles in each group (N), their average time headways ($\overline{h}$) and corresponding discharge flow rates (β) are presented in Table 2 and 3.

As it is seen in Table 2, 6 groups were obtained for Kipa intersection. The number of vehicles (N) in each group varies between 36 and 1.016 and the average time headways ($\overline{h}$) vary between 1.69 and 2.73 seconds (see Table 2.). In addition, 3 groups were obtained for CNR intersection. The number of vehicles (N) in each group varies between 126 and 332, and the average time headways ($\overline{h}$) vary between 1.75 and 2.35 seconds (see Table 2.).

Table 2. Discharge flow rate with respect to queue positions at Kipa intersection

Kipa	Queue Position					
	1–4	5–8	9–12	13–16	17–20	21–25
N	1,016	1,016	618	249	79	36
$\overline{h}$	2.73	2.03	1.91	1.85	2.03	1.69
β	1,319	1,773	1,885	1,946	1,773	2,130

Analysis of variance (ANOVA) test was used to study effects queue lengths on the discharge flow rates and the following hypothesis was tested at 0.05 significance level.

H_0: The time headways of the vehicles in all groups are the same.
H_1: Time headways of the vehicles in at least one group is different.

Table 3. Discharge flow rate with respect to queue positions at CNR intersection

CNR	Queue Position		
	1 – 4	5 – 8	9 – 13
N	332	332	126
$\overline{h}$	2.35	1.83	1.75
β	1,532	1,967	2,057

Since the green time ranges at Kipa and CNR intersections are significantly different, different green time intervals were used to analyze effects of green times on discharge flow rates at Kipa and CNR intersections. Specifically, Kipa intersection was analyzed with green time intervals of 12 seconds and CNR intersection was

analyzed with green time intervals of 6 seconds (see Figure 4). As an example, a total 801 were entered Kipa intersection from during the cycles with a green time between 25 and 35 seconds. 268 vehicles entered the intersection during the first 12 seconds of green time, 398 vehicles entered the intersection during the second 12 seconds of green time and 135 vehicles entered during the remaining green time period.

Analysis of variance (ANOVA) test was used to study effects variable green times on discharge flow rates and the following hypothesis was tested at 0.05 significance level.

H_0: Time headways of the vehicles during each 6 or 12 second intervals of the green time are the same.
H_1: Time headways of the vehicles during at least one the 6 or 12 second interval of the green time is different.

4. Results

The traffic composition was very similar for all approaches; almost 90% of the vehicles were private cars followed by the minibuses with 2.8%-4.7%. Cycle volume indicating the number of the passing vehicles during each cycle showed that arrival flow of the west direction of the Kipa intersection was almost twice of the other approaches. The higher green times were observed for the west direction of the KIPA intersection ranging from 31 sec to 72 sec with an average of 56 sec (see Table 4). The other approaches did not seem to be congested in which the green times were ranging from 20 sec to 35 sec. For the CNR intersection, green times ranged from 18 sec to 33 sec. Except for the west approach of Kipa intersection, the maximum queue lengths were almost same for the remaining three approaches with 13-15 vehicles (see Table 4). In this study, queue lengths were calculated based on the number of stopped vehicles at the end of the red time. The vehicles entering to the queue after the start of green time were not considered.

Table 4. Average time headways of vehicles at 12 and 6 second green time intervals at Kipa and CNR intersections

Green Time (sec.)	Green Interval (sec.) – Kipa Intersection											
	[0 – 12)		[12 – 24)		[24 – 36)		[36 – 48)		[48 – 60)		[60 – 72)	
	$\bar{h}$	N	$\bar{h}$	N	$\bar{h}$	N	$\bar{h}$	N	$\bar{h}$	N	$\bar{h}$	N
[15 – 25)	2.68	179	1.90	215	2.04	4	-	-	-	-	-	-
[25 – 35)	2.66	268	1.96	398	2.33	135	-	-	-	-	-	-
[35 – 45)	2.53	212	2.09	267	2.49	185	2.61	26	-	-	-	-
[45 – 55)	2.71	90	2.24	135	2.14	128	2.44	105	3.30	20	-	-
[55 – 65)	2.72	126	2.07	185	2.06	189	2.13	173	2.65	107	3.30	11
[65 – 75)	2.67	163	2.02	239	2.06	228	2.17	219	2.16	220	2.28	149
Green Time (sec.)	Green Interval (sec.) – CNR Intersection											
	[0 – 6)		[6 – 12)		[12 – 18)		[18 – 24)		[24 – 30)		[30 – 36)	
	$\bar{h}$	N	$\bar{h}$	N	$\bar{h}$	N	$\bar{h}$	N	$\bar{h}$	N	$\bar{h}$	N
[15 – 20)	2.59	40	1.92	66	1.76	66	2.12	6	-	-	-	-
[20 – 25)	2.49	80	2.08	131	1.78	139	1.89	88	-	-	-	-
[25 – 30)	2.87	18	2.20	35	1.91	40	1.63	40	2.04	10	-	-
[30 – 35)	2.18	14	2.24	20	1.89	23	1.68	24	1.77	22	1.69	5

4.1.The effects of queue length on discharge flow rate

The results obtained for Kipa and CNR intersections were consistent. It was found that the time headways of the first four vehicles in the queue were statistically larger than the time headways of the remaining vehicles in the queue (p-value<0.05). On the other hand, the time headways of the remaining vehicles in the queue were not statistically different (p-value>0.05).

Kipa intersection reached the maximum flow rate between 13th and 16th vehicles in the queue, which was about 1,950 veh/hour/lane (see Figure 3). Note that the number of vehicles in the last queue group in Kipa intersection was quite low. Therefore, it was not taken into consideration in determining the maximum discharge flow rate. The CNR intersection reached the maximum flow rate between 9th and 13th vehicles in the queue, which was about 2,050 veh/hour/lane (see Figure 3).

4.2. The effects of variable green time on discharge flow rate

For Kipa intersection, the time headways of the vehicles in the first 12 seconds of the green time were statistically larger than the time headways of the remaining vehicles during the green time (p-value<0.05).

On the other hand, it is not possible to say anything statistically about the relationship between other groups. This result indicated that the discharge flow during the first 12 seconds of the green time were lower than the discharge flow rates of remain green time period (see Figure 4). Therefore, it can be concluded that first few vehicles passing through in the first 12 seconds of the green time were subjected to significant initial losses.

For CNR intersection, the time headways of the vehicles in the first 6 seconds of the green time may said that statistically larger than the time headways of the remaining vehicles during the green time (p-value<0,05). On the other hand, it is not possible to say anything

statistically about the relationship between other groups. This result indicated that, the discharge flow during the first 6 seconds of the green time were lower than the discharge flow rates of remain green time period (see Figure 5). Therefore, it can be concluded that first few vehicles passing through in the first 6 seconds of the green time were subjected to significant initial losses. For the cycles with less than 25 seconds of green time, the maximum discharge flow rate was obtained between 12th and 18th second green. Otherwise, the maximum discharge flow rate was obtained between 18th and 24th second green (see Figure 5).

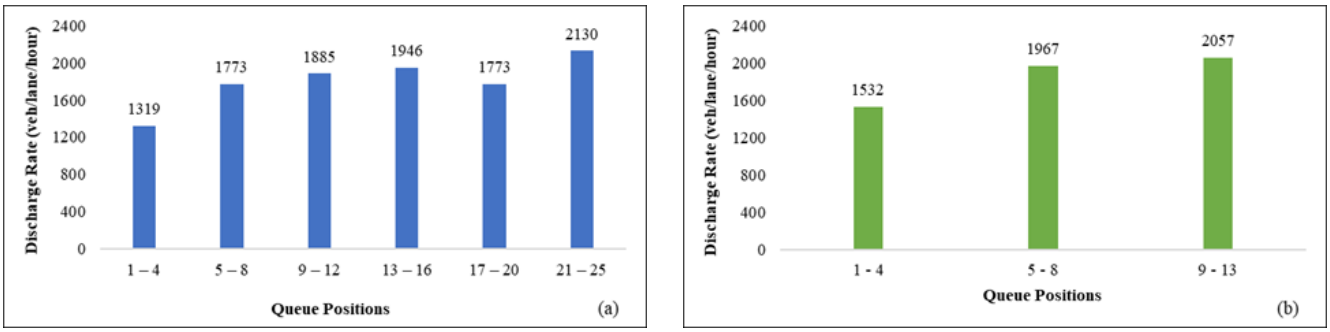

Figure 3. Discharge flow rates of queue groups at (a) Kipa and (b) CNR intersections

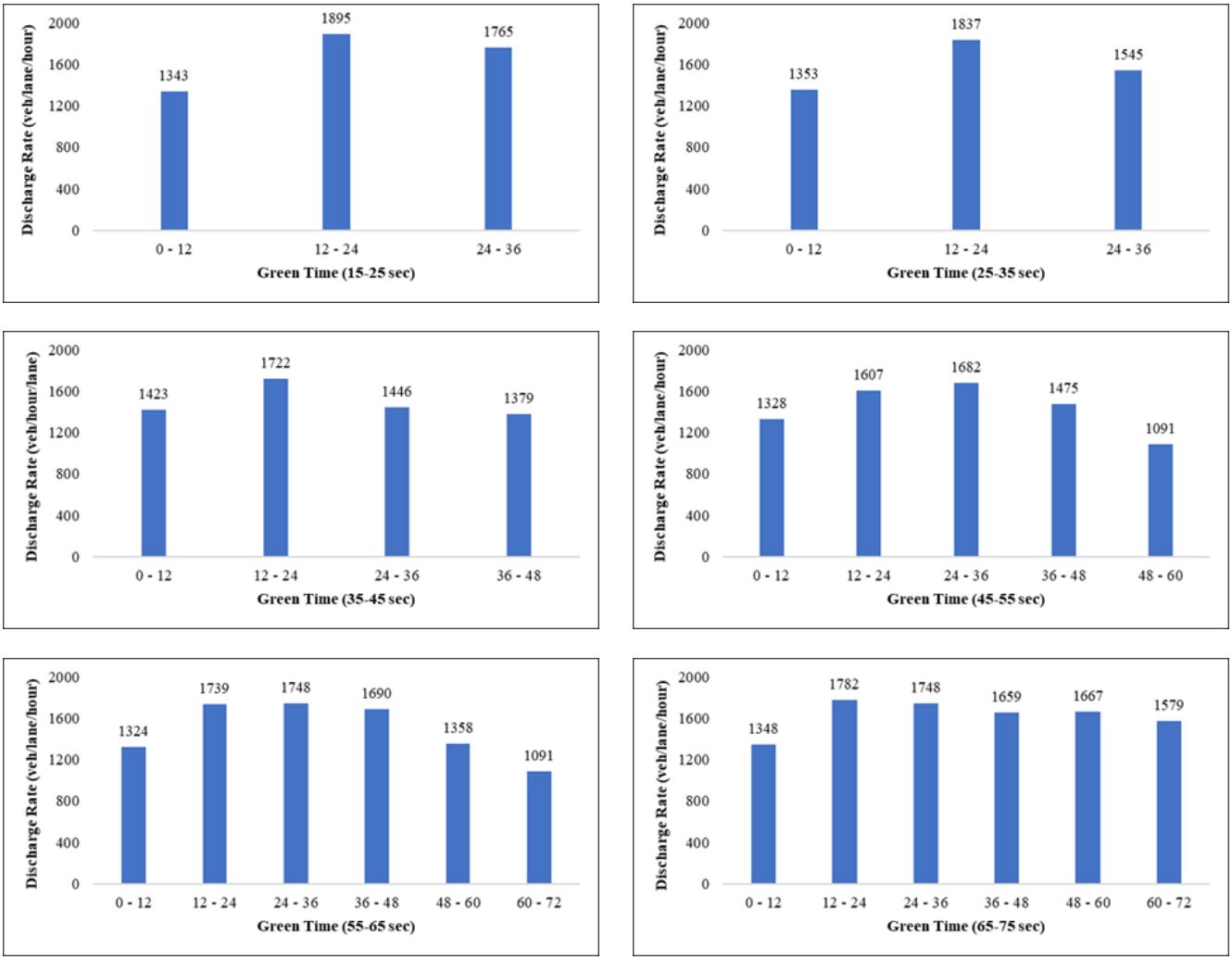

Figure 4. Discharge flow rate of vehicles entering the Kipa intersection at 12 second intervals

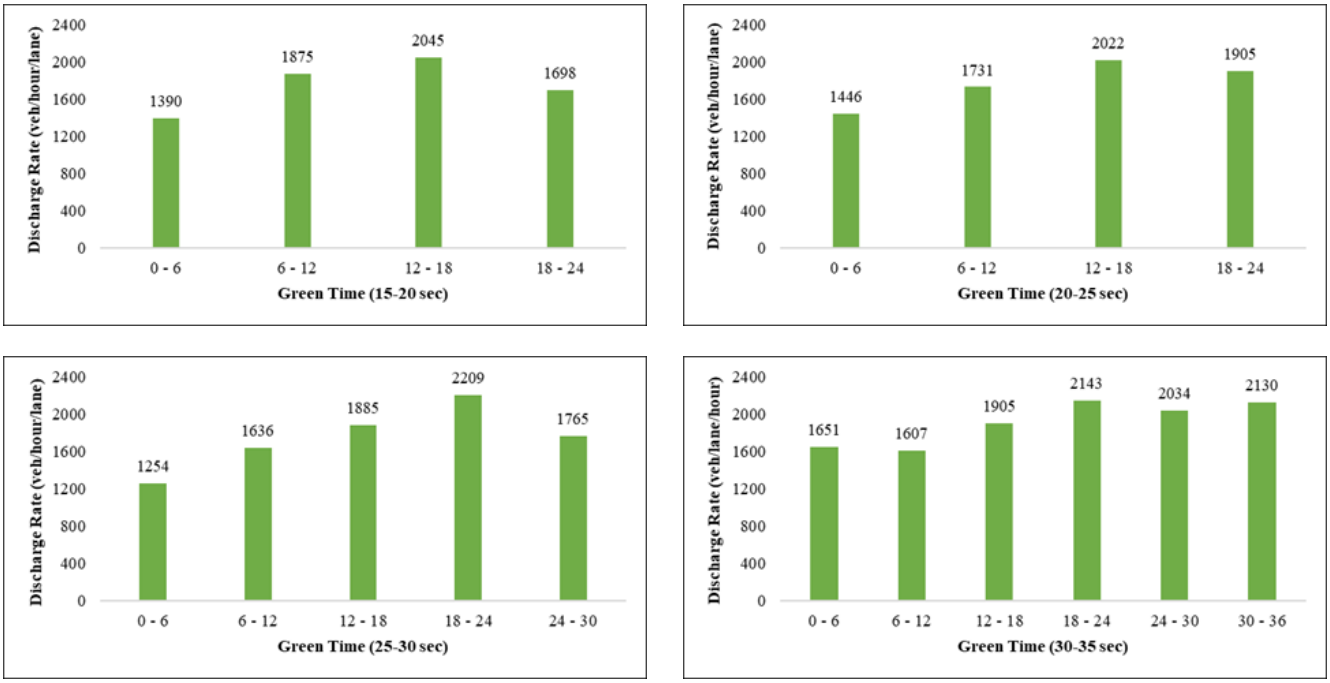

Figure 5. Discharge flow rate of vehicles entering the CNR Intersection at 6 second intervals

5. Conclusion

Two real-time signalized intersection approaches in the Mersin city center were studied to analyze the impacts variable green times and queue lengths on the discharge flow rates. The results can be summarized as follows:

- Time headways of the first four vehicles in the queue were statistically larger than the time headways of the remaining vehicles in the queue. Therefore, the discharge flow rate of the first four vehicles was lower than the discharge flow rate of the remaining vehicles. More specifically, the discharge flow rate increased almost 30% after the first four vehicles. This means that the first four vehicles in the queue were subjected to significant initial losses. In addition, time headways of the vehicles in the queue statistically remained constant after the first four vehicles in the queue. Therefore, it can be concluded that saturation flow was obtained with the fifth vehicles in the queue. This result is consistent with some studies in the literature [1, 4, 11, 12].
- Time headways of the vehicles in the first 12 seconds of the green at the Kipa intersection and in the first 6 seconds of the green time at the CNR intersection are statistically larger than the time headways of the other vehicles. Therefore, the results of the queue length green time analyses confirm each other. Therefore, it was statistically revealed that the initial lost times encountered by the first vehicles in the queue have negative effect on the traffic flow.

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Author contributions

Nihat Can Karabulut: Literature review, Software, Analysis **Murat Özen:** Conceptualization, Writing-Original draft preparation, Methodology **Oruç Altıntaşı:** Conceptualization, Writing-Original draft preparation, Methodology

Conflicts of interest

The authors declare no conflicts of interest.

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