Evaluating The Operational Performance of Signalized Intersections Involving U-turns in Aswan City, Egypt

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Abstract: This research evaluates the operational performance of Signalized Intersections involving U-turns (SIU) in Aswan city, Egypt. Furthermore, it investigates the impacts of U-turns on the capacity of an SIU, exploring the key factors influencing the performance of an SIU. To achieve those objectives, the research methodology depends on onsite video observations and field measurements. In addition, to examine the efficiency of the proposed strategies, the microscopic simulation software PTV-VISSIM has been used. The research findings revealed the adverse effects of U-turns on the performance of an SIU. This study recommends the segregation of the U-turns from the signalized intersections. It also emphasizes the urgent necessity of the overall readjustment of traffic controls signal times based on a traffic demand analysis.

Keywords: Signalized Intersections; U-turns; Performance; Egypt.

1. INTRODUCTION:

Aswan city, located in the southern region of Egypt, has experienced a significant growth in traffic volume since the 2000s (Central Agency for Public Mobilization and Statistics (CAMPS) 2013). However, the city’s four-lane rigid network has not been able to accommodate this increased traffic demand. Therefore, conflicts areas occurred inside an intersection because of complicated vehicle movements. As a result, the performance of signalized intersections has been decreased. The replacement of non-traversable and restrictive medians, as well as the use of directional median openings instead of signalized intersections, was one of the implemented solutions. Such solutions have aimed to prohibit drivers from making left turns from major streets. Furthermore, crossing a major street from a side street has been prohibited. In addition, such directional medians have been provided inside signalized intersections. Consequently, a new type of intersections has been produced, i.e., Signalized Intersection involves a U-turn (SIU) as shown in Figure 1. Thus, a new type of movement has been generated within signalized intersections. Vehicles are allowed to perform left-turns and U-turns through a shared left-turn lane within an SIU. Therefore, vehicles conducting a U-turn are mixed with left-turning ones in the left-turn lane at signalized intersections. Nevertheless, both left-turning and U-turning vehicles were protected by a traffic signal phase. This type of operating system generates a queue consisting of both U-turning and left turning vehicles. As a result, congested bottleneck regions are being produced near SIUs. In addition, U-turns at an SIU decrease the capacity of the intersection and the road efficiency (Shou-Min Tsao and Chu 1995) (Phillips et al. 2004) (Liu et al. 2007).
Furthermore, the saturation flow rates are decreased by increase of the U-turns rates (Carter et al. 2005). These new intersections became a source of merging and diverging accidents, which usually occurred with right turning vehicles with the other approaches.

![Diagram of Salah El-Deen intersection, Aswan as the case of study](image)

**Figure 1.** A plan of Salah El-Deen intersection, Aswan as the case of study

### 2. RESEARCH OBJECTIVE

This study aimed to improve the performance of SIUs in Aswan, Egypt. To do so, this study focused on exploring the strategies required to improve the performance of such intersections. As a part of this study, three objectives were required to achieve the research aims. The first objective is to assess the current performance level of existing intersections. For this purpose, calculations of certain parameters such as saturation flow rates were measured. Hence, the saturation headways of both U-turning and left-turning vehicles needed to be observed. Video observations were conducted for measuring the saturation flow rates and saturation headways. A signalized intersection located in an arterial central business area in Aswan city was selected as the study area. The second aim was to determine the factors affecting the performance of signalized intersections. Geometrical data, traffic data, and signal control data were measured. Moreover, transportation aspects such as the vehicle types and parking conditions were taken into account. Finally, strategic plans were proposed to enhance the performance of an SIU. As a part of this study, the potential for using a microscopic traffic simulation model for typical selected intersections in an assessment of the effectiveness and impacts of U-turns on the performance of an SIU was ascertained. A simulation software program, PTV-VISSIM, was used to analyse the recommended strategies.

### 3. STUDIES OF IMPACTS OF U-TURNS ON SIGNALIZED INTERSECTIONS

According to previous studies, U-turning vehicles adversely affect the capacity of a signalized intersections (Adams and Hummer 1993) (Shou Min Tsao and Chu 1995) (Liu et al. 2005) (Liu et al. 2007) (Zheng et al. 2009) (Hutchinson and Woolley 2008). In addition, U-turning vehicles result in a slowing down of the following left-turning vehicles. As a result, the capacity of signalized intersections is decreased, especially when U-turning vehicles make up more than 40% of the overall traffic. Likewise, owing to the percentage of U-turning vehicles inside left-turn lanes, U-turns adjustment factors were estimated to account for the capacity reduction. The study indicated to 8% of a capacity reduction factor for the left-turn lane with 40% U-turning vehicles (Liu et al. 2007). This analysis indicates the adverse effect of U-turns
on the capacity of a signalized intersection. The effects increase with the increase in the percentage of U-turning vehicles in the left-turn lane. This study emphasized that the discharge flow rates are significantly changed when the left and U-turning flows are mixed in a left-turn traffic stream. Moreover, the maximum steady rate becomes difficult to determine. Using two simulation packages, i.e., Synchro and Sim Traffic, a procedure was to accomplish the study aims (Zheng et al. 2009). Moreover, in the case of median openings, the capacity and average total delay models for U-turns were found to be significantly impacted by the conflicting traffic flow (Al-Masaeid 1999).

In contrast, earlier studies revealed that the Saturation Flow Rate (SFR) is dramatically decreased when U-turns are conducted within a signalized intersection. The SFR is decreased when U-turning vehicles make up more than 65% of a queue (Adams et al., 1993). Similarly, it was revealed that the effects of U-turns on the SFRs increase with the increase in percentage of U-turning vehicles (Alam et al. 2011).

However, these analyses proved that there is no correlation between the SFR and the percentage of U-turns for queues with 50% or fewer of U-turning vehicles. In addition, the study recommended using reduction factors for a tentative SFR estimation. The reduction factors were 1.0 less than 65% U-turns, and 0.9 for 65% and 85% U-turns. Finally, the reduction factor was 0.8 for greater than 85% U-turns (Adams and Hummer 1993). Similarly, a 1.8% loss in SFR was found for a left-turn lane for every 10% increase in the number of U-turns. In addition, an additional 1.5% loss in SFR was found when U-turning movements are opposite a protected right-turn overlap from the cross street. The results also revealed that a right-turn overlap at sites with a U-turn allowance could have a significant factor in reducing the SFR (Carter et al. 2005).

The average headway in the field was measured to investigate the effects of U-turns on the traffic flow in left-turn lanes (Shou-Min Tsao and Chu 1995) using the time headway technique for SFR estimations. This research team proved that the effects of U-turning vehicles basically depend on the percentage of U-turning vehicles in the left-turn lane, as well as on the order of formation in the traffic stream. Their study also revealed that the average headway of U-turning vehicles is larger than the headway of left-turning vehicles. According to this study, the average headway of U-turning passenger cars is 1.27-times that of left-turning passenger cars when preceded by a left-turning vehicle. However, when preceded by a U-turning vehicle, the average headway of a U-turning passenger car is 2.17-times that of a left-turning passenger car. The study also indicated that the larger the percentage of U-turning vehicles, the greater the impact on the traffic flows. In addition, the headway of left-turning vehicles increases significantly when proceeded by U-turning vehicles (Alam et al. 2011).

U-turning vehicles have a slower turning speed than left-turning vehicles. Thus, U-turning vehicles consume much time of the available green time (Adams and Hummer 1993). It was proved that when the volume of left-turning vehicles is less than 50 vph, or when the average queue length is less than three vehicles per cycle of the upstream signal, the total travel time of a direct left turn is less than the travel time for a right turn plus a U-turn movement (Zheng et al. 2009) (Liu et al. 2007).

The delay at a signalized intersection depends strongly on the percentage of U-turn movements. The results show that the delay at a signalized intersection increases with an increase in the number of U-turning vehicles in the left-turn lane (Zheng et al. 2009). Similarly, H. Zhou et al. carried out a study evaluating the safety and operational effects of replacing a direct left turn from a driveway with a right turn plus a U-turn movement at varying distances from the driveway (Zhou et al. 2002). Their study emphasized that the average wait delay from a direct left-turn movement is bigger than its counterpart in a right turn plus U-turn movement. Similarly, an increased stop delay of 1.5 s occurs for every 10%
increase in the number of U-turns for the left-turn lane group. However, every 10% increase in U-turns in the right-turn overlap results in an increased delay of 4.5 s (Carter et al. 2005). However, vehicles making right-turns followed by U-turns at a signalized intersection result in a longer delay than those making a direct left turn. As a result, it was found that 45 s of extra delay and more than 1 min of extra travel time are required for making right turns followed by U-turns at a signalized intersection as compared with those making a direct left turn (Liu et al. 2007). Additional time is required for slow U-turn manoeuvres inside a signalized intersection. Therefore, it was recommended that U-turns be allowed only where a fully controlled right-turn phase exists (Queensland Government 2012). Similar to previous studies, a notable reduction in travel time for vehicles on major approaches was observed (Pirdavani et al. 2011).

On the other hand, the results proved that there is a significant difference in speed of 1 to 2 mph between the upstream and downstream of a full median opening (Zhou et al. 2002). Likewise, the results referred to the correlation between the average turning speeds and the turning radius at a signalized intersection. It was proved that the turning speeds increase with an increase in the turning radius at a signalized intersection (Zheng et al. 2009). As a result, it was recommended that U-turns should be differentiated from left turns for SFR estimations (Shou Min Tsao and Chu 1995).

4. Methodologies for Measuring SFR

There are several methods are used to estimate the SFR in a signalized intersection. Fundamentally, each of these methods is based on filed observations to collect the needed data for the SFR estimation. However, the main differences between these methods are related to the technique of data collection.

Road Research Laboratory method basically depends on the data recorded using stopwatches and data forms. The concept of this method is to divide the total amount of green and amber times into short intervals. Within these divided intervals, an observer counts each vehicle crossing a stop line. By averaging the number of counted vehicles over the divided interval, the saturated flows can be calculated. The SFR is estimated by averaging the calculated flows during saturated intervals. The SFR in these intervals is affected by impact of the inertia on the starting and ending delays of the vehicles. Thus, to estimate the initial and final amount of lost time, a comparison should be conducted between the saturation flow in the middle intervals and the first and last intervals respectively (C. Singh and N.G. n.d.).

The recorder method is another manual technique for SFR estimation. It depends fundamentally on the data recorded from the observation sites. According to this type of method all information relevant to an SFR should be recorded on tapes or paper charts. The time interval between vehicles crossing within the green or amber time can be estimated by measuring the distance on the tape or charts. As a result of the variations in observers, some errors may occur. Therefore, this method does not provide accurate results. Two main methods, differentiated by their data collection techniques, typewriter and rust rack four-channel event recorder method have been used in the earlier studies (C. Singh and N.G. n.d.).

Time-lapse photography method was basically developed for in different engineering areas. However, Ashworth developed this method in 1987 as a tool for traffic data collection. Using a camera at the study site, data can be obtained in image form. Each frame contains a pictorial position of the individual vehicles. When comparing the positions of the vehicles in each frame, the vehicle movements can be clearly determined. Various traffic data can be evaluated by comparing the consecutive frames obtained. For accurate results, a series of
equidistant signs should be made along the recorded carriage side before recording. These marked signs enable the individual determination of the vehicle positions (Ashworth 1976).

Owing to the widespread use of videotape during the 1980s, the video recording method was used for traffic studies. Such a method can provide a sufficient means for collecting data. Instead of traffic behaviour, the classification of vehicle types and turning movements can be efficiently obtained. In addition, the end of the saturated flow conditions, interruptions to traffic streams and the traffic volumes can be collected simultaneously. This method basically depends on the use of a portable video recording camera on-site. Later, the recorded data can be analyzed in a laboratory. When recording, the camera should be located at a vantage point. When the shooting location is occupied, the observed traffic flow should be clearly abstracted (C. Singh and N.G. n.d.) (TANAKA, Keshuang TANG, and Sungjoon HONG 2010).

Applying remote sensing technology, GIS technology is also used for traffic data collection. Based on GIS databases, the SFR can be directly estimated. However, there are some limitations, including the satellite imagery of the project area adversely affecting the results. This method depends on placing GPS loggers on probe vehicles. The travel time, travel speed, and SFR estimations can be obtained from the data recorded by these GPS loggers (TANAKA, Keshuang TANG, and Sungjoon HONG 2010).

5. SELECTED LOCATION

Salah El-Deen intersection in Aswan City, Egypt was selected as the case study. The studied site is located in the downtown area of Aswan City, as shown in Figure 2. The adjacent area of the intersection is an arterial central business area. The intersection is formed from the cross section of Kornich El-Nile Street as the main road, and Salah El-Deen Street as a feeder road. The criteria for the studied location can be described as follows:

5.1 GEOMETRIC CRITERIA

The two intersecting roads were designed with restrictive median cross-sections and directional openings, as shown in Figure 1. They are four-lane roadways divided into two lanes in each direction. However, a shared left lane was constructed inside the direct approach for left- and U-turning movements. The shared lane has a protected traffic signal to control the left-and U-turning traffic flows. A travel distance of 1,160 m from the adjacent intersection makes this intersection the only way for U-turning vehicles to travel. Therefore, this shared lane has two types of movements. The first movements are from left-turning vehicles crossing Salah El-Deen Street, whereas the second movements are from vehicles conducting U-turns onto Kornich El-Nile Road.

In terms of geometric design, the intersection is a three-leg intersection. However, a shared left-turn lane was constructed inside the southbound direction. The intersection is at grade intersection in terms of elevation. Each approach to the intersection has two lanes; however, no divided lane lines are present. Therefore, three vehicles in the direct flow can cross the intersection in parallel during the green time period. In addition, an absence of stop lines for both direct approaches as well as the shared lane was observed. Thus, the vehicles had no stopping limitation before the pedestrian crossing lines.
5.2 TRAFFIC CRITERIA

The intersection has two traffic signals. The first signal is used to control the direct flow in the northbound direction, while the second signal controls the shared lane for left- and U-turning flows. The two phases by these signals are protected each other. Both phases are set to fixed time intervals using an optimizer timer.

6. FIELD MEASUREMENTS

Inclusive fieldwork measurements were carried out in this research. The fieldwork included measuring the geometrical data required. Moreover, the field measurements aimed to observe the traffic signal data for the studied intersections. The measured data were used to investigate the current traffic situation of the studied area. Likewise, the data obtained were necessary for the simulation analysis.

6.1 COLLECTED GEOMETRIC DATA

Using a measuring wheel, the geometrical data were directly measured in the field. The geometric characteristics included the longitudinal distances as well as the cross sections. The measured longitudinal distances involved the distances between certain locations, as shown in Table 1. These distances were the adjacent intersections and the suggested location for a new U-turn position. The adjacent northbound intersections are the El-Nasr and El-Salam intersections, as shown in Figure 2. In addition, two alternative northbound spots for the U-turn relocation were observed. According to the video observation, it was found the longest queue length equal 200m. Therefore, the new location of U-turn point was selected 200m far away from the current location. The first suggested location is 200 m from the current spot, whereas the second one is 625 m away, as shown in Table 1.
The measured road cross-sections involve the lane widths for all approaches near the study area. For efficient data, the cross-sections of each approach were measured at different sections along the approach as shown in Tables 2 and Table 3.

**Table 2. The measured widths of different cross sections along Kornich St**

<table>
<thead>
<tr>
<th></th>
<th>Southbound Approach Width (m)</th>
<th>Northbound Approach Width (m)</th>
<th>Median Width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salah El-Deen Int. Upstream</td>
<td>11.40</td>
<td>9.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Salah El-Deen Int. Downstream</td>
<td>9.0</td>
<td>7.0</td>
<td>1.6</td>
</tr>
<tr>
<td>1st suggested location for a new U-turn</td>
<td>14.0</td>
<td>9.20</td>
<td>1.9</td>
</tr>
<tr>
<td>2nd suggested location for a new U-turn</td>
<td>9.25</td>
<td>8.25</td>
<td>1.9</td>
</tr>
</tbody>
</table>

**Table 3. The measured width of different cross sections a long Salah El-Deen St**

<table>
<thead>
<tr>
<th></th>
<th>Width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kornich-Tabya Approach</td>
<td>8.85</td>
</tr>
<tr>
<td>Tabya- Kornich Approach</td>
<td>8.8</td>
</tr>
<tr>
<td>Salah El-Deen St. Median</td>
<td>0.6</td>
</tr>
<tr>
<td>Shared Lane</td>
<td>4.70</td>
</tr>
</tbody>
</table>

### 6.2 COLLECTED TRAFFIC DATA

The traffic control signal data of the studied intersection were collected from manual observations. The two phases of the intersection are protected and do not use control arrows. Both signals are of a fixed time type with only red and green phases. The absence of amber and all-red time phases was observed. Hence, the signals change directly from green to red. Two separated optimizer timers control the signals automatically. The phase times and total cycle time were recorded, as shown in Table 4. As revealed in the field observation, the red time is directly followed by the green time for the other signal. Thus, the intersection does not allow any time for traffic flow clearance. Thus, there is no clearance time for either vehicles or pedestrians. As a result, points of conflict are generated for the studied approaches, and the start-up time is increased.

**Table 4. The current signals phase’s time of Salah El-Deen intersection**

<table>
<thead>
<tr>
<th></th>
<th>Green time (s)</th>
<th>Red time (s)</th>
<th>Amber time (s)</th>
<th>All-red time (s)</th>
<th>Total cycle time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct approach signal</td>
<td>33</td>
<td>29</td>
<td>0</td>
<td>0</td>
<td>62</td>
</tr>
<tr>
<td>Shared lane signal</td>
<td>29</td>
<td>33</td>
<td>0</td>
<td>0</td>
<td>62</td>
</tr>
</tbody>
</table>
7. VIDEO OBSERVATIONS

For efficient data collection, a total of over 24-hours of video sequences for the studied intersection were recorded. A portable video camera was used to record the required data. The video camera was set up on the fourth floor of an adjacent building to achieve an adequate viewing height. The building is located 130 m away from the intersection. The weather during the entire observation time was sunny and dry. The temperature recorded was 43 to 45 °C during the daytime, and 24 to 26 °C during the night. Hence, the pavement was dry and had no traffic obstacles.

The data recorded included the traffic flow rate, capacity, and directional ratio for each approach. In addition, the traffic composition of each turning movement from the different approaches was obtained. The SFRs and queue lengths for the northbound direction, as well as the shared lane, were directly estimated from the video sequences.

Later, the recorded video sequences were reviewed in a lab to obtain precise indices. For a sufficient amount of unbiased data, the observational periods were both daytime and night. The video sequences were recorded during two different periods. The first period was during peak hours, whereas the second was during non-peak hours. Because of the hot weather, rush hour occurred during the night. Likewise, the rush hour peaks occurred on Thursday and Friday nights. Based on the observations, the peak hours were from 20:00 to 1:00. In addition, other peaks were observed between 13:00 and 15:00 when employees left their work locations.

8. VIDEO ANALYSIS

For efficient and precise data, recorded video was reviewed three times. Video editor software, Wondershare Video Editor, was used to obtain the acquired data. The following information was gathered: the traffic volume, traffic composition, and traffic movements. In addition, the time headways, queue discharge data, and direction ratios were obtained. The video reviewing process aimed to answer the research questions proposed. Hence, the factors affecting the performance of the studied signalized intersection were extracted. Moreover, the impacts of U-turns on the capacity of a signalized intersection were investigated. The following parameters were analysed to evaluate the studied intersection.

8.1 Traffic Movements

The traffic system in Egypt follows right-side driving rules. In addition, a right-turn flow has no obligation to follow the signal, whereas a left-turn flow follows the controlled traffic signals. The traffic movements observed can be divided into three main flows as shown in Figure 1. The northbound approach flow includes two types of movements, i.e., direct flows controlled by a protected signal, and free-right flows. For the direct flows, the green and red times were 33 and 29 s, respectively, as shown in Table 4. The right turning flows are free from the control signal. Thus, vehicles can turn right at all times during both green and red signals. As a result, right-turning vehicles cause diverging points of conflict with the following vehicles. Furthermore, the left-turning flows coming from the northern direction face obstructions from these free-right turning flows. Therefore, the average total delay and travel time increase for the left-turning vehicles.

The second flow is for the southbound approach of the studied signal. This approach involves three directional flows: direct, left-turning, and U-turning flows. There is no control
signal for vehicles travelling in the direct flow. However, a protected signal was set up for the other two flows. As mentioned earlier, left- and U-turning movements are both involved with this approach. The two types of flows are controlled by a fixed-time protected signal. This stream approach was considered to be a secondary approach. Therefore, according to the observations, the green and red times were 29 and 33 s, respectively, as shown in Table 4.

The third observed flow was for free-right turning vehicles travelling from the westbound Tabya Kornich approach toward Kornich El-Nile Road. This intersecting approach is also a free flow, and the vehicles can only turn right directly without constraints. Crossing priority is given to the direct flow approach. However, vehicles travelling in this direction cause a delay in the U-turning vehicles during the green period of the shared lane. As a result, merging points of conflict with the U-turning vehicles have occurred.

8.2 Traffic Directional Ratios

The directional ratios were obtained based on the traffic counting technique. For accurate and precise results, the recorded video sequences were reviewed three times. Each time, the crossed vehicles were counted for certain approaches, i.e., the northbound and southbound approaches. Finally, a cumulative analysis was conducted separately for each direction.

The directional ratios were found based on the analysed data, as shown in Figures 3 and 4. For the northbound flows, it was found that 84% of a flow is controlled into the direct flows by the signal, whereas the free-right turn flows made up 16% of the total northbound travelling flows, and the operational ratios of the southbound flows were 66%, 27%, and 7% for the direct, left-turning, and U-turning flows, respectively.

![Traffic Directional Ratios](figures/3.png) ![Traffic Directional Ratios](figures/4.png)

Figures 3 and 4. The traffic directional traffic ratios of northbound and southbound approaches

8.3 Traffic Composition

Depending on their speed, acceleration, and size, the vehicles observed can be distinguished into three categories, each of which is made up of motorized vehicles. Therefore, other types of non-motorized vehicles were eliminated. The three categories are normal vehicles, heavy vehicles, and motorbikes. Normal vehicles included private cars, taxies, and microbuses, whereas heavy vehicles included buses, minibuses, and heavy trucks. Both normal vehicles and motorbikes had an average speed of 60 km/hr, whereas the average speed of the heavy vehicles was 40 km/hr. Therefore, the normal vehicles could accelerate faster than the heavy vehicles. During the video review, the vehicles were distinguished into the above-mentioned categories for each direction. The average traffic composition of the different approaches were found 92% for the normal vehicles, 7% for the motorbikes and 1% for the heavy vehicles as shown in Figures 5.
8.4 Time Headways

For a comprehensive analysis of the queue discharge behaviour, the time headway technique was used. As mentioned earlier, this technique is highly recommended, particularly for the impact of start-up times for different vehicles in the same queue. Furthermore, the differences between different types of vehicles can be directly estimated. In addition, the saturated headways are needed for the SFR estimation. Using Wondershare Video Editor, the headways values of different queues were measured.

Based on the data analysis, the major factors that influence the queue discharge can be summarized as followed. First, the absence of amber and all-red time periods resulted in an increase in the start-up times. According to the data analysis, the average start-up time for the different approaches ranged from 3.0 to 4.0 s. However, it occasionally reached 6 s, particularly for the shared lane signal, as a secondary signal.

Second, as a result of undisciplined drivers and crossing pedestrians, the headway and start-up times were increased. The average headway time ranged between 2.5 and 4.0 s. However, the average saturated headway times were found to be between 1.25 and 1.93s.

Third, the traffic condition of the feeder approach had an adverse impact on the headway and start-up times of the signalized approaches. As a result of on-street parking in the right lane of the feeder approach, rather than from the free-right turning vehicles of the direct approach, the left-turning vehicles were unable to cross the intersection.

Fourth, the headways of the left and U-turning vehicles were adversely affected because the merging created conflicts between the free-right turning vehicles from the feeder approach and the U-turning vehicles.

Fifth, the analysis found that the vehicle types affected the headway and start-up times. It was found that vehicle acceleration and speed affected both the start-up and headway times. The start-up time was increased by 50% when a heavy vehicle started the queue. However, the headway time increased by 30% for those vehicles following a heavy vehicle. On the other hand, motorbikes can manoeuvre better than normal vehicles, and therefore motorbikes had the ability to cross the signalized intersection faster than normal vehicles. Therefore, the start-up time of those queues started by motorbikes decreased to 25% less than that for normal vehicles.
9. SFR ESTIMATION

This study followed the HCM regulations for SFR estimation, and used the headway technique. The headway technique is highly recommended, particularly for mixed traffic conditions. In addition, the impact of start-up times for different queued vehicle types could be efficiently analysed (HCM 2010, 2010).

HCM recommends eliminating the first four queued vehicles to avoid the influence of inertia. Therefore, the saturation headways were estimated by measuring the discharge headway time from the fifth queued vehicle until the last queued vehicle during the green period. However, particularly for the shared-lane signal, the signal time was found to be insufficient for discharging all queued vehicles. As a result, the headways times were measured from the fifth queued vehicle until the last vehicle crossed during the green period. The headway between vehicles could be directly observed when the vehicles crossed the stop line at a certain time. The headway times were measured as the elapsed time between crossings of the front bumper of the fifth vehicle over the stop line until the front bumper of the last queued vehicle. However, as a result of the absence of stop lines, a virtual line was assumed. As the lane marking lines are also absent, the vehicle headway times were measured not based on the lane but based on the approach. The saturated headways were calculated using the timings when the vehicles cross the virtual line.

To obtain the saturated headway time, most of the saturated phases were selected among the recorded video sequences. Although 150 cycles were selected for each signal, 50 cycles were analysed to obtain the values of the saturation headways. Later, a simple regression equation was used to estimate the SFRs. The discharge time for each two successive vehicles to cross the virtual line was estimated. As the average saturation headway for the direct approach, i.e., the northbound approach was found to be 1.56 s, whereas the average saturation headway recorded for the shared lane was 1.8 s.

Using MS Excel, a simple regression equation was estimated to forecast the SFR. The vehicles-time curves were plotted. The vertical axis represents the number of vehicles, whereas the horizontal axis represents the elapsed time from the beginning of signal green. The saturation flow rates for each selected phase were extrapolated using a linear regression equation. The regression results revealed an SFR of 0.7836 veh/s for the direct flow signal. However, the SFR for the shared lane signal was 0.5094 veh/s. The outcomes showed that the SFR for the direct approach of the direct flow signal was 2,800 veh/hr/approach. However, the SFR for the shared-lane approach was recorded as 1,882 veh/hr/ln.

![Figure 6. The estimated SFR of the northbound direct flows](image1)

![Figure 7. The estimated SFR of the southbound shared lane flows](image2)
10. SIGNAL TIMING EVALUATION

In this part, the fixed times of the two signals for the studied intersection are evaluated. This evaluation is based on determining the total cycle time and the green time for each signal. Depending on a comparison of the theoretical and observed values, the signal performances could be evaluated. First, the theoretical values for both the cycle and green times were calculated based on the data obtained. Later, a comparison was conducted to assess the signals used.

Based on Webster’s (1966) method, the total cycle and green times of the fixed time signals were determined (Indonesian Highway Capacity Manual, Part 1 Urban Roads, Urban And Semi-Urban Traffic Facilities 1993). This method mainly aims to minimize the overall delay for the vehicles inside the intersection. According to Webster’s method, the cycle time \( C \) is determined first as shown in Equation 1. Then, the green time of each phase \( g_i \) is obtained. The theoretical total cycle time and green time of each phase of the studied intersection were calculated:

10.1 SIGNAL CYCLE TIME ESTIMATION

According to Webster’s method, the total cycle time could be calculated through the following:

\[
C = \frac{(1.5 \times LTI + 5)}{(1 - \sum FR_{crit})}
\]

where,

\( C \) is the signal cycle time (s)

\( LTI \) is the lost time per cycle (s)

\( FR \) is the ratio of flow to saturation flow (Q/S)

\( FR_{crit} \) is the maximum value of \( FR \) value among the signal group for the same stage in the approaches being discharged during a signal phase

\( \sum (FR_{crit}) \) is the summation of \( FR_{crit} \) for all phases in the cycle

These parameters were estimated according to the data obtained from the observations and analyses conducted, as shown in Table 5:

| Table 5. The traffic parameters of both northbound direct and shared-lane flow signals of the studied intersection |
|---------------------------------|-----------------|-----------------|
| Flow (Q)           | veh/hr         | 1048            | 724             |
| Saturation Flow rate | veh/hr       | 2800            | 1882            |
| FR (Q/S)           |                | 0.37            | 0.38            |
| Lost time                  | s              | 5               | 5               |

Substation in equation (1) we have

\[
C_0 = \frac{(1.5 \times 10 + 5)}{(1 - 0.37 - 0.38)} = 82 \text{ s}
\]

10.2 GREEN TIME CALCULATION

\[
g_i = \frac{(C - LTI) \times FR_{crit}}{(\sum FR_{crit})}
\]
where,
\[ g_i = \text{displayed green time in phase } i \ (s) \]

Substation in equation (2) we have
\[ g_i \ (\text{shared lane signal}) = (82 - 10) \times 0.38 / (0.37 + 0.38) = 36.48 \text{ s} \]
\[ g_i \ (\text{direct flow signal}) = (82 - 10) \times 0.37 / (0.37 + 0.38) = 35.52 \text{ s} \]

Based on the results obtained, it was clearly found that the current signal times were not sufficient for the traffic demand. As a result, the signals’ times should be adaptive with the current traffic demand. In addition, for increasing the signals’ performance, both amber time and all red time should be applicable. Despite its shortness, those seconds - amber and all red time- are strongly needed for intersection flow clearness. The traffic parameters of both direct and shared lane flow signals for Salah El-Deen intersection are shown in Table 4, while the suggested changes of each signal time controller are presented in Table 6.

Table 6. The suggested changes of each signal time controller of the studied intersection

<table>
<thead>
<tr>
<th></th>
<th>Red phase (s)</th>
<th>Green phase (s)</th>
<th>All Red Time (s)</th>
<th>Amber phase (s)</th>
<th>Total cycle time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct approach signal</td>
<td>42</td>
<td>34</td>
<td>3</td>
<td>3</td>
<td>82</td>
</tr>
<tr>
<td>Shared lane signal</td>
<td>40</td>
<td>36</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

11. STRATEGY IMPLEMENTATION

The proposed strategies, i.e., the segregation of the U-turning flow from the shared lane, were drawn up based on the research hypothesis. However, the new U-turning flow is a free flow without any control signal. The location of the new U-turn lane was selected to be 200 m away from the most recent location. This new location selected is further than the length of the longest queue observed. In addition, in terms of the geometric characteristics, the widths of the approaches for the new location are wider than the current location. The widths are 14.0 and 9.20 m for the northbound and the southbound approaches respectively as shown in Table 2.

The strategies were applied with the aim of improving the performance level of the studied intersection. The proposals sought a decrease in the average travel time, i.e., a reduction in the overall delay through the intersection. In addition, they aimed to decrease the queue lengths as well as to improve the overall safety conditions near the studied area. A decline in the queue lengths, particularly for the shared-lane queues, would result in an improvement in the bottleneck areas. The proposed strategies also endeavour to equalize the quality of services for all traffic streams of the studied intersection.

The proposed solutions were provided based on the control of the traffic flows. The flow control includes setting new traffic signals and modifying the recent controller times. In addition, the solutions involved organizing the current flow rather than the traffic flow priorities. All applied strategies aimed to maximize the efficiency in the green time. Therefore, a right turn to the eastbound approach was prevented during the green time of the left-turn signal. With the aim of improving the overall safety conditions rather than decreasing the start-up time, amber and all-red times were added by all the strategies proposed. For each strategy, the simulation was carried out 20 times for proving the confidence interval. The queue lengths, average overall delay, average total travel time and the total number of
travelling vehicles were measured for each trial of the simulation. Moreover, because the performance of both SIU and non-signal U-turn lane may depend on the opposite traffic volume, the northbound flow priorities was considered.

11.1 Strategy 1

This strategy mainly depends on three main control aspects. First, the U-turning flow was separated from the shared lane. The flow of the new U-turn lane is free of traffic signals as shown in Figure 8. Priority was given to the U-turning flow over the direct flow of the northbound approach. Second, a right-turning flow of the northbound approach to the eastbound approach was prevented during the green time of the left-turning signal. As a result, the flow rate of the left-turning flow was maximized. Third, during the green time of the direct flow signal, priority was given to the direct flow of the northbound approach over the right-turning flow from the westbound approach. Lastly, the traffic signal controllers were reset, however, the signal controllers were still setup as a fixed time controller. Additionally, 3 s of amber time and 3 s of all-red time were added.

11.2 Strategy 2

The second strategy was developed based on the proposed principles of the first strategy. However, the priority of the U-turning flow of the new U-turn lane was changed. This strategy gives the priority to the direct flow of the northbound approach as shown in Figure 8.

11.3 Strategy 3

Similarly, the third strategy followed the same control principles of the first and the second strategies. Priority was still given to the direct flow of the northbound approach throughout the new U-turn lane. However, according to the observations, points of merging conflicts frequently occurred because of the free-right turning flow of the westbound direction. Hence, a new signal was installed to control the westbound traffic flow as shown in Figure 9. This new signal works as the same signal group, i.e., SG2 of the left-turning signal, as shown in Table 6. Unlike the old signal, both of the new signals are a fixed-time signal.

Figure 8. The fundamental schemes of the first and the second strategies
11.4 Strategy 4

The fourth strategy was built by pursuing the same priority rules as the third strategy. However, the traffic signal times were reset depending on the calculated signal time cycle. The total cycle time was fixed at 82 s. Consequently, the green time phases were also changed. For the first signal group, SG1, the red and green times were 42 and 34 s, respectively. However, for the second signal group, SG2, the red and green times were 40 and 36 s, respectively. The total cycle time was readjusted instead of the green time periods, as shown in Table 6.

![Figure 9. The fundamental schemes of the third and the fourth strategies](image-url)

12. RESULTS AND DISCUSSION

To evaluate the efficiency of each simulated model, the queue lengths, average overall delay, average total travel time, and the total numbers of vehicles travelled were measured. The results enhanced the research hypothesis, which is whether the segregation of U-turns from the shared lane improves the performance of an SIU. The output data emphasized the improvement of the SIU performance as a result of segregating the U-turn lane from the current location.

The queue lengths of the shared lane flow decreased significantly. The results showed shared-lane queue lengths of 166 m for the current situation. However, queue lengths of 105, 82, 86 and 110 m for the first, second, third and fourth strategies were recorded, respectively. As is clearly shown, the shared-lane queues lane were shortened by 46.89%, 29.19%, 58.85% and 47.36% for the first, second, third and fourth strategies, respectively. However, the total queue lengths for the direct flow of the northbound approach were increased. Preventing the right turning flow of the northbound right during the eastbound green time resulted in this obvious increase. The current situation had a queue length of 125 m. However, the results showed 155, 151, 151 and 152 m for the queue lengths for the first, second, third and fourth strategies respectively as shown in Figure 10. The cumulative results indicated to the significant reduction of the queues lengths for the applied strategies, as shown in Figure 11.
Similarly, the results pointed to a decrease in the average total delay time per vehicle for the applied strategies as compared with the current situation. The average total delay time for the current situation is 13.0 s per vehicle. However, it reduces to 11.9, 11.1, 10.5 and 10.8 s per vehicle for the first, second, third and fourth strategies respectively. The overall delay time was clearly decreased by 8.46 %, 14.62 %, 19.23 % and 16.92 % for the first, second, third and fourth strategies, respectively, as shown in Figure 12. The third strategy could provide the lowest overall delay value as shown in Figure 12.

The traffic volume was measured to estimate the capacity of the intersection. According to the simulation, the traffic volume is clearly increased for the SIU flows. The results showed a significant increase in the direct flow of southbound and the left- and U-turning flows. The increasing rates were considered a reasonable indication of the improvement in intersection capacity. However, the direct flows of northbound have experienced a reduction in the traffic volumes among the different proposed strategies.

The traffic volumes of the direct flows of southbound were increased by 8.02 %, 6.01 %, 6.01 % and 3.34 % for the first, third and fourth strategies, respectively. On other hand, the traffic volumes of the left-turning flow increased by 8.33 %, 1.11 % for the first and fourth

Figure 10. The queues lengths for the northbound direct flows and the southbound shared-lane flows for the current situation and the suggested strategies

Figure 11. The cumulative queues lengths for the current situation and the suggested strategies

Figure 12. The overall delay time per vehicle per hour of the northbound direct flows and the southbound shared lane flows for the current situation and the suggested strategies
strategies, respectively. However, left-turning traffic volume was decreased by 6.11% for the second strategy, while there was no changes occurred for the third strategy.

Similarly, the proposed strategies resulted in an increase in the U-turning traffic volume. According to the simulation results, the traffic volume was increased by 30.78 % and 46.51 %, 51.16 % and 51.16 % for the first, second, third and fourth strategies, respectively. However, the traffic volume of the northbound direct flow was decreased for the suggested strategies. The simulation results point to a reduction in the traffic volumes of 33.83 %, 18.63 %, 10.42 % and 17.52 % for the first, second, third and fourth strategies, respectively as shown in Figure 13. In addition, the average number of stops per vehicle for both the direct northbound and the shared lane approach was also decreased as another indicator of the improvement in the traffic situation. The results indicate to decreases of 15 %, 22.5 %, 17.5 % and 20.0 % for the first, second, third and fourth strategies, respectively. In general, the cumulative traffic volumes were improved as shown in figure 14. The optimum traffic volume was occurred in the third strategy.

![Traffic Volume](image1)

**Figure 13.** The average traffic volumes for the northbound direct flows and the southbound shared-lane flows of the current situation and the suggested strategies

![Cumulative Traffic Volume](image2)

**Figure 14.** The cumulative traffic volumes of the current situation and the suggested strategies

On the other hand, the average total travel time of the southbound direct and U-turning flows was decreased for all of the suggested strategies. First, for the direct flow of the southbound, the results showed that the average total travel time was decreased by 13.3%, 13.33%, 11.67% and 21.11% for the first, second, third and fourth strategies, respectively.

Second, the results pointed to the obvious decrease of the U-turning flow travel time after the segregation of the current shared lane. The outputs showed a significant reduction of 61.44%, 16.87%, 20.88% and 36.44% for the first, second, third and fourth strategies, respectively.

Finally, the results also showed a significant decrease in the average total travel time for the left-turning flow. The average travel time was decreased by 3.37%, 7.02%, 9.27% and 7.87% for the first, second, third and fourth strategies, respectively.
However, the average total travel time of the northbound flows was increased. The results indicated a significant growth of 107.45%, 73.57%, 47.14% and 60.47% for the first, second, third and fourth strategies, respectively as shown in Figure 15. Based on the cumulative results for the whole directions, the shortest total travel time could be achieved through the third strategy, as shown in figure 16.

Figure 15. The average total travel time of the different flows for the current situation and the suggested strategies

Figure 16. The cumulative total travel time for the current situation and the suggested strategies

Based on the illustrated results, it could be observed that the third strategy could provide the optimum results. The queues lengths, overall delay, traffic volumes and the total travel time could be improved through applying the third strategy, as shown in Figures 11, 12, 14 and 16.

13. CONCLUSION

The present study showed that there are certain adverse effects from U-turns on the SIU performance. The U-turning flows decrease the performance and capacity of a signalized intersection. In addition, these impacts are extended to all traffic flows near an SIU. As a result, both bottleneck areas and conflicts areas are clearly formed near this type of intersection. The simulated alternatives implemented emphasized that the segregation of U-turns from an SIU clearly increase the performance. The segregation of the U-turning flow from the shared lane resulted in an increase in the intersection capacity. As estimated indexes, decreases in the queue lengths, average delay time and average total travel times of the left- and U-turning flows were significantly observed for all of the proposed strategies. As a result, the bottleneck areas near the intersection were clearly decreased. On the other hand, however, the average queue lengths were increased for the direct northbound direction flows as a result of adjusting the signal time as well as preventing of the right free flows. Nevertheless, as the intersection capacity is clearly increased and the average delay time for the overall SIU flows
is significantly decreased, the proposed strategy would improve the performance of the intersection.

14. RESEARCH RECOMMENDATIONS

This study strongly emphasizes the segregation of U-turns from a signalized intersection. In addition, the traffic control signal times need to be readjusted based on an analysis of the traffic demand. The adjusted cycle times should include amber times and all-red times for all phases. As a result, the queued vehicles can be completely discharged before the beginning of the other phase. This study also emphasized the necessity of preventing free-right flows of the main streams during the green times of the intersecting flows. Therefore, the capacities of the feeder approach can be significantly increased, particularly during the green times of the studied flows.

REFERENCES


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