

Determining u-turn adjustment factor for signalized intersections in Doha, Qatar

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Abstract. This paper summarizes the work conducted to estimating a U-turn adjustment factor at selected signalized intersections in Doha, Qatar. Unfortunately, the Highway Capacity Manual (HCM) 2010 does not consider the effect of U-turn traffic on the capacity of signalized intersection; therefore, a few researchers attempted to develop U-turn adjustment factors to be added to the HCM analysis of signalized intersections when heavy U-turn traffic exists. To achieve this, the average headway was measured for U-tuning and left-turning vehicles at three different intersections in Doha. To estimate the U-turn adjustment factor, 198 queues with 2,327 U-turn vehicles and 1,564 left-turn vehicles were used to develop a regression model with the headway as the dependent variable and the U-turn percentage as the independent variable. The resulting quadratic model shows an increase in the average headway as the percentage of U-Turn traffic increases, with an R^2 of 0.591. This indicates that the presence of U-turning vehicles has a significant effect on increasing the average headway thus reducing the capacity of signalized intersection. The result shows the U-Turn adjustment factor ranges from 0.76 for 100% of U-turn traffic to 0.95 for 10% of U-turn traffic.

1 Introduction

Traffic signals are traffic control devices used to manage the flow of traffic through intersections in a safe and efficient manner. Whether it is for designing new timing plans (to allocate green times) or operational analysis of existing conditions (to determine level of service), traffic engineers require an accurate estimate of the capacity of the signal.

A traffic signal's capacity, defined as the maximum number of vehicles that can reasonably be expected to pass through the intersection under prevailing traffic, roadway, and signalization conditions during a 15-minute period, can be computed as follows [1]:

$$c = s \cdot \frac{g}{C} \quad (1)$$

where:

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- c = Capacity (vehicle/hour)
 s = Saturation flow rate (vehicle/hour)
 g = Green interval time (second)
 C = Cycle length (second)

Therefore, saturation flow rate is a key parameter in estimating a signalized intersection's capacity. The HCM defines saturation flow rate 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 at all times and no lost time is experienced [1]. Since measuring saturation flow rate in the field is challenging, many engineers opt to follow the HCM procedure to estimate saturation flow rate using the following model [1]:

$$s = s_o N f_w f_{HV} f_g f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb} \quad (2)$$

where:

- s = Saturation flow rate for subject lane group, expressed as a total for all lanes in lane group (vehicle/hour),
 s_o = Base saturation flow rate at ideal condition (passenger car/hour/lane)
 N = Number of lanes in a lane group,
 f_w = Adjustment factor for lane width,
 f_{HV} = Adjustment factor for heavy vehicles in traffic stream,
 f_g = Adjustment factor for approach grade,
 f_p = Adjustment factor for existence of a parking lane and parking activity adjacent to lane group,
 f_{bb} = Adjustment factor for blocking effect of local buses that stop within intersection area;
 f_a = Adjustment factor for area type,
 f_{LU} = Adjustment factor for lane utilization,
 f_{LT} = Adjustment factor for left turns in lane group,
 f_{RT} = Adjustment factor for right turns in lane group,
 f_{Lpb} = Pedestrian adjustment factor for left-turn movements, and
 f_{Rpb} = Pedestrian-bicycle adjustment factor for right-turn movements.

As shown in Eq. 2, there are many adjustment factors to account for the various non-ideal geometric, traffic, and environmental conditions that may influence the headway of vehicles departing the intersection. Two of these factors, the left-turning traffic (LT) and the right-turning traffic (RT), deal with turning vehicles which can significantly impact the saturation flow rate thus the operational performance of signalized intersections. In GCC countries, U-turning (UT) traffic not only it is allowed to be made from the left lane(s), it can also be significant amount. Making a UT usually takes longer time to complete than a simple left turn because of the reduction of speed the driver needs to make due to the smaller turning radius needed); therefore, assuming that they have the same effect on the capacity of a signalized intersection is not appropriate. Unfortunately, the HCM does not take into consideration the effect of UT traffic on the saturation flow rate; instead UT traffic is considered as normal LT traffic. This is clearly a simplification as the speed of U-turning vehicles is less than the speed of left-turning vehicles and this will reduce the capacity of the intersection. Moreover, the mixture of UT traffic in a LT lane will disturb the saturation headway. Thus, instead of having a stabilized discharge headway after the 4th or 5th vehicle, the discharge headway will be unpredictable changing as the order of left and U-turning vehicles changes. This will certainly affect the flow of LT traffic and as a result affect the capacity of the signalized intersection.

There is no widely-accepted method that predicts the effect of the U-turning traffic on the capacity of a signalized intersection. Moreover, few researchers attempted to study this issue and studying the local conditions to take into consideration the local driver behavior is important and has been suggested by the HCM 2010. Therefore, it is important to analyze and estimate the effect of UT under local conditions. This study is going to explore the effect of permitted UT traffic in a protected LT on the capacity of signalized intersection, which will make this study an important topic for Qatar.

2 Literature review

Several researchers have investigated the effect of U-turning traffic on signal operation. The following paragraphs summarize some of the recent research effort in this topic.

Adams and Hummer studied the effect of U-turns on the left turn saturation flow rate in 1993 in North Carolina [2]. In their study, four signalized intersections with protected left-turn were selected. They recorded the saturation flow rate and the percentage of U-turn traffic for 198 queues during midday peak periods on weekdays. After analyzing the data collected and using t-tests and regression model, the study found that there is no correlation between the saturation flow rate and the percentage of U-turns for intersections where U-turn traffic in the left-turn lane is less than 50% of the total traffic. However, for 50 to 65% of U-turn traffic, their study was inconclusive due to small sample size. They also found that a reduction factor for the saturation flow rate is necessary for left-turns when more than 65% of the traffic is U-turn traffic. From the regression model they recommended a reduction factor for U-turn traffic of 65% to 85% to be 0.9, and for 85% or more of U-turn traffic they recommended a reduction factor of 0.8.

Tsao and Chu investigated the effect of U-turning traffics on the saturation flow rate in left-turn lanes in Taiwan [3]. They recorded 600 headways of left-turning vehicles and 160 headways of U-turning vehicles from a few traffic signals. They found, as can be expected, that the headway of U-turning traffic is larger than that of left-turning traffic. Their study showed that when a vehicle is preceded by left-turning vehicle, the average headway of a U-turning passenger car is 1.27 times that of a left-turning passenger car. However, when it is preceded by U-turning vehicle the average headway of U-turning passenger cars is 2.17 times that of left-turning passenger cars.

In a study by Liu et al. in 2005, the effect of U-turning vehicles on the left-turn saturation flow rate was analyzed [4]. The data was collected from three signalized intersections in Tampa Bay, Florida. A total of 260 discharge queues were recorded, that included 1,441 left turning vehicles and 571 U-turning vehicles. From the data collected, a regression model was developed to estimate the relationship between the average queue discharge headway and the various percentages of U-turning vehicles in the left-turn traffic stream. Using a regression model, adjustment factors for various percentages of U-turning vehicles were developed. It was recommended that a capacity reduction should be done when the flow on the left-turn lane has at least 40% U-turning vehicles.

Carter et al studied the operational and safety effects of U-turns at signalized intersections in North Carolina [5]. In this study, vehicle headways at 14 signalized intersections were measured. Using regression analysis, they found that the saturation flow rate in left-turn lane is reduced by 1.8 % for every 10% of increase in U-turn percentage.

Hossain estimated the UT, LT, and RT turning adjustment factors for some signalized intersections in Malaysia [6]. Using regression analysis, the results indicated that the LT and RT adjustment factors decrease as the proportion of turning vehicles increases and the turning radius decreases. He also showed that the U-turn adjustment factor decreases with the increase in the percent of U-turning vehicles, specifically the U-turn adjustment factor

decreases 2.25% for every 10% increase of U-turn percentage. It is worth mentioning that the UT traffic adjustment factor was limited to a single LT lane only.

Jobair bin Alam et al. estimated adjustment factors for U-turn, heavy vehicles, number of lanes, and lane width in Makah, Saudi Arabia [7]. Five signalized intersections were selected for this study. The study indicated that while many of these adjustment factors have been developed by the HCM, the operation and performance of signalized intersections rely on the roadway's environmental features and users' behavioral characteristics that significantly differ among locations. Based on 1,589 headways measurements, it was found that the adjustment factor for the UT vehicles with 30% of UT vehicles is 0.95 in Makah. Moreover, the adjustment factor for heavy vehicles was found as 0.78 for 30% of heavy vehicles.

In general, these studies showed that the increase in U-turn traffic decreases the saturation flow rate which will decrease the capacity of the traffic signal. However, the magnitude of the reduction reported by the various studies was not the same. This can be justified by the different driver behavior, operational traffic conditions, and road characteristics between the different locations where these studies were conducted. In fact, the HCM clearly adds a disclaimer emphasizing the need for adapting locally measured values outside of North America [1].

The purpose of this paper is to summarize the procedure undertaken and results achieved to quantifying the impact of U-turn traffic on the operation of signalized intersections in a region known for its aggressive driver behavior, namely Doha, Qatar. This will assist local engineers to better estimate the saturation flow and capacity of signalized intersections in the city and the region, which will ultimately improve functionality of signals and reduce delays for the vehicles.

3 Methodology

As it was revealed in the literature review, and unlike other factors, the HCM does not provide much info on how to adjust for U-turn traffic at signalized intersections. Few research has developed a UT adjustment factor in their local conditions and all of them used the headway and UT percentage to develop the factor; however, some used the average discharge headway and others considered the headway of each vehicle depending on the car that preceded it, left-turning or U-turning.

In this study, an adjustment factor that takes into consideration the effect of U-turning vehicles on the capacity of signalized intersection under local conditions is developed. This is accomplished by analyzing the relation between the percent of U-turning vehicles and the average headway. Even though, there are other factors that can affect the average headway besides the U-turning vehicles, like the turning radius, they have not been considered in this study. The reason for not considering the turning radius is that all the intersections used in this study have the same turning radius.

To develop the relation between the percent of U-turning vehicles and the average headway, various models have been attempted. To find the best-fit model, the ANOVA test was implemented. After finding the best fit, the model is used to calculate the UT adjustment factor for a certain percent of U-turning vehicle. This adjustment factor can be directly used to estimate the capacity reduction due to the presence of U-turn traffic.

The following information was collected using video recordings for sample intersections:

1. Number of U-Turning vehicles in each lane
2. Number of left-turning vehicles in each lane
3. Number of heavy vehicles (buses and trucks) making a LT or UT in each lane

4. Queue discharge time, which is the time that elapses from the start of the green interval till the last vehicle in the previously queued vehicles passes the stop line) for each lane

Once this information it obtained, the average queue discharge time for each signal phase is calculated using:

$$h = \frac{T}{N_u + N_l} \quad (3)$$

where

h = the average discharge headway for each turning vehicle

T = the queue discharge time

N_u = the number of U-turning vehicles in the queue

N_l = the number of left-turning vehicles in the queue

To account for the presence of heavy vehicles, a passenger-car equivalent factor of 2.0 was used to convert the mix traffic with heavy vehicles into passenger-car only traffic.

Using the percentage of the UT traffic and the average discharge headway, a regression model is developed to relate the two variables. The following four models were attempted: Linear, Logarithmic, Quadratic, and Exponential. The best-fit model is then used to calculate the discharge headway for the various percentages of UT traffic. The model is also used to compute the base discharge headway (h_o) using a UT percentage equal to zero.

Finally, the UT adjustment factor is calculated as follows:

$$f_{UT} = \frac{s}{s_o} = \frac{3600/h}{3600/h_o} = \frac{h_o}{h} \quad (4)$$

where

f_{UT} = Adjustment factor for the U-turning vehicles

h_o = Average discharge headway without U-turn traffic, obtained from the best-fit model when UT percentage is zero

h = Average discharge headway with U-turn traffic, obtained from the best-fit model

s = Saturation flow rate

s_o = Base saturation flow (when there is no UT traffic in the lane)

The developed U-turn adjustment factor should be used, along with other factors, in calculating the saturation flow rate (Eq. 2). Including this factor will lead to better estimation of the saturation flow rate since it takes the effect of UT traffic into consideration.

4 Data collection and processing

To measure the saturation flow rate at signalized intersection, three signalized intersections in Doha, Qatar were selected. To separate the effect of other factors that can affect the capacity of a signalized intersection, the following criteria were used to select the sample intersections to be used in the study:

1. Lane width of 12 feet (3.65 m)
2. No parking adjacent to a travel lane within 250 feet (75 m) of the stop line
3. No disturbance from heavy vehicles
4. No disturbance from right turning vehicles on the other approaching lane
5. No disturbance from left turning vehicles on the other approaching lane
6. No disturbance from pedestrians
7. Approach's grade is level
8. Intersection has exclusive LT lane

9. LT lane has a protected phase
10. UT traffic is allowed
11. LT lane has significant UT traffic

Figure 1 shows the location of the study sites. These intersections have long queues for extended periods of time, especially during peak hours.

All data were recorded during peak hours on weekdays, during the period from February 2013 to May 2013. Traffic data were collected via video with each video record was expected to capture all turning movements: left turning movement, through movement, and right turning movement. Ideally, the camera has to be placed in a way that enables the viewer to see the start and end of each phase, the end of the queue for each lane, and the stop line of the lane. Figure 2 shows, for example, the location of the two video recording cameras used to collect the data needed at Al-Sadd intersection. Figure 3 is a screenshot taken from one of the video recording at the same intersection. In a few cases where it was impossible to see the end of the queue, we assumed that the end of the queue happens when there was large time gap (more than 2 seconds) between two consecutive vehicles.

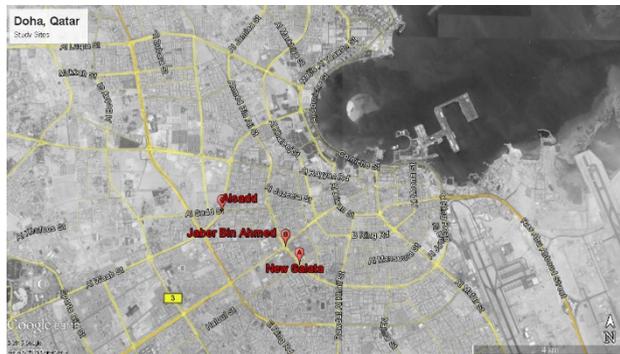


Fig. 1. Location of selected sites.

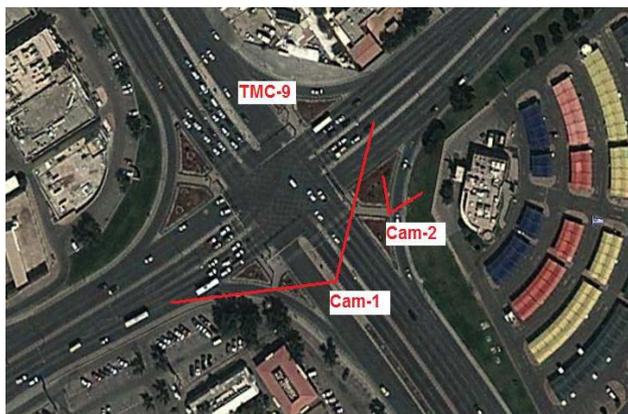


Fig. 2. Placement of video cameras at Jaber Bin Ahmed Intersection.



Fig. 3. Sample screen capture from the video recording.

Table 1 shows the sample size from the different intersections. The total number of queues considered from the three selected intersections combined was 198 and the total number of U-turning vehicles considered was 2,329. This sample size is comparable to other similar studies; for example, Adams and Hummer study utilized 198 queues.

Table 1. Chosen intersections and collected data from each intersection.

Intersection	No. of Queues	No. UT Vehicles	No. LT Vehicles	UT% in the lane
New Salata	46	512	424	55%
Jabr Bin Ahmed	105	1,135	1,056	52%
Al Sadd	47	680	84	89%
All	198	2,327	1,564	60%

Using the video recordings of the selected signalized intersection, the time frame has to be selected so that it (1) has the highest percentage of UT traffic, (2) occurred during peak hours of weekdays, and (3) has no weather disturbance.

5 Results and discussion

As previously mentioned, the first step towards developing the U-turn adjustment factor is to model the relation between the percentage of UT traffic and the average discharge headway. For each site, the following four regression models were attempted: Linear, Logarithmic, Quadratic, and Exponential. Table 2 shows the summary and the parameter estimates of the developed best-fit models for the three sample sites, as well as for all the sites combined. Figure 4 shows these models plotted against the dataset from all intersections combined, as an example.

From Table 2, it is clear that all the four models, regardless of the site, have shown acceptable results. Moreover, all of the models have reasonable R^2 values, ranging from around 0.50 to 0.64. The R^2 value indicates the percentage of the variability in the headway explained by the variability of the percent of UT traffic. Except the model for Jaber Bin Ahmed Intersection, the quadratic model outperformed the other models for the other two sites as well as for the all intersections combined. Nevertheless, the difference between the best-performing model at Jaber Bin Ahmed, i.e. exponential, and the quadratic model is only

minor (R^2 of 0.590 vs. 0.581). Therefore, we adopted the quadratic model (Eq. 5) to relate the discharge headway and UT percentage at the selected sites in Doha, Qatar.

$$h = -0.340 \times UT^2 + 0.887 \times UT + 1.721 \quad (5)$$

where

h = Average discharge headway for U-turning vehicles

UT = Percentage of U-turning vehicles

Table 2. Developed models for each intersection.

	Parameter Estimates			Model Summary		
	Constant	b_1	b_2	R^2	F	P value
New Salata Intersection						
Linear	1.811	0.505		0.640	79.871	0.000
Quadratic	1.761	0.700	-0.176	0.642	39.403	0.000
Logarithmic	2.255	0.260		0.637	79.040	0.000
Exponential	1.826	0.243		0.636	78.502	0.000
Jaber Bin Ahmed Intersection						
Linear	1.750	0.665		0.580	142.23	0.000
Quadratic	1.727	0.788	-0.136	0.581	70.76	0.000
Logarithmic	2.264	0.227		0.542	122.07	0.000
Exponential	1.763	0.327		0.590	147.92	0.000
Alsadd Intersection						
Linear	1.664	0.624		0.524	49.447	0.000
Quadratic	2.641	-1.762	1.427	0.556	27.53	0.000
Logarithmic	2.283	0.505		0.504	45.762	0.000
Exponential	1.725	0.282		0.531	50.945	0.000
All Intersections Combined						
Linear	1.826	0.481		0.569	258.996	0.000
Quadratic	1.721	0.887	-0.340	0.591	141.061	0.000
Logarithmic	2.250	0.224		0.574	264.193	0.000
Exponential	1.836	0.232		0.572	262.354	0.000

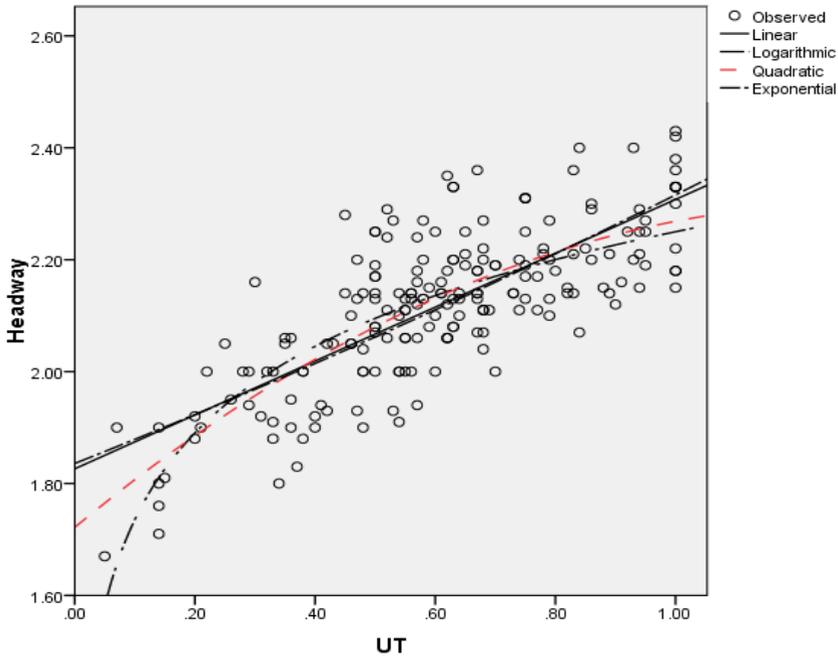


Fig. 4. Regressed models for all intersections combined.

Table 3 summarizes the results of the ANOVA test for the selected quadratic model, which also confirms that the null hypothesis can be rejected because the P-value is equal to zero. In other words, the probability that the headway was not affected by UT percentage and instead the variance was just random event is zero. To verify the basic assumption that the variance is homogeneous, the unstandardized residuals were plotted for the independent variable (Figure 5). It is clear that the variance is spread evenly across the 0-axis and that it does not have any clear pattern, Therefore, the basic assumption about the homogenous variance is valid.

Table 3. ANOVA test results for the selected quadratic model.

	Degree of Freedom	Σ of Squares	Mean ²	F	P value
Regression	2	2.264	1.132	141.061	0.000
Residual	195	1.565	0.008		
Total	197	3.830			

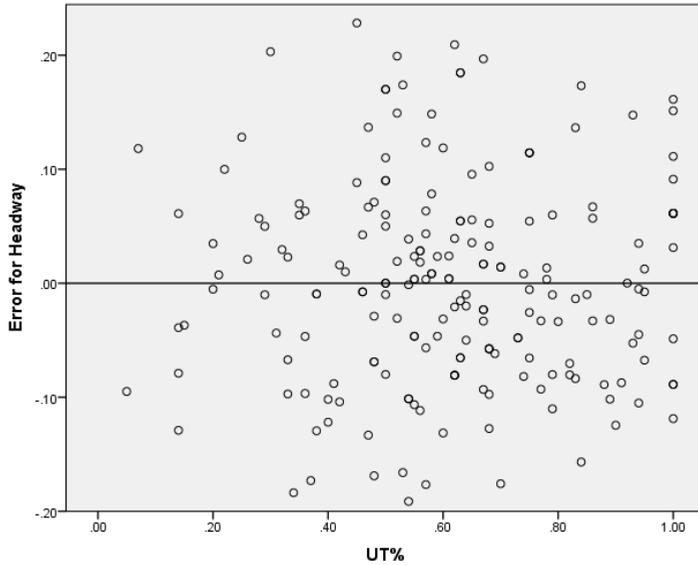


Fig. 5. Residuals of the selected quadratic model.

Using Eq. 4 and Eq. 5, the UT adjustment factor for the selected intersections in Doha, Qatar can be calculated using:

$$f_{UT} = \frac{1.721}{-0.340 \times UT^2 + 0.887 \times UT + 1.721} \tag{6}$$

where

f_{UT} = Adjustment factor for U-turning vehicles

UT = Percentage of U-turning vehicles

Using Eq. 6, we calculated the UT adjustment factor for different UT percentages ranging from 0% to 100%, with 10% incremental, as shown in Table 4.

Table 4: UT Adjustment factors for different percentages of U-turn traffic.

UT	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
h	1.72	1.81	1.88	1.96	2.02	2.08	2.13	2.18	2.21	2.24	2.27
h_o	1.72	1.72	1.72	1.72	1.72	1.72	1.72	1.72	1.72	1.72	1.72
f_{UT}	1.00	0.95	0.91	0.88	0.85	0.83	0.81	0.79	0.78	0.77	0.76

As previously mentioned, a few studies developed adjustment factors for UT traffic in many cities around the world. These studies differ in the location of the study and the methodology used. In addition, driver behavior could vary significantly from one place to the other. This has led to differences among the reported results. Therefore, it is important to compare the results of this study to other studies, namely Tsao and Chu [3], Carter et al [5], and Wang et al [8]. Figure 6 plots the values of f_{UT} vs. UT percent estimated in this study as well as their corresponding values reported in the above mentioned studies.

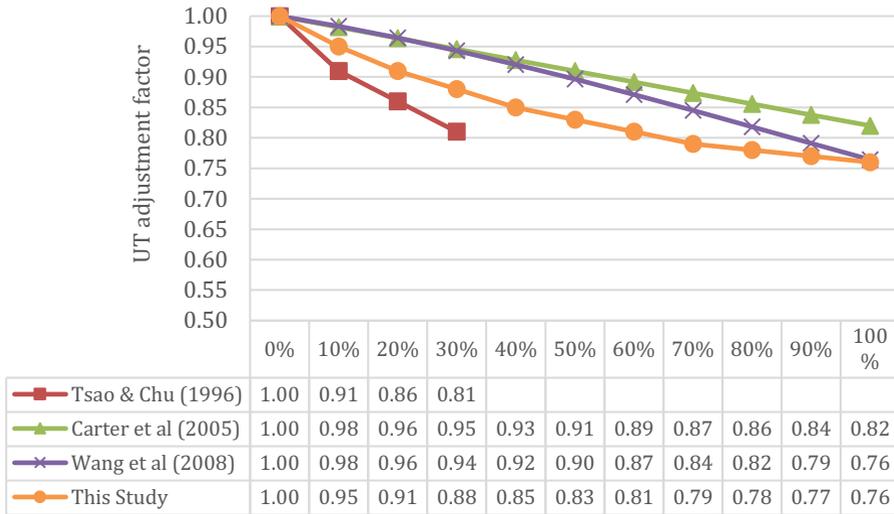


Fig. 6. Comparison of U-turn adjustment factor vs. U-turn percentages from different studies.

As can be seen in Figure 6, it is clear that this study shows a higher effect of the UT traffic on the UT adjustment factor, especially at lower percentages of U-turning vehicles, as compared to the other studies. It also shows that previous studies by Wang et al and Carter et al showed that their UT adjustment factors decrease linearly with the increase of UT percentage; whereas this study and Tsao’s show a quadratic decrease concaving upward as the UT percentage increases. However, Tsao’s study is limited in the range of the UT% [0% to 30%].

When comparing this study and Carter and Wang’s study, we can see that the effect of the U-turning traffic in low percentages is higher in this study than the other two studies. However, as the UT% increases from 50% to 100% the difference in the UT adjustment factor between this study and the other two studies decreases. This might seem unusual at first but this could be explained by the following observation: as the U-turning vehicles increases, the movement of the vehicles becomes more synchronized thus decreasing the rate at which the adjustment factor is effected by the UT%. Furthermore, this difference between the results of the various studies is expected because Carter’s and Wang’s studies were conducted in North Carolina and Florida, respectively, while this study was conducted in Doha, Qatar. Comparing this study to Tsao and Chu’s study conducted in Taiwan, we can see that the effect of UT traffic in low UT percentages is lower than those in Doha. There is no widely-accepted method that predicts the effect of the U-turning traffic on the capacity of a signalized intersection. Finally, the results of this study reaffirm the need to take into consideration local traffic conditions when modeling signal operation.

6 Conclusion

The HCM 2010 offers no adjustment factor to take into consideration the effect of U-turning vehicles on saturation flowrate at signalized intersection. A few researchers have studied this issue and developed such an adjustment factor. Furthermore, the HCM itself advises to consider the local traffic conditions and driver behavior when estimating the capacity of a signalized intersection. This study developed a U-turn adjustment factor for signalized intersections in Doha, Qatar. Towards this end, traffic data were collected from three different signalized intersections in the City.

Specifically, the discharge headways of a total of 2,327 U-turning vehicles and 1,564 left-turning vehicles from 198 queues were analyzed. To develop the U-turn adjustment factor for Doha, the first step was to model the relation between the percentage of UT traffic and the average discharge headway. Four regression models were attempted: Linear, Logarithmic, Quadratic, and Exponential. While all the four models have shown acceptable results with R^2 values ranging from around 0.50 to 0.64, the quadratic model outperformed the other models; and therefore, it was adopted. Using this model, the UT adjustment factor was computed and ranged from 0.95 at 10% U-turn traffic to 0.76 when 100% of turning traffic is making U-turns. Compared to the other studies, it was found that a higher effect of the UT traffic on the UT adjustment factor, especially at lower percentages of U-turning vehicles. Unlike two other previous studies, this study showed that the UT adjustment factors show a quadratic decrease concaving upward as the UT percentage increases. The results of this study will help local engineers to have better estimates of the capacity of signalized intersections. Eventually, this will benefit the road users as there will be less delay at traffic signals; and therefore, they will reach their destination faster. Nevertheless, the finding of this study resulted from analyzing only three selected signalized intersections in Doha, Qatar. Prior to generalizing these results whether in Doha itself or other cities in the GCC region, validating these results using a larger sample size may be necessary. Moreover, this study did not take into consideration other potentially contributing factors such as turning radius, turning speed, size of turning vehicle. All of these factors could be important factors affecting the headway of turning vehicles. Therefore, it is recommended to investigate their effect on signal capacity in a future study.

References

1. Highway Capacity Manual, Transportation Research Board of the National Academies, Washington D.C., 2010.
2. Adams, J. C., and J. E. Hummer. Effects of U-Turns on Left-Turn Saturation Flow Rates. Transportation Research Record 1398. Transportation Research Board, National Research Council, Washington, D.C., 1993.
3. Tsao, S., and S. Chu. A Study on Adjustment Factors for U-Turns in Left-Turn Lanes at Signalized Intersections. Journal of Advanced Transportation, Vol. 29, No. 2, 1996, pp.183–192.
4. Liu, P., J. Lu, J. Fan, J. Pernia, and G. Sokolow. Effect of U-turns on the capacity of signalized Intersections. TRR 1920, Journal of Transportation Research Board of the National Academies, Washington D.C., 2005, pp. 74-80.
5. Carter, D., J. Hummer, R. Foyle, and S. Phillips. Operational and safety effects of U-turns at signalized Intersections. TRR 1920, Journal of Transportation Research Board of the National Academies, Washington D.C., 2005.
6. Quazi Hossain. Estimation of Turning Adjustment Factors at Signalized Intersections According to Malaysian Traffic Conditions. Master Thesis, University Sains, Malaysia, 2007.
7. Md. Jobair Bin Alam, Khalid A. Osra, Hamid O. Al-Bar and Shaheer Z. Zahran. Signalized Intersection Capacity Adjustment Factors for Makkah, Saudi Arabia. Canadian Journal of Transportation, Volume 4, August 2011.
8. Wang, Xiaodong. Effects of U-Turns on Capacity at Signalized Intersections and Simulation of U-Turning Movement by Synchro. Master Thesis, University South Florida, Florida, 2008.